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Introduction

1.1 Scope and Organization

This book aims to promote an in-depth understanding of mobile satellite communication system technology, a branch of telecommunications enriching the lives of millions of mobile and nomadic people globally. Its relevance to modern society is best demonstrated by a few real-life situations:

- Live satellite coverage from the Mount Everest summit camp brings a realism into people's homes never experienced before – a nation rejoices as the summit is conquered.
- A passenger ship cruising in high seas collides with a rock – the crew, in a desperate attempt for survival, send a satellite distress call; a rescue party arrives shortly.
- An old man's wizened face comes alive as he talks to his son from his thatched village home, tucked away, where time stands still.
- An executive, preparing for a meeting on a trans-oceanic flight, contacts head-quarters and receives vital documents within minutes.
- A distressed community in an aftermath of a natural disaster receives vital supplies aided by communications through satellite phones.

Mobile satellite service or MSS systems provide communications to terminals that may be in motion, or moved at will anywhere within the service area. Terminals may be mounted on an aeroplane, a ship or carried by individuals; alternatively, the terminal may be a portable communicator set up at a convenient location. The vital elements are unrestricted user mobility with minimum regulatory restrictions in the service area. Mobility is achieved by the use of a radio link for tetherless connectivity and incorporating network intelligence to manage mobility. Regulatory restrictions are minimized through appropriate spectrum selection and operating licenses. Service areas of an MSS can span a country, a region or indeed the world.

There was a steady and gradual growth in MSSs until early 1990, at which juncture demands began to accelerate as new services were introduced and public awareness heightened due to the success of terrestrial mobile systems. A further spurt in aggregate world-wide demand occurred when satellite phones were introduced in the third quarter of the 1990s, despite the business failure of some MSS operators who had primarily targeted

Mobile Satellite Communications: Principles and Trends, Second Edition. M. Richharia.

Companion Website: www.satellitesandyou.com

the hand-held sector. These failures were caused by differences in user expectations in terms of cost and quality, and operators' expectations in terms of the market size and rate of penetration dented further by advances in roaming arrangements of terrestrial operators that made the satellite service unattractive to the globetrotter. Since then, many systems have been reinstated – aided by financial support, enhanced public, governmental and commercial awareness about the strengths of satellite systems; with enhanced system capabilities; a variety of new applications; elegant user terminal (UT) designs; higher throughput and tighter integration with terrestrial systems.

As it happens in rapidly evolving technologies, collating cohesive information can be time consuming and difficult, as useful information lies buried and scattered in specialist reference books, journals, conference proceedings, trade journals, and so on. This book attempts to bridge the gap through a structured compilation of such knowledge to assist understanding of system architectures, their components, applications and trends, assisted by a comprehensive list of references.

This thoroughly revised edition supplements the concepts of the first edition with recent developments adding three chapters to cover new topics. The technology has evolved quite considerably since – consider a few examples:

- Auxiliary Terrestrial Component (ATC) technology has matured enabling seamless extension of satellite services into dense urban areas systems by terrestrial re-transmissions;
- Spacecraft antennas provide hundreds of spot beams enabling an order of magnitude higher EIRP (effective isotropic radiated power) with highly sensitive on-board receivers;
- User throughput has increased several-fold;
- MSS usage has extended to the K_a band;
- A number of new standards have emerged while others have evolved;
- There is much tighter integration with terrestrial systems and technologies;
- Various improvements have been made in the underpinning technologies such as air interface, radio resource management, UTs, etc.;
- Very small aperture technology (VSAT) – a fixed satellite service (FSS) technology with associated radio regulations (RR) have evolved to provide MSS-like solutions.

The International Telecommunications Union (ITU), a United Nations body that regulates world-wide allocation of radio spectrum, has for spectrum planning categorized radio services according to their broad application – broadcast satellite service (BSS), FSS or MSS, and so on. Personal satellite communications services such as voice, facsimile and multimedia services require a radically different system design with a commercial approach quite recent to the satellite community. The ITU has termed such services as Global Mobile Personal Communications Services (GMPCS). This book deals with system level technical issues of the MSS and GMPCS. We will refer to these services together as MSS, unless a specific distinction is essential.

This chapter introduces the subject beginning with a review of the evolution of mobile communications. A subsequent section presents basic concepts of MSS architecture to familiarize the reader with the topic early in the book. A plethora of telecommunications products often leaves users uncertain regarding the most suitable solution. To enable users and prospective operators to make informed decisions, salient features of satellite and terrestrial systems are compared, followed by an overview of applications typical of an MSS. Many satellite navigation, FSS and BSS products have entered the domain of mobile communications. The system features of such systems are summarized, and finally, emerging trends introduced.

The design and implementation aspects of satellite constellations were revisited extensively in the 1990s as an alternative to the well-established geostationary orbit. After introducing the basics of orbital mechanics for the benefit of readers unfamiliar with this rather specialized topic, Chapter 2 discusses the characteristics of various types of constellations and compares them for a number of well-known constellation designs.

Chapters 3 and 4 introduce the core technical concepts of mobile satellite communication systems. Some of these topics are applicable generally to satellite communication systems but the treatment here is slanted towards an MSS perspective.

The first part of Chapter 3 outlines the main features of ITU procedures for interference management with an example of spectrum forecast methodology. The second part covers MSS radio propagation characteristics and the associated system implications in the MSS frequency bands for each environment – land, maritime and aeronautical channels. The final part of the chapter addresses the fundamentals of radio link analysis.

Chapter 4 develops an understanding of the digital modulation and coding schemes prevalent and emerging in modern mobile satellite system, followed by an introduction to multiple access techniques.

Gateways provide a radio connection between ground and space segments. Chapter 5 highlights MSS-specific features of gateways, which are otherwise identical to medium earth stations of the FSS. However, the chapter mainly focusses on the characteristics and technology of mobile terminals, which have profound implications for the success of MSS operators. Considerable public interest has arisen regarding radio frequency radiation effects to humans; a section has been devoted to this topic where current state of understanding is summarized.

Satellites are undoubtedly the most vital node of an MSS. Chapter 6 highlights the main features of MSS satellite technology including on-board processing and reconfigurable satellite antennas.

Chapters 7 and 8 explore MSS in a system context by collating concepts discussed in previous chapters. Chapter 7 covers the core areas of network architecture. Topics include air interface concepts, system synthesis methodology taking into consideration external influences, constraints-tradeoffs; network concepts such as mobility management and intersatellite routing. A vast number of mobile satellite systems have been standardized and recommended in recent years necessitating the addition of Chapter 8; the chapter introduces various satellite air interface standards, ITU recommendations for satellite component of future mobile communication systems, and an interactive mobile satellite broadcast standard.

Chapter 9 addresses key operational aspects of MSS systems, covering topics such as subscriber and gateway commissioning, spectrum and EIRP management methods, traffic analysis, radio frequency monitoring, interference and quality-of-service management.

This book views the MSS in a commercial perspective, and in this context, business and technology are intricately entwined. MSSs have grown rapidly in the recent past – and yet, despite remarkable technical achievements, many MSS companies faced bankruptcy at the outset. Hence Chapter 10 changes the emphasis to MSS economics, illustrating its inter-relationship with technology. Topics include commercial aspects such as service distribution, billing, regulatory influences, traffic forecast from a commercial perspective and a case study from a maritime user's point of view.

A number of technically interesting systems have been proposed, each with some novel features and Chapter 11 discusses representative examples to demonstrate how concepts have been translated to practice. Some of these systems could not be realized for commercial reasons, but they are of immense technical interest. The choice of system examples are made purely on the basis of their technical variety and merit, with little bearing on their commercial performance or affiliations. Thus we cover geostationary satellite systems, LEO (low earth orbit), MEO (medium earth orbit) and hybrid-orbit systems, and a system based on auxiliary terrestrial transmission. Chapter 11 in conjunction with Chapter 8 represents the current state of the art in system architecture.

The technology for reception of satellite television broadcast on mobiles on modified direct broadcast satellite receivers is well established. However, the advent of satellite broadcast systems targeting reception of television and radio on personal and portable sets is relatively recent. Chapter 12 introduces the concepts and standards of direct-to-person radio, television and multimedia broadcasts. The chapter reviews various aspects of this transmission technology including system requirements and configuration, compliant space segment, transmission technology, receiver architecture and introduces salient aspects of the DVB-SH (Digital Video Broadcast-Satellite services to Handheld) standard, which is representative of the technology trends.

In Chapter 13 we discuss systems, which offer services akin to the MSS but are not formally a part of them. In this context, we begin the chapter with an introduction to the satellite component of Global Maritime Distress and Safety System (GMDSS), which constitutes an essential element to augment the safety of the shipping industry and provides communication support to individuals and aircrafts in distress. The embedded satellite navigation receiver is an established feature of modern mobile terminals providing a variety of network functions such as timing and frequency reference and applications like location-based information. The chapter introduces satellite navigation principles with examples of existing and planned navigation systems. It includes the principles of differential global positioning system (DGPS) and satellite based augmentation system (SBAS) that provide increased positional accuracy for a variety of mobile applications. In the past few years, FSS terminal sizes have shrunk to an extent that they are portable, and hence the distinction between fixed and mobile services has become blurred in applications where such terminals can be used, as for example on ships and aircraft. The chapter discusses the rationale, underlying issues and the technology of mobile very small aperture FSS UTs. A majority of upcoming and recent MSS systems are tightly integrated with terrestrial mobile systems implying that there is now a better appreciation of terrestrial cellular system by the satellite community and vice versa. In such an environment, the treatment of mobile satellite communication cannot be taken in isolation. We will therefore outline the salient physical layer aspects of terrestrial cellular systems in this chapter.

The final chapter discusses various emerging new techniques and concepts under investigation to promote the evolution of mobile satellite systems in the medium to long term. We introduce a few market projections to demonstrate the healthy growth of MSS together with a spectrum forecast, and present some capacity enhancement technologies, which offer the potential to enhance spectrum utilization efficiency. These include – multi-user detection technology, advanced frequency planning techniques, cross-layer radio resource optimization and cognitive radio technology. Next we address advanced system architectures under investigation – the role of MSS in 4G and heterogeneous *ad hoc* networks and hybrid network architectures. In the next part we introduce a few enabling concepts and technologies currently in the research domain. These include propagation in Q/V and higher frequency bands, aspects of modulation and coding, the concept of multiple input multiple output application to MSS and the application of software defined radio in future systems. It is anticipated that there will be a shortfall in capacity of existing aeronautical communication systems and hence there is intense interest in promoting the introduction of efficient communication technologies for aeronautical communication in the period beyond ∼ 2015–2020. The role of satellite systems to meet the needs of the future aeronautical systems is addressed next. The chapter concludes on a speculative note presenting the concept of a utopian communication system where terrestrial, satellite and high altitude platform technologies are combined to provide a seamless global network.

Section A.1 provides coverage snapshots of a few representative non-geostationary satellite systems. Section A.2 provides a list of useful formulas for the system designer.

The book will be supported through the web site (www.satellitesandyou.com) with errata and updates.

1.2 Evolution of Mobile Telecommunications

For the purpose of this section, mobile communications systems are broadly categorized as terrestrial and satellite. In both, mobility is achieved by a RF link between the user and a relay station, which is connected to the fixed network that incorporates the mobility management functions. During the early phases of MSS, evolution of these two systems progressed independently. Terrestrial systems were best suited for urban environments, whereas satellites provided effective communications solutions for remote areas such as high seas, air corridors and remote land masses. By the beginning of 1990, MSS technology had matured to an extent that system planners began to evaluate benefits and techniques of integrating these two technologies, leading to the introduction of partially integrated systems by the end of the decade and full integration thereafter.

1.2.1 Terrestrial Systems

The potential of mobile communications was recognized from the outset of radio dating back to the late 1800s. Earliest use of mobile radio was for maritime navigation and safety.

Before and during World War II, mobile systems were generally confined to military users. Vacuum tubes and heavy batteries in transceivers (i.e. a transmitter-receiver unit) made them bulky, restricting their use to specialized applications. By the 1950s technology advancements enabled availability of man-pack very high frequency/frequency modulation (VHF/FM) radios, which extended the applicability of mobile systems to civil Private Mobile Radio (PMR). The growth of mobile radio was slow until the 1970s, because the problem of extending service range within the permitted frequency bands proved technically difficult. In general, mobile communication service remained an expensive communication medium. But even if the cost of mobile services had reduced significantly, the factor that hampered growth of mobile services was spectrum scarcity. A concept called ‘cellular radio’, which offered a solution to support large numbers of users in a limited spectrum, was proposed at Bell Laboratories in 1940s. However, enabling technologies to realize the concept would arrive much later, in the 1980s.

Mobile transceivers were permitted access to the public network of the United States by AT&T in 1946. The service was called Mobile Telephone Service (MTS), which operated in the 35 or 150 MHz band. The simple system was manual, where the user seized a vacant channel requesting an operator for a connection to it.

An improved MTS (IMTS) that offered duplex operation, automatic dialling and switching was launched in 1964. The system capacity was initially limited to 11 channels in the 152–158 MHz band. Due to a rise in demand, the capacity was enhanced in 1969 by 12 channels in the 454–459 MHz band. Each service zone was served by a single base station, which used a channel only once and hence the demand could not be satisfied; typically, around 550 users could be served in a zone. Other service limitations included bulky transceivers that had to be vehicle mounted, and the need for high-capacity batteries.

Introduction of the cellular concept provided the desired breakthrough in overcoming the spectrum limitations. The first cellular system known as the Advanced Mobile Phone System (AMPS) was developed in the USA by AT&T and Motorola, Inc. The analogue system was designed to operate in the 800 MHz band with a capacity of 666 paired channels.

However, the first *commercial* cellular system was deployed in Japan in 1979, followed by Nordic Mobile Telephone (NMT) system introduced in 1981 in Denmark, Finland, Norway and Sweden, the Total Access Communication System (TACS) in the United Kingdom and the AMPS system in 1983 in the USA. Yet other cellular systems were developed and introduced in other countries.

Rapid developments were made in radio, very large-scale integration (VLSI) and computer technologies, giving a huge reduction in costs through economies-of-scale and consequent increases in personal communications. Users have since been inundated with a variety of cellular phones, systems and services. Figure 1.1(a) illustrates the substantial world-wide penetration trend of the past decade for the world and by level of development. The number of mobile subscriptions increased from ∼50 per 100 inhabitants in 2001 to 122.3 in 2011 in the developed world and ∼18 to 85.7 across the world during the same period. Mobile broadband is a relatively new introduction. Figure 1.1(b) shows the penetration per 100 inhabitants of active mobile-broadband subscriptions for the period 2007–2011 for the world and by level of development. In this case, the penetration increased from ∼18 to 51.3 per 100 inhabitants in the developed world and the corresponding worldwide growth increased from ∼3 to 15.7 per 100 inhabitants.

A consequence of the runaway commercial success of cellular phones was the proliferation of a variety of systems incompatible to each other, causing inter-operability problems so that users could not operate their cellular phones outside a home territory. Concentrated efforts to harmonize evolution lead to second generation digital standards such as the Global System for Mobiles (GSMs) in Europe, which gave a cross-country roaming facility.

Despite high spectral efficiencies offered by cellular systems, capacity shortfall remained a pressing issue, and efforts to enhance capacity continued. In the United States, carrier spacing of AMPS system was reduced from 30 to 10 kHz, trebling the capacity. The second approach was to introduce digital voice compression with time-division multiple access, which resulted in a similar order of capacity enhancement. Spread spectrum modulation with code division multiple access (CDMA) was yet another approach. Its proponents claimed

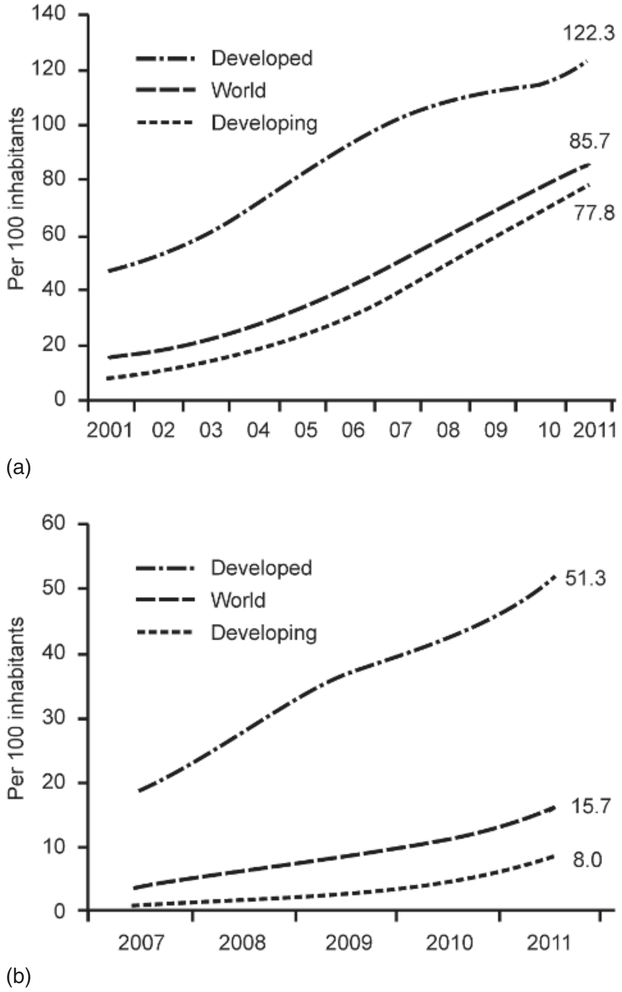

Figure 1.1 (a) Mobile-cellular subscription penetration during the period 2001–2011 for the world and by level of development. (b) Active mobile-broadband subscriptions penetration during the period 2007–2011 for the world and by level of development. (Both parts source: ITU World Telecommunication/ICT Indicators database. Reproduced with permission of ITU.)

a 10–20-fold capacity increase over the AMPS system. Subsequently personal communication system (PCS) systems were based around evolved GSM technology and a spread spectrum technology called IS-136 or D-AMPS. Satellite air interface standards based on GSM were introduced leading to a tighter integration of satellite and terrestrial systems.

Third generation cellular systems offering wideband were introduced in Europe and elsewhere to bring further homogeneity in mobile communications across the world, thereby offering benefits to users, manufacturers and operators. Satellite systems have since been integrated with the third generation terrestrial core network to offer seamless connectivity.

1.2.2 Satellite Systems

Table 1.1 summarizes some interesting milestones in the MSS evolution.

The earliest mobile communication experiments were conducted through National Association of Space Administration's (NASA) Applications Test Satellites ATS-5 and 6. A number of early MSS proposals never took off due to the perceived technical and financial risks. The potential of satellite systems to provide high reliability communications to ships was recognized by International Maritime Organization (IMO). The prevailing communication systems used high frequency (HF) band and proved unreliable under adverse propagation conditions, often requiring hours to establish communications from high seas when weather conditions were unfavourable. Ships on the high sea would occasionally be lost without trace. Satellite communications radio links are reliable under most conditions. Recognizing the advantages offered by a satellite medium, the IMO initiated the formation of an organization, then called, International Maritime Satellite Organization (Inmarsat) for provision of safety and commercial public correspondence services to ships for peaceful purpose. Inmarsat was founded in 1979 and the maritime communications services became available in 1982 using satellites leased from a number of satellite operators. The success of maritime services led to the introduction of services in land and aeronautical environments and generally vast enhancements in MSS technology. The size of terminals reduced progressively with technology evolution from heavy transportable terminals to desktop-sized personal telephones, briefcase-sized multimedia terminals, hand-held phones; high power satellites with spot beams were introduced while throughput continued to increase. The company was then renamed as International Mobile Satellite Organization to reflect its expansive portfolio, retaining the same acronym.

In the 1990s, a number of regional systems were introduced in the USA, Europe, Australia and Japan. For example, Omnitracs Inc. and EutelTRACS provided low bit rate services in the USA and Europe respectively; the American Mobile Satellite Consortium (AMSC) began voice and data services in the USA and Canada; and the Optus system was introduced for voice and data services in Australia.

Studies on non-geostationary orbits (NGSOs) were first conducted in 1960s when it was difficult to launch satellites to the GEO (geostationary earth orbit) and therefore lower orbits were considered appropriate. Subsequently, GEO became a favoured choice, due to advantages arising from static path geometry of geostationary satellites. Non-geostationary earth orbits (NGEOs) remained in use for specialized applications such as remote sensing, military reconnaissance, Earth resource survey, etc. The military were interested in the survivability and robustness offered by low orbit satellite systems due to their inherently distributed architecture (Chakraborty, 1989). Towards the end of 1980s a university group in the UK studied the feasibility of deploying a LEO satellite constellation for mobile communications with the conclusion that such systems were indeed feasible, compare favourably with geostationary satellite systems and could be implemented within a decade (Richharia *et al.*, 1989). Within a year, quite independently, Motorola Inc. announced plans of a LEO satellite system to provide personal voice communication service via hand-held phones (Nelson, 1998). The announcement triggered a feverish activity in the satellite industry and within the next three years a number of organizations and companies announced similar plans, most of them intending to use non-geostationary constellations. Notable amongst them was a MEO system, which was conceived by Inmarsat but was to be implemented by a new private company

Table 1.1 Interesting events in the evolution of mobile satellite systems

Year	Milestone	Responsible
1957	Launch of first satellite	Former Soviet Union
1965	Launch of first geostationary satellite	Comsat, USA
1976	First demonstration of intersatellite link	LES-8 satellite, USA
1977	Mobile experiments using ATS-6	NASA, USA
1978	Introduction of global positioning system (GPS)	US government for the Department of Defense
1979	Inmarsat formation	International Maritime Organization
1980	IMO decides to deploy satellite communications for maritime safety.	UN
1982	Introduction of GLONASS	Former Soviet Union
1982	First civilian mobile satellite system introduced	Inmarsat
1987–1989	An architecture of LEO for mobile satellite communication investigated and proposed	University of Surrey
1990	First commercial satellite radio broadcast system filed	CD Radio Inc., USA
1990	First commercial non-GEO hand-held system announced	Motorola/Iridium
1990–1991	Commercial land and aeronautical mobile satellite services (MSSs) introduced	Inmarsat
1992	GSM system introduced	Europe
1992	Major changes to mobile satellite frequency allocation	WARC 1992
1993	Announcement of first commercial little-LEO satellite system (with secure finance)	Orbital Sciences Corporation – ORBCOMM system; USA
1994	First non-GEO FSS for personal communications announced	Teledesic Corporation; USA
1994–1996	Announcement of several regional 'super-geostationary' satellite systems	Agrani (Indian Consortium) ; APMT (China/Thailand); ACes; Thuraya, etc.
1996	Paging services introduced	Inmarsat
1997	Desktop-sized mobile terminals introduced	Inmarsat
1997	First non-geostationary little-LEO satellite system introduced	ORBCOMM
1997	Frequency allocation for non-GEO fixed system	WRC 1997
1997	Launch of first batch of LEO satellite system for voice communications (so called 'big-LEO')	Iridium
1997	Launch of first batch of non-geostationary satellite system for low bit rate data communications ('little-LEO')	ORBCOMM
1997	Mobile experiments using ACTS	NASA
1997	Navigation system: geostationary overlay capability available	Inmarsat

(*continued overleaf*)

Table 1.1 (*continued*)

Year	Milestone	Responsible
1997–1998	Start of world-wide spot beam operation for MSS	Inmarsat
1998	Introduction of first big-LEO satellite system	Iridium
1998	Introduction of dual-mode satellite-terrestrial handsets (i.e. combined satellite and terrestrial handset)	Iridium
1998	Safety Of Life At Sea (SOLAS) treaty introduced	UN
1998	Introduction of on-board processing satellites for MSS	Iridium
1999–2000	Serious financial difficulty experienced by new and proposed NGSO MSS systems	Iridium
	Introduction of Globalstar	Globalstar
2000–2005	Consolidation of new mobile satellite system operators despite financial losses	Various
2005	Introduction of wide-band portable land mobile communication system	Inmarsat
2006–2008	Extension of portable broadband system to mobile platforms	Inmarsat
2009–2010	Announcement of next generation systems	Inmarsat, Iridium, Globalstar, ORBCOMM
2009	LightSquared proposes ATC services in USA	LightSquared
2012	ATC service license suspended in USA due to interference issues to GPS	LightSquared
2014	Introduction of upper-end MSS broadband (up to ~50 Mbps) in K_a band	Inmarsat

ACTS, Advanced Communications Technologies and Services.

called ICO (Intermediate Circular Orbit) Global Systems Limited (referred in the remaining text as the ICO system); and a LEO system known as Globalstar.

Another approach was to use low-risk technology and smaller spacecraft for low bit rate niche applications such as messaging and machine-to-machine communication ensuring an early entry in to the market as proposed, for example by companies such as Orbital Science System.

In the mid-1990s, plans for hand-held satellite phone services using GEOs were announced. These systems planned to deploy several hundreds of spot beams with powerful transmitters to compensate for the relatively higher altitudes of a geostationary orbit. Interestingly, only a few years ago geostationary systems were discarded due to the perceived complexity of payload; intense research and development in the ensuing four to five years had matured the technology. Close on its heels, a number of PCSs for fixed services were announced – converging high bit rate service offerings of the MSS with the lower end FSS products. Most FSS systems intended to operate in 20–30 GHz FSS band and in a variety of orbits. Table 1.2 (Adapted from Evans, 1998) compares the salient technical features of various MSS non-geostationary satellite proposals for hand-held voice services with an equivalent regional geostationary satellite system of that period. The geostationary satellite system compensates for the additional path loss compared to MEO/LEO systems by deploying highly directive spot beams and transmitting high EIRP. Table 1.3 presents a comparison of LEO, MEO and GEO MSS systems. LEO systems have

Table 1.2 A comparison of main technical parameters of some existing and proposed MSS proposals of 1990s

System parameter	System			
	Iridium	Globalstar	ICO global communication (original proposal)	Typical regional system
Service (voice bit rate)	Hand-held telephony/ data (4.8 kbps)	Hand-held telephony/ data (up to 9 kbps, depending on channel conditions)	Hand-held telephony/ data (4.8 kbps)	Hand-held telephony/ data (2.4–4.8 kbps)
Type of orbit	Low earth polar orbit	Low earth inclined orbit	Medium earth orbit	Geostationary
Number of spot beams/ satellites	48/66	16/48	163/10	100–300/1
Nominal capacity per satellite	1 100	2 400	4 500	16 000
Service area	Global	Global	Global	Regional
Service link frequency (up/down) in gigahertz	1.616–1.6265/ 1.616–1.6265	1.62–1.63/ 2.48–2.5	1.98–2.01/ 2.17–2.2	(1.6/1.5) MSS band
Feeder link frequency band (up/down) in gigahertz	30/20	5.1/6.9	5.2/6.9	14/12
Gateway antenna G/T (dB/K)	24.5	28.5	26.6	37.0
Multiple access	FDM/TDMA	FDM/CDMA	FDM/TDMA	FDM/TDMA
RF bandwidth per channel (kHz)	31.5	1 250	25.2	5–10
Modulation	DQPSK	SS/QPSK	QPSK	QPSK
User terminal RF power (W)	0.45	0.5	0.625	0.5
User terminal G/T (dB/K)	−23	−22	−23.8	−23.8
Typical service link margin (dB)	16.5	11	10	10

QPSK, quadrature phase shift keying; SS, Spread Spectrum. (Adapted from Evans, 1998.)

Table 1.3 A comparison of system features using various types of orbit

	Geostationary orbit	Medium earth orbit	Low earth orbit
Number of satellites (world-wide coverage)	3–4	10–12	40–300
Regional coverage	Well suited	Specific orbital design necessary (depends on region)	Specific orbital design necessary (depends on region)
Coverage limitations	Within ±76° latitude	None	None
Approximate satellite lifetime – first generation non-GEO/second generation GEO (yr)	15	7–10	5–7
Operational cost and complexity	Low	Medium-high	High
Transmission delay (ms)	250	55–80	3.5–15

the lowest transmission delay, provide true global coverage but the space segment and the network is complex. MEO systems have intermediate transmission delay provide true global coverage with a moderately complex space segment and network. GEO systems exhibit the highest transmission delay with coverage limited to ~±76° latitude; however, the network is simple and the system is supported by matured technology.

Most satellite system designers, noting the benefits of integrating satellite systems with terrestrial systems, proposed system architectures combining satellite and terrestrial system networks to various extents. Dual-mode satellite/cellular hand-held telephones were conceived.

As mentioned, the trend in space segment architecture diverged at the beginning of 1990 when a number of commercial non-geostationary satellite systems were proposed for hand-held voice and data communication services on the premises that hand-held services via geostationary satellites would require extremely complex spacecraft and suffer transmission delays. Their architecture varied widely in terms of orbit, complexity, transmission schemes, network routing and the addressed market.

Further, we observed that by mid-1990 there was a re-emergence of geostationary systems based on powerful satellites deploying several hundreds of spot beams.

International organizations, developing standards and formalizing concepts for third generation terrestrial systems, began considering role of satellite systems in future system architectures. It was well understood that cellular systems would prevail in populated areas where they are economically viable, leaving gaps in vast, sparsely populated areas best be covered by satellite systems. Thus, future systems would incorporate interfaces and interworking arrangements to support interoperability between terrestrial and satellite systems.

In parallel, an unabated growth in *satellite navigation* technology for mobile and personal use continued throughout the 1990s. The cost of GPS (global positioning system) receivers plummeted to levels affordable by the masses. A number of applications developed, combining navigation and communication capabilities. Notable progress was made

Table 1.4 Mobile satellite communications evolutionary trends

Phase	Year	Service	Satellite technology/ frequency band	Orbit
I	1980–1990	Analogue voice and 64 kbps data on 1 m dish terminals	Low power, single beam/L	GEO
II	1990–2000	Voice and low rate data on hand-held terminals; 64 kbps data on 0.8–1 m dish terminals	GEO: medium power, 1–8 spot beams/L	GEO and non-GEO
			NGEO: medium power, up to 48 spot beams, on-board processing/L and S	
III	2000–2010	GEO: first generation hand-held; broadband up to 500 kbps on portable and mobile terminals	GEO: high power, up to 200 spot beams, on-board processing/L	GEO and non-GEO
		NGEO: second generation hand-held, a wider application portfolio, first generation maritime and aeronautical products	NGEO: Enhanced first generation products and second generation proposals	
IV	2010–2020	GEO: second generation hand-held	GEO: K_a band high power satellites with multi-beam spot beams	GEO and NGEO
		Wider application portfolio, broadband up to 55 Mbps on large/portable K_a band terminals and 1 Mbps on small terminals	NGEO: second generation, high power, multi-spot beams, longer life time	
		NGEO: third generation hand-held; second generation products for maritime and aeronautical applications		

towards the introduction of *satellite radio service*, a service aimed to broadcast directly to receivers carried by individuals and such systems became available in the first decade the new millennium. The principles of these related systems are discussed in Chapter 13.

We may classify satellite system evolution on the basis of best available services and technology into a number of phases as shown in Table 1.4.

1.3 Satellite System Architecture

The main components of a mobile satellite system are shown in Figure 1.2.

The system offers communication services to a variety of mobile users within a predefined service area under the control of a network control centre (NCC). Users communicate with

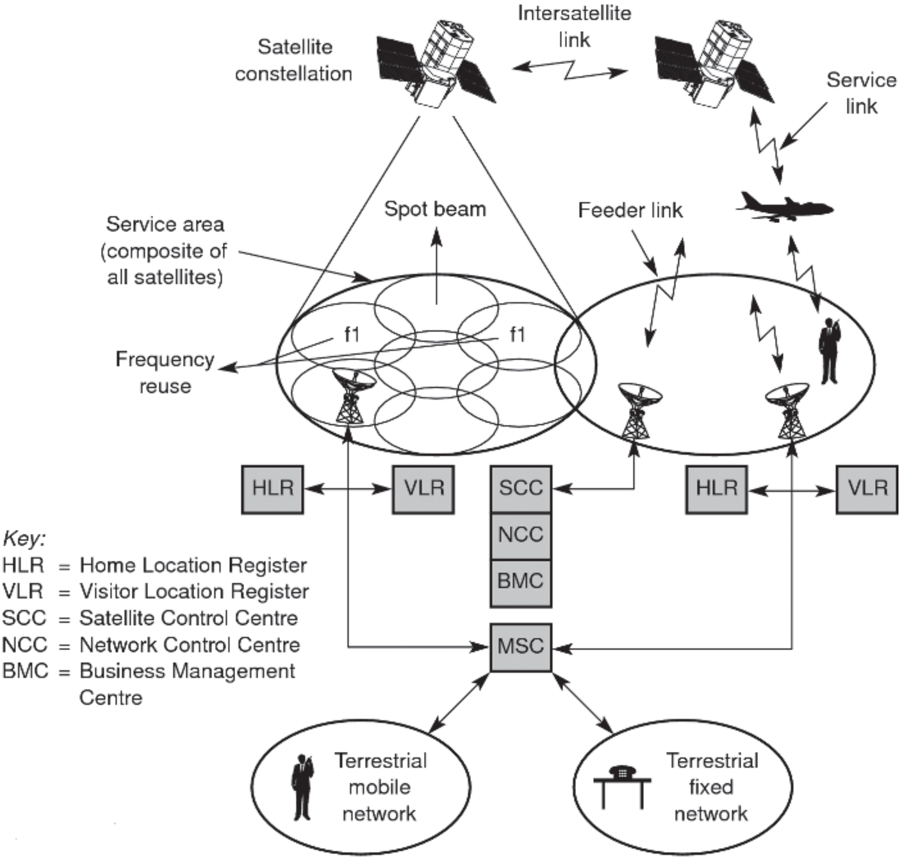

Figure 1.2 Main components of a mobile satellite system (MSC = Mobile Switching Centre)

other mobiles or with fixed users through the visible satellite. Users in the fixed network are accessed through large fixed stations called *gateways*, which must carry aggregated volumes of traffic, whereas mobiles are small portable units capable of supporting one to five channels (or the supported data rate). UTs' size and capability range from portable or handheld personal terminals, to units mounted on ships, aircraft and trucks capable of supporting several channels simultaneously. Services include paging, telephony and medium to broadband data. The fixed stations use very sensitive receivers and operate with stable radio links, whereas mobile receivers are small in size with limited sensitivity, and power received at mobiles undergoes wide fluctuations due to variations in a mobile's path profile. Hence the capacity of an MSS is governed by the power and bandwidth constraints of the service link.

Depending on the service area and application, the *space segment* consists of one or more GEO or NGEO satellites. Telemetry and control ground stations, used for monitoring and controlling satellites, constitute a part of the space segment. A satellite control centre (SCC) manages the functioning and maintenance of the satellites. To simplify the mobile terminals, complexity is shifted to the space segment and hence satellites tend to be large and complex with existing technologies typically capable of generating up to 12 kW DC power, EIRP in excess of 67 dB W in L-band with > 200 spot beams for efficient frequency reuse. A geostationary satellite remains almost fixed with respect to the Earth illuminating the service area with a *static* footprint that enables a simple network topology, whereas, NGEO space segments and network topology are complex due to non-stationary satellites.

In a centralized system, a NCC manages the traffic flow, call set-up and release, radio resources and signalling. On receiving a call request, the radio resource manager assigns the desired radio resource for the duration of the call. The home location register (HLR) and visitor location register (VLR) are responsible for mobility management. The mobile switching centre (MSC) manages call switching between the fixed network and the mobile network. A business management centre (BMC) is responsible for billing, new activations, customer support, and other business-related functions.

In an NGEO system, a call (or a data session) in progress must be re-routed to maintain connectivity as the connected satellite or spot beam moves out of visibility necessitating *handover(s)* to a rising satellite or spot beam.

A call may be routed to the final destination through intersatellite links, or via ground-satellite hops, or terrestrially. Figure 1.3(a) and (b) respectively illustrate source-destination connectivity in an NGEO satellite system deploying a terrestrial backbone and intersatellite links. The Iridium system deploys intersatellite links whereas the ICO system uses ground routing.

For non-interactive or store and forward services, a discontinuous coverage is acceptable. The message is stored in a satellite or ground station buffer and delivered to the destination via single or multiple satellite hops within a specified time limit. Figure 1.4(a) and (b) represents main entities of store and forward system with satellite and ground-based buffers, respectively. In Figure 1.4(a), the message M received at a satellite at $t = 0$, is transmitted to the destination at time t_2. In Figure 1.4(b), transmissions from a mobile van, received at a fixed site 'A' is stored and retransmitted when a satellite mutually visible with the destination N becomes available.

User data rate is commonly used to categorize MSS systems, as illustrated in Table 1.5 with example applications.

Although service requirements are the key enablers in developing the architecture of a MSS network, the outcome is often influenced by numerous constraints that include non-technical matters such as regional priorities and business goals, which lie beyond the scope of the book. Chapters 2 and 7 discuss the subject of network synthesis in detail.

1.3.1 Radio Frequency Environment

The constraints imposed by the service link impose significant limitations to the system capacity:

- *Forward link*
  - *Satellite EIRP and user's receiver sensitivity limitations*: The EIRP of a satellite, given as the product of available RF power and antenna gain, and the sensitivity of a UT set a bound to the UT throughput. The highest available EIRP cannot fully offset the link impairments and the low sensitivity of mobile terminals. Countermeasures include – transmissions in a robust format, increasing receiver sensitivity (traded

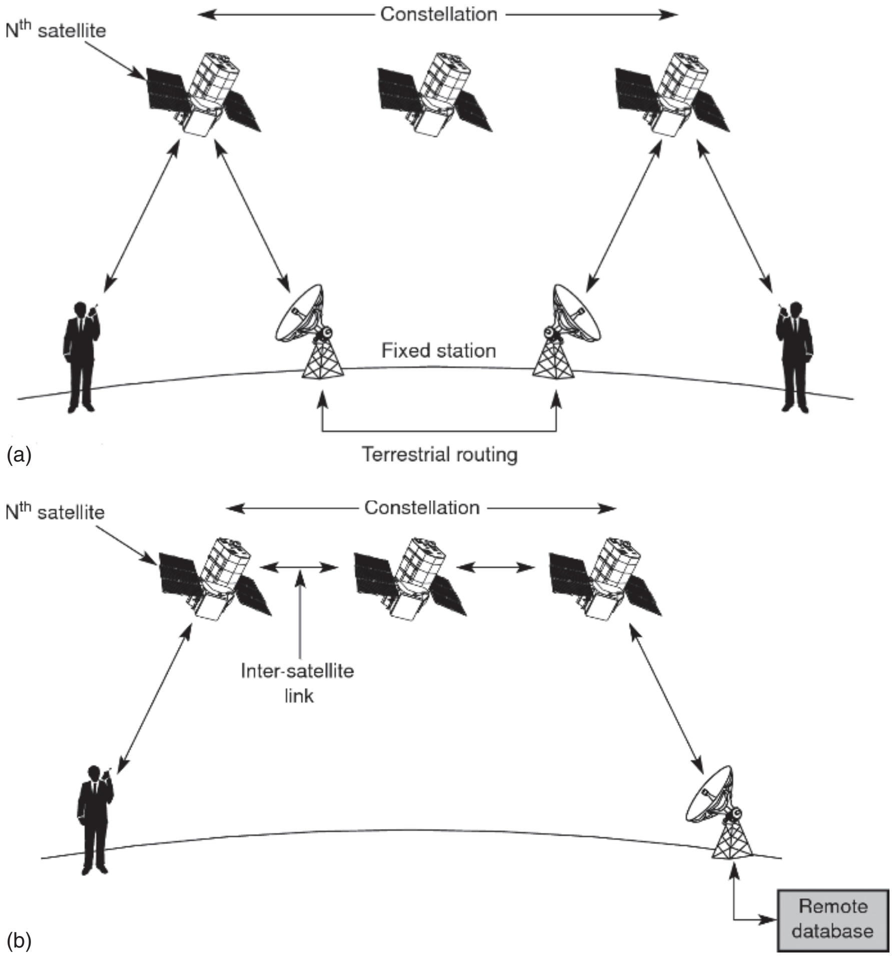

Figure 1.3 Connectivity architecture of non-geostationary satellite systems using (a) satellite-ground hops and (b) intersatellite links

with terminal weight, size and cost) and augmentation of satellite transmissions by terrestrial retransmissions.

  - *Propagation impairments*: Due to a non-stationary profile of the service link and limited multipath rejection capability of receiver antenna, the signal received at a UT is unstable necessitating a robust but rather inefficient radio link design (see Figure 1.5).

- *Return link*
  - *UT EIRP and satellite receiver sensitivity restrictions*: UT EIRP and satellite receiver sensitivity set a bound on the return link throughput (i.e. at a fixed station). The EIRP is constrained by antenna size restrictions due to space, weight and cost restrictions on portable or mobile UTs; for hand-held units EIRP is limited in compliance to radiation safety standards. Satellite receiver sensitivity is limited by the receive antenna gain of a satellite.

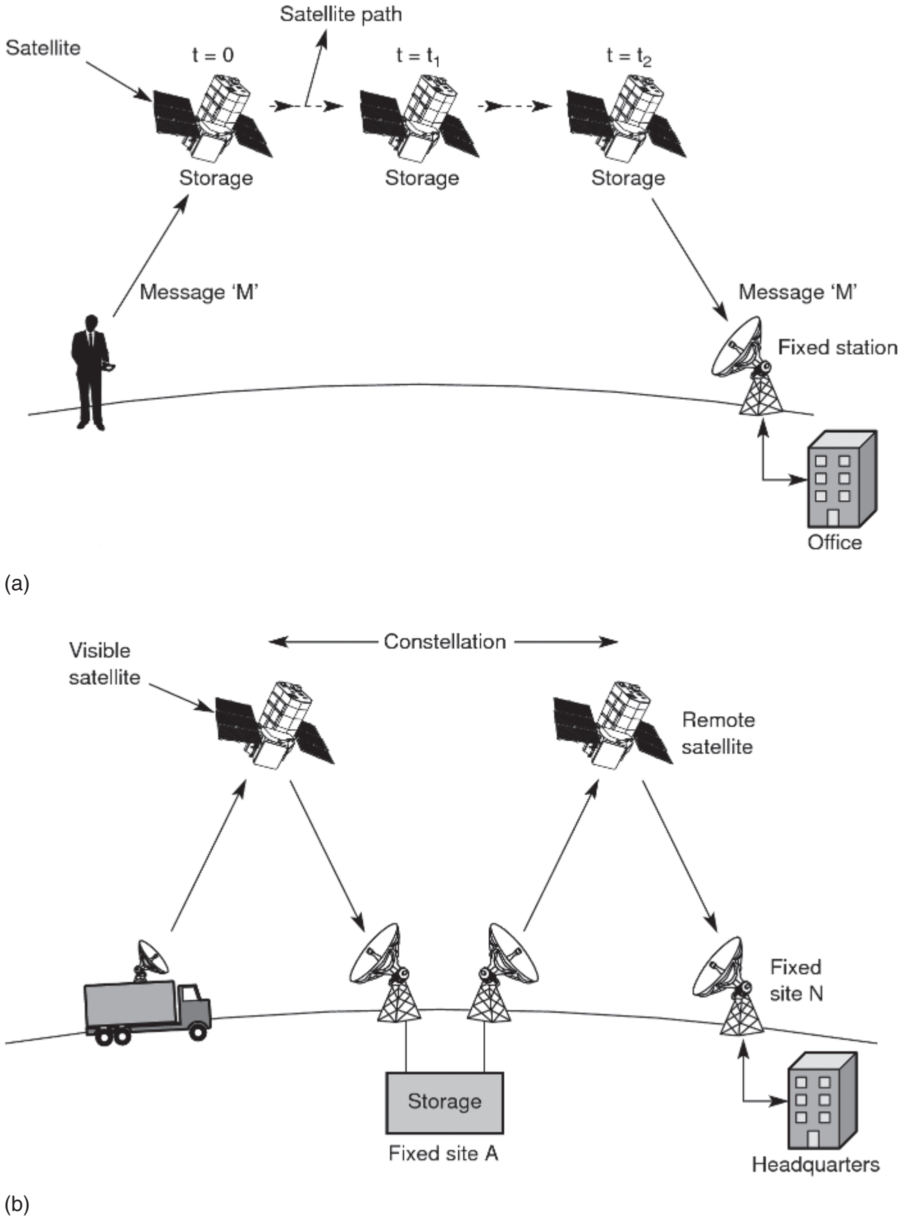

Figure 1.4 Main entities of store and forward system with (a) satellite buffer and (b) ground station buffer

Table 1.5 Categorization of mobile satellite services by throughput with example applications

Category	Throughput (forward link)	Typical applications	System example
Basic	A few bits per second to 1 kbps	Paging, message transfer, machine-machine communication, SCADA, remote monitoring	EutelTRACS (GEO); ORBCOMM (LEO)
Low bit rate	1–10 kbps	Voice, facsimile, e-mail, basic Internet	Globalstar (LEO); Iridium (LEO);
Medium bit rate	10–100 kbps	Voice, facsimile, e-mail, Internet, multimedia	Inmarsat (GEO), Thuraya (GEO)
Basic broadband	100–3 000 kbps	Internet, multimedia	Inmarsat (GEO), Thuraya (GEO), Iridium Next (LEO)
Broadband	3–10 Mbps	Terrestrial quality Internet and multimedia	–
Upper-end broadband	10–50 Mbps	Terrestrial quality fast Internet and multimedia	Inmarsat (GEO) (2014 start)

SCADA, supervisory control and data acquisition.

Figure 1.5(a) and (b) represents typical samples of L-band signals received on hand-held and stationary van-mounted terminals respectively demonstrating large receive signal variations (Jahn *et al.*, 1995). Referring to the figure we observe that signals received by the hand-held unit generally undergo peak-peak fluctuations in excess of 10 dB in 10 second segments, with a gradual variation of the mean level, while for the vehicle-mounted system the fluctuations at the most intense periods (~ 50–100, ~ 190–225 and ~ 260–300 seconds) approach similar levels with stable but gradual change in the mean value in between.

1.3.2 Orbit

Orbits are categorized by altitude, inclination and eccentricity. The altitude determines a satellite's field of view (coverage) – higher altitude satellites can cover a larger area; Inclination influences the minimum-maximum latitudes covered on the Earth; the two extremes of the of orbital inclination are an equatorial orbit, which has an inclination of 0° and a polar orbit, which has an inclination of 90°. An equatorial orbit satellite would cover a belt around the equator, whereas a polar satellite would cover a belt orthogonal to the equator thus covering the full Earth over a period due to the Earth's west-east rotation beneath. Eccentricity of an orbit determines its shape. Satellites in a circular orbit travel at a uniform velocity to provide an unbiased temporal coverage, whereas satellites in an elliptical orbit travel at variable velocities and hence dwell longer over specific areas (see Chapter 2).

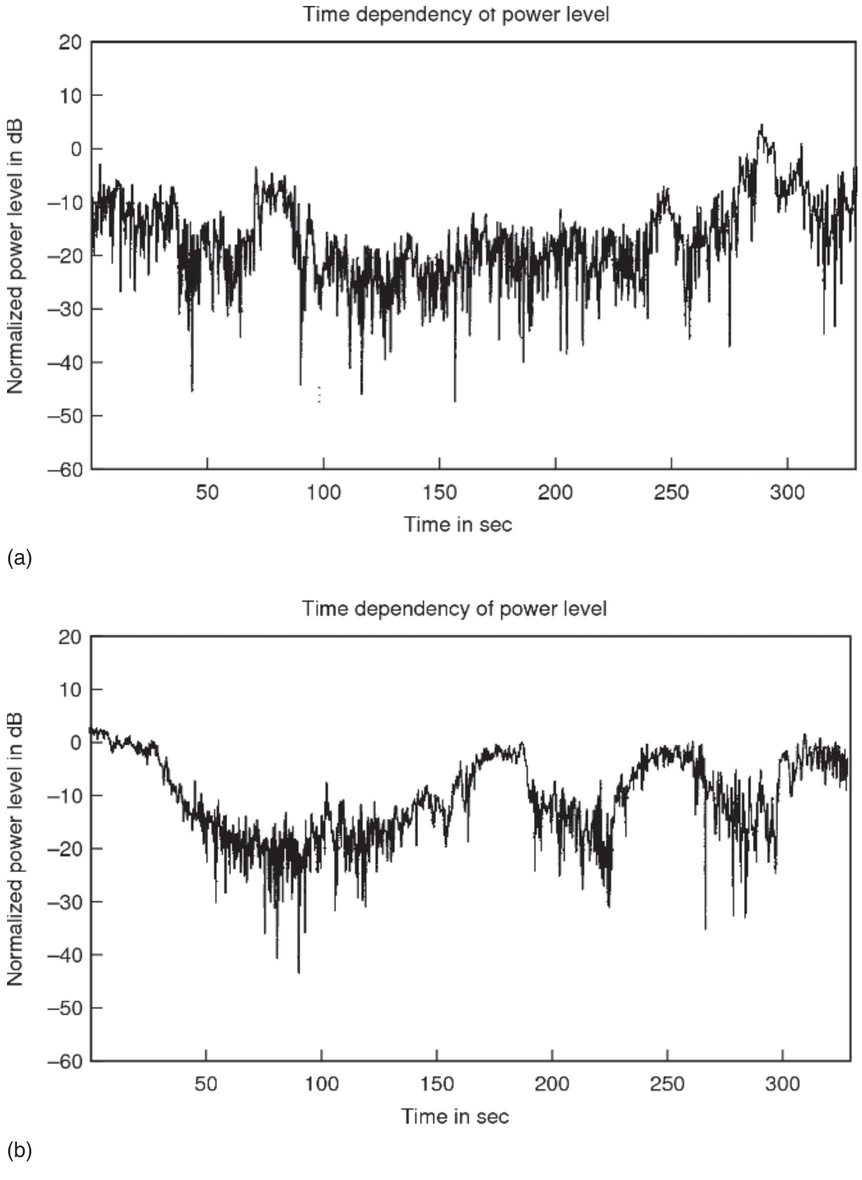

Figure 1.5 L band signals at (a) 1.8 GHz received on a hand-held terminal and (b) the same frequency received on a stationary vehicle-mounted terminal. (Both parts from source: Jahn *et al.*, 1995. Reproduced with permission of Communications Research Centre/Industry Canada and Jet Propulsion Laboratory/NASA.)

1.3.3 Tolerable Delay in Data Delivery

Delay tolerated by a system is application dependent. An end-end delay of more than ~400 ms is quite disturbing in a conversation, but delays of minutes and hours are acceptable for e-mail delivery. A non-real-time service can tolerate a break in communication link by data recovery techniques, whereas in an interactive service end-to-end connection must be maintained. The tolerable time delay influences several features of a mobile satellite communication system. For example, in a delay-tolerant system an NGEO satellite system can scale down the constellation size such that visibility statistics is restricted to the tolerable delay.

1.3.4 Handover

For a real-time geostationary system, ignoring RF link blockage due to obstructions, satellite location is static. The boundaries of spot beams are fuzzy, extending several tens of kilometres, which leads to a graceful degradation in signal quality for slow-moving vehicles. Thus, slow-moving mobiles need not handover a call to the next beam or satellite, as users spend a considerable period in this fuzzy zone where signals degrade gradually. However, handover is necessary for fast moving mobiles such as aircraft.

In non-geostationary satellite systems on the other hand, satellites are non-stationary and hence a user may have to communicate through different beams or satellites during a call, making handover a necessity.

Moreover, when intersatellite links are used handover between satellites becomes essential as path geometry is dynamic.

1.3.5 Mobility Management

The function of mobility management is to locate a called mobile, route the call efficiently and once established maintain the call, meeting the quality of service criteria.

In derivatives of the GSM system, each mobile is registered in a database, called home location register; if the mobile migrates outside the home territory, the mobile registers itself with the visiting system's VLR. The VLR conveys the location of each visitor to its HLR. Whenever a call is addressed to a mobile, the MSC interrogates the mobile's HLR to obtain the mobile's location and then establishes the call through an appropriate route. Figure 1.3(a) portrays a routing scheme in a NGSO system with satellite-ground hops, while Figure 1.3(b) represents an intersatellite link routing scheme. Various alternative routing schemes are possible and hence the routing strategy must be chosen carefully.

In an IP enabled network prior to a connection handover at the RF (physical layer) the IP address must also migrate to a new attachment. The Internet Engineering Task Force (IETF) have recommended mobility management schemes such as Mobile Internet Protocol version 6 (MIPv6), which have been adapted for satellite IP networks.

We have already introduced the concept of handover for maintaining RF link connectivity during a call in the previous section. Chapter 7 revisits the topic of mobility management in more detail.

1.3.6 Physical Environment

In a mobile satellite system, the physical medium in the vicinity of a mobile terminal and the receiver's antenna characteristics set a boundary on throughput. An area surrounded by obstructions would reduce the received signal power and hence the throughput; similarly, a reduction in antenna gain would reduce receiver sensitivity and hence throughput.

The behaviour of the received radio signals depends on the local surroundings (see Figure 1.5(a) and (b)) and receiver's antenna pattern. Low gain antennas tend to pick up multi-path signals from the surroundings, and furthermore, reduce receiver sensitivity. The size and hence gain of the mobile antennas depend on the available mounting space; for example a hand-held terminal would use a low-gain omnidirectional antenna whereas a ship-borne terminal may deploy a high gain 80 cm parabolic dish resulting in a more sensitive terminal and additionally, capable of transmitting higher power.

Figure 1.6(a–c) portrays various types of mobile terminals. Figure 1.6(a) is a mobile terminal, Figure 1.6(b) a portable wideband terminal and Figure 1.6(c) shows a satellite phone.

Impairments for narrow-band communication up to $\sim 100\,\text{kHz}$ are relatively benign in maritime and aeronautical channels at the L-band. Aeronautical channels tend to become dispersive beyond $\sim 100\,\text{kHz}$ when traversing over a quiet sea. Impairments are significantly high in land channels, tending to get worse in shadowed areas and with reduced antenna gain. Intermittent long and deep signal fades can break radio links causing discontinuity to real-time services while the rapid multipath fluctuations manifests as extraneous noise. Countermeasures include provisioning a higher link margin and robust modulation and coding.

The Doppler effect is introduced by relative motion between satellite and mobile; it affects aeronautical channels and NGEO satellite systems in particular. Countermeasure includes open and closed loop frequency correction arrangements.

Chapters 3 and 5 discuss these topics in detail.

1.3.7 Satellite Access

In an MSS environment thousands of users share satellite resources and therefore high satellite access efficiency is paramount. Demand assigned single channel per carrier (SCPC) frequency division multiple accessing (FDMA) or time division multiple accessing (TDMA) schemes, where a pool of channels is shared by all users on a per call or packet(s) basis, offer an effective solution. The channel pool can be managed by either a central or a distributed architecture. In a central architecture, a pool is managed centrally, whereas in a distributed architecture, separate pools are assigned to each participating fixed station for self-management.

In a CDMA scheme an RF channel is shared by all the users each using a unique code. This scheme offers advantage in terms of interference and multipath mitigation, and soft handover.

Data traffic tends to exhibit a variety of characteristics – ranging from sporadic bursts to continuous streams and therefore the accessing schemes are matched specifically to traffic characteristics. Common accessing schemes used for data communications include Aloha, slotted Aloha, Reservation Aloha and Time Division Multiple Access (see Chapter 4).

(a)

(b) (c)

Figure 1.6 (a) A typical large ship-borne earth station configuration – antennas enclosed in radome above deck (left) and an application in progress below deck (right). (b) A typical portable terminal in use in a remote area. (Parts (a) and (b) source: www.Inmarsat.com. Reproduced with permission of Inmarsat.) (c) A tri-mode hand-held terminal supporting satellite, analogue and CDMA digital with 2.5–4.5 h talk time and 9–14 h standby time. (Source: Globalstar. Reproduced with permission of Globalstar.)

1.3.8 Spectrum Management

Frequencies are allocated by the International Telecommunication Union (ITU) and specified in the RR and managed by the local/regional regulatory regime taking into consideration engineering, commercial and political factors. From an operator's perspective, spectrum management includes selection of an appropriate frequency band, obtaining clearance from the regulatory authorities, and managing its usage efficiently.

At present, a majority of MSS systems operate in L (~1.5 GHz) and S (2 GHz) bands; and a few in the K_u band, with some beginning to use the K_a band. The L and S bands are suitable for communication-on-the-move because of relatively benign propagation attributes in these bands and mature technology of these bands. These bands are now congested and hence unsuitable to support for broadband ($> \sim 1$ mbps). Thus some operators prefer the K_a band for broadband applications on portable terminals with directive antenna.

Due to heavy usage of the MSS spectrum, interference management is an important consideration in the planning and operation of mobile satellite systems. A certain level of interference is budgeted in the radio link design to enable inter and intra system frequency sharing. To minimize the probability of unwarranted interference, operators follow a strict regime of spectrum monitoring and procedures to manage harmful interference. Techniques to maximize spectrum efficiency include spatial frequency reuse by spot beams, efficient radio transmission formats and judicious frequency planning. Chapter 9 discusses techniques for maximizing spectrum efficiency and addresses the issue of interference management.

1.3.9 Radio Link Reliability

Techniques for improving radio link reliability include use of robust modulation and forward error correcting codes (which govern link margin), fade countermeasures embedded in the system architecture, store and forward technique to support communication in deep fades and adaptive power or code rate control.

1.4 Business Plan

A crucial element of modern mobile satellite ventures is a viable and credible business plan with a sound market analysis, investment strategy and financial returns for raising finances and revenue. In recent years, we have observed user needs rather than technology influencing mobile satellite system products and system architecture. Prospective operators have tended initially to carry out extensive market research to select services, service areas and user expectations in terms of tolerance of transmission delay, signal fades, etc. System architecture is developed after acquiring a sound understanding of anticipated market requirements and user preference. Chapters 7 and 10 capture the system perspective essential in the development of business plans, demonstrating the intertwined relationship between technical and commercial aspects of MSS.

Invariably, all market forecasts of the 1990s projected a sharp growth in demands for satellite telephony, contrary to experiences of early entrants such as Iridium or Globalstar. Conclusions regarding the total number of systems required to support demands were less clear, with estimates varying between two and four. Clearly, accurate forecasting is a vital element for the success of an expensive MSS venture. More recently, the emphasis is shifting towards mobile wideband data, shadowing the trend towards wider bandwidth in terrestrial mobile and fixed networks. Chapters 9 and 10 present methods of short-term and long-term forecasting.

1.5 Regulatory Considerations

One of the first activities at the start of a venture is that of procuring an operating licence and frequency clearance from the regulatory authorities of the service area that may comprise a number of countries. This procedure can take up considerable time due to a variety of reasons such as bureaucracy, regulatory policies, political issues and involvement of national and international authorities. Other considerations include amongst others preparation of roaming arrangements with other operators, agreement of numbering schemes and selection of distribution partners. These and a range of associated topics are covered in Chapters 3 and 7.

1.6 Operational Considerations

The operation and maintenance of an MSS system is quite challenging, involving a wide range of complex activities such as the launching and maintenance of satellites, network management, commissioning of new terminals, billing, marketing, constant review of business plans and long-term planning. The scale of effort increases as the size of the constellation and network grows.

The starting phase of a system is critical because of a need to set up technical operations, commissioning, billing, customer relations, publicity, and a variety of related tasks, while maintaining cash flow and revenue projections. First generation non-geostationary systems were most susceptible to commercial risks due to uncertain markets, the introduction of untried system designs, the lack of operational experience and the pressure to introduce services on stringent deadlines.

Deployment of a new satellite constellation is time consuming, as it involves a number of launches spread over months. Moreover, satellites generally include a number of new technologies that make the system liable to a high number of early failures. The Iridium system, comprising 66 satellites, was deployed in about 12 months with about 10% of satellite failures caused by a variety of technical problems. Globalstar lost 25% of its constellation in a single launch failure.

Constellation maintenance requires regular monitoring of satellites, performing orbital manoeuvres and changes to spacecraft configuration, replacement of malfunctioning and ageing satellites, upgrading on-board software, and regular network health checks. LEOs deploy the highest number of satellites with the lowest satellite lifetime.

Measures to provide services in the eventuality of a satellite failure include deployment of in-orbit and ground spares; and/or incorporating failure-resistant features in the network architecture. If a region is served by more than one satellite, users can communicate from the operational satellite in case of failure of any one of them, thus providing coverage redundancy as depicted in Figure 1.7 for a geostationary system.

Non-geostationary satellite systems have an inherent resistance to failure due to their distributed architecture and dynamic footprints. The consequence of a failed satellite in such a network is a coverage gap that propagates around the satellite's coverage belt. Thus, the outage is distributed and time shared by subscribers within the affected belt. The gap can be filled by readjusting the position of other satellites and subsequently by the introduction of an in-orbit spare.

Network management involves among other tasks monitoring satellite health, RF transmissions and traffic flow through the network, maintaining quality of service, traffic trend analysis, commissioning of terminals. SCCs monitor telemetered signals from satellites continuously and take corrective action when necessary. Typical actions include the firing of thrusters to maintain a satellite's orbit, reconfiguring a payload in case of failure of a subsystem or in response to an operational requirement, etc. An operational system is susceptible

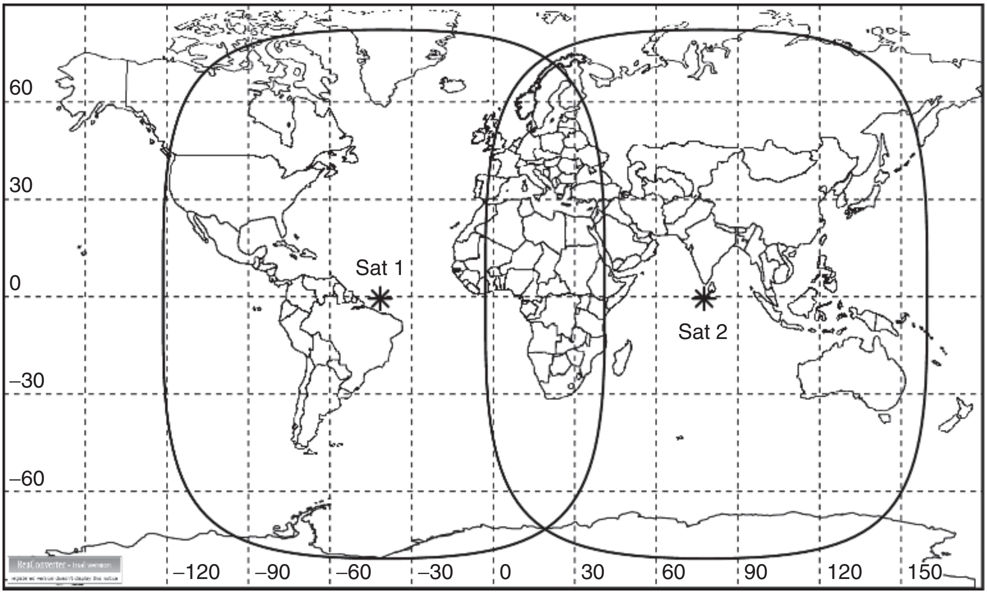

Figure 1.7 Coverage redundancy is available in the overlapping region

to a number of RF-associated problems such as inter and intra system interference and non-compliant transmissions from gateways. Satellite transmissions are therefore monitored to maintain RF integrity of the network and assist in routine RF-related tasks.

The network operator has to ensure that the user is satisfied with the quality of service, which can be measured as grade of service and signal bit errors and delay, in addition to matters related to commissioning, billing, after-sales service, etc. Sometimes failure of a critical subsystem, such as the network frequency management system, manifests itself indirectly as a loss in network traffic, and therefore monitoring of traffic flow through the network is essential. Forecasts used in the planning phase developed on theoretical assumptions and hypothesis can be refined in the operational phase by trending real data. Chapter 9 provides further details related to operational issues and network management.

The ITU has recognized personal mobile communications due to its potentially huge demands and unique technical requirements. The GMPCS is a specific category of MSS to support personal communications to individuals from hand-held personal communicators, much like the cellular telephone or pagers. A GMPCS can be categorized in various ways such as by orbit and service. Big LEO satellite systems deploy large, complex and powerful satellites in LEOs or MEOs capable of providing real-time communications, such as voice and facsimile to hand-held personal communicators; little LEO satellite systems deploy less complex and low-cost satellites operating in the lower part of the orbit designed to provide real-time or non-real-time low bit rate messaging services such as position reports, machine-machine communication and paging to pocket-sized terminals; sometimes the term ‘super’ GEO systems is used for modern GEO systems that deploy very large numbers of spot beams (> 100) enabling services to cellular telephone-sized terminals.

1.7 Mobile Systems – A Comparison

Satellite mobile systems are ideally suited for areas that are poorly served by terrestrial systems to complement terrestrial systems. The advantage of synergistic integration of terrestrial and satellite systems is well recognized. Most GMPCS systems support terrestrial services increasingly through an integrated network through dual-mode user units. Table 1.6 compares the main features of terrestrial and satellite mobile services.

Table 1.6 A comparison of the main characteristics of mobile services through satellite and terrestrial media

Satellite	Terrestrial
Wide area coverage is possible – typically thousands of kilometres	Relatively lower service area – typically hundreds of kilometres; some coverage breaks are possible
Roaming over a wide area is straightforward as coverage is seamless; roaming is limited by licensing issues; usually a single operator owns the space segment with one or more service distributors	Roaming over wide areas, encompassing several countries involves more than one operator/system requiring special system features and operational arrangements
Handsets resemble cell-phones; terminals deploying large antennas (0.3–1 m) can provide broad-band services (several tens of Mbps)	Terminals are small and attractively packaged with a wide variety of applications including broadband
Terminal costs are relatively high	Terminal costs are low
Call costs are relatively high	Call costs are low
MSS operate in aeronautical/land/maritime environments	Generally operate in land environment; limited coverage is possible in aeronautical and maritime environments
Service include voice and data with a throughput up to ~ 500 Kbps in L band and up to 50 Mbps in K_a band	Services include voice and data up to several megabits per second. higher throughputs are available in the fourth generation systems
Serve niche market – ships, aircrafts, trucks, international travellers and businessmen, cellular extension, tourism	Serve individuals for social and business needs in populated areas; coverage limited to coastal areas in maritime environments; air coverage is available in certain parts of the developed world
Frequency is reused at distances of hundreds of kilometres	Frequency is reused at distances of $\sim$100 m to $\sim$10 km
Handover between spot beams or satellites are not always essential for GEO but essential for NGEO systems	Handover is frequent and necessary in all cellular systems
Suited for wide area coverage and thin routes (e.g. traffic density < 0.1 Erlangs/km^2)	Suited for urban and suburban environment; uneconomic on thin routes (e.g. traffic density < 1 Erlang/km^2)

1.8 Example Applications

There are innumerable conventional and innovative applications of MSS. We have, therefore, categorized them generically as follows:

1. Maritime environment:
   - ship and cargo management;
   - distress;
   - social;
   - remote monitoring and control;
   - Internet access;
   - fleet broadcast;
   - tourism and leisure;
   - journalism;
   - business; and
   - others.
2. Land environment:
   - business;
   - remote monitoring and control;
   - personal;
   - fleet management;
   - tourism and leisure;
   - journalism;
   - government and aid agencies;
   - Internet access;
   - messaging; and
   - others.
3. Aeronautical environment:
   - cockpit communication;
   - passenger communications including facsimile/Internet access;
   - automatic dependence surveillance; and
   - others.

1.9 Practical Limitations

In this section, we highlight some of the existing practical problems related to the use of MSS and comment on their short- and long-term solution prospects. As illustrated in Table 1.7, many problems are likely to mitigate as technology evolves.

Voice call costs of satellite services have plummeted beginning from ~ \$8–10 per min in the early 1990s to less than 50 US cents; similarly, terminal cost and size to support voice communication has dropped from ~ \$25 000 at the outset to less than \$500 for hand-held units accompanied with phenomenal improvements in quality and ergonomics. Note that voice communication was only feasible through a large and expensive ship-borne terminal at the outset. Moreover, voice communication is increasingly being supported on shared data bearers to provide an increase in space resource efficiency.

Table 1.7 A summary of current limitations of MSS and their perspective

Current limitations	Comments
Expensive in terms of infrastructure, call and terminal costs	Terminal and call costs continue to reduce
Terminals are large compared to terrestrial systems	Hand-held units resemble mobile/cell-phones with a significant size reduction in recent years; terminal size is not crucial in many MSS applications (e.g. ship-borne, railway and aeronautical use)
User interface is complex	The limitation applies to specialist equipment such as ship-borne, airborne and large terminals; users see a simple interface similar to terrestrial systems
A general lack of awareness of the technology	Heightened awareness in recent years
Systems susceptible to local interference	Resolution of local terrestrial interference is indeed arduous
Routing arrangements can be complex and time consuming	These are one-off activities.
Concern about unauthorized bypass of a country's network	Practical solutions are feasible
Service limited to thin route	Terrestrial retransmissions allow extension to populated areas using an ancillary terrestrial component (ATC)
Service unreliable in areas susceptible to shadowing, e.g. urban and suburban locations	An ATC improves reliability

Harmful interference to MSS terminals from local transmissions has been a continuing problem in some parts of the world. Radio frequencies used for satellite communications are shared with terrestrial systems. Although the RR mandate protection of primary allocations (notably, L and S bands for the MSS) from secondary allocations, enforcement can be arduous, as it involves local operators and authorities. Sometimes transmitters in the vicinity, even if operating in a different frequency band, can saturate or overdrive the front-end of a satellite receiver, causing unacceptable degradation to signal quality. Harmonics of powerful terrestrial transmitters such as radar or television can enter receivers causing harmful interference. The probability of harmful interference increases in noisy radio environments such as busy ports. These types of problems can be minimized by practical measures such as communicating via another satellite so that the antenna points away from the interfering source, tuning the equipment to another channel, communicating through another gateway, or terminating and re-establishing a call. The operator can build a database of reported interference for alerting customers, better customer appreciation and to seek solutions formally.

Routing arrangements from the terrestrial segment to the space segment must be in place for the users to be connected efficiently. These arrangements are complex and time consuming for reasons of bureaucracy, politics, etc. The problem is compounded for an international operator, as the process has to be repeated, with each country having individual procedures and priorities, although these are one-off activities.

With the introduction of personal satellite communication services, concern has been raised regarding loss of business to local telecommunication operators because satellite systems can bypass them. Concern regarding security aspects has also been raised by countries vulnerable to antisocial activities. Operators therefore make agreements with local authorities to minimize revenue losses to local operators and build features into the system design to switch off transmissions in specified geographical regions or to permit communications only via specific gateways

1.10 Related Satellite Systems

Satellites provide a variety of mobile communication services, which are not MSS *per se* but complement or compete with the MSS offerings. Some of the more interesting ones are:

1. Mobile very small aperture terminal (M-VSAT) systems;
2. Satellite navigation systems; and
3. Direct audio/video broadcasts to personal and mobile terminals

1.10.1 M-VSAT Systems

VSATs are small FSS UTs for low-capacity/low-cost applications in use since 1970s. Advances in technology leading to high power K_u and K_a band multi-beam satellites and VLSI have enabled a reduction in size and cost of VSAT terminals such that they resemble broadband MSS terminal. Moreover, they provide higher throughput at lower cost/bit than the conventional L and S band MSS. The lower usage cost is due to the availability of larger bandwidth in the FSS bands and higher antenna gain for the same L band antenna dimension as antenna gain is proportional to $1/\lambda^2$ ($\lambda =$ wavelength). However, since VSATs belong to the FSS, there are regulatory restrictions to their mobility because FSS terminals must by definition remain fixed at a specific location. Each move requires a further series of lengthy coordination meetings, making it impractical to move terminals freely.

The demand of low-cost broadband communication on ships and aircrafts prompted the development of mobile versions of VSATs. In recognition, M-VSAT operation was formally approved by the ITU in some regions in parts of the FSS band. Some countries allow unrestricted VSAT mobility within territories under their jurisdictions to encourage growth of the technology.

Similarly MSS systems have adapted VSAT technology in the K_u/K_a band with the added advantage of unrestricted global mobility. Thus M-VSAT technology has now extended to the MSS regime, giving the user a wide choice of technologies.

Let us briefly return to the issue of competition between these two services. Competition in core MSSs, such as communication from moving land-based terminals, hand-held services, etc., is restricted at these higher frequencies. For fixed-site applications that allow use of directive antennas, both classes of services are similar from a user's perspective. The main difference lies in economics, the regulatory advantage of MSS in terms of unrestricted connection to the public network, the ease of setting up MSS terminals at will and access to the Global Maritime Distress and Safety System (see chapter 13). VSAT networks have the advantage in terms of high throughput and lower cost for large volume data transfer between fixed locations.

We discuss the underlying technologies in Chapter 13.

1.10.2 Satellite Navigation Systems

Navigation is used for estimating the position of a vehicle on sea, in air or space and on land to ensure that the chosen route is followed accurately, both in the short and long term. Short-term navigation is required for making instantaneous changes in direction, speed and acceleration to avoid an obstacle, and long-term navigation is used for making a general correction to a route. A natural by-product of navigation system is the availability of user's position at the given instant.

Satellite navigation receivers have become a personal and mobile communications accessory due to a significant reduction in receiver costs, making them a part of regular gear carried by explorers, travellers, fleet managers, rally organizers, etc. They are embedded in a variety of personal appliances and although developed to aid navigation, the accurate position and time reference available are used in location-based and timing applications.

The GPS navigation system was introduced by the US military in 1978. A constellation of 18 GPS satellites can provide continuous world-wide two-dimensional coverage; increasing the constellation to 24 satellites gives three dimensional position fixes world-wide. GPS satellites are in 55° inclined circular orbits at an altitude of 20 200 km with an orbital period of 12 h, distributed in six orbital plane with four satellites in each plane; accuracy of fixes for military users is < 10.5 m, degrading to about 100 m for civilian users. Satellites transmit atomic clock-controlled timing signals together with their orbital parameters, which are used by receivers for range estimation. A GPS receiver estimates its location by measuring range from three (or four) most favourably positioned satellites simultaneously and solving three (or four) simultaneous equations. Another navigation system known as GLONASS (Global Navigation Satellite System) using a different type of transmission format was introduced by the former USSR at about the same time.

The Galileo navigation system, under developed in Europe, will be operational in the 2014–2015. Other nations such as China are also developing such systems. Thus numerous satellite navigation systems will be available in the near future.

Satellite-aided navigation systems can be categorized on the basis of their operating principles: Doppler signature, range determination, single satellite and multiple satellite transmissions. Chapter 13 summarizes the principles of operation of the most commonly used satellite navigation systems.

1.10.3 Direct Broadcasts to Individuals and Mobiles

Satellite radio broadcast systems for direct reception on portable and vehicle mounted terminals are in regular use in several parts of the world. These systems use terrestrial retransmissions and robust transmission format to provide reliable service throughout the service area, including cities, suburbs and highways. This is the concept used in the ATC based MSS systems.

Conventional direct-to-home satellite broadcasts are received routinely on mobiles with stabilized tracking antennas (e.g. KVH Industries Online, 2012). More recently, there is an interest in providing multimedia and television directly to individuals on small portable and vehicle-mounted receivers. Direct-to-home broadcasts are designed for fixed installations using dish antennas and are therefore unsuitable for small mobile receivers. The key technologies to support mobile reception include video compression, efficient transmission schemes to operate reliably in a harsh mobile propagation environment and synchronized terrestrial re-transmissions. Several standards have been proposed by the ITU and ETSI (European Telecommunication Standards Institute) to promote the evolution of these systems. Chapter 12 addresses these issues in detail.

1.11 Trends

1.11.1 General

The urge of people to remain in contact under all circumstances has been instrumental in the success of mobile communication technology. As people tend to expect from mobile communication systems services akin to those offered by fixed services, it is anticipated that trends in the fixed services are likely to be a precursor to those in the mobile systems. However, mobile wireless services give a lower end-user throughput than generally available from wired systems because of the difficulty in maintaining a high-quality mobile radio link, and at present, a rather limited available spectrum for these services. Nevertheless access to information databases while the user is on the move brings with it a variety of unique location-based applications related to the immediate surroundings.

In addition to the unceasing demands for voice communications, there is now an escalating demand for data traffic for both personal and business applications. Examples of such applications are internet access to large database, teleworkers transferring software, e-mails, image transfer, and so on. Similar demands are already placed on the mobile communication sector due to the vigorous growth in personal computers (PCs) such as the personal digital assistant (PDA). Thus, considerable effort is under way to provide high data rate mobile telecommunication services. This is evident in the evolutionary trend of the MSS, with data rates increasing from a few kbps in the first-generation to ~50 Mbps in the fifth-generation Inmarsat system. Interestingly, both FSSs and MSSs are vying for the personal broadband service.

A considerable headway has been made in convergence of the fixed component of mobile networks with the fixed network due to a growing number of commonalities between them. It is recognized that in dense urban areas terrestrial systems are better suited, but satellite systems offer unique advantages in providing wide-area mobile communications to ships, aircraft and land mobiles. Thus, from a user's viewpoint, there are advantages in developing a unified satellite and terrestrial network. All the satellite hand-held systems offer a facility to switch from one or more of the existing cellular standards to another. Considerable research activity is in progress to unify terrestrial and mobile systems into a universal network. Since integrated satellite-terrestrial networks offer seamless connectivity irrespective of users' location, synergistic solutions are a primary theme of modern MSS paradigm.

Satellite systems have grown significantly but due to their niche services, their penetration is significantly lower. The services offered by previous mobile satellite systems were targeted for specialized applications in aeronautical, maritime and land sectors on terminals that were heavy and expensive. However, modern MSS systems provide a cellular system-like service at comparable costs and broadband multimedia terminals are about the size of desktop-size telephones. Increase in the service link (L-band) EIRP of four generations of

Inmarsat, is representative of world-wide MSS growth trends since the 1980s. The EIRP of satellite has increased by about 34 dB, that is a factor of ∼2500; if we consider four such satellites for global coverage, the increase amounts to 40 dB – a factor of ∼10 000!

1.11.2 Market

Vast, sparsely populated areas throughout the world remain unserved by fixed or cellular systems, either because the service is uneconomic or due to a lack of infrastructure. Satellite systems are ideally suited to filling such coverage gaps.

Terminal costs and call costs have dropped considerably and awareness of the technology has increased significantly. Recent reports of MSS operators demonstrate an aggressive growth in MSS markets and market surveys conclude that the trend is likely to continue in the foreseeable future. All the major operators have announced plans to upgrade their technology aiming to provide next-generation services for well over a decade. Chapter 14 provides samples of recent market projections up to the year 2020 and beyond.

1.11.3 System Architecture

Until the late 1980s, most commercial mobile satellite systems used GEOs with bent-pipe transponders. In the 1980s, extensive studies were undertaken in the UK and by the European Space Agency (ESA) to investigate the feasibility of deploying on-board processing satellites in highly eccentric elliptical orbits for mobile communications in the European region. Studies also investigated the feasibility of deploying LEO satellites for mobile satellite systems.

The trend in space segment architecture diverged at the beginning of 1990 when a number of commercial non-geostationary satellite systems were proposed for hand-held voice and data communication services. The architecture proposed LEOs or MEOs, as hand-held services via geostationary satellites would require extremely complex spacecraft and suffer transmission delays. Their architecture varied widely in orbital choice, satellite complexity, transmission schemes, network routing and the market addressed.

By mid-1990 there was a re-emergence of geostationary systems based on powerful satellites deploying several hundreds of spot beams. A comparison of various types of systems and architectures is given in Chapters 2, 7 and 8.

Third generation mobile systems have been standardized on the premise that satellites form an integral part of the network. International forums that have been instrumental in the process include the ITU forum called the International Mobile Telecommunication-2000 and the ETSI, a European forum where the third generation mobile systems are called Universal Mobile Telecommunication Systems or UMTS. These bodies have now extended their remit to the fourth generation. Chapter 8 provides an extensive review of the prevailing standards. Figure 1.8 illustrates a generic approach used in the standardization where components of each system are connected through standard interfaces.

Examples of an early air interface standard includes Geo Mobile Radio (GMR) Standard that was derived jointly by the ETSI and the Telecommunication Industry Association (TIA) of the United States from the Third Generation Partnership Programme (3GPP) family of cellular digital standard. These systems allow seamless integration of satellite systems with GSM and 3G core networks. The standard has since evolved and branched. Examples of

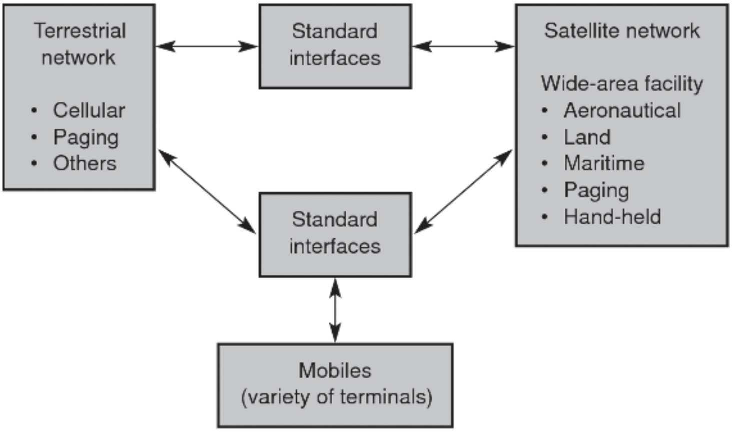

Figure 1.8 Concept of a Universal Mobile Communication System

application of these standards include Thuraya's satellite phone system based on GMR 1 (basic version) and Inmarsat phone (iSATphone) based on GMR 2 (an evolved version of GMR). GMR-1 3G technology is used by TerreStar, SkyTerra and Inmarsat's broadband system Broadband Global Area Network (BGAN). As MSS systems converge with VSAT at the upper end, it would appear to be advantageous attach a mobility component to VSAT standards – DVB RCS + M (digital video broadcast/return channel via satellite + mobility) is an example of such a standard. Work is now in progress to develop satellite architectures and standards for 4G systems.

All the major operators are beginning to introduce the next generation services. The general trends include a tighter integration with terrestrial mobile systems including the use of ATC; an increase in data throughput and provision of VSAT-like service through K_a band in direct competition with M-VSATs; and a deeper involvement in the development of MSS products and applications.

1.11.4 Spectrum

Rapid evolution of MSS fuelled by insatiable demands for broad-band services implies a greater demand on the spectrum. Since a majority of MSS systems operate in L and S bands, these bands are now congested despite the use of spectrum enhancement techniques such as spectrally efficient modulation-coding and advanced spot beam technology. There is a move towards implementing systems using MSS allocations in the K_a band for broadband applications with directive antennas. There is a growing interest in the possibility of higher bands such as V in the long term. Hand-held and other personal services are generally confined to L and S bands. Chapter 3 presents further details on spectrum-related matters.

1.11.5 Technology

To realize new services and applications and maximize spectral efficiency and revenue, several new technologies have been developed and are being refined. A few representative examples follow:

- **Satellites with regenerative transponders and on-board computing**: Regenerative transponders, by their ability to demodulate signals, can lower mobile terminal EIRP needs, reduce their size and cost and mitigate the effects of interference. The ability of regenerative transponders to decouple up- and down-links enables optimization of multiple accesses separately to maximize utilization of satellite resources. On-board processing can incorporate advanced space-based features such as signal routing and network functions. Software reconfigurable transponders minimize risk of obsolescence.
- **Intersatellite links**: Intersatellite links are space links between satellites for routing signals in space, thereby simplifying ground connectivity.
- **Spot-beam technology**: All modern mobile satellite systems deploy large numbers of spot beams to provide a dense spatial frequency ruse. Typically, several hundred spot beams are used for geostationary mobile satellite systems.
- **Multiple launch capability**: Large satellite constellations require a large number of reliable launches in quick succession; several launchers have been developed for multiple satellite delivery.
- **Mass satellite-production technique**: Traditionally, several years were spent in manufacturing a single communication satellite, clearly an unacceptable scenario for satellites that are part of large constellations. Satellite manufacturers have introduced mass-production techniques similar to those used in the automotive industry, reducing manufacturing time per satellite, in some cases, to a few weeks.
- **Software**: All aspects of satellite communications have benefited from the developments in software and workstation. Applications include computer-aided design, remote earth station operation, automated satellite control, constellation management, radio resource management, etc. Network control, data management and flow, as well as a majority of applications are now heavily dependent on software.
- **Advanced UT architecture and VLSI**: The challenge here is to produce low-cost, cellular-integrated satellite phones affordable by individuals. Phenomenal advances in VLSI, packaging, battery technology, and software have enabled introduction of affordable dual- and multi-mode hand-held portable transceivers and software configurable UTs.
- **Advancements** have been orchestrated in areas of modulation, channel coding, voice-coding, compression, access technology, system architecture, management of complex networks, and others.

Revision

1. What are the main components of a mobile satellite service? Outline the role of each component.

2. Table 1.2 gives a comparison of various technical parameters of several MSS systems. Explain the reason for different sensitivity requirement of the gateways (specified as G/T; a higher value implies a more sensitive receiver) in view of the similarity in G/T of the user terminal; Compare the total space segment capacity of each system assuming that three regional geostationary systems are required for world-wide coverage. Comment on your results.

3. Explain the difference between architectures of non-geostationary satellite systems, which provide a non-real-time communication service, and real-time communication services.
4. What is the rationale for using a low or medium earth orbit in preference to the geostationary orbit for the provision of a hand-held service?
5. The architecture of a satellite system is influenced by a number of technical considerations in addition to the service requirements. State these considerations. Briefly explain the role of each in system design.
6. Compare the characteristics of satellite and terrestrial mobile systems. Explain the reasons for a growing convergence between these systems.
7. What are the strengths and limitations of a mobile satellite service?
8. Briefly outline the factors likely to influence the evolution of mobile satellite systems.

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