CHAPTER 15

Mobile and cellular radio

15.1 Introduction

In comparison to the relative stability and modest technical developments which are occurring in long-haul wideband microwave communication systems there is rapid development and expanding deployment of new mobile personal communication systems. These range from wide coverage area pagers, for simple data message transmission, through to sophisticated cellular systems, which employ common standards and hence achieve contiguous coverage over large geographical areas, such as all the major urban centres and transport routes in Europe or the continental USA. This chapter discusses the specific channel characteristics of mobile systems and examines the typical cellular clusters, adopted to achieve continuous communication with the mobile user. It then highlights the important properties of current, and emerging, TDMA and code division multiple access (CDMA), mobile digital communication systems.

15.1.1 Private mobile radio

Terrestrial mobile radio works best at around 250 MHz as lower frequencies than this suffer from noise and interference while higher frequencies experience multipath propagation from buildings, etc. In practice modest frequency bands are allocated between 60 MHz and 2 GHz. Private mobile radio (PMR) is the system which is used by taxi companies, county councils, health authorities, ambulance services, fire services, the utility industries, etc. for mobile communications.

PMR has three spectral allocations at VHF, one just below the 88 to 108 MHz FM broadcast band and one just above this band with another allocation at approximately 170 MHz. There are also two allocations at UHF around 450 MHz. All these spectral allocations provide a total of just over 1000 radio channels with the channels placed at 12½ kHz channel spacings or centre frequency offsets. Within the 12½ kHz wide channel the analogue modulation in PMR typically allows 7 kHz of bandwidth for the signal transmission. When further allowance is made for the frequency drift in the oscillators of these systems a peak deviation of only 2 to 3 kHz is available for the speech traffic. Traffic is normally impressed on these systems by amplitude modulation or frequency modulation and again the receiver is of the ubiquitous superheterodyne design, Figure 1.4. A double conversion receiver with two separate local oscillator stages is usually required to achieve the required gain and rejection of adjacent channel signals.

One of the problems with PMR receivers is that they are required to detect very small signals, typically −120 dBm at the antenna output, corresponding to 0.2 μV (RMS into 50 Ω), and, after demodulating this signal, produce an output with perhaps 1 W of audio power. It is this stringent gain requirement which demands double conversion. In this type of equipment the first IF is normally at 10.7 MHz and the second IF is very often at 455 kHz. Unfortunately, with just over 1,000 available channels for the whole of the UK and between 20,000 and 30,000 issued licences for these systems, it is inevitable that the average business user will have to share the allocated channel with other companies in his same geographic area.

There are various modes of operation for mobile radio communications networks, the simplest of which is single frequency simplex. In simplex communication, traffic is broadcast, or one way. PMR uses half duplex where, at the end of each transmission period, there is a handover of the single channel to the user previously receiving, in order to permit them to reply over the same channel. This is efficient in that it requires only one frequency allocation for the communications link but it has the disadvantage that all units can hear all transmissions provided they are within range of the mobile and base station. An improvement on half duplex is full duplex operation where two possible frequencies are allocated for the transmissions. One frequency is used for the forward or downlink, that is base-to-mobile communications, while a second frequency is used for the reverse or uplink channel, that is mobile-to-base communications. This permits simultaneous two-way communication and greatly reduces the level of interference, but it halves the overall capacity. One possible disadvantage is that mobiles are now unable to hear each other's transmissions, which can lead to contention with two mobiles attempting to initiate a call, at the same time, on the uplink in a busy system.

Although PMR employs relatively simple techniques with analogue speech transmission there have been many enhancements to these systems over the years. Data transmission is possible in PMR systems using FSK modulation (see section 11.3.3). Data transmission allows the possibility of hard copy graphics output and it also gives direct access to computer services such as databases, etc. Data preambles can also be used, in a *selective calling* mode when initiating a transmission to address a specific receiver and thus obtain more privacy within the system.

The problems in PMR are basically two-fold. One is the very restricted number of channels which are available. The second concerns the fact that mobile equipment will only operate when it is close to the base station transmitter which is owned by the company or organisation using the system. It has been the desire to design a wider coverage system, which also overcomes the restrictions of the limited number of channels, that has given rise to cellular radio. Following the development of national coverage cellular systems, PMR has come to be used mainly by taxi operators and the emergency services.

15.1.2 Radio paging systems

Another simple communications system, which is similar to broadcast, is one way paging. These started as on-site private systems employing 1 W transmitters with, approximately, 1 μV sensitivity superheterodyne receivers. The early systems used sequential tone (FSK) transmission in the UHF band [Macario] and simply alerted a specific receiver that it had been called. Digital pagers were then further developed for wide area public paging, with the POCSAG coded service opening in London in 1981. POCSAG has a capacity of 2 million pager equipments, a message rate of 1 per second and a message length of 40 characters. This is achieved with a data rate of 512 bit/s using NRZ FSK modulation and a tone separation of 9 kHz.

A key feature, necessary to achieve long battery life, is that these simple receivers switch to standby when no message is being transmitted. Paging messages are batched and preceded by a preamble to ensure that all pager receivers are primed to receive the signals. The alphanumeric message, which is displayed on the paged receiver, is sent as sets of (32,21) $R = 2/3$ POCSAG coded data vectors, Chapter 10 and [Macario]. More recently a new European radio message system (ERMES) has been standardised within ETSI for *international* paging. At 9.6 kbit/s ERMES supports four of the current 1.2 kbit/s POCSAG messages in simultaneous transmission. Also, in 1994, INMARSAT launched a worldwide satellite based pocket pager with a £300 receiver cost.

15.2 Mobile radio link budget and channel characteristics

The mobile communications channel suffers from several, potentially serious, disadvantages with respect to static, line of sight (LOS) links. These are:

1. Doppler shifts in the carrier due to relative motion between the terminals.
2. Slow spatial fading due, principally, to topographical shadowing (i.e. diffraction) effects along the propagation path.
3. Rapid spatial fading due to regions of constructive and destructive interference between signals arriving along different propagation paths. (Such multipath fading may also occur on fixed point-to-point systems but is usually less severe and more easily mitigated.)
4. Temporal fading due, principally, to the mobile terminal's motion through the spatially varying field.
5. Frequency selective fading when the signals are broadband.
6. Time dispersion due to multipath propagation.
7. Time variation of channel characteristics due, principally, to movement of the mobile terminal.

Some of these effects are, of course, intimately connected and represent different manifestations of the same physical processes. Figure 15.1 illustrates the origin of these effects, with the signals reflecting off neighbouring buildings before being summed at the mobile terminal receiving antenna.

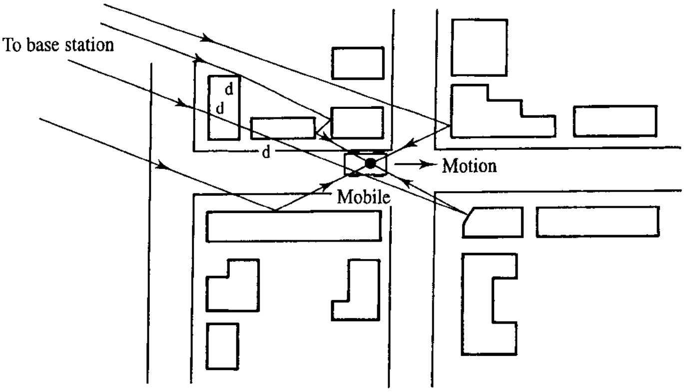

Figure 15.1 *Multipath origin of Doppler shift, fading and dispersion in a mobile radio channel (d indicates possible points of diffraction).*

15.2.1 Prediction of median signal strength

The fading processes referred to above mean that, in general, only statistical statements can be made about the signal strength in a particular place at a particular time [1]. Usually these statements are in the form of cumulative distributions of signal strength. Ideally such distributions could be measured for each possible location of mobile and base station during the design of a mobile communications system. This, however, is usually neither practical nor economic and simplified models are used to predict these cumulative distributions. A common assumption used in these models is that propagation is essentially governed by equation (12.78) with a correction factor, incorporated to account for departures from a perfectly reflecting plane earth and the resulting random fading. A semi-empirical model developed by [Ibrahim and Parsons] uses exactly this approach. The received median carrier strength in the model is derived from equation (12.78) as:

$$C = P_T + G_T - \text{PEPL} + G_R - \beta \quad \text{(dBW)} \tag{15.1(a)}$$

where:

$$\beta = 20 + \frac{f_{MHz}}{40} + 0.18L - 0.34H + K \quad \text{(dB)} \tag{15.1(b)}$$

and:

$$K = \begin{cases} 0.094U - 5.9, & \text{for inner city areas} \\ 0, & \text{elsewhere} \end{cases} \tag{15.1(c)}$$

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[1] Recent spectacular improvements in the memory size, and speed, of computers combined with a similar reduction in hardware costs have made possible the simulation of mobile radio channels using detailed topographical databases combined with geometrical optic methods. Much effort is currently being invested in producing practical systems design tools from programs using such 'deterministic' modelling techniques.

β is called a clutter factor, L is called the land usage factor and U the degree of urbanisation. L and U are defined by the percentage of land covered by buildings, and the percentage of land covered by buildings with four or more storeys, respectively, in a given 0.5 km square. These quantities were chosen as parameters for the model because they are collected, and used by, UK local authorities in their databases of land usage. H is the height difference in metres between the 0.5 km squares containing the transmitter and receiver. The RMS error between predicted and measured path loss using this model in London is about 2 dB at 168 MHz and about 6 dB at 900 MHz.

15.2.2 Slow and fast fading

Slow fading, due to topographic diffraction along the propagation path, tends to obey log-normal statistics and occurs, in urban areas, typically on a scale of tens of metres. Its statistics can be explained by the cascading (i.e. multiplicative) effects of independent shadowing processes and the central limit theorem (see section 3.2.9). Fast fading, due to multipath propagation where the receiver experiences several time delayed signal replicas, tends to obey Rayleigh statistics. This is explained by the additive effects of independently faded and phased signals and the central limit theorem (see sections 3.2.9 and 4.7.1). The spatial scale of Rayleigh fading is typically half a wavelength. On a spatial scale of up to a few tens of metres fading can, therefore, usually be assumed to be a purely Rayleigh process given by:

$$p(r) = \begin{cases} (r/\sigma^2)e^{\frac{-r^2}{2\sigma^2}}, & r \geq 0 \\ 0, & r < 0 \end{cases} \tag{15.2}$$

where r is the signal amplitude and σ is the standard deviation of the parent Gaussian distribution. The corresponding exceedance is:

$$P(r > r_{ref}) = e^{\frac{-r_{ref}^2}{2\sigma^2}} \tag{15.3}$$

And since the median value of a Rayleigh distributed quantity is related to the standard deviation of its parent Gaussian distribution by:

$$r_{median} = 1.1774\sigma \tag{15.4}$$

then the exceedence can be rewritten as:

$$P(r > r_{ref}) = e^{-\left(\frac{r_{ref}}{1.2\, r_{median}}\right)^2} \tag{15.5}$$

Equation (15.5) allows the probability that the signal amplitude exceeds any particular reference value for a given median signal level to be found if slow, i.e. log-normal, fading can be neglected. If log-normal fading cannot be neglected (which is usually the case in practice) then the signal level follows a more complicated (Suzuki) distribution [Parsons and Gardiner].

15.2.3 Time dispersion, frequency selective fading, and coherence bandwidth

Multipath propagation results in a received signal that is dispersed in time. For digital signalling, this time dispersion leads to a form of ISI whereby a given received data sample is corrupted by the responses of neighbouring data symbols. The severity of this ISI depends on the degree of multipath induced time dispersion (quantified by the multipath RMS delay spread of the radio channel) relative to the data symbol period. It is generally agreed that if the ratio of the RMS delay spread to symbol period is greater than about 0.3, then multipath-induced ISI must be corrected if the system's performance is to be acceptable.

In the 900 MHz frequency band used for cellular mobile radio, wideband propagation measurements have shown that worst-case RMS delay spreads are usually less than 12 μs. More particularly, urban areas tend to have RMS delay spreads of about 2 to 3 μs, with significant echo power up to about 5 μs, Figure 15.2, while rural and hilly areas have RMS delay spreads of about 5 to 7 μs [Parsons]. Figure 15.2 also illustrates Doppler shift due to relative motion of the transmitter, receiver or reflectors. At 900 MHz a relative velocity of approximately 1.2 km/h produces a 1 Hz Doppler shift.

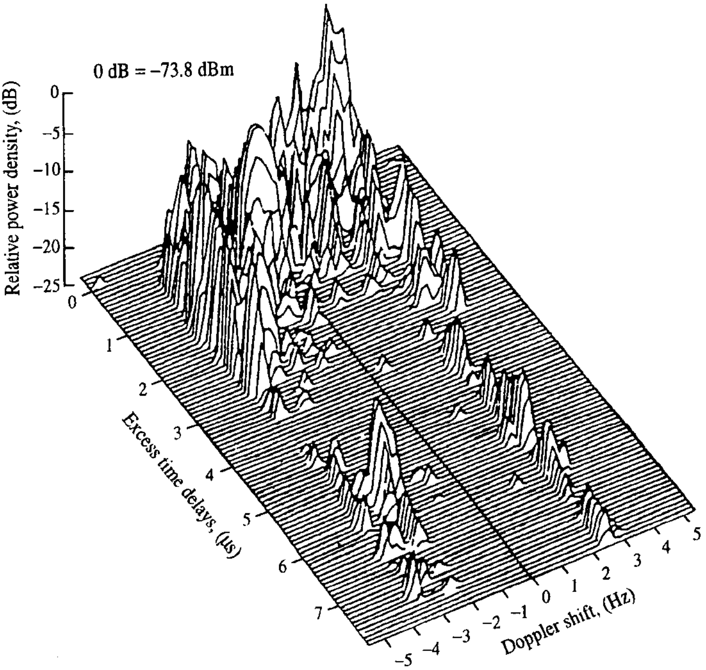


Figure 15.2 *Typical urban multipath profile (source: Parsons, 1991, reproduced with the permission of Peter Peregrinus).*

Multipath delay spread can be, equivalently, quantified in the frequency domain by the channel's coherence bandwidth, which is roughly the reciprocal of the RMS delay spread. The coherence bandwidth gives a measure of spectral flatness in a multipath channel. If two signal components are separated by greater than the coherence bandwidth of a channel, then they tend to fade independently and the overall signal is said to experience frequency-selective fading. On the other hand, if a signal's bandwidth is less than the coherence bandwidth of the channel, then the channel effectively exhibits spectrally flat fading in which all the signal components tend to fade simultaneously.

15.3 Nationwide cellular radio communications

15.3.1 Introduction

The growth in the demand for mobile radio services soon exceeded the capacity of, or possible spectral allocations for, PMR type systems. In the 1970s the concept therefore evolved of using base stations with modest power transmitters, serving all mobile subscribers in a restricted area, or cell, with adjacent cells using different operating frequencies. The key facet in cellular systems, introduced progressively through the 1980s, is that the power level is restricted so that the same frequency allocations can be reused in the adjacent cluster of cells, Figure 15.3. This constitutes a type of FDMA. Note that only cluster sizes of 3, 4, 7, 9, 12, etc. tesselate (i.e. lead to regular repeat patterns without gaps).

The protection ratio for these systems is the ratio of signal power from the desired transmitter (located at the centre of a cell) to the power received from a cochannel cell using the same operating frequency. Small clusters of 3 or 4 cells give 12 to 15 dB protection ratios which will only permit the use of a robust digital modulation method such as BPSK, Figures 11.10 and 11.21. As the cluster size increases so does the protection ratio. This arrangement is complicated as it involves handover as the mobile roams through the cells, but the ability to reuse the frequencies in close geographic proximity is a considerable advantage and this concept has now therefore been adopted worldwide for mobile telephone systems.

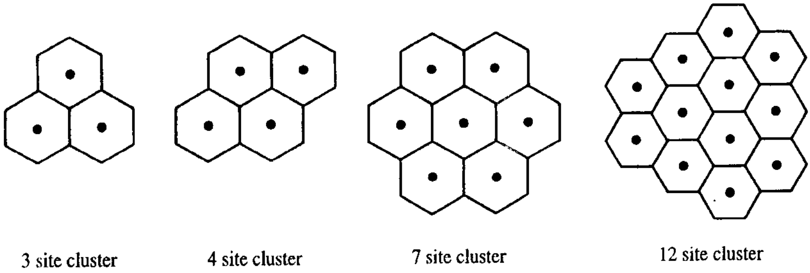


Figure 15.3 *Examples of possible cluster patterns for cellular systems.*

Cellular radio communication is experiencing rapid growth in North America, Asia and Europe. Hitherto, this unprecedented increase in user demand has been spurred on primarily by the business sector but now cellular equipment is widely used by contractors (such as plumbers and carpenters) as well as business executives. However, with the promise of personal convenience and freedom at relatively low cost, cellular radio is becoming attractive to the general public. In 1994 there were 3 million registered users of the UK cellular systems and in 1996 this grew to almost 7 million, representing 12% of the population. (Scandinavia currently has the highest market penetration worldwide (30%) for cellular telephony.)

It is predicted that, worldwide, user demand will increase ten-fold within the next five years. In fact, mobile cellular telephone systems in some large cities are currently congested to near capacity. Thus, it will be necessary to continuously increase the capacity of mobile cellular systems for the foreseeable future.

15.3.2 Personal cordless communications

The simplest of these systems is the 12 channel domestic, analogue, cordless (CT1) telephone system which operates within 50 to 100 m of the base unit. The second generation 40 channel digital telepoint equipment (CT2) with a 50 to 200 m range allows more mobility but, due to its still restricted range, needs many base stations. The UK Rabbit phone CT2 system, which operated in 1992 and 1993, was a simple system which did not allow the mobile subscriber to be called. This calling facility is, however, available in the French Bibop system. These telepoint FDMA systems, Table 15.1, use simple 32 kbit/s ADPCM speech coders (section 5.8.3), with 10 mW of output power, to achieve two-way communication on one 72 kbit/s circuit with only a 5 ms round trip delay. Channels are allocated at call setup, from the 40 available channels in the public base stations. The base stations are all connected to the PSTN giving telephony coverage similar to wired handsets.

Another system, DECT, was originally conceived as a cordless private branch exchange. However DECT is more advanced than CT2 in that it operates at 1900 MHz with TDMA, Table 15.1, has more advanced signalling and handover, and supports basic rate ISDN access (see Chapter 19). DECT uses a 10 ms frame time which is split into 5 ms for the uplink and 5 ms for the downlink transmissions, using time division duplex. Within this frame it supports 12 separate TDMA timeslots and, with 12 RF channels in the 1880 to 1900 MHz allocation, the base station capacity is approximately 140 simultaneous mobile users.

DECT is designed primarily for indoor operation where the multipath delay spread is less than 50 ns as the bit period is 870 ns. Thus it cannot be extended for use in outdoor cellular systems unless they are of the smaller coverage (microcellular) system design. Due to the simplicity of CT2 and DECT, they cannot handle significant Doppler shift due to handset motion and hence can only be used for mobiles travelling at walking pace. Also, due to the small range and hence cell sizes, DECT systems can only operate within localised areas as it is uneconomic to construct the 25,000 100 m diameter cells, for example, which would be required to achieve full central London coverage. However these microcells are significant in that they use low power transmissions of 1 to 100 mW, which is attractive for battery powered mobiles and, with the base station antenna below roof height, there is very little energy radiated into adjacent cells.

Table 15.1 *Comparison of European digital cordless and cellular telephony systems.*

	CT2	*DECT*	*GSM 900*	*DCS 1800*
Operating band (MHz)	864 – 868	1880 – 1900	890 – 960	1710 – 1880
Bandwidth (MHz)	4	20	2 × 25	2 × 75
Access method	FDMA	MF-TDMA	TDMA	TDMA
Peak data rate (kbit/s)	72	1,152	270	270
Carrier separation (kHz)	100	1,728	200	200
Channels per carrier	1	12	8	8
Speech coding	32 kbit/s	32 kbit/s	22.8 kbit/s	22.8 kbit/s
Coding/equalisation	no	no	yes	yes
Modulation	FSK	Gaussian FSK	GMSK	GMSK
Traffic channels/MHz	10	7	19	19
Mobile power output (W)	0.01	0.25	0.8 – 2.0	0.25 – 1
Typical cell size	50 – 200 m	50 – 200 m	0.3 – 35 km	0.02 – 8 km
Operation in motion	walking pace	walking pace	> 250 km/h	> 130 km/h
Capacity (erlangs/km^2)	N/A	10,000+	1,000	2,000

15.3.3 Analogue cellular radio communication

First-generation cellular systems employ analogue narrowband FM techniques [Black, Lee 1993]. For example, the North American advanced mobile phone system (AMPS) provides full duplex voice communications with 30 kHz channel spacing in the 800–900 MHz band, while the UK total access communication system, TACS – and extended TACS (ETACS) – operates with 25 kHz channel spacing in the 900 MHz band.

In a narrowband FM/FDMA cellular system the total available radio spectrum is divided into disjoint frequency channels, each of which is assigned to one user. The total available number of channels are then divided amongst the cells in each cluster and are reused in every cell cluster. Each cell in a given cluster is assigned a different set of frequency channels to minimise the adjacent channel interference while the cell size/cluster spacing is chosen to minimise co-channel interference.

15.3.4 Cell sizes

Cell size is dependent on expected call requirements. From knowledge of the total number of subscribers within an area, the probability of their requiring access and the mean duration of the calls, the traffic intensity in erlangs (see section 17.4.2) can be calculated. Erlang tables can then be used to ascertain the number of required channels for a given blocking, or lost call, probability.

For the cellular geometries of Figure 15.4 it is possible to calculate the carrier to interference ratio (C/I) close to the edge of the cell, when receiving signals from all the adjacent cofrequency cells. In an n-cell cluster, using a 4th power propagation law, the carrier to interference ratio is:

$$\frac{C}{I} = \frac{r^{-4}}{(n-1)d^{-4}} \tag{15.6}$$

where r is the cell radius and d the reuse distance between cell centres operating at the same centre frequency. (This is an approximate formula, arrived at by inspection, which is close, but not equal, to the worst case. A more accurate formula is derived in [Lee 1995].) Figure 15.4 shows the reuse distance between adjacent 7-cell clusters. The cluster size required to achieve a given d/r (and therefore the corresponding C/I) can be found using:

$$\frac{d}{r} = \sqrt{3n} \tag{15.7}$$

Although essentially general, equation (15.7) is particularly easily proved for the 7-cell cluster (Figure 15.4) as follows:

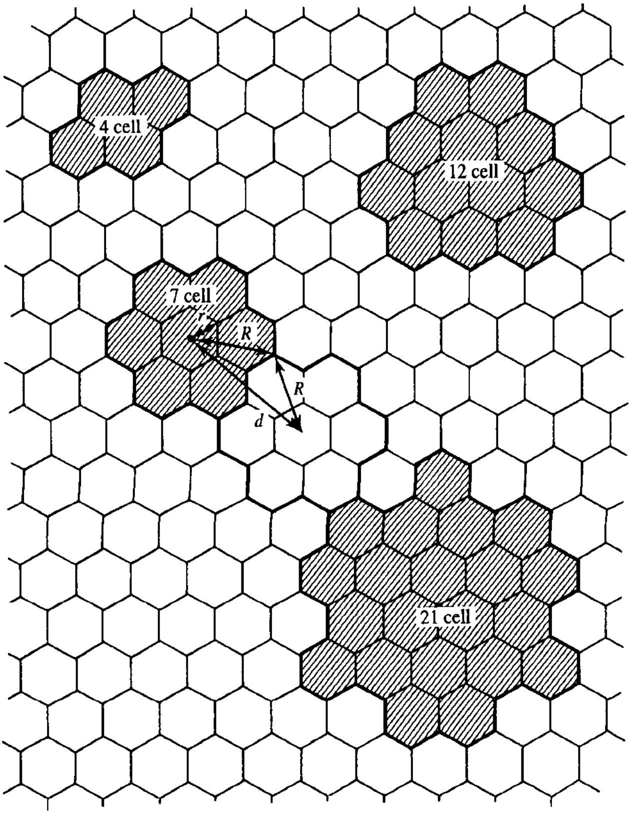


Figure 15.4 *Methods of grouping cells in order to cover a given area by repeating pattern.*

$$n = \frac{\text{cluster area}}{\text{cell area}} \tag{15.8}$$

The ratio of cluster to cell radii is therefore given by:

$$\frac{R}{r} = \frac{\sqrt{\text{cluster area}}}{\sqrt{\text{cell area}}} = \sqrt{n} \tag{15.9}$$

The angle between R and d shown in Figure 15.4 is 30°, therefore:

$$\frac{d}{2} = R\cos 30^\circ \tag{15.10}$$

i.e.:

$$d = \sqrt{3}R \tag{15.11}$$

substituting $R = \sqrt{n}r$ from equation (15.9) into (15.11) gives:

$$\frac{d}{r} = \sqrt{3n} \tag{15.12}$$

It is now possible to refer to Table 15.1 to obtain the available radio channel capacity within each cell. The total number of channels which are required to accommodate the expected traffic within a geographic area defines the required number of cells, or clusters. Division of the area covered, by the total number of cells in use, then provides the required area per individual cell. To accommodate higher traffic capacity, required in dense urban areas such as central London, necessitates smaller cell sizes, Figure 15.5, compared to more rural areas.

At the frequencies presently used for cellular radio, propagation usually follows (approximately) an inverse square law for field strength (i.e. an inverse 4th power law for power density). The median signal strength can be estimated using this law to predict the path loss by subtracting (in dB) a 'clutter factor', as described in section 15.2.1, to

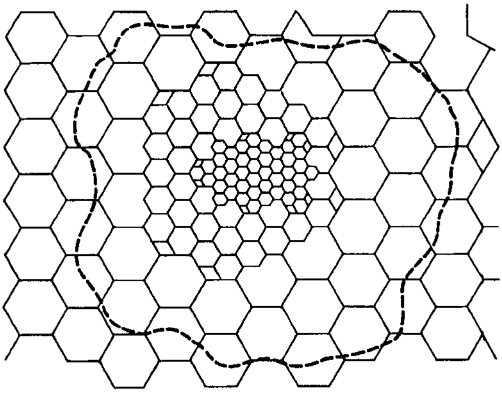


Figure 15.5 *Cell patterns used for London within the M25 orbital motorway, showing smaller cell patterns where most users are expected.*

account for deviations from ideal, plane earth, propagation.

As all cells use the same base station transmitter power, to minimise interference, the power level is set to ensure that there is adequate received signal at the edges of each cell compared to the thermal noise level. Transmission at a higher power level is not desirable as it simply wastes power. In the mobile the transmitter output power is controlled by the base station to minimise both interference and battery drain (and thus to maximise the time between recharges).

15.3.5 System configuration

In the UK cellular telephone network (operated by Vodafone and Cellnet) the base stations are connected to approximately 30 switching centres which hold information on the mobile transceivers which are active, including their location. Thus on calling a mobile transceiver from the wired PSTN one is connected first to the nearest switching centre and then on to the appropriate switching centre to route the call to the current mobile location, Figure 15.6. Within the area covered by a switching centre the mobile experiences handover as it roams from cell to cell. These digital switching centres, which form the interface between the wired PSTN and the mobile network, each have the capacity to handle 20 Merlangs of traffic and up to 100,000 subscribers. There are between six and ten switching centres for the dense London mobile traffic. The location of individual subscribers is tracked and this positional information within the overall mobile network is constantly updated in the home subscriber databases, Figure 15.6.

15.4 Digital TDMA terrestrial cellular systems

Although there are still over one million analogue cellular handsets in use in the UK, the present trend is towards digital cellular technology which has superior speech quality and improved privacy, and offers a natural extension to data transmission with ISDN compatibility. Most importantly, digital cellular systems have the potential to provide significantly higher capacity than analogue cellular systems, while utilising the same available bandwidth, and can achieve interoperability between different countries.

15.4.1 Systems

The digital vehicle mounted cellular systems for Europe, North America and Japan are all based on TDMA. The pan-European Groupe Spéciale Mobile (GSM) or global system for mobile communications [Lee 1995, Black], which was the world's first TDMA cellular system, transmits an overall bit rate of 271 kbit/s in a bandwidth of 200 kHz, with 8 TDMA users per carrier operating at 900 MHz, Figure 15.7. Thus, GSM 900 effectively supports one TDMA user per 25 kHz. On the other hand, the North American narrowband IS-54 TDMA system accommodates three TDMA users per carrier by transmitting an overall bit rate of about 48 kbit/s over the same 30 kHz bandwidth of the existing AMPS system. The Japanese system is similar to the North American system,

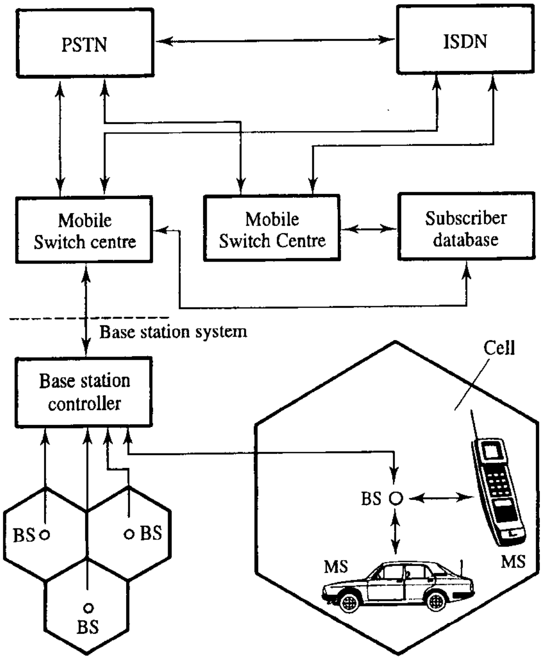


Figure 15.6 *Mobile system operation with mobile and base stations (MS) & (BS).*

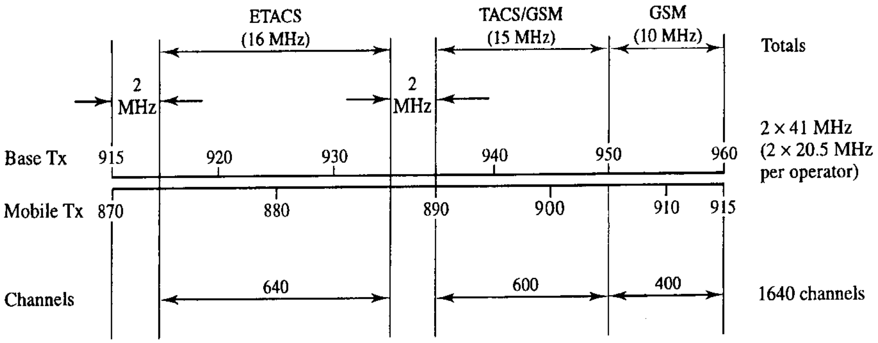


Figure 15.7 *UK allocation of 900 MHz spectrum for cellular communications.*

supporting three TDMA users per carrier with an overall bit rate of about 40 kbit/s transmitted over a 25 kHz bandwidth.

Such narrowband TDMA digital cellular systems improve system capacity by improving frequency reuse through cell size reduction and by accommodating several time-multiplexed users within essentially the same bandwidth that previously supported just one analogue user. Further capacity gains can also be realised by these digital systems through low bit-rate speech coding, higher trunking efficiency and more effective frequency reuse due to increased robustness to co-channel interference. However, TDMA digital cellular systems are susceptible to multipath-induced ISI which must be mitigated with relatively complex adaptive equalisation techniques, Table 15.1.

When it commenced operation in mid-1991, the GSM system provided duplex communications with 45 MHz separation between the frequency bands of the 890 to 915 MHz uplink, and the 935 to 960 MHz downlink. As a vehicle mounted system, the mobile power output ranges from 800 mW to 20 W, permitting up to 30 km cell sizes in low traffic density rural areas. In addition, GSM has been extended, via the DCS 1800 standard, to provide increased capacity for the, potentially larger, hand-held portable market. DCS 1800 operates in the 1800 MHz band, with three times the available bandwidth and capacity of GSM, and accommodates low-power (0.25 to 1 W), small-size portable handsets. At the higher power levels this corresponds to DCS 1800 cell sizes ranging from 0.5 km (urban) to 8 km (rural) with high grade coverage. Table 15.1 provides a comparison of these systems. DCS 1800 is thus optimised more for high density, high capacity situations (not necessarily with the facility to handle fast moving mobile subscribers), to achieve a personal communications network (PCN) meeting the current communication expectations of subscribers. The DCS 1800 system was introduced within the M25 orbital motorway area in London by Mercury in 1993 as their 'one-2-one' PCN service. Handsets are controlled by smart cards to allow several users access to the same handset with separate billing.

15.4.2 Data format and modulation

In GSM 900 and DCS 1800, eight TDMA users communicate over one carrier and share one base station transceiver, thereby reducing equipment costs. At the lowest level, the GSM TDMA format consists of eight user time-slots, each of 0.577 ms duration, within a frame of 4.615 ms duration (see Figure 15.8). This frame duration is similar to DECT

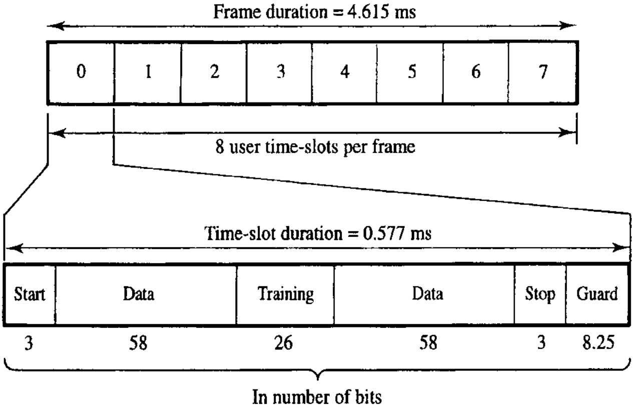


Figure 15.8 *Frame and time-slot details for data bit allocation in GSM.*

but, in GSM, the transmissions are only one way and the uplink and downlink have *separate* frequency allocations as they use frequency division duplex. TDMA users communicate by transmitting a burst of data symbols within their allotted time-slot in each frame. Each TDMA data burst contains 156.25 bits consisting of 116 coded speech bits, 26 training bits and 14.25 start, stop and guard bits (see Figure 15.8). This results in an overall transmitted bit rate of 270.8 kbit/s. GSM is relatively complex with significant overhead for control signalling and channel coding. However, because of the resulting redundancy, signal quality can be maintained even if one out of five frames is badly corrupted due to multipath, interference or noise induced errors.

GSM uses Gaussian minimum shift keying (GMSK) modulation with a bandwidth–time product of 0.3, section 11.4.6. With its Gaussian prefiltering, GMSK generates very low adjacent channel interference (greater than 40 dB below the in-band signal). The GMSK signal is transmitted at the bit rate of 270.8 kbit/s within a bandwidth of 200 kHz, resulting in a spectral (or bandwidth) efficiency of 1.35 bit/s/Hz. With 8 TDMA users sharing a 200 kHz channel, Figure 15.8, GSM has essentially the same spectral capacity (in terms of number of users per unit bandwidth) as the existing analogue TACS system. However, GSM achieves a higher overall capacity (in bit/s/Hz/km^2) by exploiting the digital signal's greater robustness to interference. Specifically, GSM operates at a signal-to-interference ratio of 9 dB while TACS requires about 18 dB. Consequently, a GSM system achieves a higher frequency reuse efficiency by being able to use smaller cells with cell cluster sizes of nine to twelve. GSM in the UK has two operators, Vodafone and Cellnet. The total available radio channels, per base station, is $8 \times 125 = 1,000$ simultaneous mobile users. DCS 1800 which, in the UK, is licensed to Mercury and the Harrison Communications Orange systems, offers three times the number of radio channels and twice the capacity of GSM, Table 15.1. The GSM system was, in 1996, used in 270 networks in 98 countries.

15.4.3 Speech and channel coding

In order to achieve spectrally efficient coding with toll quality speech, GSM employs an enhancement of LPC, section 9.7.1, with residual pulse excitation and a long term prediction [Gray and Markel]. Speech is processed in 20 ms blocks to generate 260 bits, resulting in a bit rate of 13 kbit/s. There is an inherent long delay in the coder, however, of 95 ms which necessitates echo cancellation. There are now provisions in GSM to accommodate half-rate speech coders which will essentially double the system capacity while maintaining similar speech quality.

Because of the low bit rate in this coder, speech quality is quite sensitive to bit errors. GSM overcomes this with channel coding in the form of 3-bit CRC error detection (Chapter 10) on 50 of the 182 most significant bits and half-rate convolutional coding with Viterbi decoding (Chapter 10) to protect further the 182 bits, Figure 15.9. The remaining 78 out of 260 bits are less important in achieving high speech quality and are left unprotected. The redundancy introduced by this channel coding results in an overall bit rate of 22.8 kbit/s (i.e. 456 bits transmitted in 20 ms). Furthermore, these 456 coded bits are interleaved (see Chapter 10) over eight TDMA time-slots to protect against burst

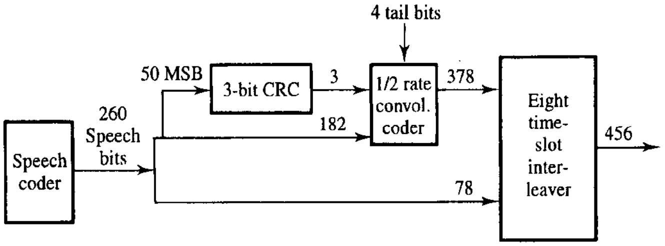


Figure 15.9 *GSM channel coding technique to assemble a 20 ms time-slot.*

errors resulting from Rayleigh fading. In addition to this channel coding, data encryption can also be used to achieve secure communications. It is this coding of digital data that gives GSM increased resilience to interference and hence more intense frequency reuse for high subscriber capacity.

15.4.4 Other operational constraints

Channel equalisation is required to overcome multipath-induced ISI. Moreover, due to the time-varying nature of the multipath fading channel, a user encounters a different channel impulse response at every TDMA burst. Thus, it is necessary to incur the overhead of transmitting a known training sequence in each time-slot, Figure 15.8, to allow the receiver to learn the channel impulse response and to adapt its filter coefficients accordingly. Furthermore, because the fading is potentially rapid in a mobile radio system, the channel response can change appreciably during a single TDMA burst. Consequently, the equaliser must be adaptively updated by tracking the channel variations. The GSM recommendations do not specify a particular equalisation approach, but the signal structure does lend itself to the method of maximum likelihood sequence estimation with Viterbi decoding.

For a given cellular layout and frequency plan, interference is reduced by proper use of adaptive power control, handover, discontinuous transmission and slow frequency hopping. For GSM, adaptive power control is mandatory for the mobile which has a transmit power dynamic range of about 30 dB (i.e. 20 mW to 20 W) adjusted at a rate of 2 dB every 60 ms, to achieve constant received signal power at the base station.

The GSM handover strategy [Lee 1995] is based on finding a base station with equal or higher received signal strength, regardless of the received signal level from the current base station. The use of slow frequency hopping (FSK) amongst carrier channels is a useful diversity method against Rayleigh fading. Since fading is independent for frequency components separated by greater than the coherence bandwidth of the channel, this frequency agility reduces the probability that the received signal will fall into a deep fade for a long duration. This is especially effective for a slowly moving or stationary mobile which might otherwise experience a deep fade for a relatively long time.

Due to the variability in cell sizes and distances, propagation times from transmitter to receiver can range from about 3 to 100 μs. To ensure that adjacent TDMA time-slots from different mobile transmitters do not overlap at the base station receiver, each mobile must transmit its TDMA bursts with timing advances consistent with its distance from the base station. This timing information is intermittently measured at the base station and sent to each mobile to ensure that this is achieved.

15.5 Code division multiple access (CDMA)

One multiple access technique widely adopted in communication systems, frequency division multiplex access (FDMA), allocates to each subscriber a narrow frequency slot within the available channel, Figure 5.12. An alternative TDMA technique allocates the entire channel bandwidth to a subscriber but constrains him to transmit only regular short bursts of wideband signal. Both these accessing techniques are well established for long haul terrestrial, satellite and mobile communications as they offer very good utilisation of the available bandwidth.

15.5.1 The CDMA concept

The inflexibility of these coordinated accessing techniques has resulted in the development of new systems based on the uncoordinated spread spectrum concept [Dixon, Lee 1993]. In these systems the bits of slow speed data traffic from each subscriber are deliberately multiplied by a high chip rate spreading code, $s_k(n)$, forcing the low rate (narrowband data signal) to fill a wide channel bandwidth, Figure 15.10. Spreading ratios, i.e. ratios of the transmitted (chip) bandwidth to data (bit) bandwidth, are typically between 100 and 10,000. (This is in contrast to the longer duration M-ary symbols of Chapter 11. In CDMA, the symbol rate is represented by the chips of spreading code which are of much shorter duration than the information digits.) Many subscribers can then be accessed by allocating a unique, orthogonal, spreading code, $s_k(n)$, to each, Figure 15.10. This constitutes a code division multiple access (CDMA) system. The signals, which are summed in the channel, have a flat, noise-like, spectrum allowing each individual transmission to be effectively hidden within the multiple access interference.

In the receiver, detection of the desired signal is achieved by correlation, section 2.6, against a local reference code, which is identical to the particular spread spectrum code employed prior to transmission, Figure 15.10, (i.e. $s_k(n)$ is used to decode the subscriber k transmissions). The orthogonal property of the allocated spreading codes means that the output of the correlator is essentially zero for all except the desired transmission. Thus correlation detection gives a processing gain or SNR improvement, G_p, equal to the spreading ratio:

$$\begin{aligned} G_p &= 10\log_{10}\left(\frac{\text{transmitted signal bandwidth}}{\text{original data bandwidth}}\right) \text{ (dB)} \\ &= 10\log_{10}\left(\frac{R_c}{R_b}\right) \text{ (dB)} \qquad (15.13(a)) \end{aligned}$$

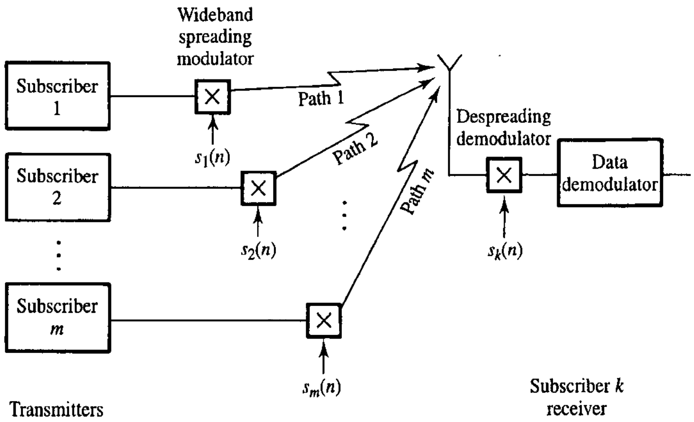


Figure 15.10 *Principle of code division multiple access (CDMA).*

where R_c is the chip rate and R_b the binary digit rate. Equivalently this can be expressed as:

$$G_p = 10\log_{10}(T_bB) \quad \text{(dB)} \tag{15.13(b)}$$

where B is the bandwidth of the spreading code and T_b is the, relatively long, bit duration of the information signal.

The following (trivial) example shows how a short 3-chip spreading code, $s(n)$, can be added modulo-2 to the slow speed data. Each data bit has a duration equal to the entire 3-chip spreading code, and is synchronised to it, to obtain the transmitted product sequence, $f(n)$.

Data	+1	+1	+1	−1	−1	−1	+1	+1	+1
Spreading code	+1	−1	+1	+1	−1	+1	+1	−1	+1
Product sequence	+1	−1	+1	−1	+1	−1	+1	−1	+1

15.5.2 Receiver design

Both coherent receiver architectures (i.e. the active correlator and matched filter, of Figure 15.11) can be used for decoding or despreading the CDMA signals. One matched filter receiver [Turin 1976] implements convolution (section 4.3.3) using a finite impulse response filter whose coefficients are the time reverse of the expected sequence, to decode the transmitted data. (Note that in the example above, however, the code is symmetric.) Thus the filter coefficients in Figure 15.11(a), which is a repeat of Figure 8.34, would be $h_1 = +1$, $h_2 = -1$ and $h_3 = +1$ for the above 3-chip code. This design of receiver is optimum from an SNR standpoint since the receiver impulse response replicates, or reproduces, the expected transmitted signal. The output is given by the convolution of the received signal with the stored weight values, as shown previously in Chapters 4 and 8.

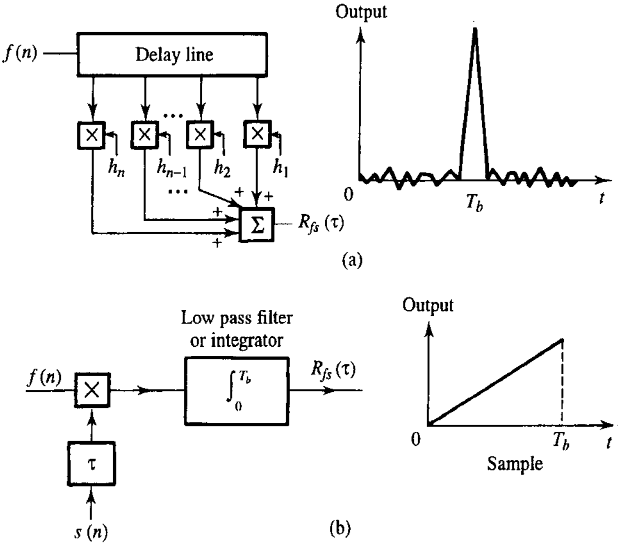


Figure 15.11 *Spread spectrum receiver typical outputs: (a) matched filter; (b) active correlator.*

The signal to interference ratio at the filter input is given by:

$$\left(\frac{S}{I}\right)_{in} = \frac{S}{I_o B} \tag{15.14}$$

where I_o is the power spectral density of all unwanted signals, S is the desired signal power and B is the bandwidth of the spread signal. The output SNR, after adding the processing gain arising from matched filter detection, equation (15.13), is then:

$$\left(\frac{S}{N}\right)_{out} = \frac{S}{I_o f_m} \tag{15.15}$$

where f_m (= R_b) is the bandwidth of the desired information signal, i.e. $1/T_b$ in equation (15.13(b)).

If the receiver is not synchronised then the received signal will propagate through the matched filter which outputs the complete correlation function. The large peak confirms that the correct code is indeed being received and provides accurate timing information for the received signal, Figure 15.11(a). Note that with binary stored weight values the filter design is especially simple. Semiconductor suppliers currently market single chip 'correlators' with up to 64 binary-weighted taps at 20 Mchip/s input rates.

When timing information is already available then the simpler active correlator receiver, Figure 15.11(b), can be used (also shown in Figure 15.10). This receiver only operates correctly when the local receiver reference $s_k(t)$ is accurately matched, and correctly timed, with respect to the spreading code within the received signal $f(t)$. Synchronisation can be obtained by sliding the reference signal through the received signal. This can be an extremely slow process, however, for large T_bB spreading waveforms.

The pseudo-random bit sequence (PRBS) or pseudo-noise (PN) sequence, as obtained using a linear feedback shift register (Figure 13.15), can be used as the spreading code. For example one 7-chip PN sequence is $1, 1, 1, -1, -1, 1, -1$ and a 15-chip PN sequence is $1, 1, 1, 1, -1, 1, -1, 1, 1, -1, -1, 1, -1, -1, -1$ [Golomb *et al.*]. As the spreading code is often phase modulated onto the carrier and coherently demodulated $+1/-1$ is a more appropriate representation for the 1/0 binary digits. These codes are repeated cyclically to form continuous spreading codes. For spread spectrum applications the most important properties of PN sequences are that the *cyclic* autocorrelation sidelobe levels are small. For a sequence of K chips the sidelobes are equal to -1, Figure 15.12(a), with a peak amplitude of K. (Figure 15.12 is a repeat of Figure 13.16 without normalisation.) The aperiodic autocorrelation for an isolated PN sequence transmission has peak sidelobes of $< \sqrt{K}$, Figure 15.12(b). The low level of cyclic autocorrelation sidelobes (-1) in Figure 15.12(a) only occurs for the zero Doppler shift case, while the plot with Doppler offset is more like the aperiodic performance of Figure 15.12(b).

The PN sequence produces an approximate balance in the number of 1 and -1 digits and its 2-valued autocorrelation function in Figure 15.12(a) closely resembles that of a white noise waveform, Figure 3.28. The origin of the name pseudo-noise is that the digital signal has an autocorrelation function which is very similar to that of a white noise signal. Note that the rise time and fall time for the peak of this function is one chip period in duration and hence its bandwidth is directly related to the clock, or chip, rate of the spreading sequence.

The key facet of the CDMA system is that there is discrimination against narrowband and wideband interference, such as signals spread with a code sequence which is different

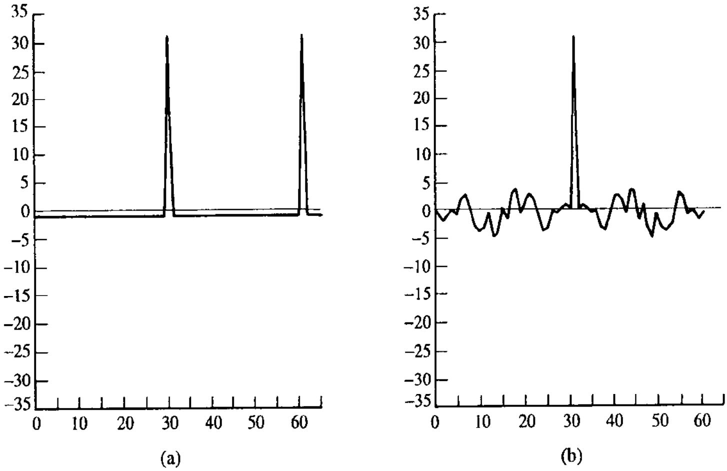


Figure 15.12 *PN code autocorrelation function: (a) for continuous $K = 31$ chip PN coded transmission; and (b) burst or aperiodic transmission again for $K = 31$.*

to that used in the receiver, Figure 15.13. The level of the suppression, which applies to CW as well as PN modulated waveforms, is given by the processing gain of equation (15.13).

15.5.3 Spreading sequence design

Maximal length sequences

Maximal length shift register sequences or m-sequences are so called due to their property that all possible shift register states except the all-zero state occur in a single, K length, cycle of the generated sequence [Golomb *et al.*]. Therefore for a shift register with n elements, the longest or maximum (m) length sequence which can be generated is $K = 2^n - 1$, section 13.4.2.

Due to the occurrence of all shift register states (except the all-zero state) each m-sequence will consist of 2^{n-1} ones and $(2^{n-1} - 1)$ zeros. There will be one occurrence of a run of n ones, and one run of $(n - 1)$ zeros. The number of runs of consecutive ones and zeros of length $(n - 2)$ and under will double for each unit reduction in run length and be divided equally between ones and zeros, see section 13.4.2 on PRBS sequences. Typical m-sequence generator feedback connections were shown in Table 13.3 and the overall size of the m-sequence set for different sequence lengths is given in Table 15.2.

The correlation properties of the m-sequence family are interesting due to their flat periodic autocorrelation sidelobes, Figure 15.12(a), which provide a good approximation to an impulsive autocorrelation function. The cross-correlation profile for a pair of m-sequences (forward and time reversed) is more typical of the generalised cross-correlation function.

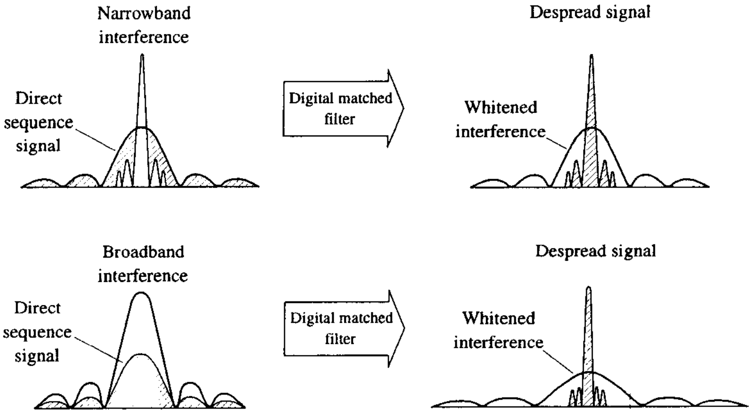


Figure 15.13 *Narrowband and wideband interference reduction in spread spectrum signals.*

Table 15.2 *Set sizes and periodic cross-correlation peak levels for m-sequences and Gold codes.*

		m-sequences		*Gold codes*	
n	K	*Set size*	*Peak level*	*Set size*	*Peak level*
3	7	2	5	9	5
4	15	2	9	17	9
5	31	6	11	33	9
6	63	6	23	65	17
7	127	18	41	129	17
8	255	16	95	257	33
9	511	48	113	513	33
10	1023	60	383	1025	65
11	2047	176	287	2049	65
12	4095	144	1407	4097	129

It can be seen from Table 15.2 that the available set size is very much smaller than the sequence length, K, particularly in the case of the even shift register orders. Therefore, as a multiple access code set, the PN sequence does not provide adequate capability for system subscribers who each require their own, unique, code assignment. An analytical expression for bounds on the maximum cross-correlation level has now become available [Pursley and Roefs] for the aperiodic sequence cross-correlation function. These sequences are not really appropriate for CDMA applications as the cross-correlation levels are too large. m-sequence sets in isolation are not, therefore, favoured for practical, high traffic capacity CDMA systems, hence the development of other sequence sets.

Gold codes

Selected pairs of m-sequences exhibit a three-valued periodic cross-correlation function, with a reduced upper bound on the correlation levels as compared with the rest of the m-sequence set. This m-sequence family subset is referred to as the preferred pair and one such unique subset exists for each sequence length. For the preferred pair of m-sequences of order n, the periodic cross-correlation and autocorrelation sidelobe levels are restricted to the values given by $(-t(n), -1, t(n)-2)$ where:

$$t(n) = \begin{cases} 2^{(n+1)/2} + 1, & n \text{ odd} \\ 2^{(n+2)/2} + 1, & n \text{ even} \end{cases} \tag{15.16}$$

The enhanced correlation properties of the preferred pair can be passed on to other sequences derived from the original pair. By a process of modulo-2 addition of the preferred pair, Figure 15.14, the resulting derivative sequence shares the same features and can be grouped with the preferred pair as a member of the newly created family. This process can be repeated for all possible cyclically shifted modulo-2 additions of the preferred pair of sequences, producing new family members at each successive shift. A zero-shift 31-chip code can be generated by modulo-2 addition of two parent Gold sequences:

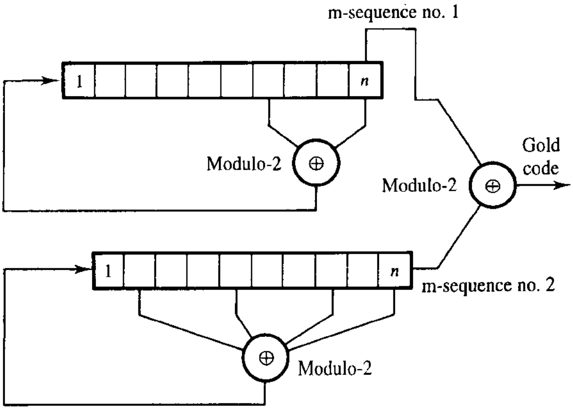


Figure 15.14 *Generation of a Gold code sequence for use in CDMA.*

$$\begin{array}{l}
+1+1+1+1+1-1-1-1+1+1-1+1+1+1-1+1-1 \quad \text{etc} \quad -1+1+1-1-1 \\
+1+1+1+1+1-1-1+1-1-1+1+1-1-1-1-1+1 \quad \text{etc} \quad -1+1+1+1-1 \\
\hline
-1-1-1-1-1-1-1+1+1+1+1-1+1+1-1+1+1 \quad \text{etc} \quad -1-1-1+1-1
\end{array}$$

and the corresponding five-chip shifted Gold code for the second sequence would be:

$$\begin{array}{l}
+1+1+1+1+1-1-1-1+1+1-1+1+1+1-1+1-1 \quad \text{etc} \quad -1+1+1-1-1 \\
-1-1+1-1-1+1+1-1-1-1-1+1-1+1+1-1+1 \quad \text{etc} \quad +1+1+1+1+1 \\
\hline
+1+1-1+1+1+1+1-1+1+1-1-1+1-1+1+1+1 \quad \text{etc} \quad +1-1-1+1+1
\end{array}$$

For this case, i.e. with an $n = 5$ generating register, any shift in initial condition from zero to 30 chip can be used (a 31-chip shift is the same as the zero shift). Thus, from this Gold sequence generator, 33 maximal length codes are available when the preferred pair are added as valid Gold codes. Extending this any appropriate two-register generator of length n can generate $2^n + 1$ maximal length sequences (of $2^n - 1$ code length) plus the preferred pair of sequences. The family of sequences derived from and including the original preferred pair are known collectively as Gold codes.

Since there are K possible cyclic shifts between the preferred pairs of m-sequences of length K, the available set size for the Gold code family is $K + 2$. The available sequence numbers for the Gold code set are compared with the available number of m-sequences in Table 15.2. It is apparent that, not only do Gold codes have improved periodic cross-correlation properties, but they are also available in greater abundance than the m-sequence set from which they are derived. However, as with the periodic m-sequence case, this attractive correlation property is lost as soon as the data traffic modulation is added.

Gold code shift register based designs exist, the direct approach consisting of two m-sequence generators employing the necessary preferred pair of feedback polynomials. This type of generator is shown in Figure 15.14 and can be used to synthesise all the preferred pair derived sequences in the Gold code by altering the relative cyclic shift through control of the shift register initial states. Switching control is also required over the output 'exclusive or' operation in order that the pure m-sequences can also be made available.

Gold codes are widely used in spread spectrum systems such as the international Navstar global positioning system (GPS), which uses 1023 chip Gold codes for the civilian clear access (C/A) part of the positioning service.

Walsh sequences

Walsh sequences have the attractive property that all codes in a set are precisely orthogonal. A series of codes $w_k(t)$, for $k = 0, 1, 2, \cdots, K$, are orthogonal with weight K over the interval $0 \leq t \leq T$, section 2.5.3, when:

$$\int_0^T w_n(t)w_m(t)\,dt = \begin{cases} K, & \text{for } n = m \\ 0, & \text{for } n \neq m \end{cases} \tag{15.17}$$

where n and m have integer values and K is a non-negative constant which does not depend on the indices m and n but only on the code length K. This means that, in a *fully synchronised* communication system where each user is uniquely identified by a different Walsh sequence from a set, the different users will not interfere with each other *at the proper correlation instant*, when using the same channel.

Walsh sequence systems are limited to code lengths of $K = 2^n$ where n is an integer. When Walsh sequences are used in communication systems the code length K enables K orthogonal codes to be obtained. This means that the communication system can serve as many users per cell as the length of the Walsh sequence. This is broadly similar to the CDMA capability of Gold codes, Table 15.2.

There are several ways to generate Walsh sequences, but the easiest involves manipulations with Hadamard matrices. The orders of Hadamard matrices are restricted to the powers of two, the lowest order (two) Hadamard matrix being defined by:

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{15.18}$$

Higher-order matrices are generated recursively from the relationship:

$$H_K = H_{K/2} \otimes H_2 \tag{15.19}$$

where $\otimes$ denotes the Kronecker product. The Kronecker product is obtained by multiplying each element in the matrix $H_{K/2}$ by the matrix H_2. This generates K codes of length K, for $K = 2, 4, 8, 16, 32$, etc. Thus for $K = 4$:

$$H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \tag{15.20(a)}$$

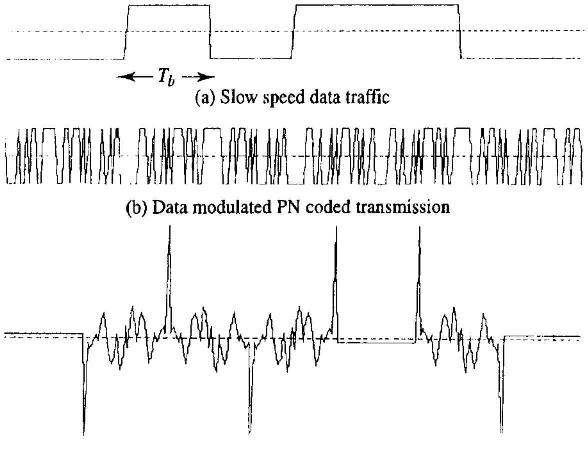
The difference between the Hadamard matrix and the Walsh sequence is only the order in which the codes appear; the codes themselves are the same. The reordering to Walsh sequences is done by numbering the Walsh sequences after the number of zero crossings the individual codes possess, to put them into 'sequency' order. The Walsh sequences thus result when the H_4 rows are reordered:

$$W_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix} \tag{15.20(b)}$$

Due to orthogonality, when the autocorrelation response peaks the cross-correlations for all other time synchronised Walsh sequenced transmissions are zero. The time sidelobes, however, in autocorrelated and cross-correlated Walsh sequences have considerably *larger* magnitudes than those for Gold or PN sequences. Also the orthogonal performance no longer applies in the imperfect (multipath degraded) channel.

15.5.4 Data modulation

Typically high chip rate short PN, Gold or Walsh coded CDMA spreading sequences are multiplied by the slower data traffic and this signal is used to phase shift key a carrier as described in Chapter 11. When the received signal is fed into a matched filter receiver then the baseband output, as shown in Figure 15.15, results. Figure 15.15 shows a 31-chip spreading code which is keyed by the low rate data traffic sequence −1, −1, +1, −1, +1, +1, −1, −1, before reception in the 31-tap matched filter of Figure 15.11(a).



(c) Receiver matched filter response to above encoded sequence

Figure 15.15 *Data modulation and demodulation on direct sequence coded signals.*

The matched filter or correlation receiver only provides a sharply peaked output if the correct codeword is received. CDMA systems thus rely on the auto and cross-correlation properties of codes such as those described above to minimise multiple access interference between subscribers.

15.5.5 Multipath responses

Multipath propagation, Figure 15.1, is experienced by nearly all mobile systems resulting in a time varying fading signal as the mobile moves position, Figure 15.16. (Figure 15.16 shows the instantaneous received power for a mobile, with respect to the local spatial average or mean power level, measured when travelling round a path, at approximately fixed range, from the base station.) This signal comprises the sum of two or more delayed path responses, with Doppler frequency offsets. (Note, therefore, that the channel multipath will destroy the orthogonal properties of the spreading codes.) If a CDMA signal has sufficiently wide bandwidth (i.e. greater than the coherence bandwidth of the channel) it is able to resolve the individual multiple paths, producing several peaks at the matched filter output at different time instants.

For efficient operation the receiver must collect and use all the multipath received signals in a coherent manner. It does this by using a channel equaliser which continuously adapts to the time varying mobile channel characteristic resulting, effectively, in a filter which is matched to this characteristic. The RAKE filter [Turin 1980], in which the weights in the sum bus of a tapped delay line are derived by measuring the channel impulse response, is an example. The RAKE filter typically provides 3 dB saving in power for a given error rate in a typical urban channel.

A RAKE receiver can also be configured to talk simultaneously to two separate base stations from different, but closely spaced, cell sites. This provides superior performance at the cell boundary, where the signal strength is weakest, and can also be used to achieve

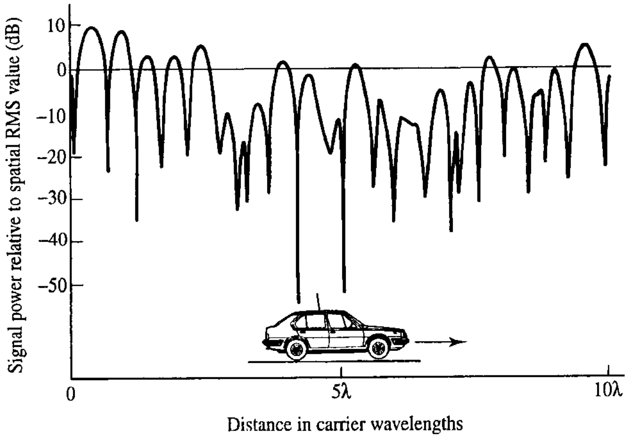


Figure 15.16 *Received power profile for a moving vehicle, as in Figure 12.28.*

a soft handover capability between cells.

15.5.6 The IS-95 system

CDMA cellular systems in which the spreading ratio, or K value, for a cell is approximately 127 are under design. In the US IS-95 CDMA standard, the basic user transmission (speech coder output) rate is 9.6 kbit/s. This is spread with a channel chip rate of 1.2288 Mchip/s (implying a total spreading factor of 128). Detailed analysis has shown that this T_bB product is sufficient to support all the expected users within a typical cell. 1.2288 Mbit/s is also an acceptable speed for the VLSI modem electronics. The spreading process deployed is different on the downlink and uplink paths.

The downlink information, transmitted to the mobile, is split into four channels. These are pilot, synchronisation, paging and traffic channels. The receiver must demodulate these channels, to acquire the necessary synchronisation and systems information etc., before data transmission can start.

The pilot channel, which is transmitted with 20% of the total base station power, contains no data and is coded only with a $2^{15} - 1 = 32,767$ chip (short) PN code and a predetermined (all zeros) Walsh sequence. This signal permits the receiver to measure the strength and delay of all the nearby base station transmissions in order to select the closest ones yielding the greatest received power. (All base stations transmit the same PN code but a different relative delay, or code phase, is allocated to each individual station.) The pilot signal also permits the measurement, using a correlator, of the channel multipath response at the mobile, Figure 15.2, this response being used to continuously adjust the timing delay and gain of the taps in the RAKE receiver. The synchronisation channel, which is convolutionally encoded, interleaved, and then coded with a separate predetermined Walsh sequence, provides the Walsh sequence allocation information for the mobile. The paging channel is convolutionally encoded, interleaved, encrypted with a long PN sequence and then coded with the user specific Walsh sequence. This provides access to the system overhead information and specific messages for the mobile handset. Finally the traffic channel data is encoded using a ½ rate convolutional code (section 10.9), interleaved, Figure 10.23, spread by one of 64 orthogonal Walsh sequences and encripted with the long PN sequence. It contains the embedded power control signals which adjust the transmitted power level every 1.25 ms.

Each mobile in a given cell is assigned a different Walsh spreading sequence, providing perfect separation among the signals from different users, at least for a single-path channel. To reduce interference between mobiles that use the same spreading sequence in different cells, and to provide the desired wideband spectral characteristics (from Walsh functions which have variable power spectral characteristics), all signals in a particular cell are subsequently scrambled using the short PN sequence which is generated at the *same* rate as the Walsh sequence (1.2288 Mchip/s). Orthogonality among users within a cell is preserved because all signals are scrambled identically and the transmissions are synchronous.

On the uplink, the individual transmissions from mobiles are asynchronous and a slightly different spreading strategy is used in which the user data stream is first convolutionally encoded by a rate 1/3 encoder (Chapter 10). Then, after interleaving, each block of six encoded symbols is mapped to one of the 64 encoded orthogonal Walsh sequences (i.e. using a 64-ary orthogonal signalling system). This concept is implied in Figure 11.45 where 3 symbols are effectively mapped into one of 8 orthogonal sequences. A final fourfold spreading, giving the same transmission rate of 1.2288 Mchip/s, is achieved by expanding each data bit in the 307.2 kchip/s data stream with a 4-chip subsequence derived from a long PN spreading code. The rate 1/3 coding and the mapping onto Walsh sequences achieves a greater tolerance to interference than would be realised from traditional PN spreading and offers the possibility of employing more sophisticated receiver (array) processing in the base station.

For CDMA systems to work effectively all signals must be received with comparable power level at the base station. If this is not so then the cross-correlation levels of unwanted stronger, nearby, signals may swamp the weaker wanted, more distant, signal. In addition to the 'near–far' problem, which arises from very different path lengths, different fading and shadowing effects are experienced by different transceivers at the same distance from the base station.

If the receiver input power from one CDMA user is η_1 then for k equal power, active multiple access users, the total receiver input power is $k\eta_1$. The receiver has a processing gain, given by G_p in equation (15.13), to discriminate against other user multiple access interference. Thus the receiver output SNR is given by:

$$\left(\frac{S}{N}\right)_{out} = \frac{\eta_1}{k\eta_1} G_p = \frac{G_p}{k} \tag{15.21}$$

or, for a (given) receiver output SNR, required to reliably detect the data, the multiple access capacity can be estimated from:

$$k = \frac{G_p}{\left(\frac{S}{N}\right)_{out}} \tag{15.22}$$

CDMA cellular systems must thus deploy power control on the uplink to adjust mobile transmitter power levels, dependent on their location in the cell, in order to ensure equal received power level at the base station for all users. Fast closed-loop control is used, commands being transmitted at a rate of 800 bit/s, within the speech frames. The reduction in transmitter power away from the cell boundary, i.e. closer to the base station, also saves battery drain further prolonging the mobile's talk time. These CDMA systems reuse identical code sets in each adjacent cell and so form a single cell cluster system.

At both the base station and the mobile, RAKE receivers are used to resolve and combine multipath components, significantly reducing fading. This receiver architecture is also used to provide base station diversity during 'soft' handoffs, whereby a mobile making the transition between cells maintains simultaneous links with both base stations during the transition. Deployment of IS-95 systems in the Los Angeles, California area started in 1995.

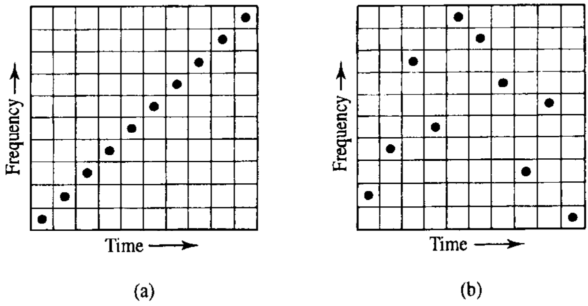
Benefits of CDMA

Although CDMA represents a sophisticated system which can only operate with accurate uplink power control, it offers some unique attractions for cellular mobile communications. The voice activity factor in a normal conversation can also be exploited to switch off transmission in the quiet periods further reducing battery power requirement and reducing CDMA interference.

Besides the potential of offering higher capacity and flexibility, there are several attributes of CDMA that are of particular benefit to cellular systems. These are summarised below:

- **No frequency planning needed** - In FDMA and TDMA, the frequency planning for a service region is critical. Because the frequency bands allocated to CDMA can be reused in every CDMA cell, no frequency planning is required. As CDMA deployment grows, there is no need to continually redesign the existing system to coordinate frequency planning.
- **Soft capacity** - For FDMA or TDMA, when a base station's frequency bands or time slots are fully occupied, no additional calls can be accommodated by that cell. Instead of facing a hard limit on the number of available channels a CDMA system can handle more users at the expense of introducing a gradual degradation of C/I, and therefore link quality. CDMA service providers can thus trade off capacity against link quality.
- **Simpler accessing** - Unlike FDMA and TDMA, coordination of signals into prespecified frequency allocations or timeslots is no longer required in CDMA.
- **Micro-diversity** - CDMA mitigates multipath propagation using a RAKE receiver. This combines all the delayed signals within the cell to improve the received signal-to-noise ratio over other cellular systems.
- **Soft handover** - Soft handover refers to a CDMA call being processed simultaneously by two base stations while a mobile is in the boundary area between two cells. CDMA is able to perform soft handover because all users in the system share the same carrier frequency, so no retuning is involved in switching from one base station to another as required by FDMA and TDMA systems.
- **Dynamic power control** - Stringent power control is essential to maximise CDMA system capacity. This is exercised by embedding power control commands into the voice traffic. The average transmitted power of a CDMA mobile is thus significantly less than that of FDMA or TDMA systems.
- **Lower battery dissipation rates** - As the transmitted power in a handset is reduced, so is the battery dissipation, prolonging the available talk time.

All these benefits are incorporated in the IS-95 specification for CDMA mobile cellular systems [IS-95]. It is also proposed to use CDMA at 1.9 GHz for personal communications from 1995 onwards. Other systems which use CDMA, or spread spectrum techniques, are the NAVSTAR-GPS satellite based navigation systems. This is a ranging system in which a correlation peak determines the time of arrival of a signal and hence the range to one of the many satellites orbiting overhead, thus establishing precise timing and position information.



(a) (b)

Figure 15.17 *(a) Representation for linear step FH waveform with* $K = 10$*; and (b) example of a* 10×10 *random frequency-hop pattern.*

15.5.7 Frequency hopped transmission

An alternative to PSK modulation with the spreading sequence is to alter, hop or shift the transmitter frequency in discrete steps across the spread bandwidth. Figure 15.17 shows in (a) a hopping pattern where the selected frequency increases linearly with time and in (b) a random hopping pattern. With these frequency hopped (FH) techniques a spread spectrum communication system can be designed, in principle, with any desired number of frequency slots, several hundred being typical. Individual frequencies are selected in a frequency synthesiser by detecting several adjacent chips of the spreading code and decoding the word to identify the transmit frequency. Orthogonality between adjacent frequency slots is ensured if the dwell time on each frequency, T_h, equals the reciprocal of the slot separation, see section 11.5.1 on MFSK. FH offers a much flatter transmitted spectrum than spread spectrum PSK, Figure 15.18. Also, for a given RF bandwidth, the FH dwell time, T_h, is much longer than the equivalent chip time, T_c, when direct sequence PSK techniques are used, easing synchronisation acquisition in the FH system. For slow FH systems, such as those sometimes used by the military, coherence between hops is not required as the hopping rate is much less than the bit rate. Here the spread spectrum technique is used primarily to achieve protection against hostile jamming signals and to overcome slow fading.

15.6 Mobile satellite based systems

A current development in satellite communications is to extend communication to the mobile subscriber. This requires the system to handle large numbers of small capacity earth stations which have relatively low gain antennas compared to the stationary antennas which are employed in the INTELSAT and VSAT systems. One mobile communications example is the INMARSAT ship-to-shore telephone and data service which is used on large cruise ships, by construction workers, and by UN peacekeepers. INMARSAT A stations, whose model M (briefcase sized) terminals cost £20,000,

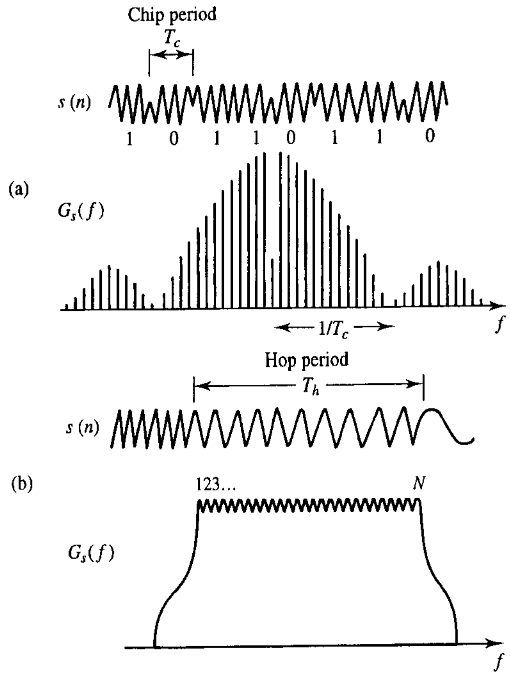


Figure 15.18 *Time domain and frequency domain representations of spread spectrum waveforms: (a) phase modulated transmissions; (b) frequency hopped transmissions.*

provide 64 kbit/s data rate links for speech on which call costs are £3 per minute (1996 prices). The cheaper C terminals have only 600 bit/s capability through the MARISAT geostationary satellites using L-band UHF transmissions. In these systems the mobile has only limited motion and hence a modest gain (10 to 25 dB) steered dish is still employed as the receiving/transmitting antenna.

Another mobile example is the Skyphone system which routes digitally coded speech traffic from commercial aircraft to a satellite ground-station using the INMARSAT satellites as the space-borne repeaters [Schoenenberger]. Here the antenna gain is lower as it has an omnidirectional coverage pattern but with sophisticated speech coding the data rate is reduced to approximately 12 kbit/s to compensate for the low power link budget.

For personal communications, with individual subscribers in mind, the 1992 World Radio Administrative Conference (WRAC) made frequency allocations at L-band (1.6 GHz) for mobile-to-satellite, and S-band (2.5 GHz) for satellite-to-mobile, channels. Here mobile receivers will again use antennas with very modest gain (0 to 6 dB). The satellites will require large antennas to provide the required spot beam coverage, particularly when the link budget is marginal. For this reason alternative systems employing inclined highly elliptical orbit (HEO) or low earth orbit (LEO) satellites are proposed, Figure 14.25.

The most promising inclined HEO is the Molniya orbit, Figure 14.25. It is asynchronous with a period of 12 hours. Its inclination angle (i.e. the angle between the orbital plane and the earth's equatorial plane) is 63.4° and its apogee (orbital point furthest from earth) and perigee (orbital point closest to earth) are about 39,000 km and 1,000 km respectively. The Molniya orbit's essential advantage is that, from densely populated northern latitudes, a satellite near apogee has a high elevation angle and a small transverse velocity relative to an earth station. Its high elevation angle reduces the potential impact on the link budget of shadowing by local terrain, vegetation and tall buildings. (The latter can be especially problematic for mobile terminals in urban areas.) Its small angular velocity near apogee makes a satellite in this orbit appear almost stationary for a significant fraction of the orbital period. Three satellites, suitably phased around a Molniya orbit, can therefore provide continuous coverage at a high elevation angle. Modest gain, zenith pointed, antennas can be used for the mobile terminals, the quasi-stationary nature of the satellite making tracking unnecessary. On either side of apogee satellites in HEOs have the disadvantage of producing large Doppler shifts in the carrier frequency due to their relatively large radial velocity with respect to the earth station. Handover mechanisms must also be employed to allow uninterrupted service as one satellite leaves the apogee region and another enters it.

LEO systems will be implemented using large constellations of satellites in low, circular, earth orbit. Their essential advantage will be the relatively low FSPL compared to GEO and HEO systems (see equation (12.71)). Proposed satellite numbers to implement these systems range from 14 to 77 with spot beams being used to achieve cellular coverage at the earth's surface and to permit the reuse of the same spectral allocation several times through each satellite. It is proposed to operate such systems with < ½ W of mobile transmitter power for only 2 W of battery power drain. One proposal for L-band satellite transmission is the Motorola Iridium system which initially aimed to use 77 LEO satellites, each with 37 spot beams or cells, Figure 14.44. The cells will move rapidly over the earth's surface with the relative satellite motion. This could provide a worldwide space-based personal cellular system for use with simple handsets sometime beyond the year 2000. It is likely that in the future subscriber mobile handsets will be reprogrammable for use with either satellite or terrestial mobile systems.

It will not be possible in the systems described above to use the fixed FDM and TDM access schemes employed in the INTELSAT systems, Chapter 14. Mobile systems may have to employ different modulation and multiple accessing formats on the uplink and on the downlink. In order to allow access from low power narrowband mobile transmissions FDMA will probably be used on the uplink with a single narrowband channel allocated to each carrier or discrete transmission. On the downlink it will be preferable to employ TDMA as this is less affected by non-linearities in the satellite high power amplifiers than FDMA. Such a scheme involves extra complexity, as an on-board processor will be required on the satellite to demodulate the individual FDMA signals, regenerate them and then remodulate them in TDMA format, Figure 15.19. Also with small antenna diameters at mobile (microterminal) ground-stations the bit rates must be low, but commensurate with the bandwidth of encoded speech, Table 9.3, to give sufficient SNR

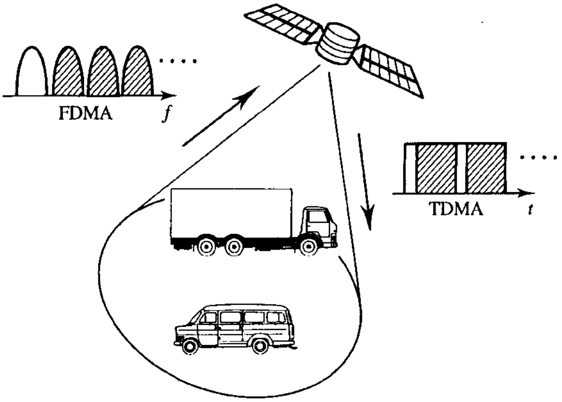


Figure 15.19 *Satellite communication to small mobile transceivers where the uplink and downlink typically use different multiple access techniques.*

for reception at the satellite. Satellite links are widely used in Europe for distributing radio pager messages to VSATs for subsequent terrestial transmission.

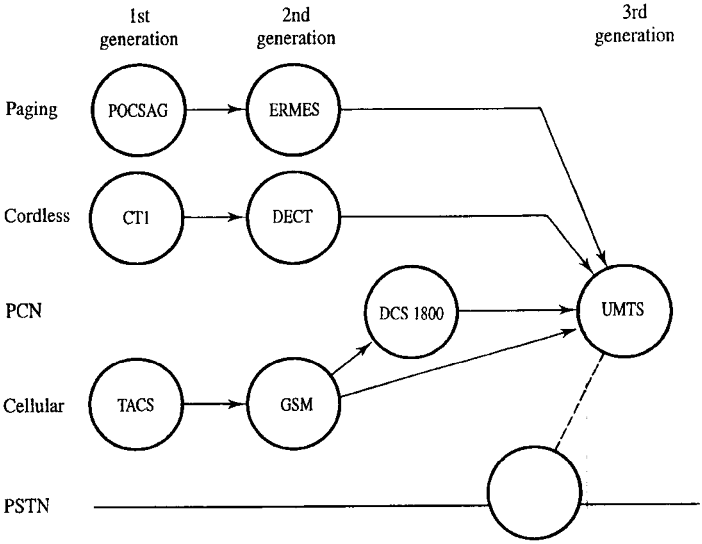


Figure 15.20 *Evolution of mobile and personal communication systems and equipment.*

15.7 The personal communications network

All the systems discussed above are progressing from first generation analogue (TACS) equipment, through second generation digital (GSM) and on to a third generation as represented by the universal mobile telecommunication service (UMTS) and future public land mobile telecommunications system (FPLMTS). These [Dasilva *et al.*] represent the personal communications network (PCN) concept, launched in 1993, for low cost mobile communications for the mass market, Figure 15.20. PCN will be a flexible service with several different price levels to meet individual subscriber needs for speech and data communication. In addressing the mass market it will offer an alternative to the wired PSTN. Figure 15.21 shows the different envisaged levels of radio communication systems in PCN. PCN aims to combine many services such as telephone, fax, teletext, etc. into one system to achieve spectral allocation benefits.

PCN also impacts on the design of short range wireless LANs, which permit interconnected equipment such as computers and printers to be quickly moved around the office. In the USA some of these products use the industrial, scientific and medical (ISM) frequency bands at 902 to 908 MHz, 2400 to 2484 MHz and 5.8 GHz where regulation is less constrained but interference may be severe.

Part of the extra PCN capacity will be achieved by using smaller microcells (picocells) or further splitting the current cellular pattern into cells which have three 120° individual sectors. With base station antennas below rooftop height the RF coverage will be very confined allowing more efficient reuse than in current, larger, cell system designs. PCN will use part of the DCS 1800 allocation, Table 15.1. The band allocations for

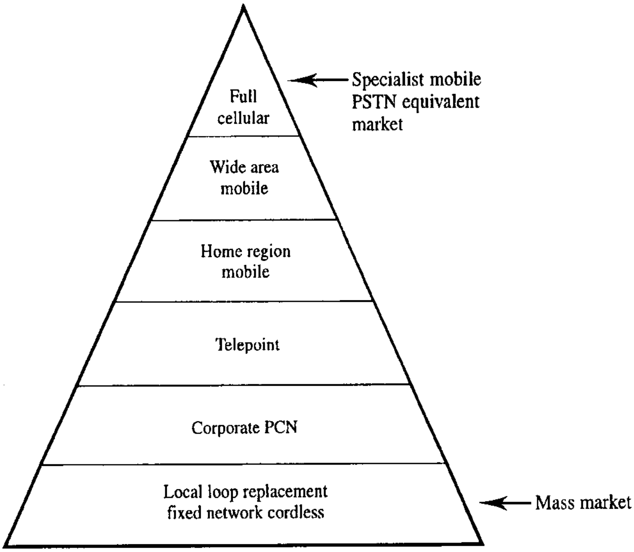


Figure 15.21 *Radio communication systems to be provided within PCN.*

FPLMTS are 1800 to 2025 MHz and 2110 to 2200 MHz which encompasses part of the DECT allocation. These systems will have to use variable rate, low delay, speech coders to carefully match the available radio channel bandwidth. In the USA PCN will be built to the personal communications service standard.

Another feature, which became available in 1997, is personal numbering to avoid the individual subscriber having separate home, office and mobile telephone numbers. This requires reprogramming of the individual handsets and the infrastructure to route incoming call to the correct destination.

15.8 Summary

Private mobile radio utilises VHF and UHF frequencies. It is not usually interfaced with the PSTN and is principally used by the emergency services, the public utilities, the haulage industry and taxi companies. The number of PMR channels available in the UK is a little over 1000. Each channel has an allocated bandwidth of 12½ kHz. Narrowband FM modulation is normally used for speech traffic while FSK modulation can be used for data transmission.

Like satellite communications, first generation cellular radio systems use analogue modulation. In the UK this generation is represented by TACS which operates using narrowband FM/FDMA with 25 kHz channels and a carrier frequency of 900 MHz. The essential feature of cellular systems is the division of the coverage area into cell clusters. The allocated frequencies are divided between the cells of a cluster. The same frequencies are also used (or reused) in the cells of the adjacent clusters. A base station at the (nominal) centre of each cluster uses modest transmit power so that interference in adjacent cells is kept to acceptable levels. Base stations are connected to the wired PSTN via switching centres. The received signal strength is subject to slow (log-normal) fading due to (multiplicative) shadowing effects and fast (Rayleigh) fading due to (additive) multipath effects.

Second generation cellular systems are digital. In Europe this generation is represented by GSM. In this system 8 TDMA users share each 200 kHz wide, 271 kbit/s, channel. The bandwidth per user is therefore 25 kHz as in TACS but overall spectrum is conserved due to the lower C/I tolerated by digital systems allowing the use of smaller cells and, consequently, more intensive frequency reuse. GSM uses GMSK modulation with $BT_b = 0.3$, LPC derivatives for speech bandwidth compression and CRC error correction. For large power delay spread the channel is frequency selective and time dispersion results in serious ISI. Adaptive equalisation is therefore required. Adaptive power control at the mobile is also used to maintain adequate received power at the base station whilst minimising interference. CDMA is more sophisticated than TDMA and it is set for major application in US cellular systems.

Third generation communications systems will integrate further the digital systems described here (and others) to provide an increased range of services to each user. These services will be based on an ISDN infrastructure and will be available to interface to all terminal equipment including those which are mobile and hand-held. This is the medium range objective at the core of the PCN concept.

This chapter has brought together many of the techniques covered in earlier chapters. It has shown how source and channel coding techniques combined with VHF, UHF or microwave transmission frequencies, and advanced receiver processing can combat ISI and multipath effects. This now permits the design and realisation of advanced communications systems which are well matched to the needs of the mobile user in the year 2000 and beyond. Such is the attraction of lightweight handsets that, in 1993, over 2% of the Western European population of 700 million individuals possessed cellular equipment and, in 1996, over 20% of the Danish population had purchased these handsets. Another major user is Asia with 6 million subscribers in 1994 and a 50% p.a. growth rate.