Chapter 1
Introduction

Commercial wireless systems and services have undergone rapid development and deployment, since first generation cellular telephone systems were introduced in the early 1980s. These first generation cellular telephone systems were based on analog frequency modulation (FM) technology and designed to carry narrow-band circuit switched voice services. The first generation cellular service providers (CSPSs) saw an exponential growth rate in their subscriptions, and by the late 1980s capacity limits were already reached in the largest markets. In response to such heavy demand, second generation (2G) digital cellular systems were developed and introduced in the early 1990s and their evolutions are still in widespread operation today. These 2G cellular systems were/are based on either time division multiple access (TDMA) or code division multiple access (CDMA) technologies, and were initially designed to carry circuit-switched voice and data. During the 1990s, these 2G systems were enhanced to provide packet-switched data in addition to circuit-switched voice. These transitional 2G cellular systems with their enhanced data transmission capabilities later became known as 2.5G systems. Third generation (3G) cellular systems were introduced after the year 2000 that allowed simultaneous use of speech and data services and still higher data rates. These higher data rate capabilities supplemented by geolocation information gave rise to location-dependent services. Currently, 4G cellular systems are under development that use voice over Internet Protocol (VoIP) and multimedia applications with ultra-broadband (gigabit peak speed) access. Most are based on multicarrier modulation/multiplexing techniques such as orthogonal frequency division multiple access (OFDMA), or advanced single-carrier modulation/multiplexing techniques such as single-carrier frequency division multiple access (SC-FDMA).

Wireless communication systems and services are now extensively deployed throughout the world. The most widespread cellular telephony standard is the Global System for Mobile Communication (GSM). As of the year 2010, GSM has four billion subscriptions out of a world population of six billion people. Likewise, the most widely deployed wireless local area network (WLAN) standard for Internet access is IEEE 802.11a/b/g commonly known as WiFi. Today we may carry around a hand-held device with access to a CSP and

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either a separate or the same internet service provider (ISP) for Internet access via WiFi and Internet-enabled applications like VoIP. Most CSPs have now deployed 3G networks that operate using one of two different standards. One is GSM/GPRS/EDGE/WCDMA/HSPA which has/is being developed by the Third Generation Partnership Project (3GPP) and accounts for roughly 80% of the global market. The other is IS-95A/B/cdma20001x/cdma2000EV-DO, which has/is been/being developed by the Third Generation Partnership Project 2 (3GPP2) and accounts for the remaining 20% of the global market. Some cellular handsets may contain both the GSM and IS-95A transceivers to enable voice services with global roaming. Third generation (3G) subscribers are roughly split equally between the WCDMA/HSPA and IS-95B/EVDO standards with roughly 500 million subscribers each as of the year 2010. The 3G standard HSPA+ has a peak downlink speed of 21 Mbps in 5 MHz bandwidth based on single-carrier TDM/CDMA technology. Currently, fourth generation (4G) cellular systems are commercially available, known as Long-Term Evolution (LTE), and Long-Term Evolution – Advanced (LTE-A) is currently under development. Unlike the 3G cellular systems that are based on CDMA technology, the 4G cellular system proposals are based on OFDMA and SC-FDMA technology. The LTE-A specification has a peak downlink speed of 22 Mbps in 5 MHz bandwidth. Based on the rather modest improvement in peak downlink speed of LTE-A over HSPA+ in a 5 MHz bandwidth, it appears that 3G systems may be operational for some time.

1.1 Brief History of Wireless Systems and Standards

Although this textbook is intended to address the fundamentals of wireless communications, it is nevertheless useful to have some basic knowledge of the history and evolution of wireless systems and standards. In what follows, we give a brief description of the major standards that have been developed or are under development for cellular radio systems, cordless phone systems, and wireless local and personal area networks.

1.1.1 First Generation (1G) Cellular Systems

The early 1970s saw the emergence of the radio technology that was needed for the deployment of mobile radio systems in the 800/900 MHz band at a reasonable cost. In 1976, the World Allocation Radio Conference (WARC) approved frequency allocations for cellular telephones in the 800/900 MHz band, thus setting the stage for the commercial deployment of cellular systems. In the early 1980s, many countries deployed incompatible first generation (1G) cellular systems based on frequency division multiple access (FDMA) and analog FM technology. With

Table 1.1 First generation (1G) cellular standards

Feature	NTT	NMT	AMPS
Frequency band RL/FL[a] (MHz)	925–940/870–885 915–918.5/860–863.5 922–925/867–870	890–915/917–950	824–849/869–894
Carrier spacing (kHz)	25/6.25 6.25 6.25	12.5[b]	30
Number of channels	600/2400 560 280	1999	832
Modulation	Analog FM	Analog FM	Analog FM

[a] *RL* reverse link, *FL* forward link
[b] Frequency interleaving using overlapping channels, where the channel spacing is half the nominal channel bandwidth

FDMA there is a single traffic channel per radio frequency carrier. When a user accesses the network two carriers (channels) are actually assigned, one for the forward (base-to-mobile) link and one for the reverse (mobile-to-base) link. Separation of the forward and reverse carrier frequencies is necessary to allow implementation of a duplexer, an arrangement of filters that isolates the forward and reverse link channels, thus preventing a radio transceiver from jamming itself.

In 1979, the first analog cellular system, the Nippon Telephone and Telegraph (NTT) system, became operational. In 1981, Ericsson Radio Systems AB fielded the Nordic Mobile Telephone (NMT) 900 system, and in 1983 AT&T fielded the Advanced Mobile Phone Service (AMPS) as a trial in Chicago, IL. Many other first generation analog systems were also deployed in the early 1980s including TACS, ETACS, NMT 450, C-450, RTMS, and Radiocom 2000 in Europe, and JTACS/NTACS in Japan. The basic parameters of NTT, NMT, and AMPS are shown in Table 1.1. All 1G cellular systems are now extinct.

1.1.2 Second Generation (2G) Cellular Systems

Second generation (2G) digital cellular systems were developed in the 1980s and early 1990s, and widely deployed throughout the world in the 1990s. These included the GSM/DCS1800/PCS1900 standard in Europe, the Personal Digital Cellular (PDC) standard in Japan, and the IS 54-/136 and IS-95 standards in the USA. Major parameters of the air interface specifications of these standards are summarized in Tables 1.2 and 1.3, and a very brief description of each is provided in the following sections.

Table 1.2 Second generation (2G) digital cellular standards, GSM and IS-54/136

Feature	GSM/DCS1800/PCS1900	IS-54/136
Frequency band RL/FL[a] (MHz)	GSM: 890–915/ 935–960 DCS1800: 1710–1785/ 1805–1880 PCS1900: 1930–1990/ 1850–1910	824–829/ 869/894 1930–1990/ 1850–1910
Multiple access	F/TDMA	F/TDMA
Carrier spacing (kHz)	200	30
Modulation	GMSK	$\pi/4$-DQPSK
Baud rate (kb/s)	270.833	48.6
Frame size (ms)	4.615	40
Slots/frame	8/16	3/6
Voice coding (kb/s)	VSELP(HR 6.5) RPE-LTP (FR 13) ACELP (EFR 12.2)	VSELP (FR 7.95) ACELP (EFR 7.4) ACELP (12.2)
Channel coding	Rate-1/2 CC	Rate-1/2 CC
Frequency hopping	Yes	No
Handoff	Hard	Hard

[a]*RL* reverse link, *FL* forward link

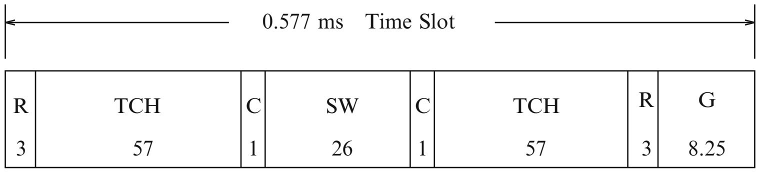
Table 1.3 Second generation (2G) digital cellular standards, PDC and IS-95

Feature	PDC	IS-95
Frequency band RL/FL[a] (MHz)	810–826/ 940–956 1429–1453/ 1477–1501	824–829/ 869–894 1930–1990/ 1850–1910
Multiple access	F/TDMA	F/CDMA
Carrier spacing (kHz)	25	1250
Modulation	$\pi/4$-DQPSK	QPSK
Baud rate (kb/s)	42	1228.8 Mchips/s
Frame size (ms)	20	20
Slots/frame	3/6	1
Voice coding (kb/s)	PSI-CELP (HR 3.45) VSELP (FR 6.7)	QCELP (8,4,2,1) RCELP (EVRC)
Channel coding	Rate-1/2 BCH	FL: rate-1/2 CC RL: rate-1/3 CC
Frequency hopping	no	N/A
Handoff	Hard	Soft

[a]*RL* reverse link, *FL* forward link

1.1.2.1 Groupe Spécial Mobile

European countries saw the deployment of incompatible 1G cellular systems that did not admit roaming throughout Europe. As as result, the Conference



R Guard time for burst transient response (Ramp time)
TCH Traffic channel
C Control bit
SW Synchronization word
G Guard bits

Fig. 1.1 Time slot format for GSM. Units are in bits

of European Postal and Telecommunications Administrations (CEPT) established Groupe Spécial Mobile (GSM) in 1982 with the mandate of defining standards for future Pan-European cellular radio systems. The GSM system (now "Global System for Mobile Communications") was developed to operate in a new frequency allocation, and made improved quality, Pan-European roaming, and the support of data services its primary objectives. GSM was deployed in late 1992 as the world's first digital cellular system.

GSM can support full-rate (8 slots/carrier) and half-rate (16 slots/carrier) voice operation, and provide various synchronous and asynchronous data services at 2.4, 4.8, and 9.6 kb/s. GSM uses TDMA with 200 kHz carrier spacings, eight channels per carrier with a time slot (or burst) duration of 0.577 ms, and Gaussian minimum shift keying (GMSK) with a raw bit rate of 270.8 kb/s. The time slot format of the GSM traffic channels is shown in Fig. 1.1. Variants of GSM have also been developed to operate in the 900 MHz and 1,800 MHz bands in Europe, and the 850 MHz and 1,900 MHz bands in North America. GSM has been a phenomenal success and is arguably the most successful cellular standard. In late 1993, already over a million subscribers were using GSM phone networks. By mid 2010, GSM had over 4.3 billion subscribers across more than 212 countries and territories.

Newer versions of the standard have been developed that are backward-compatible with the original GSM system. GSM Release '97 added packet data capabilities by aggregating all time slots together for a single user. This enhancement provides data rates up to 140 kb/s and is called General Packet Radio Service (GPRS). GSM Release '99 introduced higher speed data transmission using a higher-level 8-PSK modulation format (up to 473.6 kb/s with uncoded 8-PSK). This enhancement is called Enhanced Data Rates for GSM Evolution (EDGE). Some parameters of the EDGE standard are shown in Table 1.4. EDGE is deployed worldwide except for Japan and South Korea. GPRS and EDGE are generally branded as 2.5G systems.

Table 1.4 Parameters of the EDGE standard

Multiple access	TDMA
Duplexing	FDD
Carrier spacing (kHz)	200
Modulation	8-PSK/GMSK
Frame length (ms)	4.615
Slots/frame	8
Maximum bit rate (kb/s)	473.6 (8-PSK)/140.8 (GMSK)

1.1.2.2 IS-54/136 and IS-95

In North America, the primary driver for second generation systems was the capacity limit felt by some AMPS operators in the largest US markets by the late 1980s. One of the key objectives established by the Cellular Telephone Industry Association (CTIA) at that time was a tenfold increase in capacity over AMPS. Furthermore, since AMPS was already deployed extensively throughout North America, it was desirable that any second generation cellular system be reverse compatible with AMPS. This eventually lead to the development of dual-mode cellular standards in North America.

While Europe saw a convergence to the GSM standard based on TDMA technology, North America saw a divergence to two second generation digital cellular standards, IS-54/136 and IS-95, based on TDMA and CDMA technology, respectively. The IS-54 standard, adopted in 1990, was based on TDMA with 30 kHz carrier spacings (the same as AMPS) and $\pi/4$ phase-shifted quadrature differential phase shift keyed ($\pi/4$-DQPSK) modulation with a raw bit rate of 48.6 kb/s [86]. IS-54 and IS-136 differ in the control channel; IS-54 uses an analog control channel, whereas IS-136 uses a digital control channel. The IS-54/136 air interface specified 6 slots (or bursts) per frame, yielding three full-rate channels or six half-rate channels per carrier. The burst format for the IS-54/136 traffic channel is shown in Fig. 1.2. IS-54/136 was once deployed widely in the USA and Canada during the 1990s, but its use was discontinued in the 2007–2009 time frame often in favor of GSM/GPRS/EDGE.

Just after the CTIA adopted IS-54 in 1990, another second generation digital cellular standard was proposed by Qualcomm based on CDMA technology. In March 1992, CDMA was adopted as the IS-95 standard [87]. The introduction of IS-95 saw considerable debate and spirited exchanges over the relative capacity and merits of TDMA and CDMA cellular systems. Initial capacity claims for IS-95 were 40 times AMPS. However, commercial deployments eventually realized a capacity gain of six to ten times AMPS. The introduction of IS-95 CDMA cellular was of historical significance, because 3G cellular systems are based on CDMA technology.

With IS-95, the basic user data rate is 9.6 kb/s for Rate Set 1 (RS1) and 14.4 kb/s for Rate Set 2 (RS2), which is spread using pseudonoise (PN) sequence with a chip rate of 1.2288 Mchips/s. The forward channel supports coherent detection using an unmodulated pilot channel for channel estimation. Information on the forward link

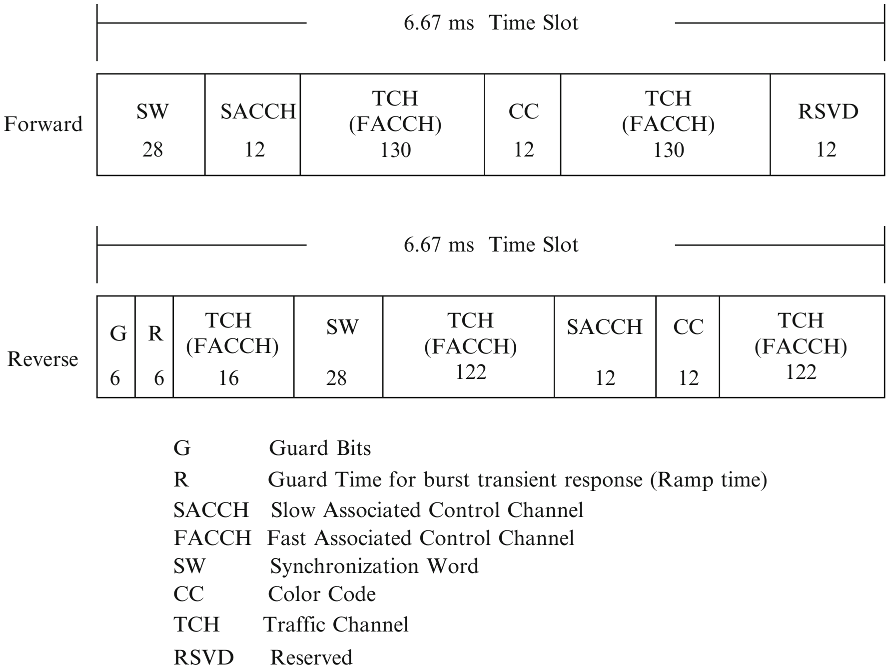
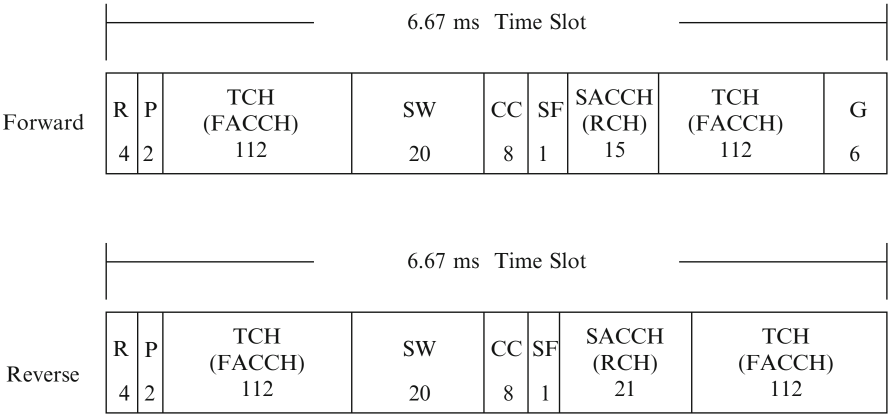


Fig. 1.2 Burst format for IS-54/136 traffic channel. Units are in bits

is encoded using a rate-1/2 convolutional code, interleaved, spread using one of 64 orthogonal Walsh codes, and transmitted in 20 ms bursts. Each MS in a cell is assigned a different Walsh code, thus providing complete orthogonality under ideal channel conditions. Final spreading with a PN code of length 2^{15}, having a phase offset that depends on each BS, is used to mitigate the multiple access interference to and from other cells.

CDMA systems are susceptible to the near-far effect, a phenomenon where MSs close into a BS will swamp out the signals from more distant MSs. For CDMA systems to function properly, all signals to be recovered must be received with (nearly) the same power. To combat the near-far effect, the IS-95 reverse link uses fast-closed loop power control to compensate for fluctuations in received signal power due to the radio propagation environment. The information on the IS-95 reverse link is encoded using a rate-1/3 convolutional code, interleaved, and mapped onto one of 64 Walsh codes. Unlike the IS-95 forward channel that uses Walsh codes for spreading, the reverse link uses Walsh codes for 64-ary orthogonal modulation. The BS receiver uses noncoherent detection, since no pilot signal is transmitted on the reverse link. Both the BSs and the MSs use RAKE receivers to provide multipath diversity. To ensure that the power control algorithm is stable, CDMA cellular systems must use soft handoff, where the MS maintains a radio link with multiple BSs when traversing between cells and softer handoff when traversing between sectors of the same cell.



R	Guard Time for burst transient response (Ramp time)
P	Preamble
TCH	Traffic Channel
FACCH	Fast Associated Control Channel
SW	Synchronization Word
CC	Color Code
SF	Steal Flag
SACCH	Slow Associated Control Channel
RCH	Housekeeping Bits
G	Guard Bits

Fig. 1.3 Time slot format for Japanese PDC. Units are in bits

In 1998, the IS-95B standard was approved to support packet-switched data with rates up to 115.2 kbps using multi-code CDMA, where up to eight Walsh codes are aggregated and assigned to a single user in a dynamic and scheduled manner.

1.1.2.3 PDC

In 1991, the Japanese Ministry of Posts and Telecommunications standardized PDC. The air interface of PDC is similar to IS-54/136. PDC uses TDMA with three full rate (six half rate) channels per carrier, 25 kHz carrier spacings, and $\pi/4$-DQPSK modulation with a raw bit rate of 42 kb/s. The burst format for the PDC traffic channels is shown in Fig. 1.3. Notice that the synchronization word is placed near the center of the PDC burst, whereas it is placed near the beginning of the IS-54/136 burst as shown in Fig. 1.2. This feature better enables the PDC receiver to track channel variations over the time slot. Another key feature of PDC standard is the inclusion MS antenna diversity. Like IS-54/136, PDC suffers from degraded performance under conditions of low delay spread due to the loss of multipath diversity. However, antenna diversity in the PDC MS receiver maintains spatial diversity under these conditions. More details on the PDC system can be found in the complete standard [224]. PDC is still in use in Japan but is being phased out in favor of 3G cellular technologies.

1.1.3 Third Generation Cellular Systems

In March 1992, WARC approved a worldwide spectral allocation in support of IMT-2000 (International Mobile Telephone by the Year 2000) in the 1,885–2,200 MHz band. The IMT-2000 standard was developed by the International Telecommunications Union Radio Communications (ITU-R) and Telecommunications (ITU-T) sectors. Various standards bodies around the world have provided inputs to the IMT-2000 standard definition. IMT-2000 was envisioned as an ubiquitous wireless system that could support voice, multimedia, and high-speed data communication. The ITU provided no clear definition of the minimum or average rates users could expect from 3G equipment or providers. However, it was generally expected that 3G networks would provide a minimum downlink peak data rate of 2 Mbit/s for stationary or walking users, and 384 kbit/s in a moving vehicle. Most 3G networks today can offer peak data rates of 14.0 Mbit/s on the downlink and 5.8 Mbit/s on the uplink.

IMT-2000 is actually a family of standards. Two of the standards are based on TDMA approaches, namely EDGE and Digital Enhanced Cordless Telephone (DECT). While the EDGE standard fulfils the requirements for IMT-2000, EDGE networks are typically branded as 2.5G networks rather than 3G networks. The most predominant forms of IMT-2000 are cdma2000 developed by 3GPP2 and the Universal Mobile Telecommunications System (UMTS) family of standards, which includes Wideband Code Division Multiple Access (WCDMA), developed by 3GPP. Sometimes WCDMA is used synonymously with UMTS. Mobile WiMAX (Worldwide Interoperability for Microwave Access), developed by the IEEE802.16 working group, is also included under the IMT-2000 umbrella as a 3.5G standard. WiMAX is a multicarrier scheme based on OFDMA.

Table 1.5 summarizes the main parameters for WCDMA and cdma2000. The common attributes of WCDMA and cmda2000 include the following:

- Provision of multirate services
- Packet data services
- Complex spreading
- A coherent uplink using a user dedicated pilot
- Additional pilot channel in the downlink for beam forming
- Seamless inter-frequency handoff
- Fast forward link power control
- Optional multiuser detection

The major differences between WCDMA and cdma2000 centers around the chip rate that is used, and synchronous (cdma2000) versus asynchronous (WCDMA) network operation. Synchronous operation with cdma2000 is achieved using a Global Positioning System (GPS) clock reference.

Table 1.5 Parameters for WCDMA and cdma2000

Feature	WCDMA	cdma2000
Multiple access	DS-CDMA	DS-CDMA
Chip rate (Mcps)	3.84	1.2288
Carrier spacing (MHz)	5	1.25
Frame length (ms)	10	5/20
Modulation	FL: QPSK RL: BPSK	FL: BPSK/QPSK RL: BPSK 64-ary orthogonal
Coding	Rate-1/2, 1/3 $K = 9$ CC Rate-1/3 $K = 4$ turbo code	Rate-1/2, 1/3, 1/4, 1/6 $K = 9$ CC Rate-1/2, 1/3, 1/4, 1/5, $K = 4$ turbo code
Interleaving	Inter/Intraframe	Intraframe
Spreading	FL: BPSK RL: QPSK	Complex
Inter BS synchronization	Asynchronous	Synchronous

1.1.3.1 cdma2000

The cdma2000 family of standards developed by 3GPP2 evolved from IS-95A/B and includes cdma20001x, cdma2000EV-DO Rev. 0, cdma2000 EV-DO Rev. A, and cdma2000 EV-DO Rev. B. cdma20001x, also known as 1x and 1xRTT, is the core cdma2000 wireless air interface standard, and was recognized by the ITU as an IMT-2000 standard in November 1999. It was the first IMT-2000 technology deployed worldwide, in October 2000. The designation “1x” stands for 1 times Radio Transmission Technology, and means that the system has the same RF bandwidth as IS-95: a duplex pair of 1.25 MHz radio channels. The cdma20001x almost doubles the capacity of IS-95 by adding 64 more traffic channels to the forward link, orthogonal to (in quadrature with) the original set of 64 forward channels. The cmda20001x Release 0 standard supports bi-directional peak data rates of up to 153 kbps and Release 1 can achieve peak data rates of up to 307 kbps in a single 1.25 MHz channel. cdma20001x supports a variety of applications including circuit-switched voice, short messaging service (SMS), multimedia messaging service (MMS), games, GPS-based location services, music and video downloads.

EV-DO, which now stands for “Evolution-Data Optimized,” was initially developed by Qualcomm in 1999 to meet the IMT-2000 requirements for a minimum 2-Mbit/s downlink speed for stationary or walking users, and sometimes referred to as IS-856. EV-DO is typically for broadband Internet access. It uses a mixture of CDMA and TDMA to maximize both individual user’s throughput and the overall system throughput. EV-DO has been adopted by many service providers in the USA, Canada, Mexico, Europe, Asia, Russia, Brazil, and Australia.

1.1.3.2 UMTS

UMTS was developed by 3GPP and is part of the global ITU IMT-2000 standard. The most common form of UMTS uses WCDMA (IMT Direct Spread) as the underlying air interface. However, UMTS also includes TD-CDMA and TD-SCDMA (both IMT CDMA TDD). The first deployment of UMTS was the Release'99 architecture. UMTS requires new base stations and new frequency allocations. However, it is closely related to GSM/EDGE as it borrows and builds upon concepts from GSM. Further, most UMTS handsets also support GSM, allowing seamless dual-mode operation. WCDMA uses paired 5 MHz channels and can support peak data rates of up to 384 kbit/s for Release'99 handsets. WCDMA systems have been criticized for their large (5 MHz) bandwidth requirement, which has delayed deployment in countries (such as the USA) that acted relatively slowly in allocating new frequencies specifically for 3G services.

Since 2006, UMTS networks in many countries have been or are in the process of being upgraded to include High Speed Packet Access (HSPA), sometimes known as 3.5G. Currently, High Speed Downlink Packet Access (HSDPA) enables peak downlink transfer speeds of 14 Mbit/s and High Speed Uplink Packet Access (HSUPA) has peak data rates of 5.8 Mbit/s in the uplink, although most HSDPA network deployments have peak downlink speeds of 7.2 Mbps. HSPA has been commercially deployed by over 200 operators in more than 80 countries. Evolved HSPA (also known as HSPA+) is an upcoming wireless broadband standard defined in 3GPP Release 7 and 8 of the WCDMA specification. Evolved HSPA will eventually provide data rates up to 42 Mbit/s in the downlink and 11 Mbit/s in the uplink (per 5 MHz carrier) using multiple-input multiple-output (MIMO) technologies and high-order modulation schemes.

1.1.3.3 WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) is a telecommunications protocol that provides fixed and fully mobile Internet access. There are several versions of the WiMAX standard. IEEE 802.16-2004, also known as 802.16d, is sometimes referred to as "Fixed WiMAX," since it does not support mobility. IEEE 802.16e-2005, often abbreviated as 802.16e, includes support for mobility among other things and is commonly known as "Mobile WiMAX". Mobile WiMAX is the version receiving the most commercial interest and is being actively deployed in many countries, sometimes being branded as 4G. Mobile WiMAX can deliver mobile broadband services, with peak data rates up to 40 Mbit/s, at vehicular speeds greater than 120 km/h while maintaining a quality of service (QoS) comparable to broadband wireline access.

Some of the key features and attributes of WiMAX include the following:

- Tolerance to delay spread and multiuser interference due to orthogonality of OFDMA sub-carriers in both the downlink (DL) and uplink (UL) directions.

- Scalable channel bandwidths ranging from 1.25 to 20 MHz through adjustment of the Fast Fourier Transform (FFT) size in the baseband modulator/demodulator. Supported FFT sizes are 128, 256, 512, 1024, 2048.
- Hybrid-Automatic Repeat Request (H-ARQ) to provide robustness in high mobility environments.
- Adaptive sub-carrier allocation (in time and frequency) to optimize connection quality based on relative signal strengths on a connection-by-connection basis.
- Advanced modulation and coding schemes that use BPSK, QPSK, 16-QAM, 64-QAM together with convolutional and turbo coding.
- Power management to ensure power-efficient operation of mobile and portable devices in sleep and idle modes.
- Network-optimized hard handoff to minimize overhead and achieve a handoff delay of less than 50 ms.
- Advanced antenna systems including MIMO, beam forming, space-time coding, and spatial multiplexing.
- Fractional frequency reuse to achieve high spectral efficiency.

1.1.4 Fourth Generation Cellular Systems

IMT-Advanced, also known as "systems beyond IMT-2000" is currently envisioned to provide even higher data rates than IMT-2000 can provide. IMT-Advanced anticipates peak data rates of 100 Mbps in high-mobility applications and 1 Gbps in stationary or low-mobility applications. IMT-Advanced is expected to have the following characteristics:

- Flexible channel bandwidth, between 5 and 20 MHz, optionally up to 40 MHz
- A nominal peak data rate of 100 Mbps in high mobility, and 1 Gbps for stationary environments
- A data rate of at least 100 Mbps between any two points in the world.
- Bandwidth efficiency of up to 15 bit/s/Hz in the downlink, and 6.75 bit/s/Hz in the uplink.
- Spectral efficiency of up to 3 bit/s/Hz/cell in the downlink
- Smooth handoff across heterogeneous networks
- Seamless connectivity and global roaming across multiple networks
- High QoS for next generation multimedia support
- Backward compatibility with existing wireless standards
- All Internet Protocol (IP) packet-switched network

The 3GPP Long Term Evolution Advanced (LTE-A) and IEEE 802.16e mobile WiMAX standards are often branded as "4G." However, they do not fully comply with the IMT-Advanced requirements.

In all 4G proposals submitted to ITU-R as 4G candidates, the CDMA technology that is prevalent in 3G systems has been abandoned in favor of multicarrier

Table 1.6 Cordless telephone standards

Feature	DECT	PHS
Frequency band (MHz)	1880–1900 (Europe) 1900–1920 (China) 1910–1930 (Latin America) 1920–1930 (USA, Canada)	1895–1918
Multiple access	F/TDMA	F/TDMA
Duplexing	TDD	TDD
Carrier spacing (kHz)	1728	300
Modulation	GFSK	$\pi/4$-DQPSK
Number of carriers	10 (Europe)	77
Number of carriers	5 (USA)	
Channels/carrier	12	4
Bit Rate (kb/s)	1152	384
Speech coding	ADPCM 32 kb/s	ADPCM 32 kb/s
Frame size (ms)	10	5
Mean TX power (mW)	10 (Europe) 4 (USA)	10
Peak TX power (mW)	250 (Europe) 100 (USA)	80

transmission schemes such as OFDMA. Basically, all 4G proposals are based on two technologies, (1) LTE-A as standardized by 3GPP, and (2) IEEE 802.16m as standardized by the IEEE.

1.1.5 Cordless Telephone Systems

Similar to cellular telephones, first generation cordless telephones were based on analog frequency modulation technology. After their introduction, cordless telephones gained high popularity, which made them victims of their own success; the voice quality was often unacceptable due to uncoordinated deployment and resulting mutual interference between cordless phones operating on the same frequency. This lead to the development of digital cordless telephones. The most predominant cordless phone standard is DECT. DECT originated in Europe, where it is the universal standard, replacing earlier cordless phone standards. It has been adopted by Australia, and most countries in Asia and South America. Adoption in the USA was delayed due to radio licensing regulations, and earlier technologies are still competitive. In the USA, DECT operates in the 1920-1930 MHz, or 1.9 GHz band, and is branded as DECT 6.0. DECT is recognized by the ITU as fulfilling the IMT-2000 requirements and, thus, it actually qualifies as a 3G system. The major technical properties of DECT are described in Table 1.6.

The Personal Handy-phone System (PHS), is a mobile network system developed by NTT Laboratory in Japan in 1989. It is deployed mainly in Japan, China, Taiwan,

Table 1.7 2.4 and 5 GHz bands for license exempt use. $B = -26$ dB emission bandwidth in MHz

Location	Frequency range (GHz)	Maximum output power (mW or dBm)
North America	2.400–2.4835	1,000 mW
Europe	2.400–2.4835	100 mW EIRP
Japan	2.471–2.497	10 mW
USA (UNII lower band)	5.150–5.250	Minimum of 50 mW or 4 dBm $+10\log_{10}B$
USA (UNII middle band)	5.250–5.350	Minimum of 250 mW or 11 dBm $+10\log_{10}B$
USA (UNII upper band)	5.725–5.825	Minimum of 1000 mW or 17 dBm $+10\log_{10}B$

and some other Asian countries. PHS is a cordless telephone like DECT, with the capability to handover from one cell to the next. PHS operates in the 1880-1930 MHz frequency band, and is far simpler to implement and deploy than cellular systems like PDC or GSM. However, the PHS cells are small due to a maximum base station transmit power of 500 mW, and cell radii are typically in the order of tens or at most hundreds of meters in non line-of-sight conditions. While the small cell size makes PHS suitable for dense urban areas, it is impractical for rural areas, and the small cell size also makes it difficult if not impossible to make calls from moving vehicles. For this reason, PHS has seen declining popularity in Japan. Nevertheless, PHS has seen a resurgence in markets like China, Taiwan, Vietnam, Bangladesh, Nigeria, Mali, Tanzania, and Honduras where its low deployment costs make it attractive to operators. The major technical properties of PHS are described in Table 1.6.

1.1.6 Wireless LANs and PANs

WLAN and wireless personal area network (WPAN) systems have been developed to operate in unlicensed bands. Table 1.7 lists the unlicensed bands that are used in various regions of the world.

In 1997, the IEEE 802.11 standards group established the first WLAN standard to provide 1 and 2 Mb/s aggregate data rates. IEEE 802.11 uses direct sequence spread spectrum with a length-11 Barker sequence for spreading, and either BPSK (1 Mbps) or QPSK (2 Mbps). Barker sequences are discussed in Chap. 9. In 1998, the IEEE 802.11b standard was defined to provide 5.5 and 11 Mbps aggregate data rates. IEEE 802.11b uses complementary code keying (CCK), which is also described in Chap. 9. In 1998, the IEEE 802.11a standard was defined for operation in the newly unlicensed 5 GHz UNII bands in the USA. IEEE 802.11a is based on a combination of orthogonal frequency division (OFDM) and time division multiplexing (TDM) and can provide a range of aggregate data rates ranging from 6

Table 1.8 Key parameters of the IEEE 802.11a OFDM standard, from [261]

Data rate	6, 9, 12, 18, 24, 36, 48, 54 Mb/s
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Coding	1/2, 2/3, 3/4 CC
Number of sub-carriers	52
Number of pilots	4
OFDM symbol duration	4 μs
Guard interval	800 ns
Sub-carrier spacing	312.5 kHz
3 dB bandwidth	16.56 MHz
Channel spacing	20 MHz

to 54 Mbps. The parameters of the IEEE 802.11a OFDM standard are summarized in Table 1.8. Since then, the same system has been adopted as IEEE 820.11g for operation in the 2.4 GHz unlicensed band. IEEE 820.11b/g is now widely deployed throughout the world.

A WPAN is a computer network used for communication among computer devices, including telephones and personal digital assistants, that are in close proximity. The physical size of a WPAN is typically less than 10 m. WPANs can be used for communication among the devices themselves, or to connect to the Internet. A key feature WPAN technology is the ability to "plug-in" devices, such that when any two WPAN-equipped devices are in close proximity, they can communicate with each other. Another important feature is the ability of each device to lock out other devices selectively, thus preventing unauthorized access.

In 1999, the IEEE802.15 Working Group was created to define WPAN standards. The Bluetooth v1.1 specification [123] was adopted as the IEEE 802.15.1-2002 standard and was later published as IEEE 802.15.1-2005 based upon the additions incorporated into Bluetooth v1.2. A Bluetooth WPAN is also called a piconet, and consists of up to eight active devices connected in a master–slave configuration (others maybe in idle mode). The first Bluetooth device in the piconet is the master, and all other devices are slaves that communicate with the master. Bluetooth uses Frequency Hop CDMA (FH-CDMA) with a set of 79 hop carriers with a spacing of 1 MHz and a hop dwell time of 625 μs. Classical Bluetooth uses Gaussian frequency shift keying (GFSK) with a modulation index of 0.3 and either a very simple rate-1/3 3-bit repetition code or a simple rate-2/3 shortened Hamming code. Classical Bluetooth supports a data rate of 1 Mbps. Extended data rate Bluetooth systems are available that use $\pi/4$-DQPSK and 8-DPSK, giving 2 and 3 Mbps, respectively.

1.2 Frequency Reuse and the Cellular Concept

A cellular land mobile radio network, is a collection of individual cells that are served by BSs. Each BS covers a small geographical area. By integrating the coverage of a plurality of BSs, a cellular network provides radio coverage over a much larger geographic area. A group of BSs is sometimes called a location area, or a routing area. A cellular land mobile radio system has two basic functions; it must locate and track both active and idle MSs, and it must always attempt to connect the MSs to the best available BSs. The former task is the subject of mobility management, and requires a location-update procedure, which allows an MS to inform the cellular network, whenever it moves from one location area to the next. The latter task is the subject of radio resource management and requires the continuous evaluation of the radio link quality with the serving BS(s), and the radio link qualities of alternate BSs. This monitoring is performed by a base station controller (BSC) or mobile switching center (MSC) that uses knowledge of the link quality evaluations on the forward and reverse channels, in addition to the system topology and traffic flow, to decide upon the best BS(s) to serve a particular MS.

A cellular land mobile radio system uses low power radio communication between an MS and a grid of BSs. Movement of the MS, however, leads to highly erratic radio link conditions, and careful monitoring and control are required to keep the radio link quality acceptable. Evaluation of radio link quality is based upon a large number of criteria, but at the core is a statistical measurement process based on prior knowledge of the expected radio channel characteristics. The time required to measure the radio link quality and the accuracy of the measurement depends on the local propagation characteristics. Time-consuming link quality measurements will limit the ability of the cellular system to react to changes in link quality and compensate by changing the set of serving BSs and the allocation of BS and MS power resources. Conversely, if the link-quality measurements can be made quickly, then the time required for the cellular system to process the link-quality measurements, make decisions, and transmit desired changes to the network entities, including the MSs, will limit the adaptability of the cellular system. Limitations on the speed of link-quality measurement and network control essentially determine overall link quality and the size and distribution of cells in modern cellular systems. The cell sizes, the ability radio links to withstand interference, and the ability of the cellular system to react to variations in traffic are the main factors that determine the spectral efficiency of a cellular system.

In cellular systems, the available spectrum is partitioned among the BSs, and a given frequency is reused at the closest possible distance that the radio link will allow. Smaller cells have a shorter distance between reused frequencies, and this results in an increased spectral efficiency and traffic-carrying capacity. Dramatic improvement in spectral efficiency is the main reason for the deployment of small cells known as microcells and picocells. However, the microcellular and picocellular propagation environment is also highly erratic and the radio links are more difficult to control due to the combination of small cell sizes and mobility. Distributed radio resource management algorithms are typically used to maintain acceptable link quality and high spectral efficiency.

Cellular systems are designed to have high spectral efficiency and offer ubiquitous service coverage. These systems require (1) effective cellular architectures, (2) fast and accurate link-quality measurements, (3) rapid control in all types of environments, (4) installation of BSs to provide radio coverage virtually everywhere, and

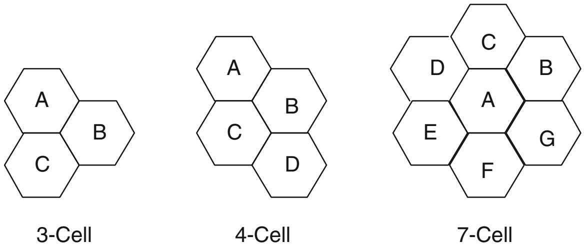


Fig. 1.4 Commonly used cellular reuse clusters

(5) power and bandwidth efficient air interface schemes that can mitigate the harsh effects of the propagation environment and tolerate high levels of interference. Since the radio links in high-capacity cellular systems will interfere with each other due to frequency reuse, it is always desirable to maintain each radio link at a target QoS while using the lowest possible transmit power. This means that radio links should not significantly exceed their target QoS since doing so will cause unnecessary interference to other radio links.

Cellular mobile radio systems rely upon frequency reuse, where users in geographically separated cells simultaneously use the same carrier frequency and/or time slot. The cellular layout of a conventional macrocellular system is very often described by a uniform grid of hexagonal cells or radio coverage zones. In reality the cells are neither hexagonal or circular, but instead are irregular and overlapping regions. The hexagon is a common choice for representing macrocellular coverage areas, because it closely approximates a circle and offers a wide range of tessellating frequency reuse cluster sizes. Tessellating frequency reuse clusters are those that will fit together without leaving any gaps. A tessellating reuse cluster of size N can be constructed if [202]

$$N = i^2 + ij + j^2, \tag{1.1}$$

where i and j are nonnegative integers, and $i \geq j$. It follows that the allowable hexagonal cluster sizes are $N = 1, 3, 4, 7, 9, 12, \ldots$ Examples of 3-, 4-, and 7-cell reuse clusters are shown in Fig. 1.4. The reuse clusters are tessellated to form a frequency plan. A simplified 7-cell frequency reuse plan is shown in Fig. 1.5, where cells marked with the same letter label use identical sets of carrier frequencies.

The co-channel reuse factor D/R, is defined as the ratio of the co-channel reuse distance D between cells using the same set of carrier frequencies and the cell radii R, where R is the distance from the center to the corner of a cell. For regular hexagonal cells, the reuse cluster size N and co-channel reuse factor D/R are related by (see Problem 1.2)

$$D/R = \sqrt{3N}. \tag{1.2}$$

For microcellular systems with lower BS antenna heights, regular hexagons may no longer appropriate for approximating the radio coverage areas. Typical microcell BSs use an antenna height of about 15 m, well below the skyline of any buildings that might be present, and acceptable link quality can be obtained anywhere within

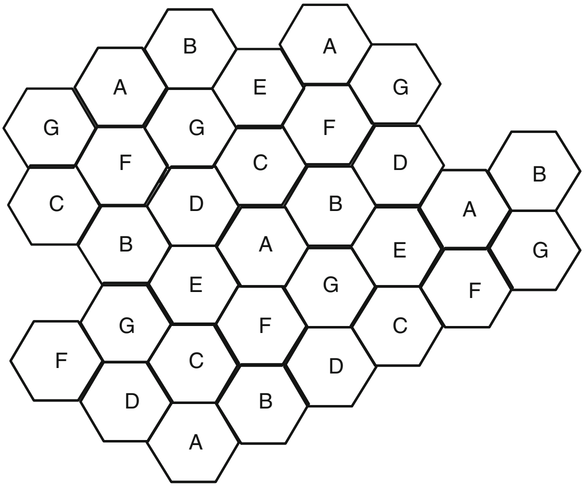


Fig. 1.5 Macrocellular deployment using 7-cell reuse pattern

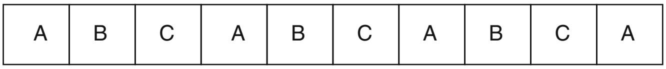


Fig. 1.6 Microcellular deployment along a highway with a 3-cell reuse pattern

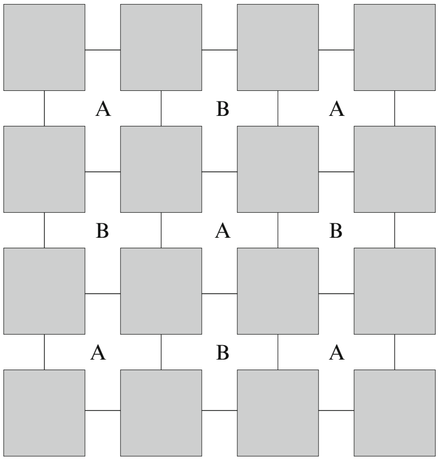


Fig. 1.7 Microcellular deployment in a dense urban area, with a rectangular grid of streets. Base stations are deployed at every intersection with a 2-cell reuse pattern

200–500 m of the BS. For microcells, the choice of cell shape depends greatly upon the local topography. For example, the linear cells shown in Fig. 1.6 can be used to model microcells that are deployed along a highway with directional antennas. In a dense metropolitan area with urban canyons, the buildings act as wave guides to channel the radio waves along the street corridors. Figure 1.7 shows a typical "Manhattan" street cell deployment that is often used to model microcells that are deployed in city centers.

1.3 Mobile Radio Propagation Environment

Radio signals in cellular land mobile radio systems generally propagate according to three mechanisms; reflection, diffraction, and scattering. Reflections arise when the plane waves are incident upon a surface with dimensions that are large compared to the wavelength. The radio wave reflects off the surface with an angle of departure equal to the angle of incidence, while the amplitude and phase of the reflected wave depend on the surface characteristics. Diffraction occurs according to the Huygens–Fresnel principle when there is an obstruction between the transmitter and receiver antennas, and secondary waves are generated behind the obstructing body. Scattering occurs when the plane waves are incident upon an object whose dimensions are on the order of a wavelength or less, and causes the energy to be redirected in many directions. A good example occurs at millimeter wave frequencies, where rain drops cause scattering that manifests itself in a phenomenon called rain attenuation. The relative importance of these three propagation mechanisms depends on the particular propagation scenario.

As a result of the above three mechanisms, cellular land mobile radio propagation can be roughly characterized by three nearly independent phenomenon; path loss with distance, shadowing, and multipath fading. Each of these phenomenon is caused by a different underlying physical principle. Multipath fading results in rapid variations in the envelope of the received signal and is caused when plane waves arrive from many different directions with random phases and combine vectorially at a receiver antenna. Typically, the amplitude of a narrow band received envelope can vary by as much as 30–40 dB over a fraction of a wavelength due to constructive and destructive addition. Multipath also causes time dispersion, because the multiple replicas of the transmitted signal propagate over transmission paths of different lengths and, therefore, reach the receiver antenna with different time delays. Time dispersion can be combatted and exploited using time-domain equalization in TDMA systems, RAKE receivers in CDMA systems, and frequency-domain equalization in OFDM systems.

Free space propagation does not apply in a land mobile radio environment and the propagation path loss depends not only on the distance and frequency but also on the antenna heights and topography. The empirical propagation models due to W. C. Y. Lee [151] assume that the received power is

$$\Omega_{\mathrm{p\ (dBm)}}(d) = \mu_{\Omega_{\mathrm{p\ (dBm)}}}(d_{\mathrm{o}}) - 10\beta \log_{10}\{d/d_{\mathrm{o}}\} + \varepsilon_{(\mathrm{dB})}, \tag{1.3}$$

where $\mu_{\Omega_{\mathrm{p\ (dBm)}}}(d_{\mathrm{o}}) = \mathrm{E}[\Omega_{\mathrm{p\ (dBm)}}(d_{\mathrm{o}})]$ is the average received signal power (in dBm) at a known reference distance that is in the far field of the transmitting antenna. Typically, d_{o} is on the order of 1.6 km for macrocells, 100 m for outdoor microcells, and 1 m for indoor picocells. The value of $\mu_{\Omega_{\mathrm{p\ (dBm)}}}(d_{\mathrm{o}})$ will depend on the frequency, antenna heights and gains, and other factors. The parameter β is called the path loss exponent and is a key parameter that describes the slope of the path loss characteristic (in dB) as a function of distance. This parameter is strongly

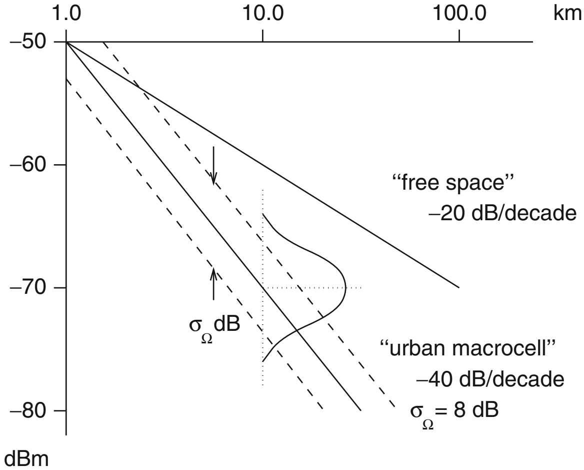


Fig. 1.8 Path loss in free space and typical macrocellular environments; $\beta = 4$, $\sigma_\Omega = 8$ dB. The received signal strength (in dBm units) at a distance of 10 km is Gaussian distributed with a mean of -70 dBm and a variance of σ_Ω^2 dB

dependent on the cell size and local terrain characteristics. The path loss exponent ranges from 3 to 4 for a typical urban macrocellular environment, and from 2 to 8 for a microcellular environment. As mentioned earlier, path loss exponents are often determined by curve fitting to measured data. Lee's model is discussed in further detail in Sect. 2.7.3.2.

The parameter $\varepsilon_{(\mathrm{dB})}$ in (1.3) is a zero-mean Gaussian random variable when expressed in decibel units, and represents the error between the actual and predicted path loss. This statistical variation in $\Omega_{\mathrm{p\ (dBm)}}(d)$ is caused by shadowing. Shadows are generally modeled as being log-normally distributed, meaning that the probability density function of $\Omega_{\mathrm{p\ (dBm)}}(d)$ has the normal distribution

$$p_{\Omega_{\mathrm{p\ (dBm)}}(d)}(x) = \frac{1}{\sqrt{2\pi}\sigma_\Omega} \exp\left\{ -\frac{\left(x - \mu_{\Omega_{\mathrm{p\ (dBm)}}}(d)\right)^2}{2\sigma_\Omega^2} \right\}, \quad (1.4)$$

where

$$\mu_{\Omega_{\mathrm{p\ (dBm)}}}(d) = \mu_{\Omega_{\mathrm{p\ (dBm)}}}(d_{\mathrm{o}}) - 10\beta \log_{10}\{d/d_{\mathrm{o}}\} \ \ (\mathrm{dBm}) \quad (1.5)$$

is the average received signal power.

The parameter σ_Ω is the shadow standard deviation. A more accurate path loss model will result in a smaller σ_Ω. However, there will always be some residual error between the actual and predicted path loss due to terrain irregularities. For macrocells σ_Ω typically ranges from 5 to 12 dB, with $\sigma_\Omega = 8$ dB being a commonly used value. Furthermore, σ_Ω has been observed to be nearly independent of the radio path length d. The received signal power in the absence of shadowing as defined by (1.5) is called the area mean, while the received signal power in the presence of shadowing as defined by (1.3) is called the local mean. Figure 1.8 illustrates the above concepts by plotting the received signal strength as a function of the radio path length for both free space and a typical macrocellular environment. Shadowing is discussed in further detail in Sect. 2.6.

1.4 Co-channel Interference and Noise

Frequency reuse in cellular systems introduces co-channel interference (CCI), which is the primary factor that limits cellular spectral efficiency. CCI arises when the same carrier frequency is used in different cells and/or cell sectors. In this case, the power density spectra of the desired and interfering signals overlap. Frequency reuse also introduces adjacent channel interference. This type of interference arises when neighboring cells use carrier frequencies that are spectrally adjacent to each other. In this case, the power density spectrum of the desired and interfering signals partially overlap. However, since adjacent frequencies are used at close distances, the interference can still be significant. Consequently, the transmit power is regulated to fit within a regulatory emission mask. Modulation schemes along with their power spectra is the subject of Chap. 4.

Radio links often exhibit a performance threshold, where the link QoS is deemed acceptable when both the carrier-to-noise ratio Γ and carrier-to-interference ratio Λ exceed certain defined thresholds, denoted by Γ_{th} and Λ_{th}, respectively [96]. Otherwise, the QoS is considered unacceptable and an outage is said to occur. The thresholds Γ_{th} and Λ_{th} depend on many parameters of the radio link, including the modulation and coding scheme that is used, and the particular receiver processing algorithms that are implemented. Sometimes the thresholds can be very sharp, especially when powerful modulation and coding techniques are used. Once the air interface is specified and the receiver-processing algorithms are implemented, Γ_{th} and Λ_{th} will be defined and the particular propagation environment encountered on the radio link will determine whether or not an outage occurs.

Here, we introduce two types of outages. The first is the thermal noise outage, defined as

$$O_{\text{N}} = \text{P}[\Gamma < \Gamma_{\text{th}}] \tag{1.6}$$

and the second is the CCI outage, defined as

$$O_I = \text{P}[\Lambda < \Lambda_{\text{th}}]. \tag{1.7}$$

For lightly loaded cellular systems thermal noise will dominate the outage performance, while for fully loaded cellular systems CCI will dominate the outage performance. CCI outage is the subject of Chap. 3.

1.5 Receiver Sensitivity and Link Budget

Receiver sensitivity refers to the ability of the receiver to detect signals in the presence of noise. The ratio of the desired carrier power to noise power before detection is commonly called the carrier-to-noise ratio, Γ. The parameter Γ is a function of the communication link parameters, such as the transmitted power or effective isotropic radiated power (EIRP), path loss, receiver antenna gain, and the effective input-noise temperature of the receiving system. The formula that relates Γ to the link parameters is called the link budget . A simplified link budget for cellular radio systems can be expressed in terms of the following parameters:

$$\begin{aligned}
\Omega_{\rm t} &= \text{transmit carrier power} \\
G_{\rm T} &= \text{transmit antenna gain} \\
L_{\rm p} &= \text{path loss} \\
G_{\rm R} &= \text{receiver antenna gain} \\
\Omega_{\rm p} &= \text{receive signal power} \\
E_{\rm c} &= \text{receive energy per modulated symbol} \\
T_{\rm o} &= \text{receiving system noise temperature in degrees Kelvin} \\
B_{\rm w} &= \text{receiver noise equivalent bandwidth} \\
N_{\rm o} &= \text{thermal noise power spectral density} \\
R_{\rm c} &= \text{modulation symbol rate} \\
k &= 1.38 \times 10^{-23} Ws/K = \text{Boltzmann's constant} \\
F &= \text{noise figure, typically 5–6 dB} \\
L_{\rm R_X} &= \text{receiver implementation losses} \\
L_{\rm I} &= \text{interference margin} \\
M_{\rm shad} &= \text{shadow margin} \\
G_{\rm HO} &= \text{handoff gain} \\
\Omega_{\rm th} &= \text{receiver sensitivity}
\end{aligned}$$

Many other parameters may be included in a detailed link budget, such as cable losses, but they are not included here.

The average received carrier power (or local mean) can be expressed as

$$\Omega_{\rm p} = \frac{\Omega_{\rm t} G_{\rm T} G_{\rm R}}{L_{\rm R_X} L_{\rm p}}. \tag{1.8}$$

Receiver implementation losses are included in the denominator of (1.8), since imperfect receiver implementation often results in a loss of effective received signal energy. Sometimes it also increases the effective noise power as well. The total input thermal noise power to the detector is [97]

$$N = kT_{\mathrm{o}}B_{\mathrm{w}}F. \tag{1.9}$$

The value of kT_{o} at a room temperature of 17°C (290°K) is $kT_{\mathrm{o}} = -174$ dBm/Hz. The received carrier-to-noise ratio, Γ, defines the link budget, where

$$\Gamma = \frac{\Omega_{\mathrm{p}}}{N} = \frac{\Omega_{\mathrm{t}}G_{\mathrm{T}}G_{\mathrm{R}}}{kT_{\mathrm{o}}B_{\mathrm{w}}FL_{\mathrm{R_X}}L_{\mathrm{p}}}. \tag{1.10}$$

The carrier-to-noise ratio, Γ, and modulated symbol energy-to-noise ratio, $E_{\mathrm{s}}/N_{\mathrm{o}}$, are related as follows [97]

$$\frac{E_{\mathrm{s}}}{N_{\mathrm{o}}} = \Gamma \times \frac{B_{\mathrm{w}}}{R_s}. \tag{1.11}$$

Hence, we can rewrite the link budget as

$$\frac{E_{\mathrm{s}}}{N_{\mathrm{o}}} = \frac{\Omega_{\mathrm{t}}G_{\mathrm{T}}G_{\mathrm{R}}}{kT_{\mathrm{o}}R_sFL_{\mathrm{R_X}}L_{\mathrm{p}}}. \tag{1.12}$$

Converting to decibel units gives

$$\begin{aligned} E_{\mathrm{s}}/N_{\mathrm{o}(\mathrm{dB})} &= \Omega_{\mathrm{t\ (dBm)}} + G_{\mathrm{T\ (dB)}} + G_{\mathrm{R\ (dB)}} \\ &\quad - kT_{\mathrm{o(dBm)/Hz}} - R_{s\ \mathrm{(dBHz)}} - F_{\mathrm{(dB)}} - L_{\mathrm{R_X\ (dB)}} - L_{\mathrm{p\ (dB)}}. \end{aligned} \tag{1.13}$$

The receiver sensitivity is defined as

$$\Omega_{\mathrm{th}} = L_{\mathrm{R_X}}kT_{\mathrm{o}}F(E_{\mathrm{s}}/N_{\mathrm{o}})R_s \tag{1.14}$$

or converting to decibel units

$$\Omega_{\mathrm{th\ (dBm)}} = L_{\mathrm{R_X\ (dB)}} + kT_{\mathrm{o(dBm)/Hz}} + F_{\mathrm{(dB)}} + E_{\mathrm{s}}/N_{\mathrm{o(dB)}} + R_{s\ \mathrm{(dBHz)}}. \tag{1.15}$$

In (1.15), all parameters are usually fixed except for $E_{\mathrm{s}}/N_{\mathrm{o(dB)}}$. To determine the receiver sensitivity, we first find the minimum $E_{\mathrm{s}}/N_{\mathrm{o(dB)}}$ that will yield an acceptable link QoS, and then substitute this value into (1.15). Then by substituting the resulting value for $\Omega_{\mathrm{th\ (dBm)}}$ into (1.13) and solving for $L_{\mathrm{p\ (dB)}}$, we obtain the maximum allowable path loss

$$L_{\mathrm{max\ (dB)}} = \Omega_{\mathrm{t\ (dBm)}} + G_{\mathrm{T\ (dB)}} + G_{\mathrm{R\ (dB)}} - \Omega_{\mathrm{th\ (dBm)}}. \tag{1.16}$$

Once the maximum allowable path loss is known, we can apply a path-loss model to determine the maximum radio path length, which is equal to the cell radii. Because we are interested in the link budget for cellular radio systems, there are three other relevant link budget parameters; (1) the margin for system loading or interference loading, (2) the shadow margin, and (3) the handoff gain. The first two quantities will reduce the maximum allowable path loss, while the third increases it.

1.5.1 Interference Loading

Frequency reuse results in co-channel and adjacent channel interference. As the system load increases the level of interference will also increase. This increase in interference will cause the cell radii to shrink since the radio receivers will be subjected to interference in addition to the thermal noise. Once the cell radii shrink, MSs that are located near the edges of the cells will experience an unacceptably low QoS. This will result in some links being dropped. However, as the connections are dropped the level of interference will decrease. This in turn will expand the cell radii and MSs located near the edges of the cells will again be able to establish links. This will once again increase the system load, and the entire process repeats itself. This phenomenon is sometimes called cell breathing.

If we wish to ensure coverage and prevent dropped links as the system load increases, then we must include an interference margin in the link budget. To do so, we note that the received carrier-to-interference-plus-noise ratio is

$$\Gamma_{IN} = \frac{\Omega_{\mathrm{p}}}{I+N} = \frac{\Omega_{\mathrm{p}}/N}{1+I/N}, \tag{1.17}$$

where I is the total interference power. A key parameter in this equation is the interference-to-noise ratio, I/N. The net effect of such interference is to reduce the carrier-to-noise ratio Ω_{p}/N by the factor $L_{\mathrm{I}} = (1+I/N)$. To allow for system loading, we must reduce the maximum allowable path loss in (1.16) by an amount equal to $L_{\mathrm{I\ (dB)}}$, otherwise known as the interference margin. The required $L_{\mathrm{I\ (dB)}}$ depends on the particular cellular system under consideration and the traffic load. The interference margin can be quite difficult to derive since it depends not only on the parameters of the radio link but also on the detailed resource management algorithms being used for power control and handoff. CDMA systems typically require a higher interference margin than TDMA systems due to their universal frequency reuse. With universal frequency reuse, every cell sector in the network can reuse the same set of carrier frequencies, and the emitter will act as a source of interference to a relatively large number of receivers (compared to larger reuse clusters) due to the small reuse distance. In any case, comparisons between different systems should always be made using the same total bandwidth and the same level of traffic loading.

1.5.2 Shadow Margin and Handoff Gain

Suppose that an outage due to thermal noise occurs whenever the received carrier-to-noise ratio at distance d, $\Gamma = \Omega_p(d)/N$ drops below some threshold Γ_{th}. Once the noise power N in (1.9) is specified, an outage will occur when the local mean drops below the receiver sensitivity, that is, $\Omega_{p\ (dBm)}(d) < \Omega_{th\ (dBm)}$. The outage probability due to noise on the cell boundary is defined as the probability that $\Omega_{p\ (dBm)}(R) < \Omega_{th\ (dBm)}$, where $d = R$ for a MS located on the cell edge. The area averaged noise outage probability is defined as the probability that $\Omega_{p\ (dBm)}(d) < \Omega_{th\ (dBm)}$, where the average is taken over the random location of an MS in the entire cell area. If the spatial distribution of MSs are unknown, then we may assume that the MSs are uniformly distributed throughout the cell area. To ensure a specified edge or area averaged outage probability we must include a shadow margin, M_{shad}, into the link budget. Finally, the outage probability will depend on the transmit power. In cellular systems, the BSs and MSs are power controlled so an outage is generally calculated under the condition of maximum allowable transmit power.

The outage probability due to noise on the cell edge is

$$\begin{aligned} O_N(R) &= P[\Omega_{p\ (dBm)}(R) < \Omega_{th\ (dBm)}] \\ &= \int_{-\infty}^{\Omega_{th(dBm)}} \frac{1}{\sqrt{2\pi}\sigma_\Omega} \exp\left\{ -\frac{\left(x - \mu_{\Omega_{p\ (dBm)}}(R)\right)^2}{2\sigma_\Omega^2} \right\} dx \\ &= Q\left(\frac{M_{shad}}{\sigma_\Omega}\right), \end{aligned} \tag{1.18}$$

where

$$Q(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy \tag{1.19}$$

and

$$M_{shad} = \mu_{\Omega_{p\ (dBm)}}(R) - \Omega_{th\ (dBm)}. \tag{1.20}$$

is the shadow margin. The outage probability, $O_N(R)$ is plotted against M_{shad} in Fig. 1.9 for various shadow standard deviations.

Example 1.1

Suppose that we wish to have $O_N(R) = 0.1$. To determine the required shadow margin, we choose M_{shad} so that the shaded area under the Gaussian density function in Fig. 1.10 is equal to 0.1. Hence, we solve

$$0.1 = Q\left(\frac{M_{shad}}{\sigma_\Omega}\right). \tag{1.21}$$

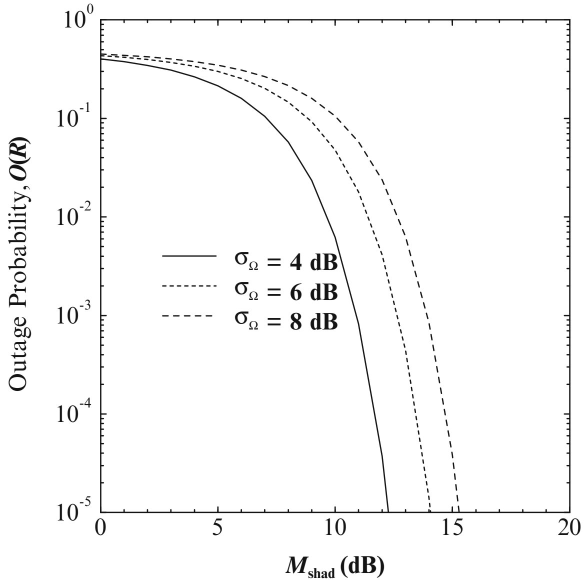


Fig. 1.9 Outage probability due to noise on the cell edge, $O_{\mathrm{N}}(R)$, against the shadow margin M_{shad}

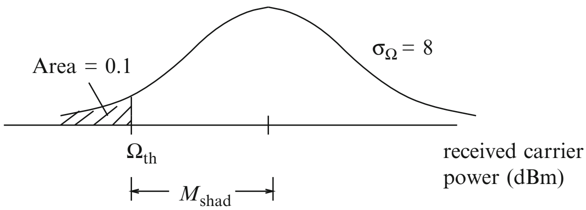


Fig. 1.10 Determining the required shadow margin

We have

$$\frac{M_{\mathrm{shad}}}{\sigma_{\Omega}} = Q^{-1}(0.1) = 1.28. \tag{1.22}$$

For $\sigma_{\Omega} = 8\,\mathrm{dB}$, the required shadow margin is

$$M_{\mathrm{shad}} = 1.28 \times 8 = 10.24\,\mathrm{dB}. \tag{1.23}$$

To obtain a relationship between the edge and area-averaged noise outage probabilities, we need models for the propagation path loss and spatial distribution of MSs. It is common to assume that the MSs are uniformly distributed throughout the cell area. This assumption along with the path loss model in (1.5) yields an area noise outage probability [96]

$$O_{\mathrm{N}} = \frac{1}{\pi R^2}\int_0^R O_{\mathrm{N}}(r) 2\pi r \mathrm{d}r$$
$$= Q(X) - \mathrm{e}^{XY+Y^2/2} Q(X+Y), \tag{1.24}$$

where

$$X = \frac{M_{\mathrm{shad}}}{\sigma_\Omega}, \qquad Y = \frac{2\sigma_\Omega \xi}{\beta}, \tag{1.25}$$

where $\xi = \ln(10)/10$. The first term of this expression is equal to the noise outage probability on the cell edge, $O_{\mathrm{N}}(R)$, while the second term is a correction factor. This obviously means that the edge outage probability is higher than the area averaged outage probability.

The above argument applies to the case of a single isolated cell. For cellular systems where the geographical area is covered by multiple cells, the situation is more complicated. As an MS moves from one cell to the next, handoffs will be executed to maintain service continuity. Consider a MS that is located in the boundary area between two cells. Although the link to the serving BS may be shadowed and be in an outage condition, the link to an alternate BS may at the same time provide an acceptable link quality. This is due to the fact that different shadowing conditions are usually encountered on links with different BSs. Hence, at the boundary area between two cells, we obtain a macrodiversity gain. The word macrodiversity is used to describe the case where the multiple receiver antennas are located in different base stations, as opposed to microdiversity where the multiple antennas are collocated in the same base station. Handoffs take advantage of macrodiversity, and they will increase the maximum allowable path loss by an amount equal to the handoff gain, G_{HO}. There are a variety of handoff algorithms that are used in cellular systems. CDMA cellular systems such as IS-95A/B, cdma2000 and WCDMA use soft handoff, while TDMA cellular systems such as GSM/GPRS/EDGE and OFDMA cellular systems such as WiMAX typically use hard handoff.

To illustrate the principle of handoff gain, consider a cluster of 7 cells; the target cell is in the center and surrounded by 6 adjacent cells. Although the MS is located in the center cell, it is possible that the MS could be connected to any one of the 7 BSs. We wish to calculate the area averaged noise outage probability for the target cell assuming that the MS location is uniformly distributed over the target cell area. This can be done quite effectively using Monte Carlo approaches with a large number of trials. Our results assume that the links to the serving BS and the six neighboring BSs experience correlated log-normal shadowing. To generate the required shadow gains, we express the shadow gain at BS_i as

$$\varepsilon_i = a\zeta + b\zeta_i, \tag{1.26}$$

where

$$a^2 + b^2 = 1$$

and ζ and ζ_i are generated once each simulation trial, and constitute independent Gaussian random variables with zero mean and variance σ_Ω^2. It follows that the shadow gains (in decibel units) have the correlation

$$\mathrm{E}[\varepsilon_i \varepsilon_j] = a^2\sigma_\Omega^2 = \rho\sigma_\Omega^2 \ , \ \ i \neq j. \tag{1.27}$$

where $\rho = a^2$ is the correlation coefficient. Here we assume that $\rho = 0.5$.

Let $\Omega_{\mathrm{p},k\ (\mathrm{dBm})}, k = 0,\ldots,6$ denote the received signal strength associated with the target BS ($k = 0$) and each of the six neighboring BSs ($k = 1,\ldots,6$). Three cases are considered; a single isolated cell to compare with earlier results, soft handoffs, and hard handoffs. For the case of a single isolated cell, no handoffs are used and the outage probability is identical to that obtained in (1.18) or (1.24). With a soft handoff algorithm, the BS that provides the largest instantaneous received signal strength is selected as the serving BS. The instantaneous received signal strength is affected by not only the path loss and shadowing variations, but envelope fading as well. However, for the present purpose envelope fading is not considered.[1] If any BS has an associated received signal power that is above the receiver sensitivity, $\Omega_{\mathrm{th\ (dBm)}}$, then the link quality is acceptable; otherwise, an outage will occur. Other more sophisticated and effective soft handoff and power control strategies are the subject of Chaps. 12 and 13.

With a hard handoff algorithm, the received signal power at the MS from the serving BS is denoted as $\Omega_{\mathrm{p,0\ (dBm)}}$. If this value exceeds the receiver sensitivity, $\Omega_{\mathrm{th\ (dBm)}}$, then the link quality is acceptable. Otherwise, the six surrounding BSs are evaluated for handoff candidacy using a mobile assisted handoff (MAHO) algorithm. BS k is included in the neighbor set if $\Omega_{\mathrm{p},k\ (\mathrm{dBm})} - \Omega_{\mathrm{p,0\ (dBm)}} \geq H_{(\mathrm{dB})}$, where $H_{(\mathrm{dB})}$ is the handoff hysteresis. If the received signal power for any member of the neighbor set is above the receiver sensitivity, $\Omega_{\mathrm{th\ (dBm)}}$, then link quality is acceptable; otherwise an outage occurs. A more detailed description and analysis of hard handoff is provided in Chap. 13.

Figure 1.11 compares hard and soft handoffs, for $H_{(\mathrm{dB})} = 6$ dB. Note that a 10% area noise outage probability (90% coverage) requires a shadow margin of 5.6 dB for a single isolated cell (no handoff). With soft handoffs, the required shadow margin is only 1.8 dB. The difference of 3.8 dB between the two is the soft handoff gain. The corresponding hard handoff gain is about 2.8 dB. Note that the soft handoff gain is always greater than the hard handoff gain. However, the true relative advantage depends on many factors and is difficult to predict.

The maximum allowable path loss with the inclusion of the margins for shadowing, interference loading, and handoff gain is

$$\begin{aligned} L_{\max\ (\mathrm{dB})} &= \Omega_{\mathrm{t\ (dBm)}} + G_{\mathrm{T\ (dB)}} + G_{\mathrm{R\ (dB)}} - \Omega_{\mathrm{th\ (dBm)}} \\ &\quad - M_{\mathrm{shad\ (dB)}} - L_{\mathrm{I\ (dB)}} + G_{\mathrm{HO\ (dB)}}. \end{aligned} \tag{1.28}$$

[1] As discussed in Sect. 2.6.2.1, a composite Nakagami-log-normal random variable can be approximated by a purely log-normal random variable with an appropriate area mean and shadow variance.

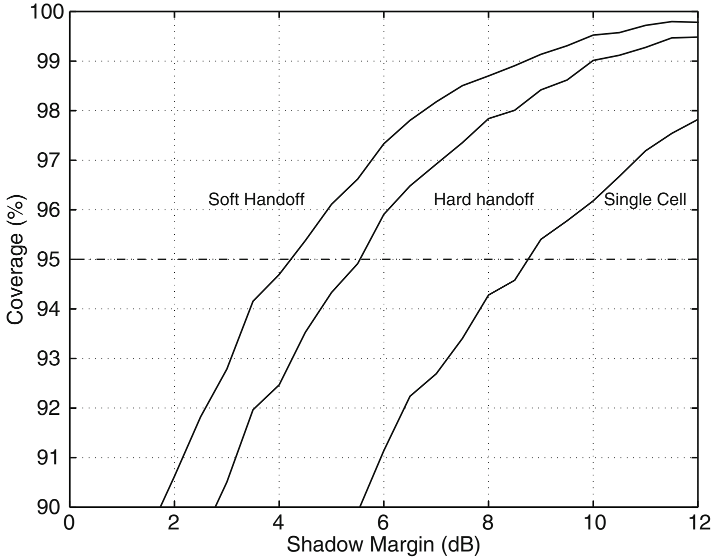


Fig. 1.11 Required shadow margin with hard and soft handoffs and 95% coverage; handoff hysteresis $H_{(\mathrm{dB})} = 6\,\mathrm{dB}$

1.6 Coverage

Coverage refers to the number of base stations or cell sites that are required to cover or provide service to a given geographical area with an acceptable QoS. This is an important consideration when a new cellular network is deployed. Clearly the choice of cellular system that requires the fewest number of cell sites to cover a given geographic area has an infrastructure cost advantage. However, it is always important to include interference margin into the coverage calculation to allow for system loading and this is often where the difficulty lies in comparing the different options. First, the traffic loads must be the same to allow for a fair comparison. Second, the function relating the required interference margin, $L_{\mathrm{I}\ (\mathrm{dB})}$ to the system load can be quite complicated, especially for CDMA cellular systems with universal frequency reuse.

The number of cell sites that are required to cover a given area is determined from the knowledge of the maximum allowable path loss and the path loss characteristic with distance. To compare the coverage of different cellular systems, we first determine the maximum allowable path loss for the different systems for the same QoS. From (1.5), it is apparent that

$$L_{\max\ (\mathrm{dB})} = C + 10\beta \log_{10}\{d_{\max}\} \quad (\mathrm{dB}), \tag{1.29}$$

where d_{max} is the distance corresponding to the maximum allowable path loss and C is some constant that depends on factors that are common to different cellular systems, such as the antenna heights and operating frequency. The quantity d_{max} is equal to the radius of the cell. To provide good coverage it is desirable that d_{max} be as large as possible. A variety of theoretical and empirical path loss models will be considered in detail in Sect. 2.7.

Once L_{max} has been determined for the various cellular systems to be evaluated, the relative coverage of the different systems can be compared, all other factors being equal. As an example of how this is done, suppose that System 1 has $L_{max\,(dB)} = L_1$ and System 2 has $L_{max\,(dB)} = L_2$, with corresponding radio path lengths of d_1 and d_2, respectively. The difference in the maximum allowable path loss is related to the cell radii through the following relationship

$$\begin{aligned} L_1 - L_2 &= 10\beta\left(\log_{10}\{d_1\} - \log_{10}\{d_2\}\right) \\ &= 10\beta\log_{10}\left\{\frac{d_1}{d_2}\right\}. \end{aligned} \tag{1.30}$$

Looking at things another way

$$\frac{d_1}{d_2} = 10^{(L_1-L_2)/(10\beta)}. \tag{1.31}$$

Since the area of a cell is equal to $A = \pi d^2$ (assuming a circular cell) the ratio of the cell areas is

$$\frac{A_1}{A_2} = \frac{d_1^2}{d_2^2} = \left(\frac{d_1}{d_2}\right)^2 \tag{1.32}$$

and, hence,

$$\frac{A_1}{A_2} = 10^{2(L_1-L_2)/(10\beta)}. \tag{1.33}$$

Suppose that A_{tot} is the total geographical area to be covered. Then the ratio of the required number of cell sites for Systems 1 and 2 is

$$\frac{N_1}{N_2} = \frac{A_{tot}/A_1}{A_{tot}/A_2} = \frac{A_2}{A_1} = 10^{-2(L_1-L_2)/(10\beta)}. \tag{1.34}$$

As an example, suppose that $\beta = 3.5$ and $L_1 - L_2 = 2\,\text{dB}$. Then $N_2/N_1 = 1.30$. Hence, System 2 requires 30% more base stations to cover the same geographical area. In conclusion, a seemingly small difference in link budget translates into a substantial difference in infrastructure cost. Since parameters such as the $E_c/N_{o(dB)}$ required, handoff gain and interference margin can each vary considerably from one system to the next, careful consideration is required.

1.7 Spectral Efficiency and Capacity

Spectral efficiency is of primary concern to cellular system operators. There are a variety of definitions for spectral efficiency, but an appropriate definition measures spectral efficiency in terms of the spatial traffic density per unit bandwidth. For a cellular system that consists of a deployment of uniform cells, the spectral efficiency with circuit-switched call traffic can be expressed in terms of the following parameters:

$$\begin{aligned} G_c &= \text{offered traffic per channel (Erlangs/channel)} \\ N_{slot} &= \text{number of channels per RF carrier} \\ N_c &= \text{number of RF carriers per cell area (carriers/m}^2) \\ W_{sys} &= \text{total system bandwidth (Hz)} \\ A &= \text{area per cell (m}^2). \end{aligned}$$

One Erlang is the traffic intensity in a channel that is continuously occupied, so that a channel occupied for $x\%$ of the time carriers $x/100$ Erlangs. Adjustment of this parameter controls the system loading and it is important to compare systems at the same traffic load level. For an N-cell reuse cluster, we can define the spectral efficiency as follows:

$$\eta_S = \frac{N_c N N_{slot} G_c}{W_{sys} A} \text{ Erlangs/m}^2\text{/Hz}. \tag{1.35}$$

Recognizing that the bandwidth per channel, W_c, is $W_{sys}/(N N_c N_{slot})$, the spectral efficiency can be written as the product of three efficiencies, viz.,

$$\eta_S = \frac{1}{W_c} \cdot \frac{1}{A} \cdot G_c \tag{1.36}$$

$$= \eta_B \cdot \eta_C \cdot \eta_T, \tag{1.37}$$

where

$$\begin{aligned} \eta_B &= \text{bandwidth efficiency} \\ \eta_C &= \text{spatial efficiency} \\ \eta_T &= \text{trunking efficiency} \end{aligned}$$

Unfortunately, these efficiencies are not at all independent so the optimization of spectral efficiency can be quite complicated.

For cellular systems, the number of channels per cell (or cell sector) is sometimes used instead of the Erlang capacity. We have

$$N_c N_{\rm slot} = \frac{W_{\rm sys}}{W_c \cdot N} \tag{1.38}$$

where, again, W_c is the bandwidth per channel and $N_{\rm slot}$ is the number of traffic channels multiplexed on each RF carrier. The number of channels per cell or cell sector is called the cell or sector capacity. However, the cell capacity does not account for trunking efficiency.

1.7.1 Bandwidth Efficiency

Bandwidth efficiency is measured in bits per second per unit bandwidth (b/s/Hz). High bandwidth efficiency can be achieved using bandwidth efficient modulation and coding techniques, along with effective receiver signal processing techniques that produce radio links that are tolerant to interference.

1.7.2 Spatial Efficiency

High spatial efficiency can be achieved by (1) minimizing the area per cell, and (2) minimizing the co-channel reuse distance. The first of these explains the intense interest in microcell and picocell technologies, where cell radii on the order of 50–500 m are used. The co-channel reuse distance D/R is minimized by (1) controlling the generation of CCI, and (2) mitigating the effect of any CCI that is present. The generated levels of CCI can be controlled using techniques such as cell sectoring, smart antennas, power control, scheduling, effective hand-off algorithms, macroscopic BS diversity, and a whole host of other techniques. The impact of CCI on the radio link can be mitigated using techniques such as optimum combining, single antenna interference cancelation, equalization, antenna diversity, and others.

Consider the situation shown in Fig. 1.12, depicting a simplified worst case forward link channel CCI condition. The MS is located at distance d_0 from the serving BS and at distances $d_k, k = 1, 2, \cdots, N_{\rm I}$ from the first tier of $N_{\rm I} = 6$ interfering co-channel BSs. If we let $\mathbf{d} = (\mathrm{d}_0,\ \mathrm{d}_1, \cdots,\ \mathrm{d}_{N_{\rm I}})$ denote the vector of distances at a particular MS location, then the forward link carrier-to-interference ratio as a function of the distance vector $\mathbf{d}$ is

$$\Lambda_{(\rm dB)}(\mathbf{d}) = \Omega_{\rm p\ (dBm)}(\mathrm{d}_0) - 10\log_{10}\left\{\sum_{k=1}^{N_{\rm I}} 10^{\Omega_{\rm p\ (dBm)}(d_k)/10}\right\}. \tag{1.39}$$

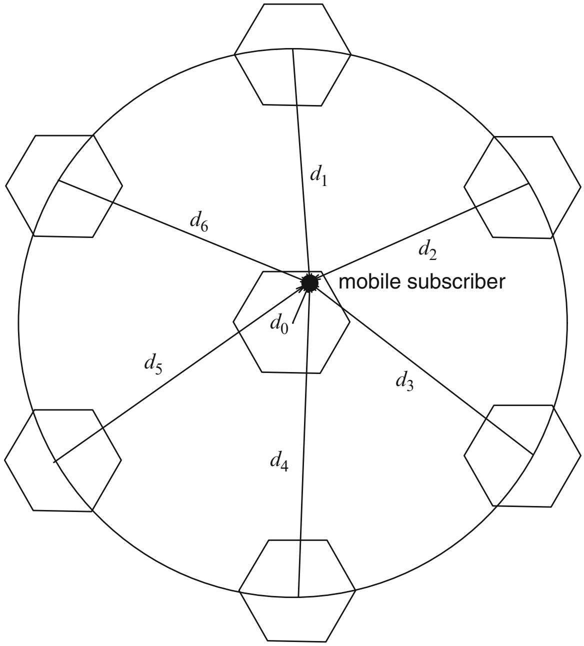


Fig. 1.12 CCI on the forward channel at a desired MS. There are six first-tier interfering BSs

At this point, we must account for the handoff gain. Consider, for example, the case of soft handoff. Let $\Lambda_{k\ (\mathrm{dB})}(\mathbf{d}), k = 0,\ldots,M$ denote the carrier-to-interference ratio for serving BS and M surrounding BSs. Note that the vector **d** is different for each candidate BS. With soft handoff, the BS that provides the most robust link is always selected such that the resulting carrier-to-interference ratio is

$$\Lambda_{(\mathrm{dB})} = \max\{\Lambda_{0\ (\mathrm{dB})}(\mathbf{d}), \Lambda_{1\ (\mathrm{dB})}(\mathbf{d}), \ldots, \Lambda_{M\ (\mathrm{dB})}(\mathbf{d})\}. \tag{1.40}$$

The area averaged probability CCI outage is

$$O_I = \mathrm{P}\left[\Lambda_{(\mathrm{dB})} < \Lambda_{\mathrm{th}\ (\mathrm{dB})}\right], \tag{1.41}$$

where the calculation is performed by averaging the probability of outage over the random location of a MS within the reference cell. Finally, we note that the outage depends on the number of interferers, N_{I} that are present. Due to the statistical nature of the user traffic, the number of interferers present is random. In the case of Fig. 1.12, it ranges from 0 to 6.

Finally, Fig. 1.13 depicts the CCI on the reverse link at the serving BS. Note that the CCI may not be exactly the same on the forward and reverse links, because the vector **d** is different in each direction and the propagation and interference conditions are different. This phenomenon is known as link imbalance.

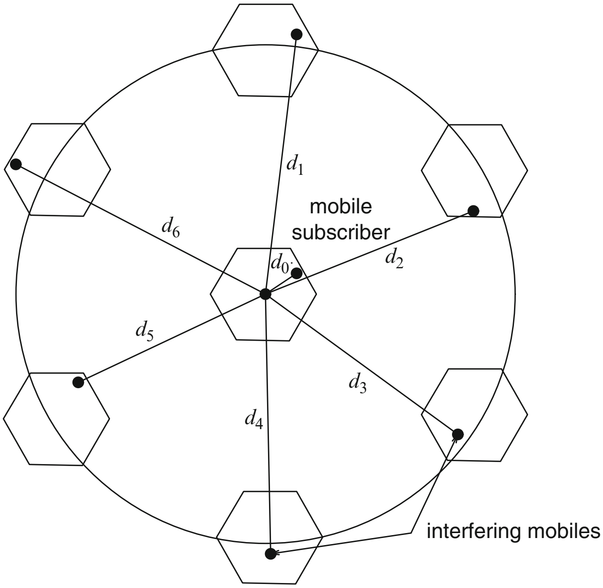


Fig. 1.13 CCI on the reverse channel at a desired BS. There are six first-tier interfering MSs

1.7.3 Trunking Efficiency

High trunking efficiency can be achieved using channel-assignment schemes that maximize channel utilization. There is usually a trade-off between trunking efficiency (or offered traffic per channel) and grade of service in terms of new call and handoff blocking probabilities. Various fundamental formula were developed by Erlang almost a century ago that laid the foundation of modern teletraffic theory. One of Erlang's most famous results is the Erlang-B formula, first derived in 1917, that gives the probability that a newly arriving call will not find any available channel in a trunk of m channels and is blocked. Sometimes this policy is called the blocked calls cleared queueing discipline, meaning that blocked calls are not buffered or queued and, if no free channels are available, they are dropped. The Erlang-B formula is not entirely applicable to cellular systems, because it does not account for handoff calls. Furthermore, the total offered traffic per cell may be time varying due to the spatial movement of the subscribers, whereas the offered traffic in the Erlang-B formula is assumed to be constant. The Erlang-B formula is

$$B(\rho_{\mathrm{T}}, m) = \frac{\rho_{\mathrm{T}}^m}{m! \sum_{k=0}^{m} \frac{\rho_{\mathrm{T}}^k}{k!}}, \tag{1.42}$$

where m is the total number of channels in the trunk and $\rho_{\mathrm{T}} = \lambda_{\mathrm{a}} \mu_{\mathrm{d}}$ is the total offered traffic (λ_{a} is the call arrival rate and μ_{d} is the mean call duration). The Erlang-B

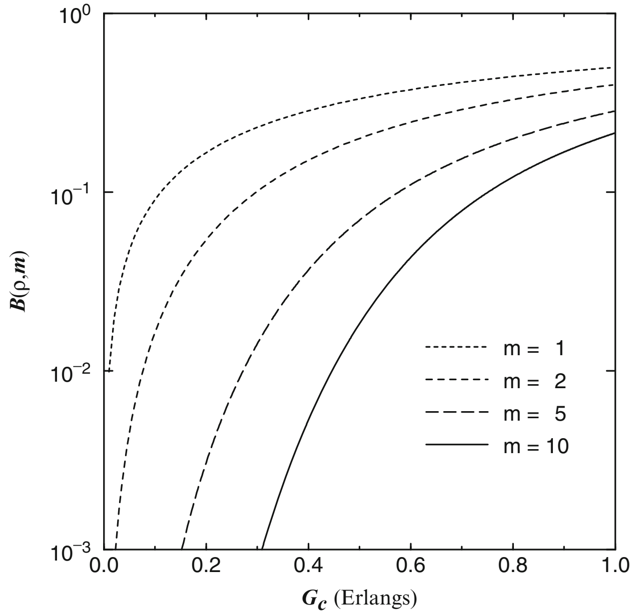


Fig. 1.14 Erlang-B blocking probability $B(\rho_T, m)$ versus offered traffic per channel $G_c = \rho_T/m$. Trunking is shown to improve the spectral efficiency

formula is derived under the so-called standard Markovian assumptions, including an infinite population of users, Poisson call arrivals with rate λ_a calls/s, and exponentially distributed call durations with a mean call duration μ_d s/call. Note that the total offered traffic ρ_T is a dimensionless quantity, but the quantity is expressed as Erlangs.

Figure 1.14 plots the blocking probability $B(\rho_T, m)$ as a function of the offered traffic per channel $G_c = \rho_T/m$. The benefit from trunking is obvious, since the offered traffic per channel, G_c, increases as the number of trunked channels increases, at any blocking probability. Note that diminishing returns are obtained as the number of trunked channels becomes larger. Finally, it is important to realize that doubling the number of channels in a cell or cell sector will double the cell or sector capacity. However, the Erlang capacity will more than double due to trunking efficiency.

1.7.4 Capacity

The capacity of a cellular system is often measured in terms of two quantities:

1. The cell capacity or sector capacity equal to the number of available channels per cell or cell sector.

2. The cell Erlang capacity equal to the traffic-carrying capacity of a cell (in Erlangs) for a specified call blocking probability.

Note that difference between spectral efficiency and cell Erlang capacity is that spectral efficiency accounts for the spatial efficiency and bandwidth efficiency. If the area per cell is the same in two different cellular systems, then their relative spectral efficiencies and Erlang capacities will be the same all other things being equal.

Comparing the spectral efficiency of different cellular systems can be difficult, because the various systems may be in different evolutionary stages. However, a fair comparison between suitably optimized digital cellular systems without deployment constraints will probably show roughly equal spectral efficiency. Indeed this is what we are seeing with EV-DO Rev B., HSPA+, LTE-A. HSPA+ achieves peak downlink speeds of 21 Mbps in 5 MHz, while LTE-A achieves 22 Mbps. Both systems are highly optimized. Recall that LTE-A downlink uses OFDMA, while the EV-DO downlink uses TDM/CDMA.

1.7.4.1 GSM Cell Capacity

A 3/9 (3-cell/9-sector) reuse pattern is achievable for most GSM systems that use frequency hopping; without frequency hopping, a 4/12 reuse pattern may be possible. A capacity gain is achieved with frequency hopping, since the CCI is averaged over the set of hop frequencies. GSM has 8 logical channels that are time division multiplexed onto a single radio frequency carrier, and the carriers are spaced 200 kHz apart. Therefore, the bandwidth per channel is roughly 25 kHz, which was common in first generation European analog mobile phone systems. The analog AMPS system in North America had 30 kHz carrier spacings. In a nominal bandwidth of 1.25 MHz (uplink or downlink), there are $1250/25 = 6.25$ carriers spaced 200 kHz apart.[2] Hence, there are $6.25/9 \approx 0.694$ carriers per sector or $6.25/3 = 2.083$ carriers/cell. Each carrier commonly carries half-rate traffic, such that there are 16 channels/carrier. Hence, the 3/9 reuse system has a sector capacity of 11.11 channels/sector or a cell capacity of 33.33 channels/cell in 1.25 MHz.

1.7.4.2 IS-95 Cell Capacity

The cell capacity of IS-95 was a topic of historical debate. CDMA systems were initially reported to achieve 40 times AMPS cell capacity, which made GSM appear to have a rather meager capacity. The key attribute of CDMA systems that leads to high capacity is universal frequency reuse, where all cells and cell sectors reuse

[2]Fractional carriers are used for the capacity calculation but can be eliminated in practice using a larger nominal bandwidth.

the same carrier frequency. About 20% of the global market went with the promise of CDMA. Ironically, GSM, which has 80% of the global market, has evolved to WCDMA in its 3GPP evolution.

For even the basic IS-95 system, the cell capacity is quite elusive because the universal frequency reuse means that every transmitter interferes with every receiver within radio range. To illustrate the difficulty in evaluating CDMA cell capacity, consider the following simplified analysis. Suppose there are N users in a cell; one desired user and $N-1$ interfering users. For the time being, ignore the interference from surrounding cells. Consider the reverse link, and assume perfectly power controlled MS transmissions that arrive chip and phase asynchronous at the BS receiver. Treating the co-channel signals as a Gaussian impairment, the effective carrier-to-noise ratio is

$$\Gamma = \frac{3}{N-1} \tag{1.43}$$

and the effective received bit energy-to-noise ratio is

$$\begin{aligned}\frac{E_\mathrm{b}}{N_\mathrm{o}} &= \Gamma \times \frac{B_\mathrm{w}}{R_\mathrm{b}} \\ &= \frac{3G}{N-1} \approx \frac{3G}{N},\end{aligned}$$

where $G = B_\mathrm{w}/R_\mathrm{b}$. The factor of 3 in the numerator of (1.43) arises from the assumption of randomly generated spreading sequences and the signals arriving at the receiver antenna in a chip and phase asynchronous fashion [183]. For a required $E_\mathrm{b}/N_\mathrm{o}$, $(E_\mathrm{b}/N_\mathrm{o})_\mathrm{req}$, the cell capacity is

$$N \approx \frac{3G}{(E_\mathrm{b}/N_\mathrm{o})_\mathrm{req}}.$$

Suppose that 1.25 MHz of spectrum is available and the source coder operates at $R_\mathrm{b} = 4$ kbps. Then $G = 1250/4 = 312.5$. If $(E_\mathrm{b}/N_\mathrm{o})_\mathrm{req} = 6$ dB (a typical IS-95 value), then the cell capacity is roughly $N = 3 \cdot 312.5/4 \approx 234$ channels per cell. This is roughly 7 times the cell capacity of GSM. However, this rudimentary analysis did not include out-of-cell interference which is typically 50–60% of the in-cell interference. This will result in a reduction of cell capacity by a factor of 1.5 and 1.6, respectively. Also, with CDMA receivers, great gains can be obtained by improving receiver sensitivity. For example, if $(E_\mathrm{b}/N_\mathrm{o})_\mathrm{req}$ can be reduced by 1 dB, then the cell capacity N increases by a factor of 1.26. Finally, CDMA systems are known to be sensitive to power control errors. An rms power control error of 2 dB will reduce the capacity by roughly a factor of 2 as discussed in Chap. 12.

Problems

1.1. Show that the area averaged outage probability due to thermal noise is given by (1.24).

1.2. Using geometric arguments, show that the co-channel reuse factor, D/R, for cellular deployments based on hexagonal cells is given by $D/R = \sqrt{3N}$.

1.3. Plot and compare the path loss (dB) for the free-space and flat specular surface models at 800 MHz versus distance on a log-scale for distances from 1 m to 40 km. Assume that the antennas are isotropic and have a height of 10 m. You may need material from Sects. 2.7.1 and 2.7.2 to do this problem.

1.4. A brief measurement campaign indicates that the median propagation loss at 420 MHz in a mid-size North American city can be modeled by the following path loss equation

$$L_{\mathrm{p}} = 25\ \mathrm{dB} + 10\log_{10}\{d^{2.8}\},$$

that is, the path loss exponent is $\beta = 2.8$ and there is a 25 dB fixed loss.

(a) Assuming a cell phone receiver sensitivity of −95 dBm, what transmitter power is required to service a circular area of radius 10 km?
(b) Suppose the measurements were optimistic and $\beta = 3.1$ is more appropriate. What is the corresponding increase in transmit power (in decibels) that would be required?
(c) If log-normal shadowing is present with $\sigma_\Omega = 8$ dB, how much additional transmit power is required to ensure 10% thermal noise outage at a distance of 10 km?

1.5. A receiver in an urban cellular radio system detects a 1 mW signal at $d_{\mathrm{o}} = 1$ m from the transmitter. In order to mitigate CCI effects, it is required that the CCI power that is received from any co-channel base station be no more than −100 dBm. A measurement team has determined that the average path loss exponent in the system is $\beta = 3$.

(a) Determine the radius R of each cell if a 7-cell reuse pattern is used.
(b) What is the radius R if a 4-cell reuse pattern is used?

1.6. Consider the worst case forward channel CCI situation shown in Fig. 1.15 The path loss is described by the following flat earth model

$$\mu_{\Omega_{\mathrm{p}}} = \frac{\Omega_{\mathrm{t}}(h_{\mathrm{b}}h_{\mathrm{m}})^2}{d^4}$$

where

$$\mu_{\Omega_{\mathrm{p}}} = \text{average received power}$$

$$\Omega_{\mathrm{t}} = \text{transmitted power}$$

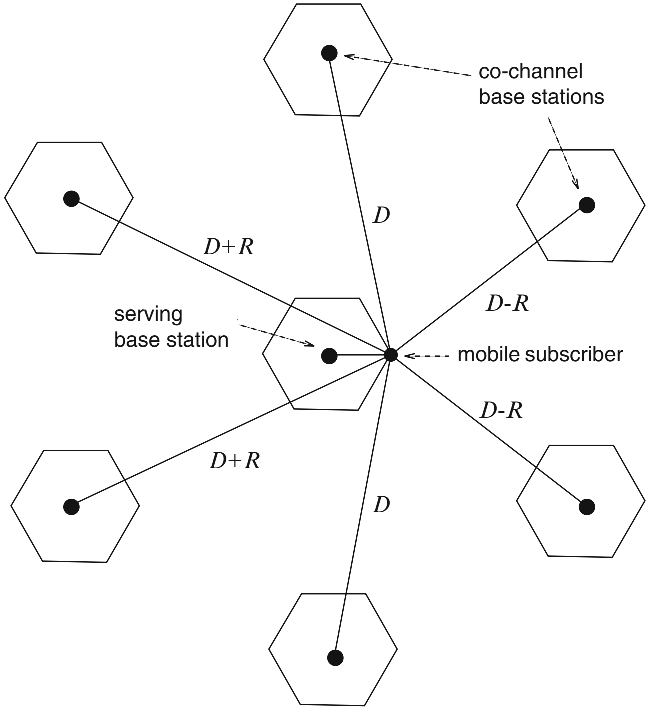


Fig. 1.15 Worst case CCI on the forward channel

$$h_{\mathrm{b}} = \text{base station antenna height}$$
$$h_{\mathrm{m}} = \text{mobile station antenna height}$$
$$d = \text{radio path length}$$

(a) Assume that $h_{\mathrm{b}} = 30$ m, $h_{\mathrm{m}} = 1.5$ m, and Ω_{t} is the same for all BSs. What is the worst case carrier-to-interference ratio Λ for a cluster size $N = 4$?

(b) Now suppose that the antenna height of the serving BS (in the center) is increased to 40 m while the other BS antenna heights remain at 30 m. This has the effect of enlarging the center cell. Assuming that we wish to maintain the same worst case Λ value obtained in part (a), what is the new radius of the center cell?

(c) Now suppose that the antenna height of one of the co-channel BSs is increased to 40 m while the antenna heights of the other BSs antenna heights, including the serving BS, remain at 30 m. This has the effect of shrinking the center cell. Assuming, again, that we wish to maintain the same worst case Λ value obtained in part (a), what are the new dimensions of the center cell?

1.7. A TDMA cellular system consists of a deployment of uniform radii hexagonal cells with a 9-cell reuse pattern. The cell diameter (corner-to-corner) is equal to 8 km. The system has a total bandwidth of 12.5 MHz (for both uplink and downlink). The channels have a channel spacing of 30 kHz. Calculate the following:

(a) Number of traffic channels/cell.
(b) Number of cells required to cover a total area of $3600\,\text{km}^2$. In this problem use the exact area of the hexagon cell rather than approximating the hexagon cell by a circle cell with the same cell radius.
(c) Co-channel reuse distance D.

1.8. Whenever a mobile station crosses a cell boundary a handoff occurs to the target cell. However, sometimes a handoff will occur because there are no channels available in the target cell. One method to decrease the probability of handoff failure is to queue the handoff calls. A handoff call that does not find an available channel in the target cell is allowed to remain in a queue for t_q seconds and is dropped from the queue, that is, it will experience a handoff failure, if no channel becomes available in that time.

Suppose the queue is serviced using a "first-come first-served" discipline. If m is the total number of channels in the trunk and ρ is the total offered traffic, then the probability of queueing is given by the famous Erlang-C formula

$$C(\rho_\mathrm{T},m) = \frac{\rho_\mathrm{T}^m}{\rho_\mathrm{T}^m + m!\left(1-\frac{\rho_\mathrm{T}}{m}\right)\sum_{k=0}^{m-1}\frac{\rho_\mathrm{T}^k}{k!}}.$$

The probability that a queued call will have to wait more than t_q seconds in the queue is

$$P[W > t_\mathrm{q}] = \exp\left\{-\frac{(m-\rho_\mathrm{T})t_\mathrm{q}}{\mu}\right\},$$

where μ is the mean call duration. Assuming that $\mu = 120\,\text{s}$ and $t_\mathrm{q} = 5\,\text{s}$, plot the blocking probability against the normalized offered traffic per channel $G_\mathrm{c} = \rho_\mathrm{T}/m$, for $m = 5, 10$, and 15. Comment on your results.

1.9. A GSM cellular service provider uses base station receivers that have a carrier-to-interference ratio threshold $\Lambda_\mathrm{th} = 9\,\text{dB}$.

(a) Find the optimal cluster size N for the following cases;

    (i) Omni-directional antennas
    (ii) 120° sectoring
    (iii) 60° sectoring

    Ignore shadowing and use path loss model in (1.5) with path loss exponents of $\beta = 3$ and $\beta = 4$.

(b) Assume that there are 200 traffic channels in the cellular system and that a blocked calls cleared queueing discipline is used with a target blocking probability of 1%. Further, assume that each cell or sector has approximately the same number of channels, and the cells have uniform traffic loading. Ignore any handoff traffic. The average call duration is equal to 120 s. Determine the offered traffic load (per cell) in units of *Erlangs* and *calls per hour* for each of the cases in part (a).

1.10. Suppose that an urban area has three competing trunked mobile networks (systems A, B, and C) to provide cellular service. System A has 400 cells with 15 channels/cell, System B has 50 cells with 100 channels/cell, and System C has 100 cells with 60 channels/cell. Ignore handoff traffic and assume uniform cell traffic loading.

(a) Plot the (Erlang-B) blocking probability, $B(\rho_{\mathrm{T}}, m)$, for each system versus ρ_{T}.
(b) Find the number of users that can be accommodated by each system for a blocking probability of 2% if the traffic loading offered by each user is 0.1 Erlangs.

1.11. A service area is covered by a cellular radio system with 84 cells and a cluster size N. A total of 300 voice channels are available for the system. Users are uniformly distributed over the service area, and the offered traffic per user is 0.04 Erlang. Assume a "blocked calls cleared queueing discipline, and the designated blocking probability from the Erlang-B formula is $B = 1\%$.

(a) Determine the carried traffic per cell if cluster size $N = 4$ is used. Repeat for cluster sizes $N = 3, 7$, and 12.
(b) Determine the number of users that can be served by the system for a blocking probability of 1% and cluster size $N = 4$. Repeat for cluster sizes $N = 7$ and 12.

In this question, the offered traffic per user is 0.04 Erlang. This is not the same as the offered traffic per channel. However, we can write

$$\rho_{\mathrm{T}} = U\rho_{\mathrm{u}},$$

where

$$\rho_{\mathrm{u}} = \textit{offered traffic per user}$$
$$U = \textit{number of users}$$

Note that ρ_{T} *in this case is the total offered traffic per cell and* U *is the number of users per cell.*