

1 Introduction: The Wireless Communication Channel

'I think the primary function of radio is that people want company.'

Elise Nordling

1.1 INTRODUCTION

Figure 1.1 shows a few of the many interactions between electromagnetic waves, the antennas which launch and receive them and the environment through which they propagate. All of these effects must be accounted for, in order to understand and analyse the performance of wireless communication systems. This chapter sets these effects in context by first introducing the concept of the wireless communication *channel*, which includes all of the antenna and propagation effects within it. Some systems which utilise this channel are then described, in order to give an appreciation of how they are affected by, and take advantage of, the effects within the channel.

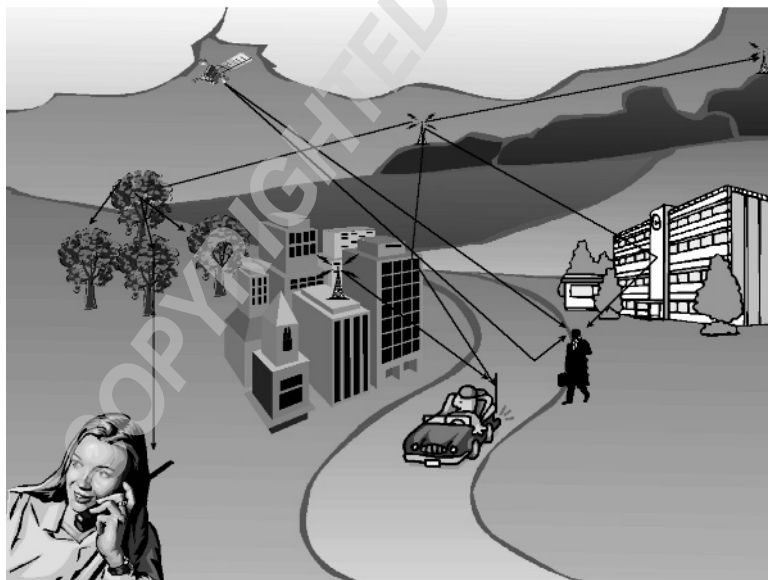


Figure 1.1: The wireless propagation landscape

1.2 CONCEPT OF A WIRELESS CHANNEL

An understanding of the wireless channel is an essential part of the understanding of the operation, design and analysis of any wireless system, whether it be for cellular mobile phones, for radio paging or for mobile satellite systems. But what exactly is meant by a *channel*?

The architecture of a generic communication system is illustrated in Figure 1.2. This was originally described by Claude Shannon of Bell Laboratories in his classic 1948 paper

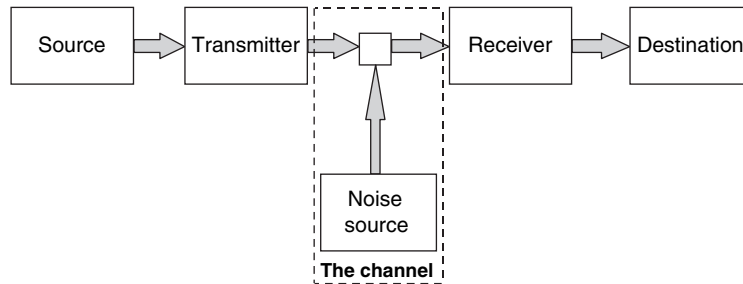


Figure 1.2: Architecture of a generic communication system

‘*A Mathematical Theory of Communication*’ [Shannon, 48]. An information source (e.g. a person speaking, a video camera or a computer sending data) attempts to send information to a destination (a person listening, a video monitor or a computer receiving data). The data is converted into a signal suitable for sending by the transmitter and is then sent through the channel. The channel itself modifies the signal in ways which may be more or less unpredictable to the receiver, so the receiver must be designed to overcome these modifications and hence to deliver the information to its final destination with as few errors or distortions as possible.

This representation applies to all types of communication system, whether wireless or otherwise. In the wireless channel specifically, the noise sources can be subdivided into multiplicative and additive effects, as shown in Figure 1.3. The additive noise arises from the noise generated within the receiver itself, such as thermal and shot noise in passive and active components and also from external sources such as atmospheric effects, cosmic radiation and interference from other transmitters and electrical appliances. Some of these interferences may be intentionally introduced, but must be carefully controlled, such as when channels are reused in order to maximise the capacity of a cellular radio system.

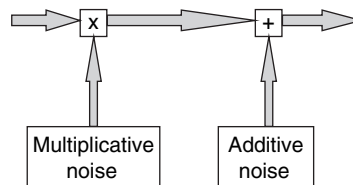


Figure 1.3: Two types of noise in the wireless communication channel

The multiplicative noise arises from the various processes encountered by transmitted waves on their way from the transmitter antenna to the receiver antenna. Here are some of them:

- The directional characteristics of both the transmitter and receiver antennas;
- reflection (from the smooth surfaces of walls and hills);
- absorption (by walls, trees and by the atmosphere);
- scattering (from rough surfaces such as the sea, rough ground and the leaves and branches of trees);
- diffraction (from edges, such as building rooftops and hilltops);
- refraction (due to atmospheric layers and layered or graded materials).

It is conventional to further subdivide the multiplicative processes in the channel into three types of fading: *path loss*, *shadowing* (or *slow fading*) and *fast fading* (or *multipath fading*), which appear as time-varying processes between the antennas, as shown in Figure 1.4. All of these processes vary as the relative positions of the transmitter and receiver change and as any contributing objects or materials between the antennas are moved.

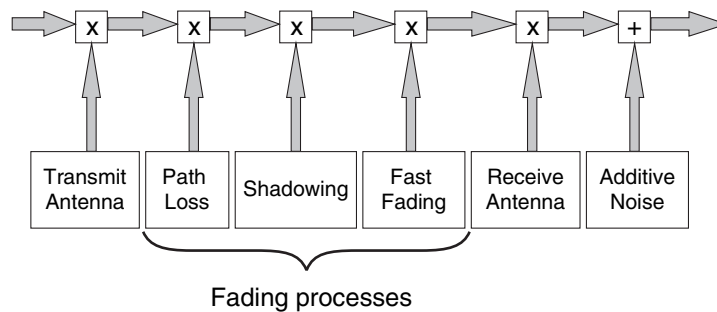


Figure 1.4: Contributions to noise in the wireless channel

An example of the three fading processes is illustrated in Figure 1.5, which shows a simulated, but nevertheless realistic, signal received by a mobile receiver moving away from a transmitting base station. The path loss leads to an overall decrease in signal strength as the distance between the transmitter and the receiver increases. The physical processes which cause it are the outward spreading of waves from the transmit antenna and the obstructing effects of trees, buildings and hills. A typical system may involve variations in path loss of around 150 dB over its designed coverage area. Superimposed on the path loss is the shadowing, which changes more rapidly, with significant variations over distances of hundreds of metres and generally involving variations up to around 20 dB. Shadowing arises due to the varying nature of the particular obstructions between the base and the mobile, such as particular tall buildings or dense woods. Fast fading involves variations on the scale of a half-wavelength (50 cm at 300 MHz, 17 cm at 900 MHz) and frequently introduces variations as large as 35–40 dB. It results from the constructive and destructive interference between multiple waves reaching the mobile from the base station.

Each of these variations will be examined in depth in the chapters to come, within the context of both fixed and mobile systems. The path loss will be described in basic concept in

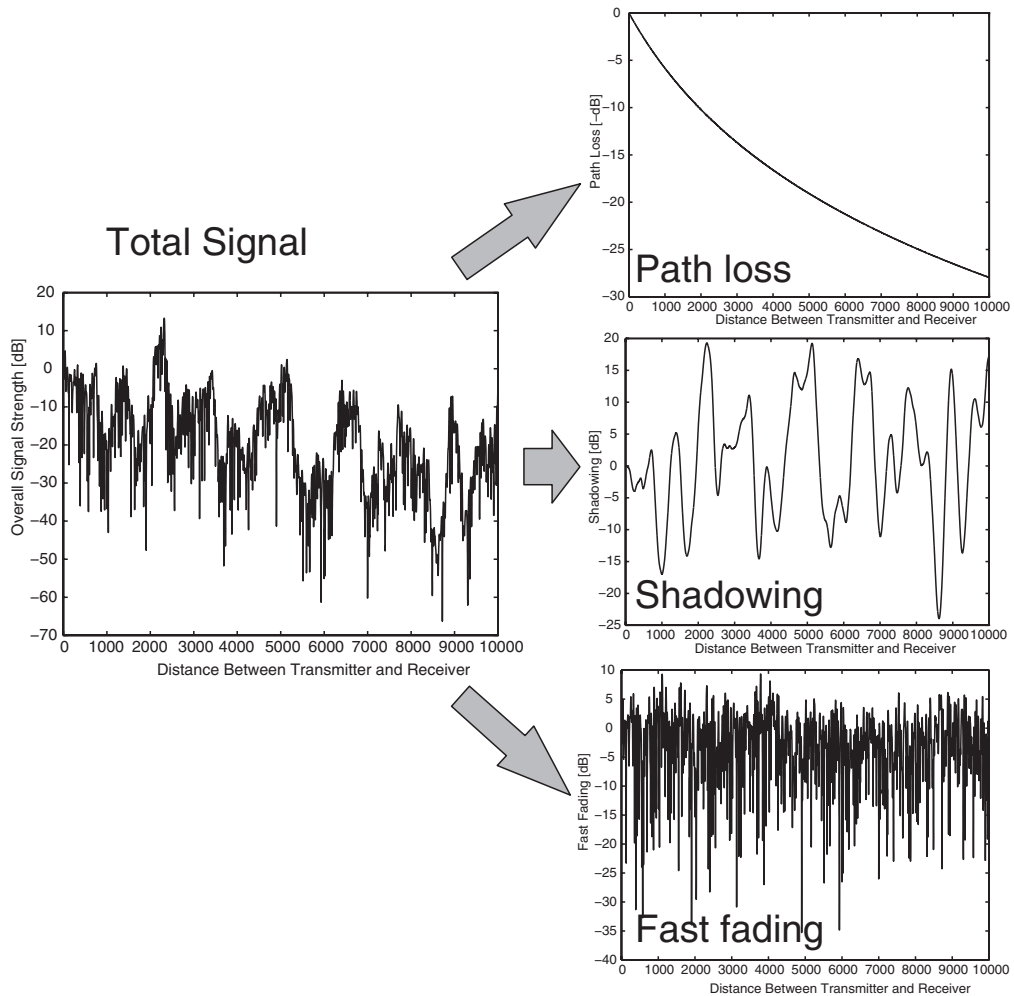


Figure 1.5: The three scales of mobile signal variation

Chapter 5 and examined in detail in Chapters 6, 7 and 8 in the context of fixed terrestrial links, fixed satellite links and terrestrial macrocell mobile links, respectively. Shadowing will be examined in Chapter 9, while fast fading comes in two varieties, narrowband and wideband, investigated in Chapters 10 and 11, respectively.

1.3 THE ELECTROMAGNETIC SPECTRUM

The basic resource exploited in wireless communication systems is the electromagnetic spectrum, illustrated in Figure 1.6. Practical radio communication takes place at frequencies from around 3 kHz [kilohertz] to 300 GHz [gigahertz], which corresponds to wavelengths in free space from 100 km to 1 mm.

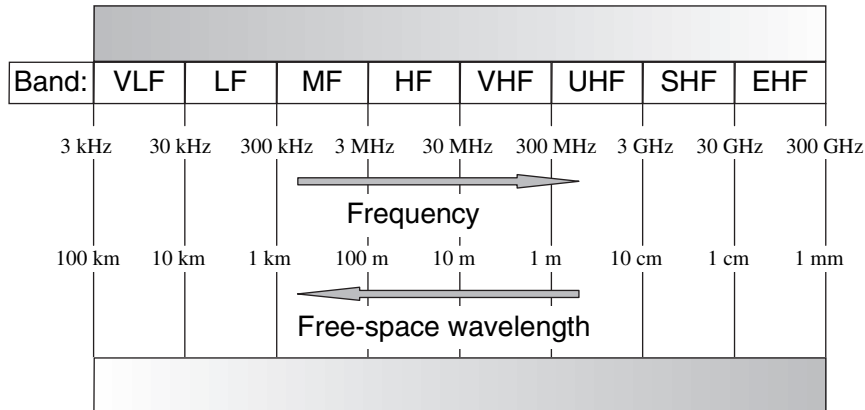


Figure 1.6: The electromagnetic spectrum

Table 1.1 defines two conventional ways of dividing the spectrum into frequency bands.

The frequencies chosen for new systems have tended to increase over the years as the demand for wireless communication has increased; this is because enormous bandwidths are available at the higher frequencies. This shift has created challenges in the technology needed to support reliable communications, but it does have the advantage that antenna structures can be smaller in absolute size to support a given level of performance. This book will be concerned only with communication at VHF frequencies and above, where the wavelength is typically small compared with the size of macroscopic obstructions such as hills, buildings and trees. As the size of obstructions relative to a wavelength increases, their obstructing effects also tend to increase, reducing the range for systems operated at higher frequencies.

1.4 HISTORY

Some of the key milestones in the development of wireless communications are listed in Table 1.2. Mobile communication has existed for over a hundred years, but it is only in the last

Table 1.1: Naming conventions for frequency bands

Band name	Frequency range	Band name	Frequency range [GHz]
Very low frequency	3–30 kHz	L band	1–2
Low frequency (long wave)	30–300 kHz	S band	2–4
Medium frequency (medium wave)	0.3–3.0 MHz	C band	4–8
High frequency (short wave)	3–30 MHz	X band	8–12
Very high frequency	30–300 MHz	Ku band	12–18
Ultra high frequency	0.3–3.0 GHz	K band	18–26
Super high frequency (centimetre wave)	3–30 GHz	Ka band	26–40
Extra high frequency (millimetre wave)	30–300 GHz	V band	40–75
		W band	75–111

two decades that the technology has advanced to the point where communication to every location on the Earth's surface has become practical. Communication over fixed links has been practical for rather longer, with terrestrial fixed links routinely providing telephone services since the late 1940s, and satellite links being used for intercontinental communication since the 1960s.

The cellular mobile communications industry has recently been one of the fastest growing industries of all time, with the number of users increasing incredibly rapidly. As well as stimulating financial investment in such systems, this has also given rise to a large number of technical challenges, many of which rely on an in-depth understanding of the characteristics of the wireless channel for their solution. As these techniques develop, different questions

Table 1.2: Key milestones in the development of wireless communication

1873	Maxwell predicts the existence of electromagnetic waves
1888	Hertz demonstrates radio waves
1895	Marconi sends first wireless signals a distance of over a mile
1897	Marconi demonstrates mobile wireless communication to ships
1898	Marconi experiments with a land 'mobile' system – the apparatus is the size of a bus with a 7 m antenna
1916	The British Navy uses Marconi's wireless apparatus in the Battle of Jutland to track and engage the enemy fleet
1924	US police first use mobile communications
1927	First commercial phone service between London and New York is established using long wave radio
1945	Arthur C. Clarke proposes geostationary communication satellites
1957	Soviet Union launches Sputnik 1 communication satellite
1962	The world's first active communications satellite 'Telstar' is launched
1969	Bell Laboratories in the US invent the cellular concept
1978	The world's first cellular phone system is installed in Chicago
1979	NTT cellular system (Japan)
1988	JTACS cellular system (Japan)
1981	NMT (Scandinavia)
1983	AMPS cellular frequencies allocated (US)
1985	TACS (Europe)
1991	USDC (US)
1991	GSM cellular system deployed (Europe)
1993	DECT & DCS launched (Europe)
1993	Nokia engineering student Riku Pihkonen sends the world's first SMS text message
1993	PHS cordless system (Japan)
1995	IS95 CDMA (US)
1998	Iridium global satellite system launched
1999	Bluetooth short-range wireless data standard agreed
1999	GPRS launched to provide fast data communication capabilities (Europe)
2000	UK government runs the world's most lucrative spectrum auction as bandwidth for 3G networks is licensed for £22.5 billion
2001	First third-generation cellular mobile network is deployed (Japan)
2002	Private WLAN networks are becoming more popular (US)
2003	WCDMA third-generation cellular mobile systems deployed (Europe)
2004	First mobile phone viruses found
2006	GSM subscriptions reach two billion worldwide. The second billion took just 30 months.

concerning the channel behaviour are asked, ensuring continuous research and development in this field.

Chapter 20 contains some predictions relating to the future of antennas and propagation. For a broader insight into the future development of wireless communications in general, see [Webb, 07].

1.5 SYSTEM TYPES

Figure 1.7 shows the six types of wireless communication system which are specifically treated in this book. The principles covered will also apply to many other types of system.

- *Satellite fixed links (chapter 7)*: These are typically created between fixed earth stations with large dish antennas and geostationary earth-orbiting satellites. The propagation effects are largely due to the Earth's atmosphere, including meteorological effects such as rain. Usually operated in the SHF and EHF bands.
- *Terrestrial fixed links (chapter 6)*: Used for creating high data rate links between points on the Earth, for services such as telephone and data networks, plus interconnections between base stations in cellular systems. Also used for covering wide areas in urban and suburban environments for telephone and data services to residential and commercial buildings. Meteorological effects are again significant, together with the obstructing effects of hills, trees and buildings. Frequencies from VHF through to EHF are common.
- *Megacells (chapter 14)*: These are provided by satellite systems (or by high-altitude platforms such as stratospheric balloons) to mobile users, allowing coverage of very wide areas with reasonably low user densities. A single satellite in a low earth orbit would typically cover a region of 1000 km in diameter. The propagation effects are dominated by objects close to the user, but atmospheric effects also play a role at higher frequencies. Most systems operate at L and S bands to provide voice and low-rate data services, but

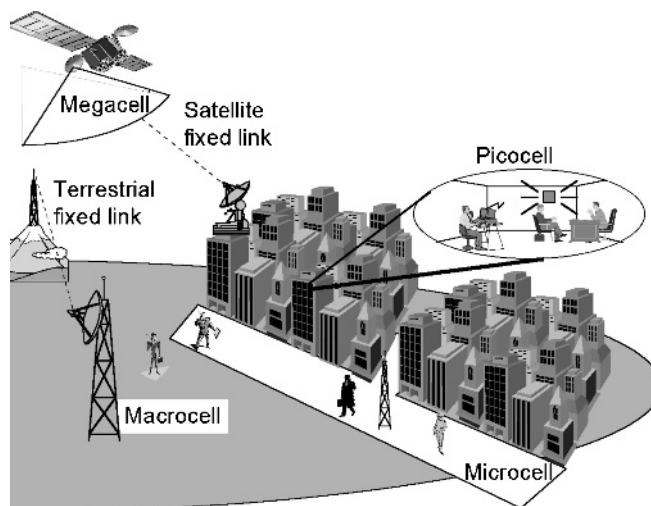


Figure 1.7: Wireless communication system types

systems operating as high as Ka band can be deployed to provide Internet access at high data rates over limited areas.

- *Macrocells (chapter 8)*: Designed to provide mobile and broadcast services (including both voice and data), particularly outdoors, to rural, suburban and urban environments with medium traffic densities. Base station antenna heights are greater than the surrounding buildings, providing a cell radius from around 1 km to many tens of kilometres. Mostly operated at VHF and UHF. May also be used to provide fixed broadband access to buildings at high data rates, typically at UHF and low SHF frequencies.
- *Microcells (chapter 12)*: Designed for high traffic densities in urban and suburban areas to users both outdoors and within buildings. Base station antennas are lower than nearby building rooftops, so coverage area is defined by street layout. Cell length up to around 500 m. Again mostly operated at VHF and UHF, but services as high as 60 GHz have been studied.
- *Picocells (chapter 13)*: Very high traffic density or high data rate applications in indoor environments. Users may be both mobile and fixed; fixed users are exemplified by wireless local area networks between computers. Coverage is defined by the shape and characteristics of rooms, and service quality is dictated by the presence of furniture and people.

Used together, these six system types provide networks capable of delivering an enormous range of service to locations anywhere on the Earth.

1.6 AIMS OF CELLULAR SYSTEMS

The complexity of systems that allow wide area coverage, particularly cellular systems, influences the parameters of the channel which have the most significance. These systems have three key aims:

- *Coverage and mobility*: The system must be available at all locations where users wish to use it. In the early development of a new system, this implies outdoor coverage over a wide area. As the system is developed and users become more demanding, the *depth of coverage* must be extended to include increasing numbers of indoor locations. In order to operate with a single device between different systems, the systems must provide *mobility* with respect to the allocation of resources and support of interworking between different standards.
- *Capacity*: As the number of users in a mobile system grows, the demands placed on the resources available from the allocated spectrum grow proportionately. These demands are exacerbated by increasing use of high data rate services. This necessitates the assignment of increasing numbers of channels and thus dense reuse of channels between cells in order to minimise problems with *blocked* or *dropped* calls. If a call is blocked, users are refused access to the network because there are no available channels. If a call is dropped, it may be interrupted because the user moves into a cell with no free channels. Dropped calls can also arise from inadequate coverage.
- *Quality*: In a mature network, the emphasis is on ensuring that the services provided to the users are of high quality – this includes the perceived speech quality in a voice system and the bit error rate (BER), throughput, latency and jitter in a data system.

Subsequent chapters will show that path loss and shadowing dominate in establishing good coverage and capacity, while quality is particularly determined by the fast-fading effects.

1.7 CELLULAR NETWORKS

Figure 1.8 shows the key elements of a standard cellular network. The terminology used is taken from GSM, the digital cellular standard originating in Europe, but a similar set of elements exists in many systems. The central hub of the network is the mobile switching centre (MSC), often simply called the *switch*. This provides connection between the cellular network and the public switched telephone network (PSTN) and also between cellular subscribers. Details of the subscribers for whom this network is the home network are held on a database called the home location register (HLR), whereas the details of subscribers who

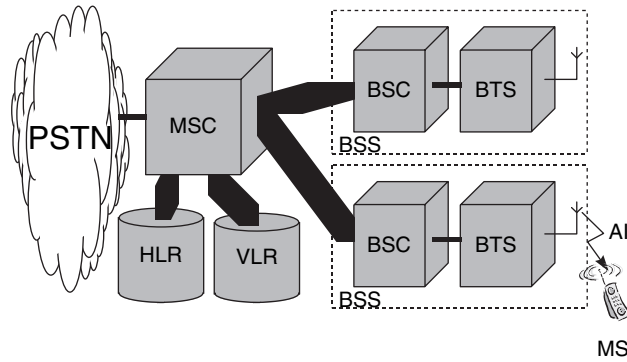


Figure 1.8: Elements of a standard cellular system, using GSM terminology

have entered the network from elsewhere are on the visitor location register (VLR). These details include authentication and billing details, plus the current location and status of the subscriber. The coverage area of the network is handled by a large number of base stations. The base station subsystem (BSS) is composed of a base station controller (BSC) which handles the logical functionality, plus one or several base transceiver stations (BTS) which contain the actual RF and baseband parts of the BSS. The BTSs communicate over the air interface (AI) with the mobile stations (MS). The AI includes all of the channel effects as well as the modulation, demodulation and channel allocation procedures within the MS and BTS. A single BSS may handle 50 calls, and an MSC may handle some 100 BSSs.

1.8 THE CELLULAR CONCEPT

Each BTS, generically known as a base station (BS), must be designed to cover, as completely as possible, a designated area or *cell* (Figure 1.9). The power loss involved in transmission between the base and the mobile is the *path loss* and depends particularly on antenna height, carrier frequency and distance. A very approximate model of the path loss is given by

$$\frac{P_R}{P_T} = \frac{1}{L} = k \frac{h_m h_b^2}{r^4 f^2} \quad (1.1)$$

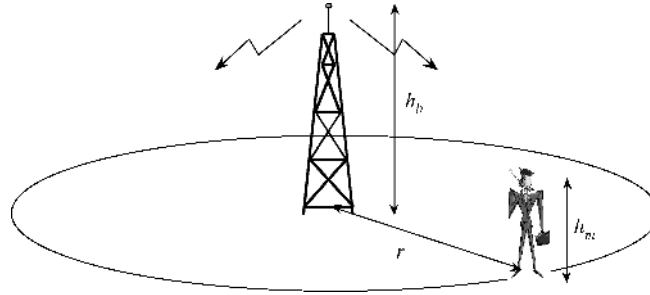


Figure 1.9: Basic geometry of cell coverage

where P_R is the power received at the mobile input terminals [W]; P_T is the base station transmit power [W]; h_m and h_b are the mobile and base station antenna heights, respectively [m]; r is the horizontal distance between the base station and the mobile [m]; f is the carrier frequency [Hz] and k is some constant of proportionality. The quantity L is the path loss and depends mainly on the characteristics of the path between the base station and the mobile rather than on the equipment in the system. The precise dependencies are functions of the environment type (urban, rural, etc.) At higher frequencies the range for a given path loss is reduced, so more cells are required to cover a given area. To increase the cell radius for a given transmit power, the key variable under the designer's control is the antenna height: this must be large enough to clear surrounding clutter (trees, buildings, etc.), but not so high as to cause excessive interference to distant co-channel cells. It must also be chosen with due regard for the environment and local planning regulations. Natural terrain features and buildings can be used to increase the effective antenna height to increase coverage or to control the limits of coverage by acting as shielding obstructions.

When multiple cells and multiple users are served by a system, the system designer must allocate the available channels (which may be frequencies, time slots or other separable resources) to the cells in such a way as to minimise the interaction between the cells. One approach would be to allocate completely distinct channels to every cell, but this would limit the total number of cells possible in a system according to the spectrum which the designer has available. Instead, the key idea of cellular systems is that it is possible to serve an *unlimited* number of subscribers, distributed over an *unlimited* area, using only a *limited* number of channels, by efficient *channel reuse*. A set of cells, each of which operates on a different channel (or group of channels), is grouped together to form a *cluster*. The cluster is then repeated as many times as necessary to cover a very wide area. Figure 1.10 illustrates the use of a seven-cell cluster. The use of hexagonal areas to represent the cells is highly idealised, but it helps in establishing basic concepts. It also correctly represents the situation when path loss is treated as a function of distance only, within a uniform environment. In this case, the hexagons represent the areas within which a given base station transmitter produces the highest power at a mobile receiver.

The smaller the cluster size, therefore, the more efficiently the available channels are used. The allowable cluster size, and hence the *spectral efficiency* of the system, is limited by the level of interference the system can stand for acceptable quality. This level is determined by the smallest ratio between the wanted and interfering signals which can be tolerated for reasonable quality communication in the system. These levels depend on the types of

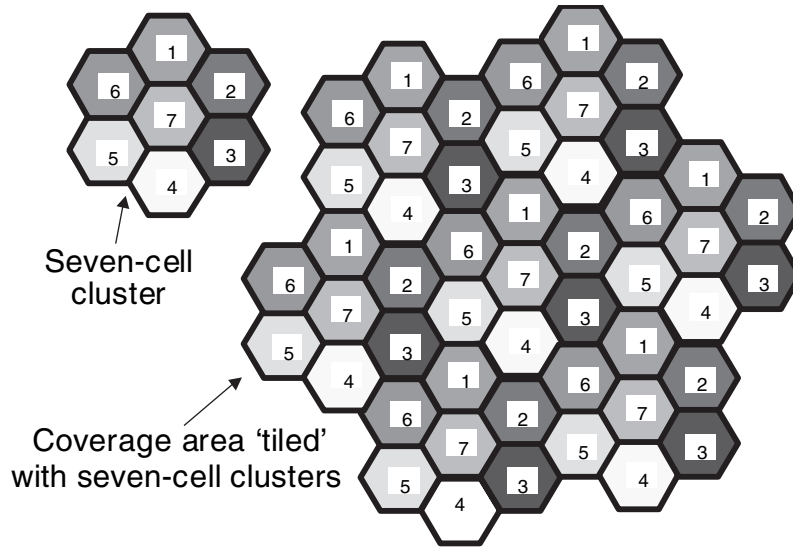


Figure 1.10: Cellular reuse concept

modulation, coding and synchronisation schemes employed within the base station and the mobile. The ratio is called the *threshold carrier-to-interference power ratio* (C/I or CIR). Figure 1.11 illustrates a group of co-channel cells, in this case the set labelled 3 in Figure 1.10. There will be other co-channel cells spread over a wider area than illustrated, but those shown here represent the first *tier*, which are the nearest and hence most significant interferers. Each cell has a radius R and the centres of adjacent cells are separated by a distance D , the *reuse distance*.

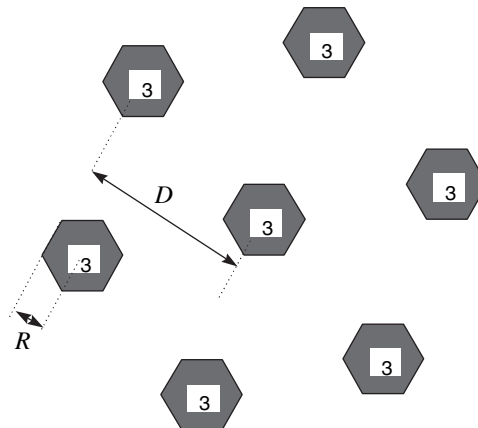


Figure 1.11: A group of co-channel cells

Considering the central cell in Figure 1.11 as the wanted cell and the other six as the interferers, the path loss model from (1.1) suggests that a mobile located at the edge of the wanted cell experiences a C/I of

$$\frac{C}{I} \approx \frac{1}{R^4} / \sum_{k=1}^6 \frac{1}{D^4} = \frac{1}{6} \left(\frac{D}{R} \right)^4 \quad (1.2)$$

This assumes that the distances between the interferers and the mobile are all approximately equal and that all the base stations have the same heights and transmit powers. The geometry of hexagons sets the relationship between the cluster size and the reuse distance as:

$$\frac{D}{R} = \sqrt{3N} \quad (1.3)$$

where N is the cluster size. Hence, taking (1.2) and (1.3) together, the cluster size and the required C/I are related by

$$\frac{C}{I} = \frac{1}{6} (3N)^2 \quad (1.4)$$

For example, if the system can achieve acceptable quality provided the C/I is at least 18 dB, then the required cluster size is

$$N = \sqrt{\frac{2}{3} \times \frac{C}{I}} = \sqrt{\frac{2}{3} \times 10^{18/10}} = 6.5 \quad (1.5)$$

Hence a cluster size of $N = 7$ would suffice. Not all cluster sizes are possible, due to the restrictions of the hexagonal geometry. Possible values include 3, 4, 7, 12, 13, 19 and 27. The smaller the value of C/I , the smaller the allowed cluster size. Hence the available channels can be reused on a denser basis, serving more users and producing an increased capacity. Had the dependence on r in (1.1) been slower (i.e. the path loss exponent was less than 4), the required cluster size would have been greater than 7, so the path loss characteristics have a direct impact on the system capacity. Practical path loss models in various cell types are examined in depth in Chapters 8, 12–14.

Note this is only an approximate analysis. In practice, other considerations such as the effect of terrain height variations require that the cluster size is different from the theoretical value, or is varied in different parts of the system in order to suit the characteristics of the local environment.

One way to reduce cluster size, and hence increase capacity, is to use *sectorisation*. The group of channels available at each cell is split into say three subgroups, each of which is confined in coverage to one-third of the cell area by the use of directional antennas, as shown in Figure 1.12. Chapters 4 and 15 will describe how this directionality is achieved. Interference now comes from only 2, rather than 6, of the first-tier interfering sites, reducing interference by a factor of 3 and allowing cluster size to be increased by a factor of $3^{0.5} = 1.7$ in theory. Sectorisation has three disadvantages:

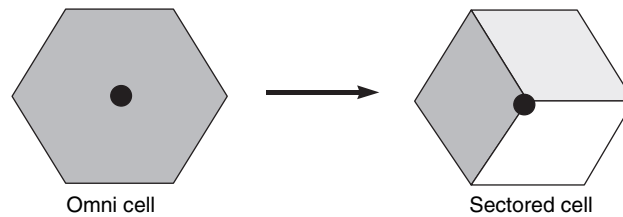


Figure 1.12: Sectorisation of an omnidirectional cell into three sectors

- More base station equipment is needed, especially in the radio frequency (RF) domain.
- Mobiles have to change channels more often, resulting in an increased signalling load on the system.
- The available pool of channels has to be reduced by a factor 3 for a mobile at any particular location; this reduces the trunking efficiency (Section 1.9).

Despite these issues, sectorisation is used very widely in modern cellular systems, particularly in areas needing high traffic density. More than three sectors can be used to further improve the interference reduction; the ultimate is to have very narrow-beam antennas which track the position of the mobile, and these are examined in Chapter 18.

As the mobile moves through the system coverage area, it crosses cell boundaries and thus has to change channels. This process is *handover* or *handoff* and it must be performed quickly and accurately. Modern fast-switching frequency synthesisers and digital signal processing have allowed this process to be performed with no significant impact on call quality.

The handover process needs to be carefully controlled: if handover occurs as soon as a new base station becomes stronger than the previous one, then ‘chatter’ or very rapid switching between the two BSs will occur, especially when the mobile moves along a cell boundary. An element of hysteresis is therefore introduced into the handover algorithm: the handover occurs only when the new BS is stronger than the old one by at least some *handover margin*. If this margin is too large, however, the mobile may move far into the coverage area of a new cell, causing interference to other users and itself suffering from poor signal quality. The optimum handover margin is set crucially by the level of shadowing in the system, as this determines the variation of signal level along the cell boundaries (Chapter 9). Handover accuracy is usually improved by *mobile-assisted handover*, also known as MAHO, in which the mobile monitors both the current cell and several neighbouring cells, and sends signal strength and quality reports back to the current serving BS.

1.9 TRAFFIC

The number of channels which would be required to guarantee service to every user in the system is impractically large. It can, however, be reduced by observing that, in most cases, the number of users needing channels simultaneously is considerably smaller than the total number of users. The concept of *trunking* can then be applied: a common pool of channels is created and is shared among all the users in a cell. Channels are allocated to particular users when they request one at the start of a call. At the end of the call, the channel is returned to the pool. This means there will be times when a user requests a channel and none is left in the pool: the call is then *blocked*. The probability of blocking for which a system is designed is the *grade of service*. Traffic is measured in *erlangs*: one erlang (E) is equivalent to one user

making a call for 100% of the time. A typical cellular voice user generates around 2–30 mE of traffic during the busiest hour of the system, that is, a typical user is active for around 0.2–3.0% of the time during the busy-hour. These figures tend to increase for indoor environments, fluctuating around 50–60 mE.

The *traffic per user* A_u is required if the traffic per cell is to be computed. Therefore, a *user traffic profile* is often described, in which an average mobile phone user makes λ calls of duration H during the busy-hour. λ is known as the call request rate and H is the holding time. Hence, the average traffic per user is

$$A_u = \lambda H \quad (1.6)$$

For U users in the cell, the total *carried traffic* A is given by:

$$A = UA_u \quad (1.7)$$

To predict the number of channels needed to support a given number of users to a certain grade of service, it is usual to apply the *Erlang-B formula*:

$$\Pr(\text{blocking occurs}) = \frac{A^C / C!}{\sum_{k=0}^C \frac{A^k}{k!}} \quad (1.8)$$

where A is the total offered traffic in erlangs and C is the total number of channels available. This formula is plotted in Figure 1.13. The Erlang-B formula is idealised in that it makes particular assumptions about the call request rate and holding time, but it provides a useful starting point for estimating the number of channels required.

In summary, *capacity* for a cellular system can be dimensioned if blocking, number of channels and offered traffic can be estimated. A network is often dimensioned for busy-hour operation, as network congestion limits the number of available resources. Example 1.1 illustrates how this capacity dimensioning is performed in practice.

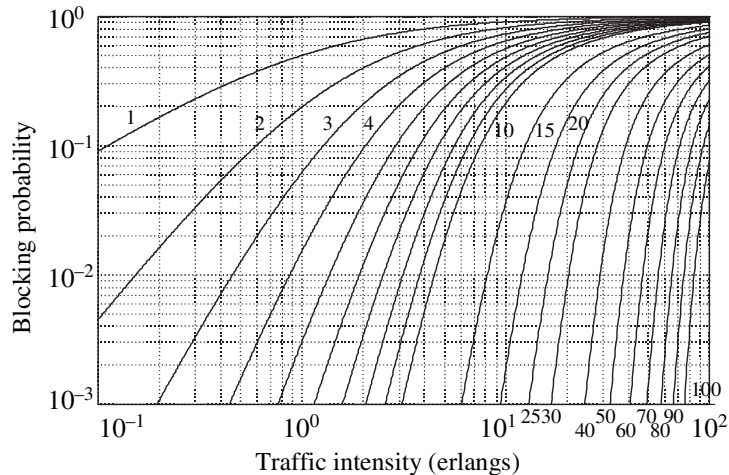


Figure 1.13: Erlang-B graph: each curve is marked with the number of channels

Example 1.1

A cellular operator is interested in providing GSM coverage at 900 MHz in an international airport. Surveys show that approximately 650 000 passengers make use of the airport every year, of which it is believed that around 80% are mobile phone users. The airport layout is shown in Figure 1.14.

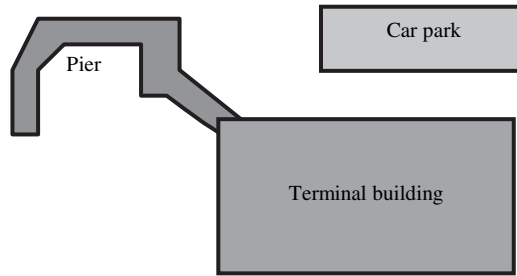


Figure 1.14: Airport layout for example 1.1

The following assumptions apply for this airport:

- (a) Busy-hour traffic takes about 25% of the total daily traffic.
- (b) The traffic in the airport is distributed in the following proportions: 70% is carried in the terminal building, 20% in the pier and 10% in the car park.
- (c) Each airport user makes an average of three phone calls of 2 min of duration during the busy-hour.
- (d) Three cells are required for this system: one in the terminal, one in the car park and the other one in the pier.
- (e) This operator has a market penetration in the airport of 28%.

Determine the required number of channels per cell, if only 2% of the users attempting to make a phone call are to be blocked when no free channels are available.

Solution

The busy-hour number of mobile phone users needs to be calculated. If 650 000 passengers per year use the airport, then:

$$\frac{650\,000 \text{ passengers}}{\text{Year}} \times \frac{1 \text{ year}}{365 \text{ days}} \approx 1781 \text{ passengers/day}$$

As only 80% of the passengers use a mobile phone, the cellular operator with 28% of market penetration carries

$$1781 \times 0.8 \times 0.28 \approx 399 \text{ mobile phone users/day}$$

This number represents only the number of mobile phone users per day for this cellular operator. As capacity needs to be dimensioned on a per busy-hour basis:

$$\frac{399 \text{ mobile phone users}}{\text{Day}} \times 0.25 \approx 100 \frac{\text{Mobile phone users}}{\text{Busy-hour}}$$

Next, it is necessary to split this number of users per cell. As the terminal takes 70% of the traffic, the car park only 10% and the pier, 20%, then:

$$U_{\text{terminal}} = 100 \frac{\text{mobile phone users}}{\text{busy-hour}} \times 0.7 = 70 \text{ mobile users}$$

$$U_{\text{pier}} = 100 \frac{\text{mobile phone users}}{\text{busy-hour}} \times 0.2 = 20 \text{ mobile users}$$

$$U_{\text{car park}} = 100 \frac{\text{mobile phone users}}{\text{busy-hour}} \times 0.1 = 10 \text{ mobile users}$$

The offered traffic per cell must now be estimated. For this, an average traffic profile per user has been given, from which an average traffic per user can be computed. Given that a mobile user makes three phone calls of 2 min of duration during the busy-hour, the traffic per user is

$$A_u = \lambda H = \frac{3 \text{ calls}}{\text{hour}} \times 2 \text{ min} \times \frac{1 \text{ hour}}{60 \text{ min}} = 100 \text{ mE/user}$$

Given this number of users per cell, and the traffic per user, it is now possible to compute the total traffic per cell:

$$A_{\text{terminal}} = 70 \frac{\text{users}}{\text{cell}} \times 100 \frac{\text{mE}}{\text{user}} = 7 \text{ Erlangs}$$

$$A_{\text{pier}} = 20 \frac{\text{users}}{\text{cell}} \times 100 \frac{\text{mE}}{\text{user}} = 2 \text{ Erlangs}$$

$$A_{\text{car park}} = 10 \frac{\text{users}}{\text{cell}} \times 100 \frac{\text{mE}}{\text{user}} = 1 \text{ Erlang}$$

With a 2% blocking probability, an estimate of the required number of channels per cell is possible, as the traffic per cell is available. Referring to the Erlang-B graph in Figure 1.13:

$$C_{\text{terminal}} \approx 13 \text{ channels}$$

$$C_{\text{pier}} \approx 6 \text{ channels}$$

$$C_{\text{car park}} \approx 4 \text{ channels}$$

Note that it is necessary to round to the next highest integer in all cases, to guarantee a minimum number of channels to provide the required traffic A . It is also worth noting that the Erlang-B formula can be applied only on a *per-cell* basis, as Eq. (1.8) is not linear.

1.10 MULTIPLE ACCESS SCHEMES AND DUPLEXING

Given a portion of the frequency spectrum, multiple users may be assigned channels within that portion according to various techniques, known as *multiple access schemes*. The three most common schemes are examined here. The *duplexing scheme* is also examined, whereby simultaneous two-way communication is enabled from the user's point of view. The multiple access schemes are

- frequency division multiple access (FDMA)
- time division multiple access (TDMA)
- code division multiple access (CDMA).

Chapters 17 and 18 will introduce two further multiple access schemes, orthogonal frequency division multiple access (OFDMA) and space division multiple access (SDMA). The duplexing schemes described here are

- frequency division duplex (FDD)
- time division duplex (TDD).

1.10.1 Frequency Division Multiple Access

Figure 1.15 illustrates a system using FDMA and FDD. The total bandwidth available to the system operator is divided into two sub-bands and each of these is further divided into a number of frequency channels. Each mobile user is allocated a pair of channels, separated by the *duplex spacing*, one in the uplink sub-band, for transmitting to the base station, the other in the downlink sub-band, for reception from the base station.

This scheme has the following features:

- Transmission and reception are simultaneous and continuous, so RF duplexers are needed at the mobile to isolate the two signal paths, which increase cost.
- The carrier bandwidth is relatively narrow, so equalisers are not usually needed (Chapter 17).
- The baseband signal processing has low complexity.
- Little signalling overhead is required.
- Tight RF filtering is needed to avoid adjacent channel interference.
- Guard bands are needed between adjacent carriers and especially between the sub-bands.

FDMA is the most common access scheme for systems based on analogue modulation techniques such as frequency modulation (FM), but it is less commonly used in modern digital systems.

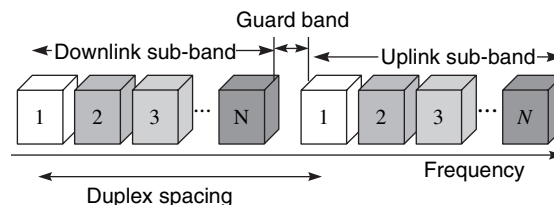


Figure 1.15: Frequency division multiple access used with FDD

1.10.2 Time Division Multiple Access

The scheme illustrated in Figure 1.16 combines TDMA and FDD, requiring two frequencies to provide duplex operation, just as in FDMA. Time is divided into *frames* and each frame is further divided into a number of slots (four in this case). Mobiles are allocated a pair of *time slots*, one at the uplink frequency and the other at the downlink frequency, chosen so that they do not coincide in time. The mobile transmits and receives *bursts*, whose duration is slightly less than the time slot to avoid overlap and hence interference between users.

This scheme has several features:

- Transmission and reception are never simultaneous at the mobile, so duplexers are not required.
- Some bits are wasted due to burst start and stop bits and due to the guard time needed between bursts.
- The wide channel bandwidth needed to accommodate several users usually leads to a need for equalisation (Chapter 17).
- The time between slots is available for handover monitoring and channel changing.
- The receiver must resynchronise on each burst individually.
- Different bit rates can be flexibly allocated to users by allocating multiple time slots together.

TDMA can also be used with TDD, by allocating half the slots to the uplink and half to the downlink, avoiding the need for frequency switching between transmission and reception and permitting the uplink channel to be estimated from the downlink, even in the presence of frequency-dependent fading (Chapter 11).

1.10.3 Code Division Multiple Access

In CDMA or *spread spectrum* systems, each user occupies a bandwidth much wider than is needed to accommodate their data rate. In the form usually used for cellular mobile systems, this is achieved by multiplying the source of data by a *spreading code* at a much higher rate, the *chip rate*, thereby increasing the transmitted signal bandwidth (Figure 1.17). At the receiver, the reverse process is performed to extract the original signal, known as *despreading*. This is *direct sequence* spread spectrum, described in more detail in Chapter 17. When this is applied to multiple access, the users are each given different codes, and the codes are specially

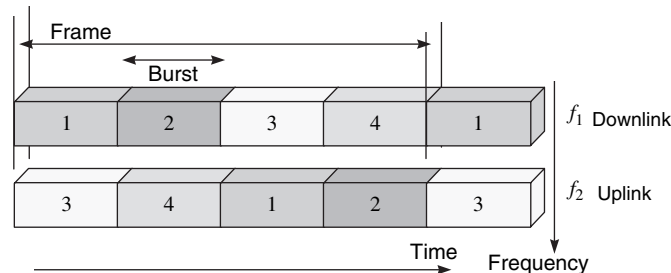


Figure 1.16: Time division multiple access used with FDD

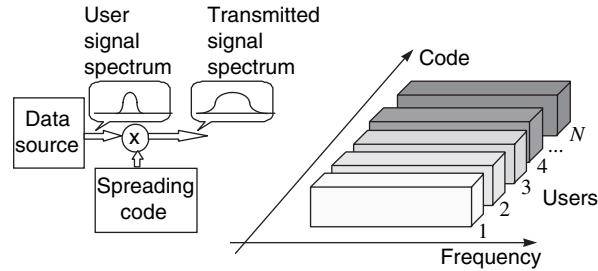


Figure 1.17: Code division multiple access

chosen to produce low *multiple access interference* following the despreading process. The duplex method is usually FDD. Here are some of its features:

- Increasing the number of users increases interference gradually, so there is no specific limit to the number of users, provided that codes with low mutual interference properties are chosen. Instead, system performance degrades progressively for all users.
- The high bandwidth leads to a requirement for an equaliser-like structure, a *Rake receiver* (Chapter 17). This allows multipath diversity gain to be obtained (Chapter 16).
- The power of all users must be equal at the base station to allow the despreading process to work effectively, so some complex power control is required.
- The baseband processing may be complex compared with FDMA and TDMA, but this is less important with modern silicon integration densities.

CDMA is increasingly being applied in modern cellular mobile systems, placing increasing emphasis on the need for characterisation of wideband channel effects (Chapter 11).

1.11 AVAILABLE DATA RATES

The access schemes introduced in the previous section allow multiple users to access portions of the available system bandwidth. Another relevant consideration, particularly for multimedia and data services, is the data rate available to each user. This is sometimes loosely referred to as the ‘bandwidth’, but in fact the user data rate is not a simple function of the bandwidth occupied, being influenced by three important elements:

- the spectrum efficiency of the modulation scheme employed;
- the error correction and detection schemes in use;
- the channel quality.

The modulation scheme efficiency for digital signals is measured as a ratio of the data rate transmitted over the air to the bandwidth occupied and is thus typically measured in bits per second per Hertz [$\text{bit s}^{-1} \text{Hz}^{-1}$ or bps Hz^{-1}]. For example, the simple binary phase shift keying (BPSK) scheme analysed in Chapter 10 achieves a spectral efficiency of $1 \text{ bit s}^{-1} \text{Hz}^{-1}$, whereas a quaternary phase shift keying (QPSK) scheme signals two binary bits in the same period as a single BPSK bit and thus achieves twice the channel data rate in the same bandwidth, i.e. $2 \text{ bit s}^{-1} \text{Hz}^{-1}$ [Proakis, 89]. This process can be continued almost indefinitely, with sixty-four level quadrature amplitude modulation (64-QAM), for example, achieving $6 \text{ bit s}^{-1} \text{Hz}^{-1}$. The price for this increased bit rate, however, is an increased

sensitivity to noise and interference, so that more errors are caused and the useful error-free data rate may actually be reduced by signalling faster.

In order to increase the robustness of the modulation scheme, error correction and detection schemes are applied. At a basic level, this is achieved by adding extra checksum bits at the transmitter, which allow the receiver to detect whether some bits have been received in error and to correct at least some of those errors. This process of ‘forward error correction’ (FEC) adds redundancy according to some coding rate, so every user data bit is represented in the transmission by multiple coded data bits. This ratio is the coding rate of the coder. For example, if there are two coded bits for every one data bit, the coding rate = 1/2. Thus the user data rate is the channel data rate multiplied by the coding rate. Selection of the most appropriate FEC scheme involves a trade-off between acceptable error rates and the transmission rate.

When errors are detected by the coding scheme and cannot be corrected by FEC, it is common for the receiver to request retransmission of the suspect part of the transmitted data. Such *automatic repeat request* or ARQ schemes can produce very reliable data transmission, at the expense of further reduced user data rates. The actual user data rate achieved depends directly on the channel quality.

The upper limit for the useful data rate, or *channel capacity* C [bit s⁻¹] achieved in a channel of bandwidth B [Hz] at a signal power to noise power ratio S/N was predicted by [Shannon, 48] as:

$$C = \log_2 \left(1 + \frac{S}{N} \right) \quad (1.9)$$

This implies that, for an ideal system, the bit error rate can be reduced to zero by the application of appropriate coding schemes, provided the user data rate is less than the channel capacity. Shannon did not, however, provide any constructive techniques for creating such codes and the five decades following his original paper saw researchers expending very significant effort on constructing codes which approached ever closer to this limit. The practical impact of this effort is illustrated by the increasing user data rate available from real-world systems in Figure 1.18, which appears to double approximately every 18 months, the same as the rate predicted by Moore’s law for the increase in integrated circuit complexity [Cherry, 04].

One of the developments which has allowed such high data rates was the development of *turbo codes* in 1993, a form of FEC which allows the attainment of performance virtually at the Shannon capacity, albeit at the expense of high decoder complexity [Berrou, 93]. The fact that user data rates have actually continued to increase even beyond this limit may seem mysterious, but arises directly from a detailed understanding of the characteristics of both antennas and the propagation channel. See Chapter 18 for further details of the MIMO techniques which permit this – but the reader is advised to study the intervening chapters to gain the best possible appreciation of these!

1.12 STRUCTURE OF THIS BOOK

The preceding sections have given an indication of the significance and effect of antennas and propagation in wireless communication systems. Following on from this introduction, the book is loosely structured into five major sections.

The first section is concerned with the key features of radio wave propagation and antennas which are common to all wireless communication systems. Chapter 2 examines the

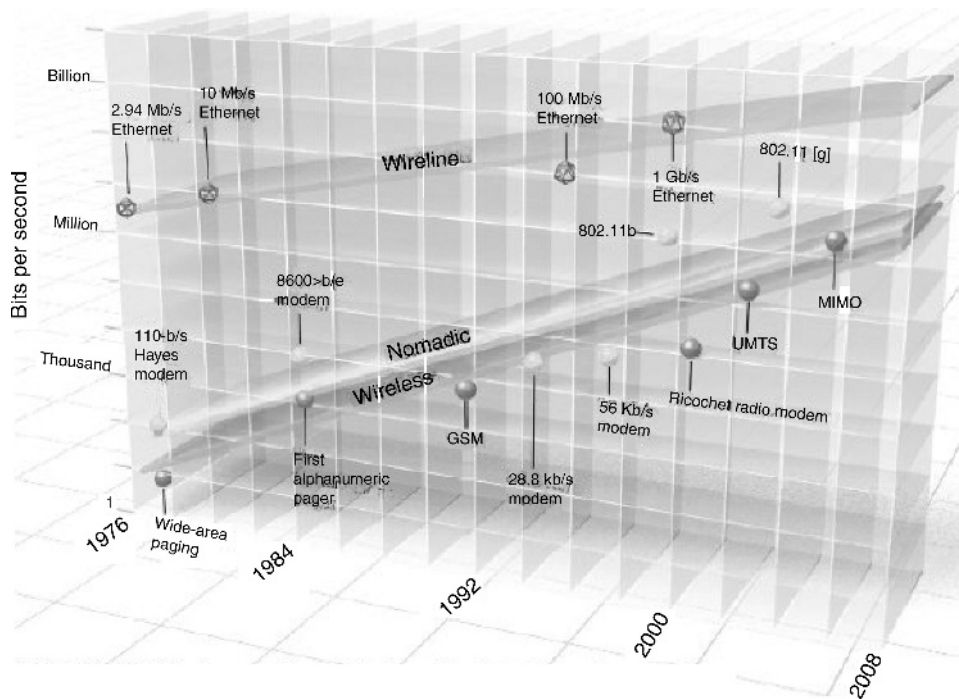


Figure 1.18: Edholm's law of bandwidth (Reproduced by permission of IEEE, © 2004 IEEE)

fundamental properties of electromagnetic waves travelling in uniform media. These are developed in Chapter 3 in order to describe the basic mechanisms of propagation which occur when waves encounter boundaries between different media. Chapter 4 then shows how such waves can be launched and received using antennas, which have certain key requirements and properties and for which there are a number of generic types.

Starting a new section, Chapter 5 introduces the concept of a propagation model, together with the basic techniques for analysing communication systems; these must be understood in order to predict system performance. The theory in Chapter 5 and the first section is then used to analyse two practical types of fixed communication system – terrestrial fixed links in Chapter 6 and satellite fixed links in Chapter 7.

The next section (Chapters 8–11) examines propagation and channel effects in macrocell mobile systems. Chapter 8 describes the path loss models which establish the basic range and interference levels from such systems. Chapter 9 describes the shadowing effects which cause statistical variations relative to these levels and which determine the percentage of locations in a given area at which the system is available. Chapter 10 explains the mechanisms and statistical characterisation of the narrowband fast-fading effects in macrocells, which affect the quality of individual links between mobiles and macrocell base stations. These are generalised to wideband systems in Chapter 11.

The macrocell concepts are then broadened in the next section to microcells, picocells and megacells in Chapters 12–14, respectively, including all the major differences in propagation and antennas for such cells.

Chapters 15–19 inclusive establish methods which the system and equipment designer can use to overcome many of the limitations of the wireless channel. Chapter 15 first explains the antennas in use for mobile systems. This chapter also covers other specifics of antennas such as health and safety considerations, and specific requirements for mobile applications. Chapter 16 explains how *diversity* provides a means of overcoming narrowband fast fading using multiple antennas. Chapter 17 then provides a similar treatment for overcoming wideband fading, using *equalisation*, *Rake receivers* and *OFDM*. Chapter 18 then indicates the potential of adaptive antenna systems for overcoming co-channel interference effects and hence for increasing the capacity of wireless systems, in terms of both user density and data rates. Chapter 19 highlights essential practical issues to consider when performing mobile radio channel measurements, which affect the accuracy of both radio wave propagation predictions and system designs.

Finally, Chapter 20 gives some indications of the developments expected in the research, development and usage of wireless channels in the future.

1.13 CONCLUSION

This chapter has described a wide range of wireless communication systems, each with differing applications, technologies and requirements. All of them are unified by their reliance on the characteristics of the wireless communication channel, incorporating both antennas and propagation, to accurately and efficiently deliver information from source to destination. For further details of these systems, texts such as [Molisch, 05], [Parsons, 00] and [Maral, 02] are recommended. The rest of this book will detail the principles and applied practical techniques needed to understand, predict and evaluate the channel effects which have impact on these systems.

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PROBLEMS

- 1.1 A cellular operator has created a system for 900 MHz which covers the desired service area with 500 cells and a base station antenna height of 15 m. The operator is given a new frequency allocation at 1800 MHz. How many cells would be needed at the new frequency using the same antenna heights and transmit powers? How much higher would the antennas need to be to produce the same range as the 900 MHz system?
- 1.2 What is the ratio of the cluster sizes needed for two systems with a 9 dB C/I requirement and a 19 dB C/I requirement?
- 1.3 A certain cell has 4000 users, who generate an average of 2 mE of busy-hour traffic each. How many channels are needed to serve these users with no more than 2% blocking probability? How many users can be served, with the same number of channels and grade of service, if the cell is divided into three sectors?
- 1.4 A leading cellular operator wants to provide cellular coverage in one of the busiest international airports in the world. The cellular operator's research indicates that around 31 650 potential mobile users per month during the high season pass through the airport for domestic and international flights. Radio measurements have shown that sufficient coverage is provided with three cells: one in the main terminal building, one in the international flights building and one in the domestic flights building, as shown in Figure 1.19.

Clipboard research shows that mobile users at this airport make two phone calls of 3 min of duration on average.

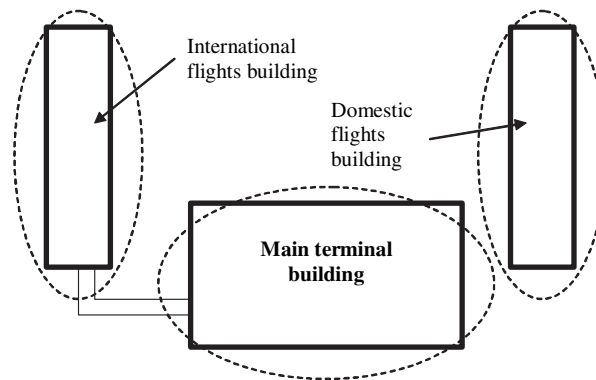


Figure 1.19: International airport scenario for Problem 1.4

- (a) Determine the number of required channels to deploy at each base station per cell, if the system is to be dimensioned for a maximum blocking of 2% for an Erlang-B system. Assume that the main terminal carries the 60% of the total traffic and each other building carries only 20%. Approximately 25% of the daily traffic is carried during the busy-hour.
- (b) What is the total traffic that is carried at this airport?
- (c) Suggest a method for making a more efficient use of the radio spectrum if the traffic is variable in the three cells, as this traffic tends to be bursty.

