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ZHILI SUN

SATELLITE COMMUNICATIONS SYSTEMS

SYSTEMS, TECHNIQUES AND TECHNOLOGY

SIXTH EDITION

WILEY

SATELLITE COMMUNICATIONS SYSTEMS

Sixth Edition

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Systems, Techniques and Technology

Sixth Edition

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This edition first published 2020

Edition History
John Wiley & Sons Ltd: 1e, 1986; 2e, 1993; 3e, 1998; 4e, 2002; 5e, 2009

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

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Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data

Names: Maral, Gérard, author. | Bousquet, Michel, author. | Sun, Zhili, author.
Title: Satellite communications systems : systems, techniques and technology / Gérard Maral, Ecole Nationale Supérieure des Télécommunications, Site de Toulouse, France, Michel Bousquet, Ecole Nationale Supérieure de l'Aéronautique et de l'Espace (SUPAERO), Toulouse, France, Zhili Sun, University of Surrey, UK.
Other titles: Systémes de télecommunications par satellites. English
Description: Sixth edition. | Hoboken, N.J. : John Wiley & Sons, 2020. | Translation of: Systémes de télecommunications par satellites. | Includes bibliographical references and index.
Identifiers: LCCN 2019044958 (print) | LCCN 2019044959 (ebook) | ISBN 9781119382089 (hardback) | ISBN 9781119382072 (adobe pdf) | ISBN 9781119382126 (epub)
Subjects: LCSH: Artificial satellites in telecommunication.
Classification: LCC TK5104 .M3513 2020 (print) | LCC TK5104 (ebook) | DDC 621.382/5–dc23
LC record available at https://lccn.loc.gov/2019044958
LC ebook record available at https://lccn.loc.gov/2019044959

Cover Design: Wiley
Cover Image: © BlackJack3D/Getty Images

Set in 9/11pt, PalatinoLTStd by SPi Global, Chennai, India

Printed and bound by CPI Group (UK) Ltd, Croydon, CR0 4YY

10 9 8 7 6 5 4 3 2 1

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ACKNOWLEDGEMENT

Reproduction of figures extracted from the 1990 edition of the ITU (formerly CCIR) volumes (XVIIth CCIR Plenary Assembly, Düsseldorf 1990), the *Handbook on Satellite Communications* (ITU Geneva, 1988), and the ITU-R recommendations are made with the authorisation of the International Telecommunication Union (ITU) as copyright holder.

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ACRONYMS

3GPP	3rd Generation Partnership Project
5G	5th generation mobile communications
AAL	ATM adaptation layer
ACI	adjacent channel interference
ACK	acknowledgement
ACM	adaptive coding and modulation
ACTS	advanced communications technology satellite
ADC	analogue to digital converter
ADM	adaptive delta modulation
ADPCM	adaptive pulse code modulation
ADSL	asymmetric digital subscriber line
AKM	apogee kick motor
ALC	automatic level control
AM	amplitude modulation
AMP	amplifier
AOCS	attitude and orbit control system
AOR	Atlantic ocean region
AOS	advanced orbiting systems
APD	avalanche photodetector
APSK	amplitude and phase shift keying
AR	available retio; also: axial ratio
ARQ	automatic repeat request
ARQ-GB(N)	automatic repeat request-go back n
ARQ-SR	automatic repeat request-selective repeat
ARQ-SW	automatic repeat request-stop and wait
ARTES	Advanced Research in Telecommunications Systems
ASCII	American Standard Code for Information Interchange
ASIC	application-specific integrated circuit
ASS	amateur satellite service
ATA	auto-tracking antenna
ATM	asynchronous transfer mode
AVBDC	absolute volume-based dynamic capacity
BAPTA	bearing and power transfer assembly
BAT	bouquet association table
BBS	baseband switch
BBP	baseband processor
BCH	Bose-Chaudhuri-Hocquenghem
BCR	battery charge regulator
BDR	battery discharge regulator
BEP	bit error probability
BER	bit error rate
BFN	beam forming network
BFSK	binary frequency shift keying
BGMP	border gateway multicast protocol
BGAN	broadband global area network
BGP	border gateway protocol
BHCA	busy hour call attempts
BHCR	busy hour call rate
BISDN	broadband ISDN
BIS	broadband interactive system
BITE	built-in test equipment
BOL	beginning of life
BPF	band pass filter
BPSK	binary phase shift keying
BSM	broadband satellite multimedia
BSS	broadcasting satellite service
BTP	burst time plan
C2P	connection control protocol
CAMP	channel amplifier
CAT	conditional access table
CBR	constant bit rate
CC	command and control
CCB	Common Core Booster
CCI	co-channel interference
CCIR	Comité Consultatif International des Radiocommunications (International Radio Consultative Committee); replaced by ITU-R
CCITT	Comité Consultatif International Télégraphe et Téléphone (International Telegraph and Telephone Consultative Committee); replaced by ITU-T
CCSDS	Consultative Committee for Space Data Systems

CDMA	code division multiple access
CEC	Commission of the European Communities
CELP	code excited linear prediction
CENELEC	Comité Européen pour la Normalisation en Electrotechnique (European Committee for Electrotechnical Standardisation)
CEPT	Conférence Européenne des Postes et des Télécommunications (European Conference of Post and Telecommunications)
CFM	companded frequency modulation
CIR	committed information rate
CIS	Commonwealth of Independent States
CLTU	command link transmission unit
CMOS	complementary metal oxide semiconductor
CNES	Centre National d'Etudes Spatiales (French space agency)
COFDM	coded orthogonal frequency division multiplexing
CoS	class of service
COTS	commercial off the shelf
CPS	chemical propulsion system
CRA	continuous rate assignment
CRC	cyclic redundancy check
CSC	common signal channel
CSMA	carrier sense multiple access
CTM	correction message table
CTU	central terminal unit
DAB	digital audio broadcasting
DAC	digital to analogue converter
DAMA	demand assignment multiple access
DARPA	Defense Advanced Research Project
dB	decibel
dBm	unit for expression of power level in dB with reference to 1 mW
dBmO	unit for expression of power level in dBm at a point of zero relative level (a point of a telephone channel where the 800 Hz test signal has a power of 1 mW)
DBS	direct broadcasting satellite
DC	direct current
DCE	data circuit terminating equipment
DCME	digital circuit multiplication equipment
DCS	digital cellular system (GSM At 1800 MHz)
DCT	discrete cosine transform
DCU	distribution control unit
DE	differentially encoded
DE-MPSK	differentially encoded M-ary phase shift keying
DES	data encryption standard
DM	delta modulation
DNS	domain name service (host name resolution protocol)
DOD	depth of discharge
DOF	degree of freedom
DSCP	differentiated service code point
DSI	digital speech interpolation
DSL	digital subscriber loop
DSM	digital storage medium
DSP	digital signal processing
DST	destination host address
DTE	data terminating equipment
DTH	direct to home
DTS	decoding timestamp
DVB	digital video broadcasting
DVB-S	DVB-Satellite
DVB-S2	DVB-Satellite 2nd generation
DVB-S2X	DVB-Satellite 2nd generation extension
DVB-RCS	DVB-Return Channel via Satellite
DVB-RCS2	DVB-Return Channel via Satellite 2nd generation
DVB-RCS2X	DVB-Return Channel via Satellite 2nd generation extension
EBU	European Broadcasting Union
ECN	explicit congestion notification
ECSS	European Cooperation for Space Standardization
EESS	Eutelsat earth station standards
EFS	error-free seconds
EIRP	effective isotropic radiated power (W)
EIT	event information table
EITA	electron-bombardment ion thruster assembly
ELSR	edge label switch router
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EN	European standard
EOC	edge of coverage
EOL	end of life
EPC	electric power conditioner
EPIRB	emergency position indicating radio beam
ERC	European Radiocommunications Committee
ERO	European Radiocommunications Office (of the ERC)
ES	earth station; also: ETSI specification
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre

ESS	earth exploration satellite service
ETR	Eastern Test Range
ETSI	European Telecommunications Standards Institute
EUTELSAT	European Telecommunications Satellite Organisation
FCA	free capacity assignment
FCC	Federal Communications Commission
FCS	frame check sequence
FCT	frame composition table
FDM	frequency division multiplex
FDMA	frequency division multiple access
FEC	forward error correction
FES	fixed earth station
FET	field effect transistor
FETA	field effect transistor amplifier
FFT	fast Fourier transform
FIFO	first in first out
FLS	forward link signalling
FM	frequency modulation
FMA	fixed-mount antenna
FMT	fade mitigation technique
FODA	FIFO ordered demand assignment
FPGA	field-programmable gate array
FS	fixed service
FSK	frequency shift keying
FSS	fixed satellite service
FTP	file transfer protocol
GaAs	gallium arsenide
GAN	global area network
GBN	go back N
GC	global coverage
GCE	ground communication equipment
GCS	ground control station
GDE	group delay equaliser
GEO	geostationary earth orbit
GMDSS	Global Maritime Distress and Safety System
GMSK	Gaussian-filtered minimum shift keying
GMT	Greenwich Mean Time
GOS	grade of service
GPRS	general packet radio service
GPS	global positioning system
GRE	generic routing encapsulation
GSE	generic stream encapsulation
GSM	global system for mobile communications
GSO	geostationary satellite orbit
GTO	geostationary transfer orbit
GW	satellite gateway
HDB3	high-density binary 3 code
HDLC	high-level data link control
HDTV	high-definition television
HEMT	high electron mobility transistor
HEC	header error check
HEO	highly elliptical orbit
HIO	highly inclined orbit
HLR	home location register
HPA	high-power amplifier
HPB	half-power beamwidth
HTML	hypertext markup language
HTS	high throughput satellite
HTTP	hypertext transfer protocol
IAT	interarrival time
IAU	international astronomical unit
IBO	input back-off
IBS	International Business Service
ICMP	Internet control message protocol
ICO	intermediate circular orbit
IGMP	internet group management protocol
IDC	intermediate rate digital carrier
IDR	intermediate data rate
IDU	indoor unit
IEEE	Institute of Electrical and Electronic Engineers
IESS	Intelsat earth station standards
IETF	Internet Engineering Task Force
IF	intermediate frequency
IFRB	International Frequency Registration Board
IGMP	Internet group management protocol
IHM	input hybrid matrix
ILS	International Launch Services
IM	intermodulation
IMP	intermodulation product
IMSI	international mobile subscriber identity
IMUX	input multiplexer
INIRIC	International Non-Ionising Radiation Committee
INMARSAT	International Maritime Satellite Organisation
INTELSAT	International Telecommunications Satellite Consortium
IOR	Indian Ocean region
IOT	in-orbit test
IP	Internet protocol
IPA	intermediate power amplifier
IPDR	IP packet duplicate ratio
IPER	IP packet error ratio
IPE	initial pointing error
IPSLBR	IP packet severe loss block ratio
IPLR	IP packet loss ratio
IPRR	IP packet reordered ratio
IPsec	IP security
IRD	integrated receiver decoder
ISDN	integrated services digital network
ISI	inter-symbol interference

ISL	intersatellite link
ISO	International Organisation for Standardisation
ISS	inter-satellite service
ITU	International Telecommunication Union
IVOD	interactive video on demand
IWU	Internet working unit
JPEG	Joint Photographic Expert Group
LAN	local area network
LAPB	link access protocol balanced
LDPC	low-density parity check
LES	land-earth station
LEO	low earth orbit
LH2	liquid hydrogen
LHCP	left-hand circular polarisation
LLC	logical link control
LLM	L band land mobile
LMSS	land mobile satellite service
LNA	low-noise amplifier
LNB	low-noise block
LO	local oscillator
LOS	line of sight
LOX	liquid oxygen
LPC	linear predictive coding
LPF	low-pass filter
LR	location register
LRB	liquid rocket booster
LRE	low-rate encoding
M-PSK	M-ary phase shift keying
MAC	medium access control
MAC	multiplexed analogue components; also: monitoring, alarm, and control
MAMA	multiple ALOHA multiple access
MAN	metropolitan area network
MCD	multicarrier demodulator
MCPC	multiple channels per carrier
MEO	medium earth orbit
MES	mobile earth station
MESFET	metal semiconductor field effect transistor
MF	multi frequency
MIC	microwave integrated circuit
MIFR	master international frequency register
MMDS	multipoint multichannel distribution system
MMIC	monolithic microwave integrated circuit
MMT	multicast map table
MNMC	mission and network management centre
MODEM	modulator/demodulator
MOS	mean opinion score
MPE	multi-protocol encapsulation
MP	measurement point
MPEG	Motion Picture Expert Group
MPLS	multi-protocol label switching
MPSK	M-ary phase shift keying
MS	mobile station; also management station
MSK	minimum shift keying
MSS	mobile satellite service
MTBF	mean time between failure
MTBO	mean time between outages
MTU	maximum transferable unit
MUX	multiplexer
NACK	no acknowledgment
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Aeronautics and Space Development Agency (Japan)
NAT	network address translation
NCC	network control centre
NCS	network coordination station
NGSO	non-geostationary satellite orbit
NGEO	non-geostationary orbit
NH	Northern hemisphere
NIS	network information system
NIT	network information table
NMC	network management centre
NOAA	National Oceanic and Atmospheric Administration
NORM	NACK-oriented reliable multicast
NRZ	non-return to zero
NSE	network section ensemble
NTP	network time protocol
NVOD	near video on demand
OBC	on-board computer
OBO	output back-off
OBP	on-board processing
OBDH	on-board data handling
ODU	outdoor unit
OFDM	orthogonal frequency division multiplexing
OHM	output hybrid matrix
OICETS	optical inter-orbit communications engineering test satellite
OMUX	output multiplexer
OQPSK	offset QPSK
OSI	Open System Interconnection
OSPF	open shortest path first
OSR	optical solar reflector
PAM	payload assist module
PAT	program association table
PCM	pulse code modulation
PDF	probability density function
PDH	plesiochronous digital hierarchy
PDU	protocol data unit
PEP	performance enhancement protocol

PER packet error rate
PFD power flux density
PHEMT pseudomorphic high electron mobility transistor
PHB per-hop behaviour
PIA percent IP service unavailability
PICH pilot channel
PID packet identifier
PIMP passive intermodulation product
PIU percent IP service unavailability
PKM perigee kick motor
PL physical layer
PLL phase locked loop
PM phase modulation
PMT program map table
PN pseudorandom number
PODA priority oriented demand assignment
POR Pacific Ocean region
PPP point to point protocol
PRBS pseudorandom binary sequence
PRMA packet reservation multiple access
PSD power spectral density
PSI programme-specific information
PSK phase shift keying
PSPDN packet switched public data network
PSTN public switched telephone network
PTA programmed tracking antenna
PTS presentation timestamp
PVA perigee velocity augmentation
QEF quasi-error-free
QoS quality of service
QPSK quaternary phase shift keying
RAAN right ascension of the ascending node
RACH random access channel
RADIUS remote authentication dial in user service
RAM random access memory
RBDC rate-based dynamic capacity
RCS return channel via satellite; also: reaction control system
RCVO receive only
Rec recommendation
Rep report
RF radio frequency
RFHMA random frequency hopping multiple access
RFI radio frequency interference
RHCP right-hand circular polarisation
RIP routing information protocol
RIPR replicated IP packet ratio
RITA RF ion thruster assembly
RMA random multiple access
RMT RCS map table
RR Radio Regulations
RRC Regional Radio Conference
RS Reed Solomon (coding)
RSS radiodetermination satellite service
RSVP resource reservation protocol
RTCP real-time transport control protocol
RTP real-time transport protocol
RTT round-trip times
RTU remote terminal unit
Rx receiver
S-ALOHA slotted ALOHA protocol
SAP service access point
SAW surface acoustic wave
SC suppressed carrier
SCADA supervisory control and data acquisition
SCH synchronisation channel
SCPC single channel per carrier
SCT superframe composition table
SDH synchronous digital hierarchy
SDT service description table
SEP symbol error probability
SEU single event upset
SFH slow frequency hopping
SH Southern hemisphere
SHF super-high frequency (3–30 GHz)
SI service information
SIA Satellite Industry Association
SIM subscriber identity module
SKW satellite-keeping window
SLA service-level agreement
SLC satellite link control
SMAC satellite medium access control
SMATV satellite-based master antenna for TV distribution
SMS satellite multi-services
SMTP simple mail transfer protocol
SNG satellite news gathering
SNMP simple network management protocol
SNR signal-to-noise ratio
SOC state of charge
SORF start of receive frame
SOS space operation service
SOTF start of transmit frame
SPT satellite position table; also: stationary plasma thruster
SR selective repeat
SRC source host address
SRS space research service
SS satellite switched
SSB solid support booster
SSMA spread spectrum multiple access
SSO sun-synchronous orbit
SSPA solid state power amplifier

SS-TDMA	satellite-switched TDMA
ST	Sidereal time
STM	synchronous transport module
STS	space transportation system
SW	stop and wait
SWR	standing wave ratio
SYNC	synchronisation
TA	ETSI Technical Assembly
TACS	total access communication system
TCB	transmission control block
TBTP	terminal burst time plan
TC	telecommand; also: turbo-coding
TCP	transmission control protocol
TCT	time-slot composition table
TDM	time division multiplex
TDMA	time division multiple access
TDRS	tracking and data relay satellite
TDT	time and date table
TELNET	remote terminal application
TIA	Telecommunications Industry Association
TIM	terminal information messages
TIR	internal reflection
TM	telemetry
TS	transport stream
TR	technical report
TS	transport stream; also: technical specification
TTC	telemetry, tracking, and command
TTCM	telemetry, tracking, command, and monitoring
TTL	transistor–transistor logic; also: time to live
TWT	travelling wave tube
TWTA	travelling wave tube amplifier
Tx	transmitter
UDP	user datagram protocol
UHF	ultra-high frequency (300 MHz – 3 GHz)
UHTV	ultra high definition television
ULE	ultra-lightweight encapsulation; also: unidirectional lightweight encapsulation
USAT	ultra small aperture terminal
UT	universal time, user terminal
UW	unique word
VBR	variable bit rate
VBDC	volume-based dynamic capacity
VC	virtual channel; also: virtual container
VCI	virtual channel identifier
VEB	vehicle equipment bay
VHF	very-high-frequency (30–300 MHz)
VLSI	very large scale integration
VPI	virtual path identifier
VPN	virtual private network
VSAT	very small aperture terminal
WAN	wide area network
WARC	World Administrative Radio Conference
XPD	cross-polarisation discrimination
XPI	cross-polarisation isolation

NOTATIONS

a	orbit semi-major axis
A	azimuth angle (*also* attenuation, area, availability, traffic density, and carrier amplitude)
A_{eff}	effective aperture area of an antenna
A_{AG}	attenuation by atmospheric gases
A_{RAIN}	attenuation due to precipitation and clouds
A_{P}	attenuation of radio wave by rain for percentage p of an average year
B	bandwidth
b	voice channel bandwidth (3100 Hz from 300 to 3400 Hz)
B_{n}	noise measurement bandwidth at baseband (receiver output)
B_{N}	equivalent noise bandwidth of receiver
Bu	burstiness
c	velocity of light $= 3 \times 10^8\ \mathrm{m\,s^{-1}}$
C	carrier power
C/N_0	carrier power-to-noise power spectral density ratio (W/Hz)
$(C/N_0)_{\mathrm{U}}$	uplink carrier power-to-noise power spectral density ratio
$(C/N_0)_{\mathrm{D}}$	downlink carrier power-to-noise power spectral density ratio
$(C/N_0)_{\mathrm{IM}}$	carrier power-to-intermodulation noise power spectral density ratio
$(C/N_0)_{\mathrm{I}}$	carrier power-to-interference noise power spectral density ratio
$(C/N_0)_{\mathrm{I,U}}$	uplink carrier power-to-interference noise power spectral density ratio
$(C/N_0)_{\mathrm{I,D}}$	downlink carrier power-to-interference noise power spectral density ratio
$(C/N_0)_{\mathrm{T}}$	carrier power-to-noise power spectral density ratio for total link
D	diameter of a reflector antenna (*also* used as a subscript for downlink)
e	orbit eccentricity
E	elevation angle (also energy and electric field strength)
E_{b}	energy per information bit
E_{c}	energy per channel bit
f	frequency (Hz)
F_{c}	nominal carrier frequency
f_{d}	antenna focal length
f_{m}	frequency of a modulating sine wave
$f_{\max}$	maximum frequency of the modulating baseband signal spectrum
f_{D}	downlink frequency
f_{U}	uplink frequency
F	noise figure
$\Delta F_{\max}$	peak frequency deviation of a frequency modulated carrier
f_{S}	sampling frequency
g	peak factor
G	power gain (also gravitational constant)
G_{sat}	gain at saturation
G_{R}	receiving antenna gain in direction of transmitter
G_{T}	transmitting antenna gain in direction of receiver
G_{Rmax}	maximum receiving antenna gain
G_{Tmax}	maximum transmitting antenna gain
G_{SR}	satellite repeater gain
G_{SRsat}	saturation gain of satellite repeater
G/T	gain to system noise temperature ratio of a receiving equipment
G_{CA}	channel amplifier
G_{FE}	front-end gain from satellite receiver input to satellite channel amplifier input
G_{ss}	small signal power gain
i	inclination of the orbital plane
k	Boltzmann's constant $= 1.379 \times 10^{-23}\ \mathrm{W\,KHz^{-1}}$
k_{FM}	FM modulation frequency deviation constant (MHz/V)
k_{PM}	PM phase deviation constant (rad/V)
K_{P}	AM/PM conversion coefficient
K_{T}	AM/PM transfer coefficient
l	earth station latitude

L	earth station-to-satellite relative longitude also loss in link budget calculations, and loading factor of FDM/FM multiplex also message length (bits)
L_A	atmospheric attenuation
L_e	effective path length of radio wave through rain (km)
L_{FRX}	receiver feeder loss
L_{FTX}	transmitter feeder loss
L_{FS}	free space loss
L_{POINT}	depointing loss
L_{POL}	antenna polarisation mismatch loss
L_R	receiving antenna depointing loss
L_T	transmitting antenna depointing loss
m	satellite mass
mc	power reduction associated with multicarrier operation
M	mass of the earth (kg) (*also* number of possible states of a digital signal)
N_0	noise power spectral density (W/Hz)
$(N_0)_U$	uplink noise power spectral density (W/Hz)
$(N_0)_D$	downlink noise power spectral density (W/Hz)
$(N_0)_T$	total link noise power spectral density (W/Hz)
$(N_0)_I$	interference power spectral density (W/Hz)
N	noise power (W) (*also* number of stations in a network)
p	pre-emphasis/companding improvement factor (*also* rainfall annual percentage)
p_w	rainfall worst month time percentage
P	power (*also* number of bursts in a TDMA frame)
P_b	information bit error rate
P_c	channel bit error rate
P_{HPA}	rated power of high power amplifier (W)
P_T	power fed to the antenna (W)
P_{Tx}	transmitter power (W)
P_R	received power (W)
P_{Rx}	power at receiver input (W)
P_{is}	input power in a single-carrier operation mode
$P_{o\,1}$	output power in a single-carrier operation mode
$(P_{i\,1})_{sat}$	input power in a single-carrier operation mode at saturation
$(P_{o\,1})_{sat}$	saturation output power in a single-carrier operation mode
$P_{i\,n}$	input power in a multiple-carrier operation mode (n carriers)
$P_{o\,n}$	output power in a multiple-carrier operation mode (n carriers)
$P_{IMX\,n}$	power of intermodulation product of order X at output of a nonlinear device in a multicarrier operation mode (n carriers)
Q	quality factor
r	distance between centre of mass (orbits)
R	slant range from earth station to satellite (km) (also symbol or bit rate)
R_b	information bit rate (s^{-1})
R_c	channel bit rate (s^{-1})
R_{call}	mean number of calls per unit time
R_E	earth radius = 6378 km
R_o	geostationary satellite altitude = 35 786 km
R_p	rainfall rate (mm/h) exceeded for time percentage p of a year
R_s	symbol (or signalling) rate (s^{-1})
S	user signal power (W)
S/N	signal-to-noise power ratio at user's end
T	period of revolution (orbits) (s) (*also* noise temperature (K))
T_A	antenna noise temperature (K)
T_{AMB}	ambient temperature (K)
T_b	information bit duration (s)
T_B	burst duration (s)
T_c	channel bit duration (s)
T_e	effective input noise temperature of a four-port element system (K)
T_E	mean sidereal day = 86 164.15
T_{eATT}	effective input noise temperature of an attenuator (K)
T_{eRx}	effective input noise temperature of a receiver
T_F	frame duration (s) (*also* feeder temperature)
T_m	effective medium temperature (K)
T_0	reference temperature (290 K)
T_{eRX}	effective input noise temperature of a receiver (K)
T_S	symbol duration (s)
T_{SKY}	clear key contribution to antenna noise temperature (K)
T_{GROUND}	ground contribution to antenna noise temperature (K)
U	subscript for uplink
υ	true anomaly (orbits)
V_s	satellite velocity (m/s)
$V_{Lp/p}$	peak-to-peak luminance voltage (V)
$V_{Tp/p}$	peak-to-peak total video signal voltage (including synchronisation pulses)
V_{Nms}	root-mean-square noise voltage (V)
w	psophometric weighting factor

X intermodulation product order (IMX)
α angle from boresight of antenna
γ vernal point
Γ spectral efficiency (bit/s Hz)
δ declination angle (*also* delay)
η antenna aperture efficiency
λ wavelength (=c/f) (*also* longitude, message generation rate [s^{-1}])
φ latitude
τ propagation time
θ_{3dB} half-power beamwidth of an antenna wavelength = c/f
θ_R receiving antenna pointing error
θ_T transmit antenna pointing error
μ = GM (G = gravitational constant, M = mass of earth; $G = 6.67 \times 10^{-11}$ m^3 kg^{-1} s^{-2}, $M = 5.974 \times 10^{24}$ kg; $\mu = GM = 3.986 \times 10^{14}$ m^3 s^{-2}
ρ code rate
σ Stefan-Boltzmann constant = 5.67×10^{-8} Wm^{-2} K^{-4}
ϕ satellite-earth station angle from the earth's centre
Φ power flux density (w/m^2)
Φ_{max} maximum power flux density at transmit antenna boresight
Φ_{nom} nominal power flux density at receive end required to build up a given power assuming maximum receive gain (no depointing)
Φ_{sat} power flux density required to operate receive amplifier at saturation
ψ polarisation angle
ω argument of perigee
Ω right ascension of the ascending node
Ω_E angular velocity of rotation of the earth = 15.0469° h^{-1} = 4.17×10^{-3}° s^{-1} = 7.292×10^{-5} rad s^{-1}

1 INTRODUCTION

This chapter provides introductions to the characteristics of satellite communication systems and technology development. It aims to satisfy the curiosity of an impatient reader and facilitate a deeper understanding by directing him or her to appropriate chapters without imposing the need to read the whole work from beginning to end.

1.1 BIRTH OF SATELLITE COMMUNICATIONS

Satellite communications are the outcome of research in the area of communications and space technologies whose objective is to achieve ever-increasing ranges and capacities with the lowest possible costs.

The World War II stimulated the expansion of two very distinct technologies – missiles and microwaves. The expertise eventually gained in the combined use of these two techniques opened up the era of satellite communications. The service provided in this way usefully complements that previously provided exclusively by terrestrial networks using radio and cables.

The space era started in 1957 with the launching of the first artificial satellite (Sputnik). Subsequent years have been marked by various experiments including the following: Christmas greetings from President Eisenhower broadcast by Score (1958), the reflecting satellite ECHO (1960), store-and-forward transmission by the Courier satellite (1960), powered relay satellites (Telstar and Relay in 1962), and the first geostationary satellite Syncom (1963).

In 1965, the first commercial geostationary satellite Intelsat I (or Early Bird) inaugurated the long series of Intelsats; in the same year, the first Soviet communications satellite of the Molniya series was launched.

1.2 DEVELOPMENT OF SATELLITE COMMUNICATIONS

The first satellites provided a low capacity at a relatively high cost; for example, Intelsat I weighed 68 kg at launch for a capacity of 480 telephone channels and an annual cost of $32 500 per channel at the time. This cost resulted from a combination of the cost of the launcher, that of the satellite, the short lifetime of the satellite (1.5 years), and its low capacity. The reduction in cost is the result of much effort, which has led to the production of reliable launchers that

Satellite Communications Systems: Systems, Techniques and Technology, Sixth Edition.
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can put heavier and heavier satellites into orbit (typically 5900 kg at launch in 1975, reaching 10 500 kg by Ariane 5 ECA and 13 000 kg by Delta IV in 2008). Today, Delta IV Heavy is capable of sending a payload of 28 790 kg to low earth orbit (LEO) and 14 220 kg to geostationary transfer orbit (GTO); SpaceX Falcon Heavy can send payload of 63 700 kg to LEO, 26 700 kg to GTO, and 3500 kg to Mars.

In addition, increasing expertise in microwave techniques has enabled realisation of contoured multibeam antennas whose beams adapt to the shape of continents, frequency reuse from one beam to the other, and incorporation of higher-power transmission amplifiers. Increased satellite capacity has led to a reduced cost per telephone channel in recent history and now is calculated as reduction of the cost per bit in the digital age.

In addition to the reduction in the cost of communication, the most outstanding feature is the variety of services offered by satellite communications systems. Originally these were designed to carry communications from one point to another, as with cables, and the extended coverage of the satellite was used to set up long-distance links; hence Early Bird enabled stations on opposite sides of the Atlantic Ocean to be connected. However, as a consequence of the limited performance of the satellite, it was necessary to use earth stations equipped with large antennas and therefore of high cost (around $10 million for a station equipped with a 30 m diameter antenna).

The increasing size and power of satellites has permitted a consequent reduction in the size of earth stations, and hence their cost, leading to an increase in number from thousands to millions. In this way it has been possible to exploit another feature of the satellite: its ability to collect or broadcast signals from or to several locations. Instead of transmitting signals from one point to another, transmission can be from a single transmitter to a large number of receivers distributed over a wide area; or, conversely, transmission can be from a large number of stations to a single central station, often called a *hub*. In this way, multipoint data-transmission networks and data-collection networks have been developed under the name *very small aperture terminal networks* (VSATs) [MAR-95]. Over 1 000 000 VSATs had been installed up to 2008 and about 6 000 000 in 2018.

For TV services, satellites are of paramount importance for satellite news gathering (SNG), for the exchange of programmes between broadcasters, and for distributing programmes to terrestrial broadcasting stations and cable heads, or directly to the individual consumer. The latter are commonly called *direct broadcasting by satellite* (DBS) systems, or direct-to-home (DTH) systems. A rapidly growing service is digital video broadcasting by satellite (DVB-S), developed in early 1991; the second generation (DVB-S2) has been standardised by the European Telecommunication Standard Institute (ETSI); and DVB-S2X as an extension of DVB-S2 was completed in 2014. These DBS systems operate with small earth stations having antennas with a diameter from 0.5 to 1 m.

In the past, customer stations were receive only (RCVO) stations. With the introduction of two-way communications stations, satellites are a key component in providing interactive TV and broadband Internet services, thanks to the implementation of the digital video broadcasting satellite return channel (DVB-RCS) standard for service providers' facilities that was started in 1999 and completed in 2008; DVB-RCS2 as the next generation of DVB-RCS, completed in 2009; and DVB-RCS2X as an extension of DVB-RCS2, which became an ETSI standard in 2014. It uses Transmission Control Protocol (TCP)/Internet Protocol (IP) to support Internet, multicast, and web-page caching services over satellite with the forward channel operating at several Mbps and enables satellites to provide broadband service applications for the end user, such as direct access and distribution services. IP-based triple-play services (telephony, Internet, and TV) are more and more popular. Satellites cannot compete with terrestrial asymmetric digital subscriber line (ADSL) or cable to deliver these services in high-density population areas. However, they complement nicely the terrestrial networks around cities and in rural areas where the distance to the telephone router is too large to allow delivery of the several Mbps required to run the service.

A further reduction in the size of the earth station antenna is exemplified in digital audio broadcasting (DAB) systems, with antennas on the order of 10 cm. The satellite transmits multiplexed digital audio programmes and supplements traditional Internet services by offering one-way broadcast of web-style content to the receivers.

Furthermore, satellites are effective in mobile communications. Since the end of the 1970s, INMARSAT satellites have been providing distress-signal services along with telephone and data communications services to ships and planes and, more recently, to portable earth stations (Mini M or satphone). Personal mobile communication using small handsets is available from constellations of non-geostationary satellites (such as Iridium and Globalstar), and geostationary satellites equipped with very large deployable antennas (typically 10–15 m and today can be more than 25 m), as with the Intelsat, Inmarsat, and Eutelsat satellites. The next step in bridging the gaps between fixed, mobile, and broadcasting radiocommunications services concerns satellite multimedia broadcast to fixed and mobile users. Satellite digital mobile broadcasting (SDMB) is based on hybrid integrated satellite–terrestrial systems to serve small hand-held terminals with interactivity.

Finally, high-throughput satellites (HTSs) have taken advantage of technology developments, further reducing the cost per bit over satellite with increased total capacity of a satellite from megabits per second (Mbps) to gigabits per second (Gbps), or even terabits per second (Tbps). Further, mega-LEO satellite constellations such as OneWeb will be able to have hundreds or even thousands of satellites delivering a total capacity of 7 Tbps.

1.3 CONFIGURATION OF A SATELLITE COMMUNICATIONS SYSTEM

Figure 1.1 gives an overview of a satellite communication system and illustrates its interfacing with terrestrial entities. The satellite system is composed of a space segment, a control segment, and a ground segment:

— The *space segment* contains one or several active and spare satellites organised into a constellation.
— The *control segment* consists of all ground facilities for the control and monitoring of the satellites, also named tracking, telemetry, and command (TTC) stations, and for the management of the traffic and the associated resources on board the satellite for communication networks.
— The *ground segment* consists of all the traffic earth stations. Depending on the type of service considered, these stations can be of different size, from a few centimetres to tens of metres.

Table 1.1 gives examples of traffic earth stations in connection with the types of service discussed in Section 1.7. Earth stations come in three classes, as illustrated in Figure 1.1: *user stations*, such as handsets, portables, mobile stations, and VSATs, which allow the customer direct access to the space segment; *interface stations*, known as *gateways*, which interconnect the space segment to a terrestrial network; and *service stations*, such as hub or feeder stations, which collect or distribute information from and to user stations via the space segment.

Communications between users are set up through *user terminals* – which consisted of equipment such as telephone sets, fax machines, and computers in the past and laptops and smartphones today – that are connected to the terrestrial network or to the user station (e.g. a VSAT), or are part of the user station (e.g. if the terminal is mobile).

The path from a source user terminal to a destination user terminal is called a *simplex connection*. There are two basic schemes: *single connection per carrier* (SCPC), where the modulated carrier supports one connection only; and *multiple connections per carrier* (MCPC), where the

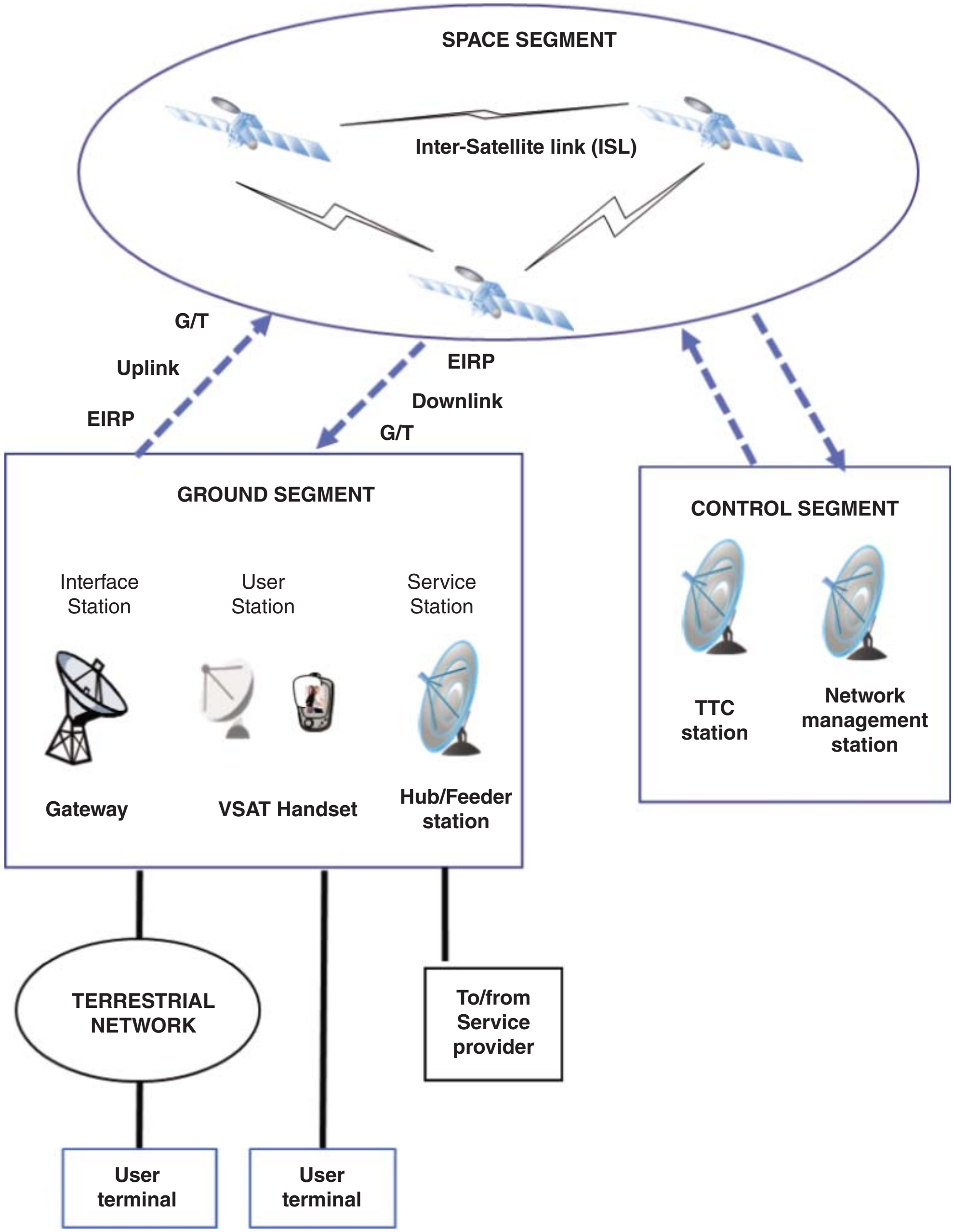

Figure 1.1 Satellite communications system interfacing with terrestrial entities.

Table 1.1 Services from different types of traffic and earth stations

Type of service	Type of earth station	Typical size (m)
Point-to-point	Gateway, hub	2–10
	VSAT	1–2
Broadcast/multicast	Feeder station	1–5
	VSAT	0.5–1.0
Collect	VSAT	0.1–1.0
	Hub	2–10
Mobile	Handset, portable, mobile	0.1–0.5
	Gateway	2–10

modulated carrier supports several time- or frequency-multiplexed connections. Interactivity between two users requires a duplex connection between their respective terminals, i.e. two simplex connections, each in one direction. Each user terminal should then be capable of sending and receiving information.

A connection between a service provider and a user goes through a hub (for collecting services) or a feeder station (e.g. for broadcasting services). A connection from a gateway, hub, or feeder station to a user terminal is called a *forward* connection. The reverse connection is the *return* connection. Both forward and return connections entail an uplink and a downlink, and possibly one or more intersatellite links (ISLs).

1.3.1 Communications links

A link between transmitting equipment and receiving equipment consists of a radio or optical modulated carrier. The performance of the transmitting equipment is measured by its *effective isotropic radiated power* (EIRP), which is the power fed to the antenna multiplied by the gain of the antenna in the considered direction. The performance of the receiving equipment is measured by G/T, the ratio of the antenna receive gain, G, in the considered direction and the system noise temperature, T; G/T is called the receiver's *figure of merit*. These concepts are detailed in Chapter 5.

The types of link shown in Figure 1.1 are:

— *Uplinks* from the earth stations to the satellites
— *Downlinks* from the satellites to the earth stations
— *Intersatellite links* between the satellites

Uplinks and downlinks consist of radio frequency modulated carriers, while ISLs can be either radio frequency or optical. Some large-capacity data-relay satellites also use optical links with their ground stations. Carriers are modulated by baseband signals conveying information for communications purposes.

The link performance can be measured by the ratio of the received carrier power, C, to the noise power spectral density, N_0, and is denoted as the C/N_0 ratio, expressed in hertz (Hz). The values of C/N_0 for the links that participate in the connection between the end terminals determine the quality of service, specified in terms of *bit error rate* (BER) for digital communications.

Another parameter of importance for the design of a link is the bandwidth, B, occupied by the carrier. This bandwidth depends on the information data rate, the channel coding rate (forward error correction, [FEC]), and the type of modulation used to modulate the carrier. For satellite links, the trade-off between required carrier power and occupied bandwidth is paramount to the cost-effective design of the link. This is an important aspect of satellite communications, as power impacts both satellite mass and earth station size, and bandwidth is constrained by regulations.

According to the Shannon-Hartley theorem, the maximum rate at which information can be transmitted over a communication channel of a specified bandwidth in the presence of noise can be calculated as the following:

$$R = B \log_2(1 + S/N)$$

where R is the maximum rate, B is the bandwidth, S is the signal power, and N is the noise power.

Moreover, a service provider that rents satellite transponder capacity from the satellite operator is charged according to the highest share of either power or bandwidth resource available from the satellite transponder. The service provider's revenue is based on the number of established connections, so the objective is to maximise the throughput of the considered link while keeping a balanced share of power and bandwidth usage. This is discussed in Chapter 4.

In a satellite system, several stations transmit their carriers to a given satellite, and therefore the satellite acts as a network node. The techniques used to organise access to the satellite by the carriers are called *multiple-access techniques* (Chapter 6).

1.3.2 The space segment

A satellite consists of the *payload* and the *platform*. The payload consists of the receiving and transmitting antennas and all the electronic equipment that supports the transmissions of the carriers. The two types of payload organisation are illustrated in Figure 1.2. Some experiments have also been carried out for IP routers on board satellites.

Figure 1.2a shows a *transparent* payload (sometimes called a *bent pipe* type) where carrier power is amplified and frequency is downconverted. Power gain is on the order of 100–130 dB required to raise the power level of the received carrier from a few tens of picowatts to the power level of the carrier fed to the transmit antenna (a few watts to a few tens of watts). Frequency conversion is required to increase isolation between the receiving input and the transmitting output. Due to technology power limitations, the overall satellite payload bandwidth is split into several sub-bands, and the carriers in each sub-band are amplified by a dedicated power amplifier. The amplifying chain associated with each sub-band is called a *satellite channel*, or transponder. The bandwidth splitting is achieved using a set of filters called the *input multiplexer* (IMUX). The amplified carriers are recombined in the *output multiplexer* (OMUX).

The transparent payload in Figure 1.2a belongs to a single-beam satellite where each transmit and receive antenna generates one beam only. One could also consider multiple-beam antennas. The payload would then have as many inputs/outputs as upbeams/downbeams. Routing of carriers from one upbeam to a given downbeam implies either routing through different satellite channels; *transponder hopping*, depending on the selected uplink frequency; or *on-board switching with transparent on-board processing*. These techniques are presented in Chapter 7.

Figure 1.2b shows a multiple-beam *regenerative* payload where the uplink carriers are demodulated. The availability of the baseband signals allows *on-board processing* and routing of information from upbeam to downbeam through *on-board switching at baseband*. The frequency conversion is achieved by modulating on-board-generated carriers at downlink frequency. The modulated carriers are then amplified and delivered to the destination downbeam.

Figure 1.3 illustrates a multiple-beam satellite antenna and its associated coverage areas. Each beam defines a *beam coverage area*, also called a *footprint*, on the earth surface. The aggregate beam coverage areas define the *multibeam antenna coverage area*. A given satellite may have several multiple-beam antennas, and their combined coverage defines the *satellite coverage area*.

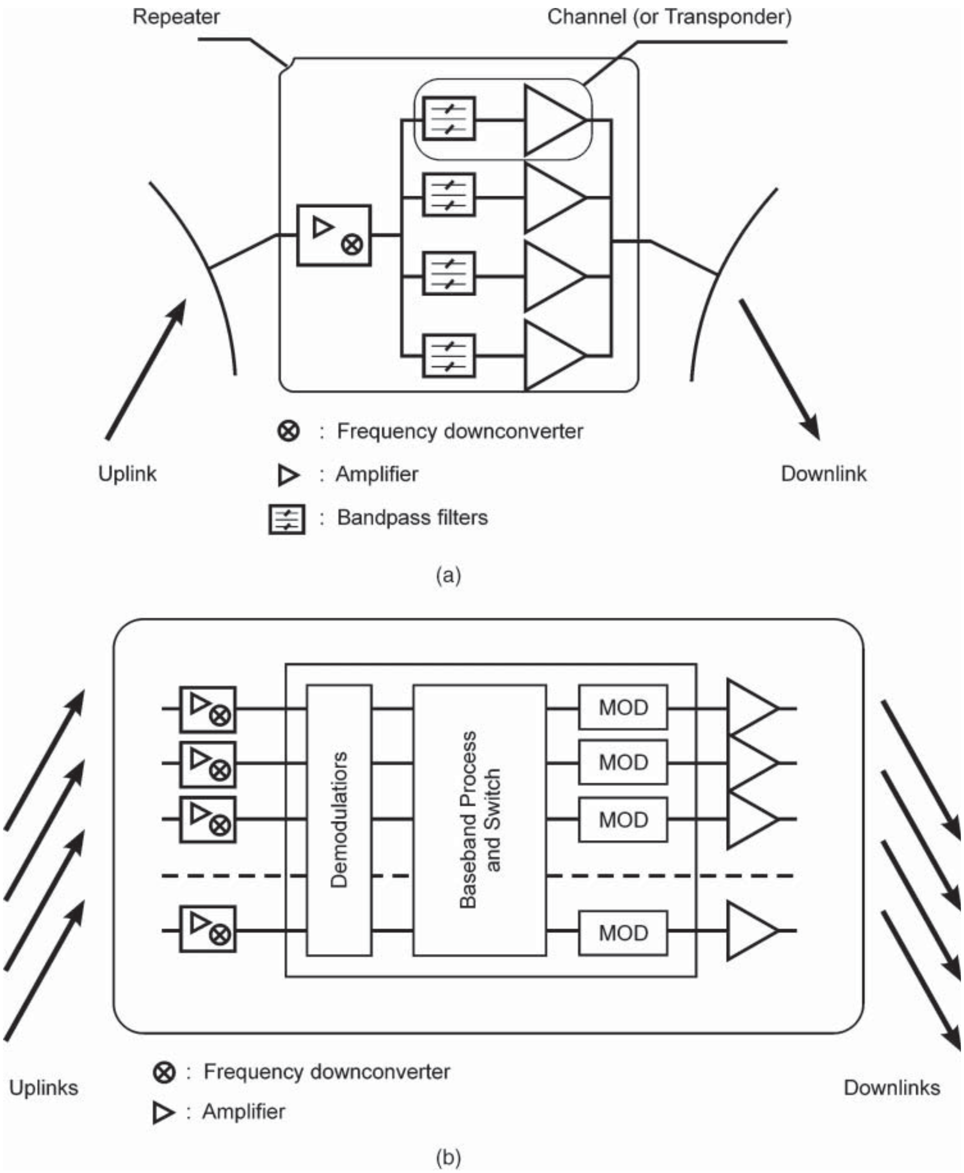

Figure 1.2 Payload organisation: (a) transparent; (b) regenerative.

Bandwidth reuse based on multibeam antennas is a key technology to achieve high capacity for HTS to reduce the cost per bit for information delivery. The available bandwidth can be divided into three or four sub-bands (also called three- or four-colour techniques, according to arrangement of the spot beams) so that different sub-bands (colours) can be allocated to different spot beams; adjacent spot beams use different sub-bands (colours) to avoid interference between adjacent spot beams. Figure 1.3b shows an example of four-colour reuse.

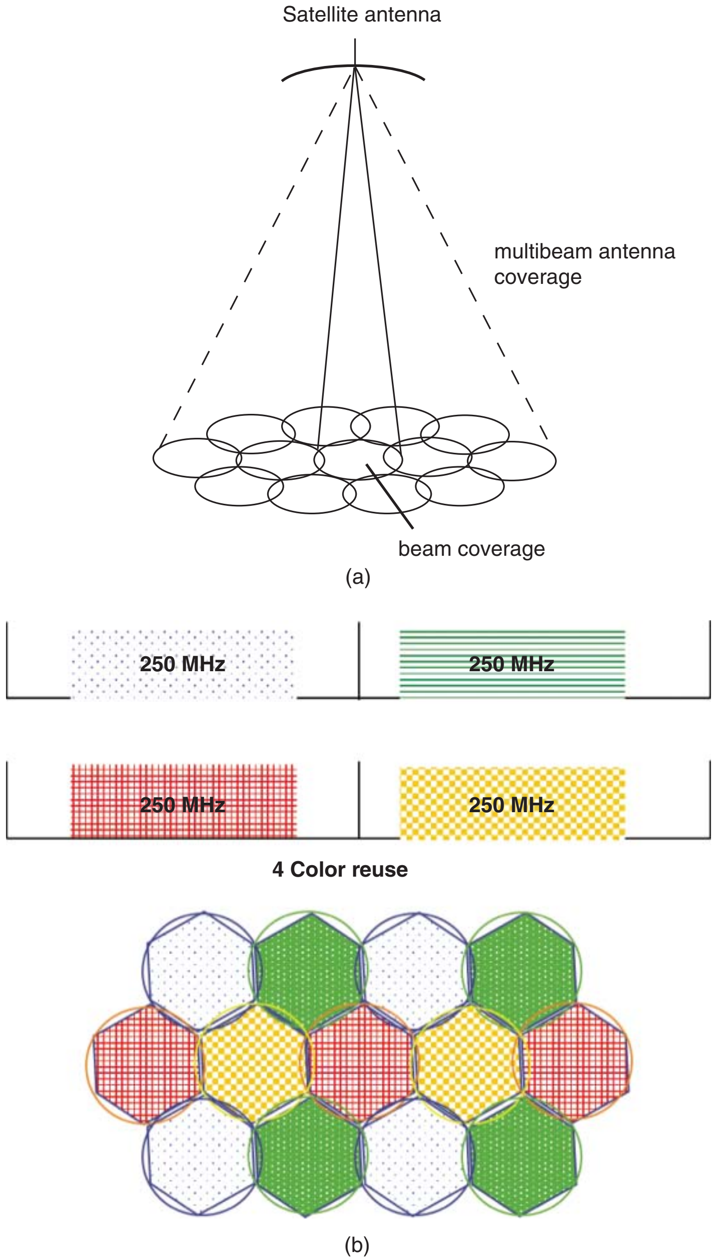

Figure 1.3 (a) Multiple-beam satellite antenna and associated coverage area; (b) example of four-colour reuse.

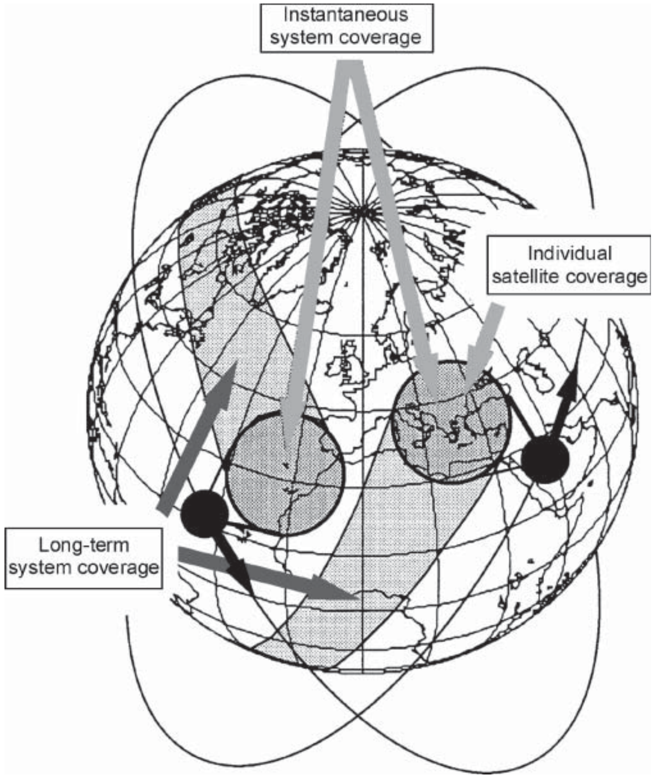

Figure 1.4 Types of coverage.

Figure 1.4 illustrates the concept of instantaneous system coverage and long-term coverage. *Instantaneous system coverage* consists of the aggregation at a given time of the coverage areas of the individual satellites participating in the constellation. *Long-term coverage* is the area on the earth scanned over time by the antennas of the satellites in the constellation.

The coverage area should encompass the *service zone*, which corresponds to the geographical region where the stations are installed. For real-time services, the instantaneous system coverage should at any time have a footprint covering the service zone, while for non-real-time (store-and-forward) services, it should have long-term coverage of the service zone.

For LEO or medium earth orbit (MEO) satellites, a large number of satellites are needed to provide continuous global coverages. In cases of LEO, the Iridium Next (constellation of second-generation Iridium satellites) has 66 satellites plus 6 spares; OneWeb plans to have 648 satellites plus 252 spares; and Starlink by SpaceX plans to have 4425 satellites plus some spares. In case of MEO, O3b has 20 satellites including 3 on-orbit spares, all operating in equatorial orbit.

The platform consists of all the subsystems that permit the payload to operate. Table 1.2 lists these subsystems and indicates their respective main functions and characteristics.

The detailed architecture and technology of the payload equipment are explained in Chapter 9. The architecture and technologies of the platform are considered in Chapter 10. The operations of orbit injection and the various types of launcher are the subject of Chapter 11. The space environment and its effects on the satellite are presented in Chapter 12.

Table 1.2 Platform subsystems

Subsystem	Principal functions	Characteristics
Attitude and orbit control system (AOCS)	Attitude stabilisation, orbit determination	Accuracy
Propulsion	Provision of velocity increments	Specific impulse, mass of propellant
Electric power supply	Provision of electrical energy	Power, voltage stability
Telemetry, tracking, and command (TTC)	Exchange of housekeeping information	Number of channels, security of communications
Thermal control	Temperature maintenance	Dissipation capability
Structure	Equipment support	Rigidity, lightness

To ensure service with a specified availability, a satellite communication system must make use of several satellites in order to provide redundancy. A satellite can cease to be available due to a failure or because it has reached the end of its lifetime. In this respect, it is necessary to distinguish between the reliability and the lifetime of a satellite. *Reliability* is a measure of the probability of a breakdown and depends on the reliability of the equipment and any schemes to provide redundancy. The *lifetime* is conditioned by the ability to maintain the satellite on station in the nominal attitude, and depends on the quantity of fuel available for the propulsion system and attitude and orbit control system (AOCS). In a system, provision is generally made for an operational satellite, a backup satellite in orbit, and a backup satellite on the ground. The reliability of the system involves not only the reliability of each of the satellites but also the reliability of launching. An approach to these problems is treated in Chapter 13.

1.3.3 The ground segment

The ground segment consists of all the earth stations; these are most often connected to the end user's terminal by a terrestrial network or, in the case of small station VSATs, directly connected to the end user's terminal. Stations are distinguished by their size, which varies according to the volume of traffic to be carried on the satellite link and the type of traffic (telephone, television, data, or multimedia Internet services). In the past, the largest were equipped with antennas 30 m diameter (Standard A of the Intelsat network). The smallest have 0.6 m antennas (receiving stations from DBSs) or even smaller (0.1 m) antennas (mobile stations, portable stations, or handsets). Some stations both transmit and receive. Others are RCVO stations; this is the case, for example, with receiving stations for a broadcasting satellite system or a distribution system for television or data signals. Figure 1.5 shows the typical architecture of an earth station for both transmission and reception. Chapter 5 introduces the characteristic parameters of the earth station that appear in the link budget calculations. Chapter 3 presents the characteristics of signals supplied to earth stations by the user terminal, either directly or through a terrestrial network; the signal processing at the station (such as source coding and compression, multiplexing, channel coding, scrambling, and encryption); and transmission and reception (including modulation and demodulation). Chapter 7 explains the concepts of satellite networks, as satellite communication systems are integrated more closely with terrestrial networks to provide broadband multimedia services as well as mobile networks services. Chapter 8 treats the organisation and equipment of earth stations.

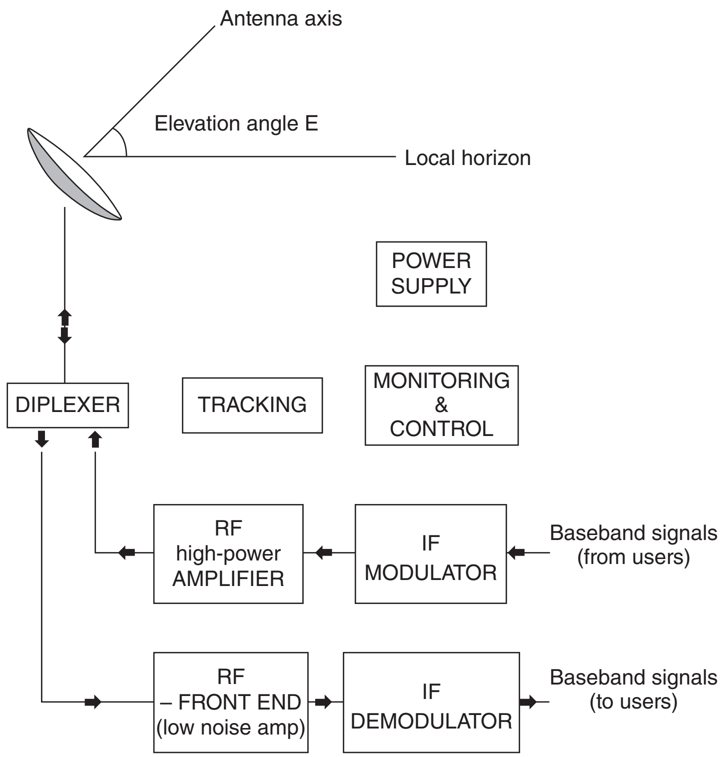

Figure 1.5 The organisation of an earth station. RF = radio frequency, IF = intermediate frequency.

1.4 TYPES OF ORBIT

The *orbit* is the trajectory followed by the satellite. The trajectory is within a plane and shaped like an ellipse with a maximum extension at the apogee and a minimum at the perigee. The satellite moves more slowly in its trajectory as the distance from the earth increases, according to the laws of physics. Chapter 2 provides a definition of the orbital parameters.

The most favourable orbits are as follows:

— *Elliptical orbits* inclined at an angle of 64° with respect to the equatorial plane. This type of orbit is particularly stable with respect to irregularities in terrestrial gravitational potential and, owing to its inclination, enables the satellite to cover regions of high latitude for a large fraction of the orbital period as it passes to the apogee. This type of orbit has been adopted by Russia for the satellites of the Molniya system with a period of 12 hours. Figure 1.6 shows the geometry of the orbit. The satellite remains above the regions located under the apogee for a time interval on the order of eight hours. Continuous coverage can be ensured with three phased satellites in different orbits. Several studies relate to elliptical orbits with a period of 24 hours (Tundra orbits) or a multiple of 24 hours. These orbits are particularly useful for satellite systems for communication with mobiles, where the masking effects caused by surrounding obstacles such as buildings and trees and multiple-path

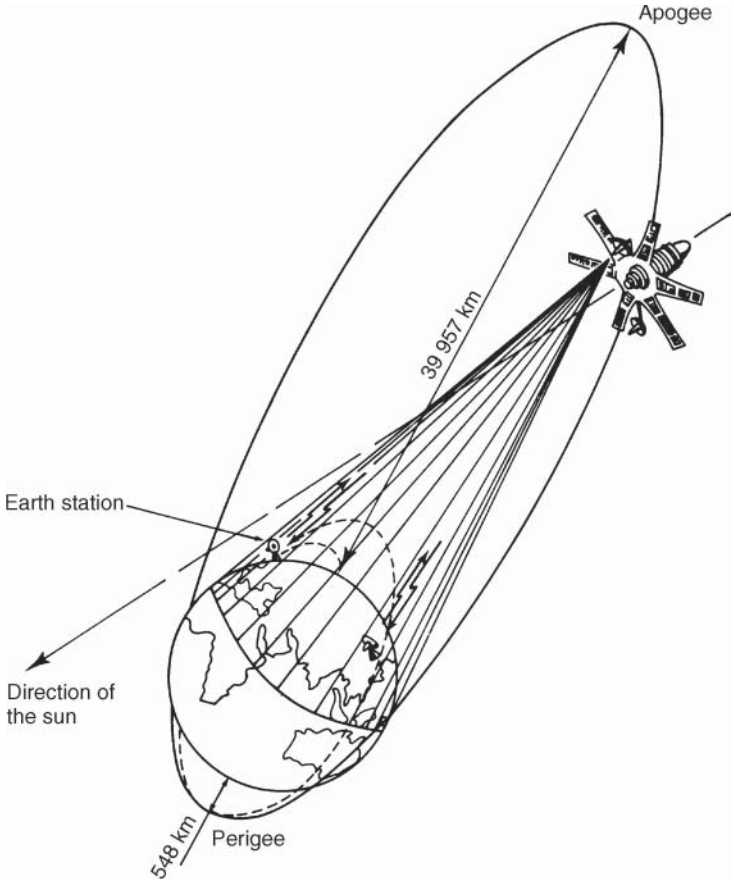

Figure 1.6 The orbit of a Molniya satellite.

effects are pronounced at low elevation angles (say, less than 30°). In fact, inclined elliptic orbits can provide the possibility of links at medium latitudes when the satellite is close to the apogee with elevation angles close to 90°; these favourable conditions cannot be provided at the same latitudes by geostationary satellites. In the late 1980s, the European Space Agency (ESA) studied the use of elliptical highly inclined orbits (HEOs) for DAB and mobile communications in the framework of its Archimedes programme. The concept became reality at the end of the 1990s with the Sirius system delivering satellite digital audio radio services to millions of subscribers (mainly automobiles) in the United States using three satellites in HEO Tundra-like orbits [AKT-08]. Both Molnya and Tundra orbits provide users with higher elevation angles than geostationary earth orbit (GEO) orbit at high latitude.

— *Circular LEOs:* The altitude of the satellite is constant and equal to several hundreds of kilometres. The period is on the order of one and a half hours. With near 90° inclination, this type of orbit guarantees worldwide long-term coverage as a result of the combined motion of the satellite and earth rotation, as shown in Figure 1.7. This is the reason for choosing this type of orbit for observation satellites (for example, the SPOT satellite: altitude

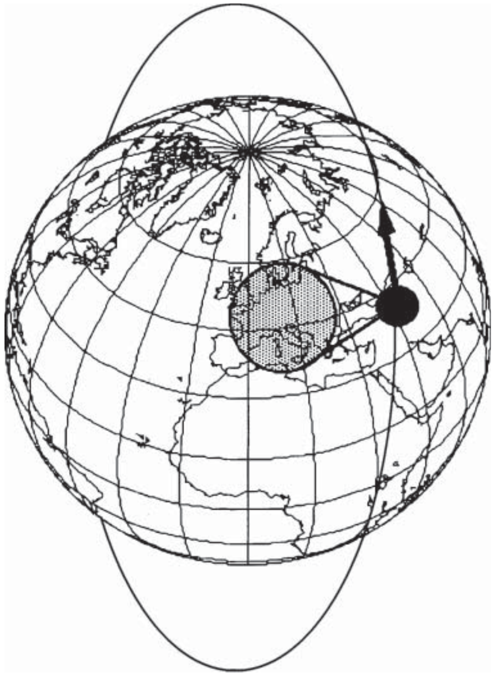

Figure 1.7 Circular polar low earth orbit (LEO).

830 km, orbit inclination 98.7°, period 101 minutes). One can envisage the establishment of store-and-forward communications if the satellite is equipped with a means of storing information. A constellation of several tens of satellites in low-altitude (e.g. IRIDIUM with 66 satellites at 780 km) circular orbits can provide worldwide real-time communication (see Figure 1.8). Non-polar orbits with less than 90° inclination can also be envisaged. For instance, the GLOBALSTAR constellation incorporates 48 satellites at 1414 km with 52° orbit inclination.

— *Circular MEOs*, also called intermediate circular orbits (ICOs), have an altitude of about 10 000 km and an inclination of about 50°. The period is six hours. With constellations of about 10–15 satellites, continuous coverage of the world is guaranteed, allowing worldwide real-time communications. A planned system of this kind was the ICO system (which emerged from Project 21 of INMARSAT but was not implemented) with a constellation of 10 satellites in two planes at 45° inclination. O3b is a special case of a MEO circular orbit satellite constellation with altitude at 8063 km and 20 satellites. Each satellite has 12 steerable Ka band antennas of which 2 are for gateways and 10 are for user terminals (see Figure 1.9).

— *Circular orbits with zero inclination (equatorial orbits)*: The most popular is the geostationary satellite orbit; the satellite orbits around the earth in the equatorial plane according to the earth's rotation at an altitude of 35 786 km. The period is equal to that of the rotation of the earth. The satellite thus appears as a point fixed in the sky and ensures continuous operation as a radio relay in real time for the area of visibility of the satellite (43% of the earth's surface).

— *Hybrid systems*: Some systems may include combinations of circular and elliptical orbits. Studies have been carried out to determine how to combine satellites from different orbits to achieve communication and network objectives, though these have been used in navigation satellite systems.

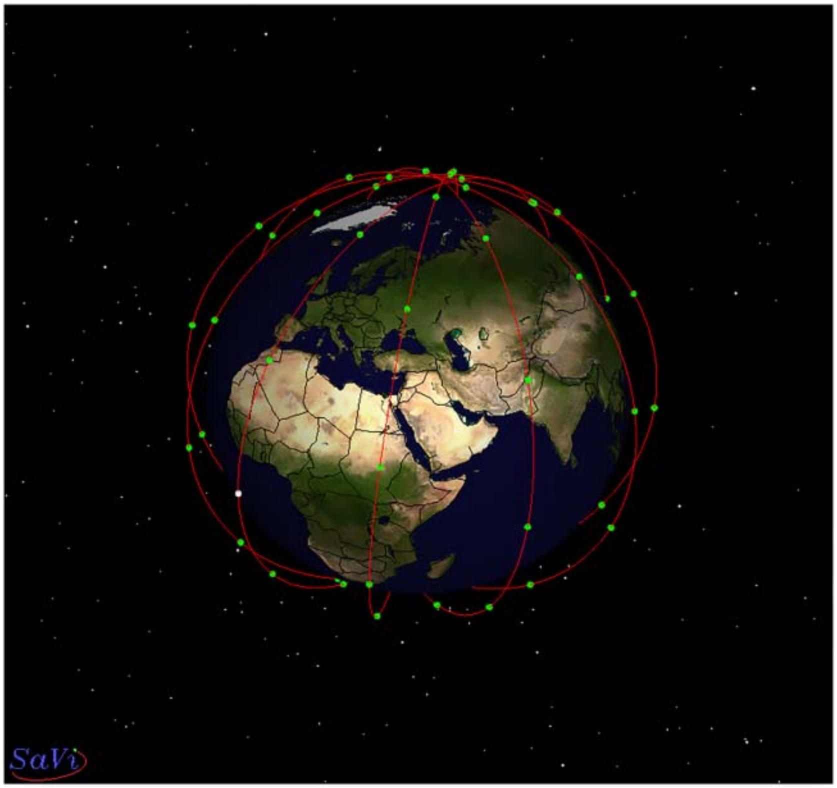

Figure 1.8 Illustration of Iridium as an example of a low earth orbit (LEO) satellite constellation.

The choice of orbit depends on the nature of the mission, the acceptable interference, and the performance of the launchers:

— *The extent and latitude of the area to be covered*: Contrary to widespread opinion, the altitude of the satellite is not a determining factor in the link budget for a given earth coverage. Chapter 5 shows that the propagation attenuation varies as the inverse square of the distance, and this favours a satellite following a low orbit on account of its low altitude; however, this disregards the fact that the area to be covered is then seen through a larger solid angle. The result is a reduction in the gain of the satellite antenna, which offsets the distance advantage. A satellite following a low orbit provides only limited earth coverage at a given time and limited time at a given location. Unless low-gain antennas (on the order of a few dB) that provide low directivity and hence almost omnidirectional radiation are installed, earth stations must be equipped with satellite-tracking devices, which increases the cost. The geostationary satellite thus appears to be particularly useful for continuous coverage of extensive regions. However, it does not permit coverage of the polar regions, which are accessible by satellites in inclined elliptical orbits or polar orbits.
— *The elevation angle*: A satellite in an inclined or polar elliptical orbit can appear overhead at certain times, which enables communication to be established in urban areas without encountering the obstacles that large buildings constitute for elevation angles between 0°

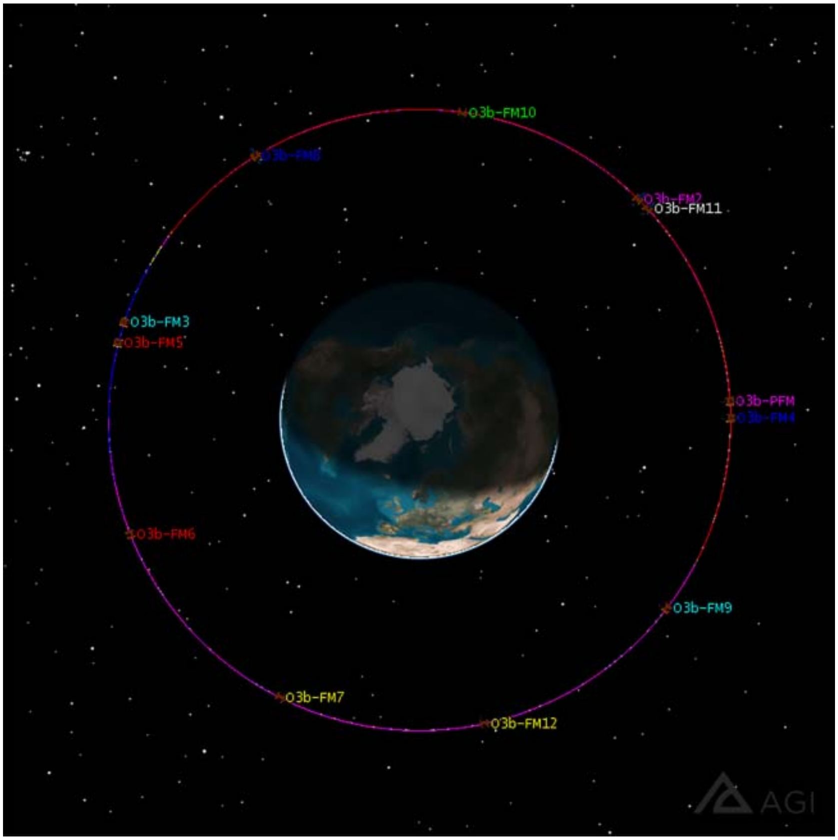

Figure 1.9 Illustration of O3B as an example of a medium earth orbit (MEO) satellite constellation.

and approximately 70°. With a geostationary satellite, the angle of elevation decreases as the difference in latitude or longitude between the earth station and the satellite increases.

— *Transmission duration and delay*: A geostationary satellite provides a continuous relay for stations within visibility, but the propagation time of the radio waves from one station to the other is on the order of 0.25 seconds. This requires the use of echo control devices on telephone channels or special protocols for data transmission. For the Internet, performance enhancement protocols (PEPs) have been introduced for efficient utilisation of satellite link resources. A satellite moving in a low orbit confers a reduced propagation time. The transmission time is thus low between stations that are close and simultaneously visible to the satellite, but it can become long (several hours) for distant stations if only store-and-forward transmission is considered. For large mega-LEO satellite constellations, complicated dynamic routing mechanisms are needed, and the satellites in the constellations must be managed.

— *Interference*: Geostationary satellites occupy fixed positions in the sky with respect to the stations with which they communicate. Protection against interference between systems is ensured by planning the frequency bands and orbital positions. The small orbital spacing between adjacent satellites operating at the same frequencies leads to an increase in the level of interference, and this impedes the installation of new satellites. Different systems could use different frequencies, but this is restricted by the limited number of frequency bands assigned for space radiocommunications by the International Telecommunication Union (ITU) Radio Regulations (RR). In this context, one can refer to an *orbit-spectrum* resource that is limited. With orbiting satellites, the geometry of each system changes with time, and the relative geometries of one system with respect to another are variable and difficult to synchronise. The probability of interference is thus high.

— *The performance of launchers*: The mass that can be launched decreases as the altitude increases.

The geostationary satellite is certainly the most popular. At the present time there are around 600 geostationary satellites in operation within the 360° of the whole orbital arc. Some parts of this orbital arc, however, tend to be highly congested (for example, above the American continent and Europe). Figure 1.10 illustrates the satellite orbit altitudes (LEO/MEO/GEO) and coverage areas.

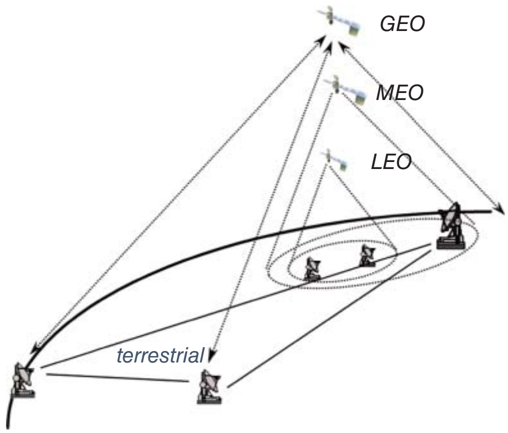

Figure 1.10 Illustration of orbit altitudes and coverages.

1.5 RADIO REGULATIONS

The latest publication is the 2016 edition of the ITU Radio Regulations Articles [ITU-16], freely available from the ITU publications on the Internet. Radio regulations are necessary to ensure an efficient and economical use of the radio-frequency spectrum by all communications systems, both terrestrial and satellite. While so doing, the sovereign right of each state to regulate its telecommunications must be preserved. It is the role of the ITU to promote, coordinate, and harmonise the efforts of its members to fulfil these possibly conflicting objectives. Further studies have been carried out for global satellite communications [ITU-12].

1.5.1 The ITU organisation

The ITU, a United Nations organ, operates under a convention adopted by its member administrations. The ITU publishes the Radio Regulations (RR), which are reviewed by the delegates from ITU member administrations at periodic World Radio Conferences/Regional Radio Conferences (WRCs/RRCs).

From 1947 to 1993, technical and operational matters were administered by two committees: the CCIR (Comité Consultatif International des Radiocommunications) and the CCITT (Comité Consultatif International Télégraphique et Téléphonique). The International Frequency Registration Board (IFRB) was responsible for the examination of frequency-use documentation submitted to the ITU by its member administrations, in compliance with the RR, and for maintaining the Master International Frequency Register (MIFR).

Since 1994, the ITU has been reorganised into three sectors:

— The Radiocommunications Sector (ITU-R) deals with all regulatory and technical matters that were previously handled, respectively, by the IFRB and the CCIR.
— The Telecommunication Standardisation Sector (ITU-T) continues the work of the CCITT, and those studies by the CCIR dealing with the interconnection of radiocommunications systems with public networks.
— The Development Sector (ITU-D) acts as a forum and an advisory structure for the harmonious development of communications in the world.

The abundant and useful technical literature previously published in the form of reports and recommendations by the CCIR and the CCITT has now been reorganised in the form of ITU-R and ITU-T series recommendations.

1.5.2 Space radiocommunications services

The RR refer to the following space radiocommunications services, defined as transmission or reception of radio waves for specific telecommunications applications [ITU-16]:

— *Fixed-satellite service (FSS)*: A radiocommunication service between earth stations at given positions, when one or more satellites are used. The given position may be a specified fixed point or any fixed point within specified areas. In some cases this service includes satellite-to-satellite links, which may also be operated in the inter-satellite service (ISS). The FSS may also include feeder links for other space radiocommunication services.
— *Mobile satellite service (MSS)*: A radiocommunication service between mobile earth stations and one or more space stations, or between space stations used by this service; or between mobile earth stations by means of one or more space stations. This service may also include feeder links necessary for its operation.
— *Broadcasting satellite service (BSS)*: A radiocommunication service in which signals transmitted or retransmitted by space stations are intended for direct reception by the general public. In the BSS, the term *direct reception* encompasses both individual reception and community reception.
— *Earth exploration satellite service (EES)*: A radiocommunication service between earth stations and one or more space stations, which may include links between space stations, in which: information relating to the characteristics of the earth and its natural phenomena, including data relating to the state of the environment, is obtained from active sensors or passive sensors on earth satellites. Similar information is collected from airborne or earth-based platforms; such information may be distributed to earth stations within the system concerned, and platform interrogation may be included. This service may also include feeder links necessary for its operation.
— *Space research service (SRS)*: A radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes.

— *Space operation service (SOS)*: A radiocommunication service concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry, and space telecommand. These functions will normally be provided within the service in which the space station is operating.
— *Radiodetermination satellite service (RSS)*: *A* radiocommunication service for the purpose of radiodetermination involving the use of one or more space stations. This service may also include feeder links necessary for its own operation.
— *Inter-satellite service (ISS)*: A radiocommunication service providing links between artificial satellites.
— *Amateur satellite service (ASS)*: A radiocommunication service using space stations on earth satellites for the same purposes as those of the amateur service.

The main services for satellite communications are FSS, MSS, and BSS. Now all shift from the traditional fixed voice and data services toward mobile IP-based broadband multimedia Internet services; and from basic channel-based standard TV services to HD, 4K and even 8K TV on-demand services.

1.5.3 Frequency allocation

Frequency bands are allocated to the various radiocommunications services to allow compatible use. The allocated bands can be either exclusive for a given service or shared among several services. *Allocations* refer to the following division of the world into three regions (refer to Figure 1.11):

— *Region 1:* Includes the area limited on the east by line A (lines A, B, and C are defined shortly) and on the west by line B, excluding any of the territory of the Islamic Republic of Iran that lies between these limits. It also includes the whole of the territory of Armenia, Azerbaijan, the Russian Federation, Georgia, Kazakhstan, Mongolia, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan, Turkey, and Ukraine and the area to the north of the Russian Federation that lies between lines A and C.
— *Region 2:* Includes the area limited on the east by line B and on the west by line C.
— *Region 3:* Includes the area limited on the east by line C and on the west by line A, except any of the territory of Armenia, Azerbaijan, the Russian Federation, Georgia, Kazakhstan, Mongolia, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan, Turkey, and Ukraine and the area to the north of the Russian Federation. It also includes that part of the territory of the Islamic Republic of Iran lying outside of those limits.

The lines A, B, and C are defined as follows:

— *Line A:* Extends from the North Pole along meridian 40° East of Greenwich to parallel 40° North; thence by great circle arc to the intersection of meridian 60° East and the Tropic of Cancer; thence along the meridian 60° East to the South Pole.
— *Line B:* Extends from the North Pole along meridian 10° West of Greenwich to its intersection with parallel 72° North; thence by great circle arc to the intersection of meridian 50° West and parallel 40° North; thence by great circle arc to the intersection of meridian 20° West and parallel 10° South; thence along meridian 20° West to the South Pole.
— *Line C:* Extends from the North Pole by great circle arc to the intersection of parallel 65° 30′ North with the international boundary in the Bering Strait; thence by great circle arc to the intersection of meridian 165° East of Greenwich and parallel 50° North; thence by great circle

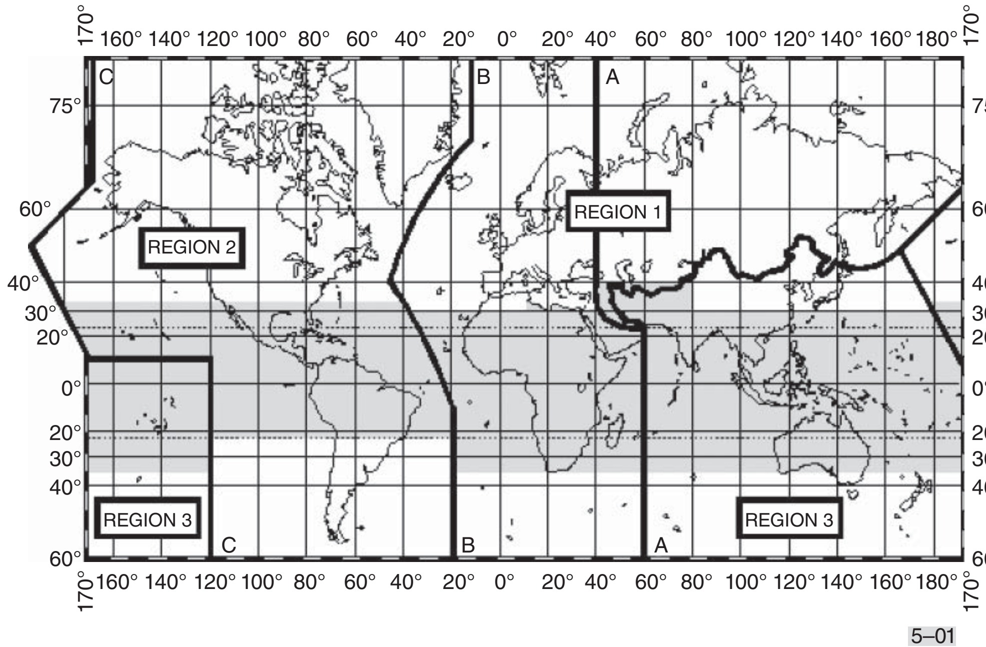

Figure 1.11 Map of regions and areas for frequency allocation in the ITU Radio Regulations (RR) [ITU-16].

arc to the intersection of meridian 170° West and parallel 10° North; thence along parallel 10° North to its intersection with meridian 120° West; thence along meridian 120° West to the South Pole.

For example, the FSS makes use of the following bands:

— Around 6 GHz for the uplink and around 4 GHz for the downlink (systems described as 6/4 GHz or C band). These bands are occupied by the oldest systems (such as Intelsat, American domestic systems, etc.) and tend to be saturated.
— Around 8 GHz for the uplink and around 7 GHz for the downlink (systems described as 8/7 GHz or X band). These bands are reserved, by agreement between administrations, for government use.
— Around 14 GHz for the uplink and around 12 GHz for the downlink (systems described as 14/12 GHz or Ku band). This corresponds to current operational developments (such as Eutelsat, etc.).
— Around 30 GHz for the uplink and around 20 GHz for the downlink (systems described as 30/20 GHz or Ka band).

Since 2010, large numbers of satellites have been launched and many more operational satellites have been planned on Ka band to exploit the benefit of its available large bandwidth. In combination with multispot beams and bandwidth-reuse technologies in Ka band, the capacity of each satellite has been increased significantly with 10–100 fold increases known as HTS.

The bands above 30 GHz will be used eventually in accordance with developing requirements and technology. Table 1.3 summarises this discussion.

Table 1.3 Frequency allocations

Radiocommunications service	Typical frequency bands for uplink/downlink (GHz)	Usual terminology
Fixed-satellite service (FSS)	6/4	C band
	8/7	X band
	14/12–11	Ku band
	30/20	Ka band
	50/40	V band
Mobile satellite service (MSS)	1.6/15	L band
	30/20	Ka band
Broadcasting satellite service (BSS)	2/2.2	S band
	12	Ku band
	2.6/2.5	S band

The MSS makes use of the following bands:

— VHF (very high frequency, 137–138 MHz downlink, and 148–150 MHz uplink) and UHF (ultra-high frequency, 400–401 MHz downlink, and 454–460 MHz uplink). These bands are for non-geostationary systems only.
— About 1.6 GHz for uplinks and 1.5 GHz for downlinks, mostly used by geostationary systems such as INMARSAT; and 1610–1626.5 MHz for the uplink of non-geostationary systems such as GLOBALSTAR.

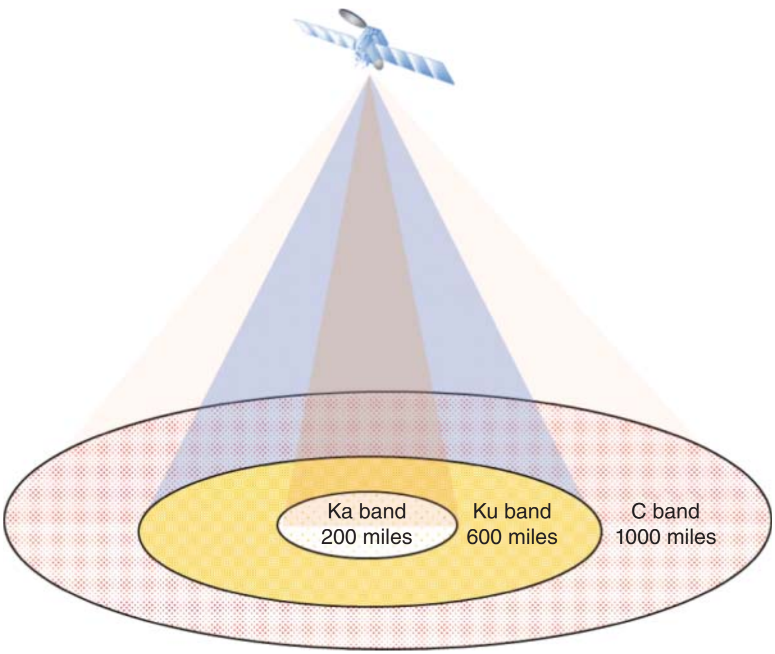

Figure 1.12 Relationship between coverage and frequency bands.

— About 2.2 GHz for downlinks and 2 GHz for uplinks for the satellite component of IMT2000 (International Mobile Telecommunications).
— About 2.6 GHz for uplinks and 2.5 GHz for downlinks.
— Frequency bands have also been allocated at higher frequencies such as Ka band.

The BSS makes use of downlinks at about 12 GHz. The uplink is operated in the FSS bands and is called a *feeder link*. Table 1.3 summarises the main frequency allocation and indicates the correspondence with some usual terminology.

Figure 1.12 shows the relationship between coverage and frequency bands. It can be seen that the higher the frequency band, the smaller the spot beam size.

1.6 TECHNOLOGY TRENDS

Figure 1.13 shows the developments since the start of the satellite communication era.

The start of commercial satellite telecommunications can be traced back to the commissioning of Intelsat I (Early Bird) in 1965. Until the beginning of the 1970s, the services provided were telephone and television (TV) signal transmission between continents. Satellites were designed to complement submarine cables and played essentially the role of telephone trunk connections. The goal of increased capacity has led rapidly to the institution of multibeam satellites and the reuse of frequencies first by orthogonal polarisation and subsequently by angular separation (see Chapter 5).

Communication techniques (see Chapter 4) have changed from analogue to digital. The second-generation DVB-S2, although backward compatible with DVB-S, has made use of the many novel technologies developed in recent years, including modulation techniques of 8 phase shift keying (8PSK) and 16 and 32 amplitude and phase shift keying (16-APSK and 32-APSK) in addition to quadrature phase shift keying (QPSK); efficient FEC with new low-density parity check (LDPC) codes; adaptive coding and modulations (ACMs); and performance close to the Shannon limit. This makes DVB-S2 30% more efficient than DVB-S. Furthermore, DVB-S2X (the extension of DVB-S2) has made efficient gains up to 51% compared to DVB-S2, with higher modulation schemes (including 64/128/256 APSK) and smaller roll-off factors (including 5%, 10%, and 15%).

DVB-RCS can provide up to a 20 Mbps forward link to the user terminal and a 5 Mbps return link from the user terminal, which is comparable to ADSL technology. DVB-RCS2 improved the performance of DVB-RCS by 30%. Multiple access to the satellite (see Chapter 6) was resolved by frequency division multiple access (FDMA). The increasing demand for a large number of low-capacity links, such as for national requirements or for communication with ships, led in 1980 to the introduction of demand assignment (see Chapter 6), first using FDMA with single channel per carrier/frequency modulation (SCPC/FM) or PSK and subsequently using time division multiple access/phase shift keying (TDMA/PSK) in order to profit from the flexibility of digital techniques (see Chapter 4).

Simultaneously, the progress of antenna technology (see Chapter 9) enabled the beams to conform to the coverage of the service area. In this way, the performance of the link was improved while reducing interference between systems.

Multibeam satellites emerged, with interconnection between beams achieved by transponder hopping or on-board switching using satellite-switched time division multiple access (SS-TDMA). Scanning or hopping beams have been implemented in connection with on-board processing on modern satellites.

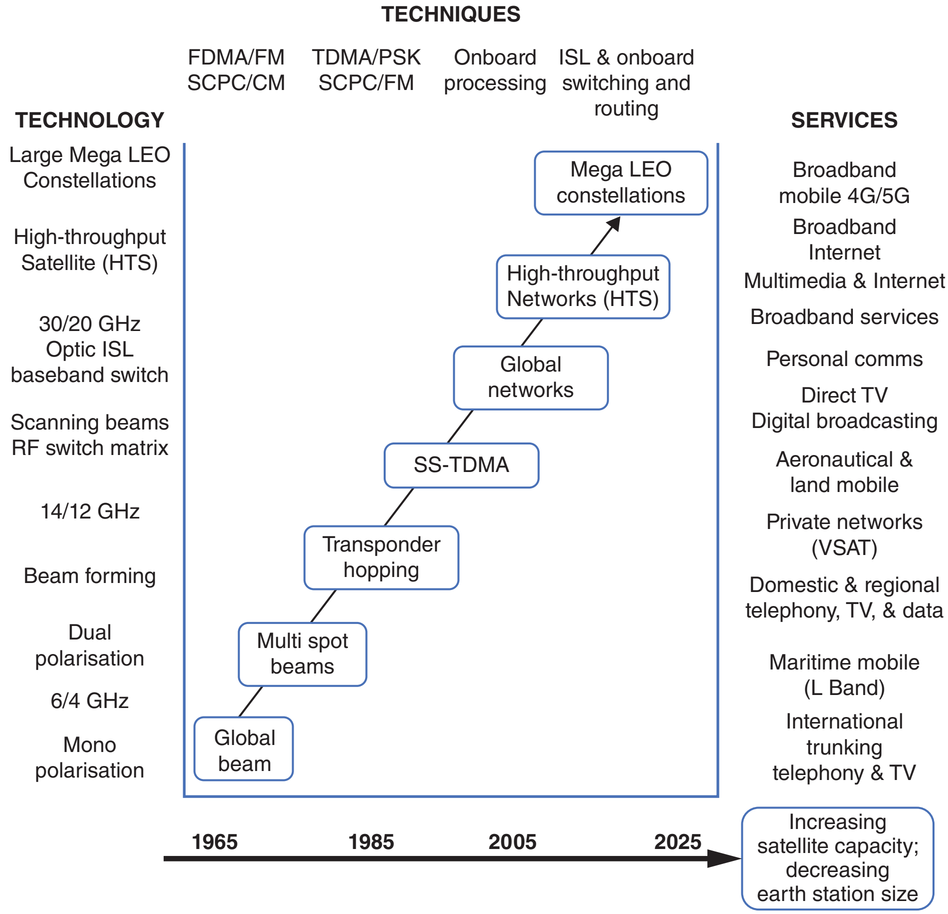

Figure 1.13 The evolution of satellite communication technologies.

Multiple-beam antennas today may produce hundreds of beams. This provides a twofold advantage: the link budget is improved to small user terminals, thanks to the high satellite antenna gain obtained with very narrow beams; and capacity is increased by reusing the frequency band allocated to the system many times.

Flexible interconnectivity between beams is required more than ever and may be achieved at different network layers by transparent or regenerative on-board processing. Regenerative payloads take advantage of the availability of baseband signals thanks to carrier demodulation. This is discussed in Chapters 7 and 9. Inter-satellite links were developed for civilian applications in the framework of multi-satellite constellations, such as IRIDIUM for mobile applications, and eventually will develop for geostationary satellites (Chapters 5 and 7). The use of higher frequencies (Ka band at 30/20 GHz) enables the emergence of broadband services and development of HTS, thanks to the large amount of bandwidth currently available, despite the propagation problems caused by rain effects (Chapter 5).

1.7 SERVICES

Initially designed as *trunks* that duplicate long-distance terrestrial links, satellite links have rapidly conquered specific markets. A satellite telecommunication system has three properties that are not found in terrestrial networks, or are found only to a lesser extent:

— The possibility of broadcasting with large coverage
— Wide bandwidth
— Rapid setup and ease of reconfiguration

With these properties, satellites can provide telecommunication services everywhere in the world. It is also possible to support mobile communication including services to airplanes, cruise ships, and high-speed trains.

It is possible to combine cellular networks and fibre for most users (including back-haul support for cellular networks such as 3G/4G and 5G mobile communications). Providing broadcasting services for large populations on a global scale has been one of the main advantages of satellite systems.

Further, it is possible to communicate in places with hostile terrain or a poorly developed terrestrial infrastructure; as well as in niche markets where obtaining the right of way for laying fibre is difficult or unduly expensive, such as remote rural areas, islands, and oil rigs. Finally, satellite service is very important when rapid deployment is critical, such as disaster relief and rescue services and government/military communication systems, as well as scientific explorations. Figure 1.14 illustrates typical satellite services and applications [SUN-14].

The preceding sections describe the state of technical development and show the development of the ground segment with respect to reduction in the size of stations and decreasing station cost. Initially, satellite systems contained a small number of earth stations: several stations per country, equipped with large 15–30 m diameter antennas collecting traffic from an extensive area by means of a ground network. Subsequently, the number of earth stations has increased, with

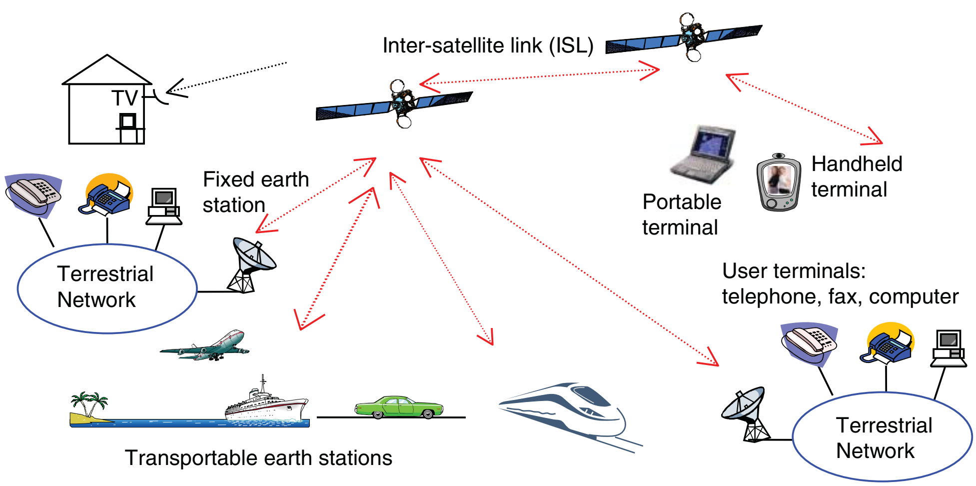

Figure 1.14 Illustration of typical satellite services and applications.

a reduction in size (1–4 m antennas) and greater geographical dispersion. The stations are closer to the user, and may be transportable or mobile. The potential of the services offered by satellite telecommunications has thus diversified:

— *Trunking telephony and television programme exchange*: This is a continuation of the original service. The traffic concerned is part of a country's international traffic. It is collected and distributed by the ground network on a scale appropriate to the particular country. Examples are Intelsat and Eutelsat (broadband connectivity for Internet and digital broadcasting services). The earth stations are equipped with 15–30 m diameter antennas.
— *Multiservice systems:* Telephone and data for user groups that are geographically dispersed. Each group shares an earth station and accesses it through a ground network whose extent is limited to one district of a town or an industrial area. Today these are mainly used for broadband Internet services. The earth stations are equipped with 3–10 m diameter antennas.
— *VSAT systems:* Low-capacity data transmission (uni- or bidirectional), television, or digital sound programme broadcasting [MAR-95]. Most often, the user is directly connected to the station. VSATs are equipped with antennas 0.6–1.2 m in diameter. The introduction of Ka band will allow even smaller antennas (ultra-small aperture terminal [USATs]) to provide even larger capacity for data transmission, allowing multimedia interactivity, data-intensive business applications, residential and commercial Internet connections, two-way videoconferencing, distance learning, and telemedicine.
— *Digital audio, video, and data broadcasting:* The emergence of standards for compression, such as the MPEG (Motion Picture Expert Group) standard for video, has triggered the implementation of digital services to small earth stations installed at the user's premises with antennas on the order of a few tens of centimetres. For *television*, such services using the DVB-S/S2/S2X standards have all become digital and can support HD TV, 4K, and even 8K TV. For *sound*, several systems incorporating on-board processing have been launched in such a way as to allow FDMA access by several broadcasters on the uplink and time-division multiplexing (TDM) on a single downlink carrier of the sound programmes. This approach avoids the delivery of programmes to a single feeder earth station, and allows operation of the satellite payload at full power; thus combining flexibility and efficient use of the satellite. The ability of the user terminal to process digital data paves the way for satellite distribution of files on demand through the *Internet*, with a terrestrial request channel or even a satellite-based channel such as DVB-RCS or DVB-RCS2. This anticipates broadband multimedia satellite services [TS-15].
— *Mobile and personal communications:* Despite the proliferation of cellular and terrestrial personal communication services around the world, there are still vast geographic areas not covered by any wireless terrestrial communications. These areas are open fields for mobile and personal satellite communications, and they are key markets for the operators of geostationary satellites, such as INMARSAT, and of non-geostationary satellite constellations, such as IRIDIUM and GLOBALSTAR. The next step in bridging the gaps between fixed, mobile, and broadcasting services concerns satellite multimedia broadcast to fixed and mobile users. Smart overlay broadcast networks based on hybrid satellite–terrestrial mobile systems will efficiently provide end users with a full range of entertainment services with interactivity [WER-07]. Studies of internetworking between satellite and terrestrial networks have been carried out by the ETSI [ETSI-13] and the 3rd Generation Partnership Project (3GPP) [3GPP-17].
— *Multimedia services:* These services aggregate different media, such as text, data, audio, graphics, fixed or slow-scan pictures, and video in a common digital format to offer potential for online services, teleworking, distance learning, interactive television, telemedicine, etc. Interactivity is therefore an embedded feature. This requires increased bandwidth compared to

conventional services, such as telephony, and has triggered the concept of an *information superhighway*. Satellites complement terrestrial, high-capacity fibre, and cable-based networks with the following characteristics: use of Ka band, multibeam antennas, wideband transponders (typically 125 MHz), on-board processing and switching, a large range of service rates (from tens of kbps to hundreds of Mbps), and quasi-error-free transmission (typically 10^{-11} BER).

1.8 THE WAY FORWARD

In the last 50 years, since the first commercial satellite, Early Bird, started its operation in 1965, the satellite telecommunications landscape has changed significantly. Advances in satellite technology have enabled satellite telecommunications providers to expand service offerings. The mix of satellite telecommunications is continuously evolving. Point-to-point trunking for analogue voice and television was the sole service initially provided by satellites; today, telecommunications satellites also provide digital audio and video broadcasting, mobile communications, on-demand narrowband data services, and broadband multimedia and Internet services. The mix of service offerings will continue to change significantly in the future.

Satellite services can be characterised as either satellite relay applications or end-user applications (fixed or mobile). For *satellite relay applications*, a content provider or carrier leases capacity from a satellite operator, or uses its own satellite system to transmit content to and from terrestrial ground stations where the content is routed to the end user. Relay applications accounted for around $10 billion in 2000. *End-user satellite applications* provide information directly to individual customers via consumer devices such as small antennas (less than earth station) and hand-held satellite user terminals. End-user applications accounted for about $25 billion in 2000.

It was reported by the Satellite Industry Association (SIA) on 11 June 2008 that the worldwide market in 2007 was $123 billion; average annual growth was 11.5% from 2002–2007 and jumped to 16% in 2007; satellite services grew 18% in 2007 to $37.9 billion, of which TV accounted for three quarters; launch was $3.2 billion, up 19%; ground equipment was $34.3 billion, up 19%; and satellite manufacture was $11.6 billion, dipping slightly (reflecting a larger number of microsatellites). In June 2017, SIA reported satellite industry indicators [SIA-17] that 2016 global revenue was $260.5B, of which satellite service was $127.7B; ground equipment 113.4B, satellite manufacture $13.9B and launch $5.5B.

The DVB-S2 standard was published in March 2005 and it was quickly adopted by industry. It is reported by the DVB forum that major broadcasters in Europe have started to use DVB-S2 in conjunction with MPEG-4 for high definition television (HDTV) services; examples include BSkyB in UK and Ireland, Premiere in Germany, and Sky in Italy. It has also been deployed in America, Asia, and Africa. DVB-S2X was completed as an extension to the DVB-S2 by ETSI in 2014.

There were also many initiatives for satellites in 2008 to deliver a range of multimedia services targeting fixed terminals at Ka band (Telesat Anik F2 multispot Ka band, Eutelsat Ka-Sat) [FEN-08]; broadband mobile terminals on board planes, trains, and ships at Ku or Ka band (satellite-on-the-move communications) [GIA-08]; and fixed and mobile users with hybrid terrestrial/satellite systems at S band [SUE-08, CHU-08]. Other initiatives include the provision of air traffic management services [WER-07]. According to the 2017 SIA report on satellite service revenue, satellite TV accounted for $97.8B; satellite radio $4.6B; satellite broadband $1.9B; fixed transponder agreement and managed services $12.4B and $5.5B, respectively; mobile $3.4B; and earth observation $1.8B.

Numerous new technologies are under development in response to the tremendous demand for emerging global telecommunications applications. Improved technology leads to the production of individual satellites that are more powerful and capable than earlier models. With larger satellites (up to 10 000 kg) able to carry additional transponders and more powerful solar arrays and batteries, these designs will provide a higher power supply (up to 20 kW) to support a greater number of transponders (up to 150). New platform designs allowing additional capacity for station-keeping propellant and the adoption of new types of thrusters are contributing to increased service life of up to 20 years for geostationary satellites. This translates into increased capacity from satellites with more transponders, longer lives, and the ability to transmit more data through increasing rates of data compression.

In recent years, satellite services have grown by 5% per year, including revenue from Ku and Ka band satellite FSS capacity provided by MSS operators to provide services to maritime, airborne, and other mobile applications. FSSs has decreased by 3% per year due to decreased transponder agreement revenue, although revenue for managed services has grown 12% driven primarily by HTS capacity on the supply side and in-flight services on the demand side.

As an example, ViaSat-1 launched on 19 October 2011, it had the world's highest-capacity communications satellite with a total capacity of more than 140 Gbps – more than all the satellites covering North America combined, at the time of its launch. ViaSat-2 launched on 2 June 2017 with a capacity of 300 Gbps. The main technologies included multiple spot beams, spectrum reuse, high-gain spot beams, and a high-gain antenna. The main services included broadband access, data relay, mobile communications, and broadcasting, including 4K TV.

In addition to HTS, MEO, and LEO, satellite orbits have also had rapid development: typical examples are O3B, OneWeb, and Starlink, in addition to the Iridium Next. Table 1.4 shows some examples of next-generation LEO Mega constellations, and Table 1.5 shows some frequency and optical wavelength allocations for ISL.

Table 1.4 Examples of next-generation LEO mega constellation

	Iridium Next	LeoSat	OneWeb	Starlink	Hongyun project
Number of satellites	66	108	648 (+1972)	4425 +7518	156
Orbit altitude	781 km	1400 km	1200 km	1200 and 340 km	1000 km
Signal transmission frequency	L band Ka band	Ka band	Ku band (V band)	Ku band Ka band V band	Ka band
Capacity per satellite	N/A	11.6 Gbps	N/A	N/A	4 Gbps
Data speed	128 kbps 1.5 Mbps 8 Mbps	50 Mbps–1.6 Gbps 5.2 Gbps	50 Mbps	Gigabit per second	40 Mbps
Transmission latency	N/A	<20 ms	N/A	~25 ms	N/A
Year of operation	2015	2022	2019	2019	2024
Supporting enterprises	Iridium Inc.	LeoSat	Qualcomm, Virgin Group, Airbus, etc.	SpaceX	China Aerospace Science and Industry Corporation (CASIC)

Table 1.5 Frequency or optical wavelength allocations for intersatellite links (ISLs)

RF or laser	Frequency band or wavelength range	Available bandwidths or technologies
Microwave	22.55–23.55 GHz	1 000 MHz
	24.45–24.75 GHz (zones 1 and 3)	300 MHz
	25.25–27.50 GHz	2 250 MHz
mm wave	32–33 GHz	1 000 MHz
	54.25–58.20 GHz	3 950 MHz
	59–64 GHz	5 000 MHz
	65–71 GHz	6 000 MHz
	116–134 GHz	18 000 MHz
	116–134 GHz	18 000 MHz
	170–182 GHz	12 000 MHz
THz	0.3–30 THz	To be specified
Laser	10.6 μm	CO_2 lasers
	1.06 μm	Nd:YAG lasers
	0.532 μm	Nd:YAG lasers
	0.8–0.9 μm	Al GaAs lasers

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2 ORBITS AND RELATED ISSUES

This chapter examines various aspects of the satellite's motion around the earth; these include Keplerian orbits, orbit parameters, perturbations, eclipses, and the geometric relationships between satellites and earth stations. Such aspects will be used in Chapter 5 in relation to radio-frequency link performance and Chapters 7–12 dealing with the operation of earth stations and the launching and operation of the satellite.

2.1 KEPLERIAN ORBITS

These orbits are named after Johannes Kepler (a German mathematician, astronomer, and astrology, 27 December 1571–15 November 1630), who established, at the start of the seventeenth century, that the trajectories of planets around the sun were ellipses and not combinations of circular movements as had been thought since the time of Pythagoras (a Greek philosophy, around 570–4950 BC. Keplerian movement is the relative movement of two point bodies under the sole influence of their Newtonian attractions.

2.1.1 Kepler's laws

These laws arise from observation by Kepler of the movement of the planets around the sun:

(a) The planets move in a plane; the orbits described are ellipses with the sun at one focus (1602).
(b) The vector from the sun to the planet sweeps equal areas in equal times (the law of areas, 1605).
(c) The ratio of the square of the period T of revolution of a planet around the sun to the cube of the semi-major axis a of the ellipse is the same for all planets (1618).

2.1.2 Newton's law

Sir Isaac Newton (an English mathematician, astronomer, theologian, author, and physicist, 25 December 1642–20 March 1726) extended the work of Kepler and, in 1667, discovered the

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Gérard Maral, Michel Bousquet, and Zhili Sun.

universal law of gravitation. This law states that two bodies of mass m and M attract each other with a force that is proportional to their masses and inversely proportional to the square of the distance r between them:

$$F = GM\,m/r^2 \tag{2.1}$$

where G is a constant, called the *universal gravitation constant*, and $G = 6.672 \times 10^{-11}$ m^3 kg^{-1} s^{-2}.

As the mass of the earth $M = 5.974 \times 10^{24}$ kg, the product GM has a value $\mu = GM = 3.986 \times 10^{14}$ m^3 s^{-2}.

From the universal law of gravitation and using the work of Galileo Galilei (an Italian polymath, 15 December 1564–8 January 1642), a contemporary of Kepler, Newton proved Kepler's laws mathematically and identified the assumptions (the problem of two spherical and homogeneous bodies). He also modified these laws by introducing the concept of orbit perturbations to take actual movements into account.

2.1.3 Relative movement of two point bodies

The movement of satellites around the earth observes Kepler's laws to a first approximation. The proof results from Newton's law and the following assumptions:

— The mass m of the satellite is small with respect to the mass M of the earth, which is assumed to be spherical and homogeneous.
— Movement occurs in free space; the only bodies present are the satellite and the earth.

The actual movement must take into account the fact that the earth is neither spherical nor homogeneous, the attraction of the sun and moon, and other perturbing forces.

2.1.3.1 Keplerian potential

Kepler's laws can be explained by treating the relative movement of two bodies by applying Newton's law. It is convenient to consider the body of greater mass to be fixed, with the other moving around it (as the force of attraction is the same for the two bodies, the resulting acceleration is much greater for the body of low mass than for the higher mass).

Consider an orthogonal coordinate system as illustrated in Figure 2.1 whose origin is at the centre of the earth and whose z axis coincides with the line of the poles (assumed fixed in space). The satellite SL of mass m ($m \ll M$)is at a distance r from the centre of the earth O (**r** is the vector O–SL).

The force of gravitation **F** acting on the satellite can be written:

$$\mathbf{F} = -GMm\,\mathbf{r}/r^3 (\mathrm{N}) \tag{2.2}$$

(**F** is a vector centred on SL along SL–O)

This force always applies to the centre of gravity of the two bodies and, in particular, to the centre of the earth O. It is a central force. It derives from a potential gradient U such that $U = GM/r = \mu/r$. The attraction force per unit mass is given by:

$$F/m = \mathrm{d}/\mathrm{d}r[\mu/\mathrm{r}] = \mathrm{grad}\ U \quad (\mathrm{ms}^{-2}) \tag{2.3}$$