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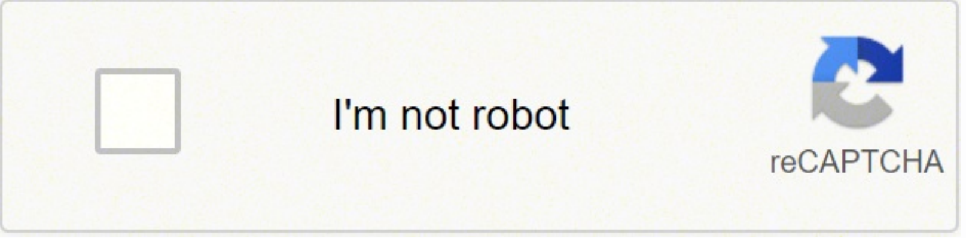

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First communications using artificial satellites of the earth were implemented at the beginning of the sixties, using low earth orbit (LEO) satellites like Echo (1960), Telstar (1962), and Relay (1962).KeywordsSatellite SystemFederal Communication CommissionSatellite CommunicationEuropean Economic CommunityGeostationary Earth Orbit Satellite Communication Systems Engineering is a comprehensive book for undergraduate students of communication and systems engineering. The book comprises of chapters on the basic concepts of satellite communications, orbits, earth-satellite geometry, launch vehicles and propulsion, spacecraft, the RF Link, modulation and multiplexing, satellite transponders and special problems in satellite communications. About Pearson Pearson Education has been publishing books on all genres like science, technology, law, business, humanities and others, and has been educating more than a hundred million people across the world. 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Second Edition Satellite Communication Engineering K21636_Book.indb 3 10/22/13 4:09 PM Second Edition Satellite Communication Engineering Michael Olorunfunmi Kolawole Boca Raton London New York CRC Press is an imprint of the Taylor & Francis Group, an informa business K21636_Book.indb 3 10/22/13 4:09 PM CRC Press Taylor & Francis Group 6000 Broken Sound Parkway NW, Suite 300 Boca Raton, FL 33487-2742 Version Date: 20130715 International Standard Book Number-13: 978-1-4822-1011-8 (eBook - PDF) Contents Preface........xi Acknowledgments........xv The Author........ xvii 1 Basic Principles of Satellite Communications........1 1.1 The Origin of Satellites........2 1.2 Communications via Satellite........3 1.3 Characteristic Features of Communication Satellites........4 1.4 Message Security........6 1.4.1 Basic Cryptographic Functions........6 1.4.2 Ciphering in Satellite Communication Systems........7 1.4.3 Ciphering Techniques........9 1.4.3.1 Block Ciphering........9 1.4.3.2 Feedback 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Notations........ 259 Appendix B: Glossary of Terms........ 263 Index........ 269 K21636_Book.indb 9 10/22/13 4:09 PM Preface This second edition of Satellite Communication Engineering is an undeniably rich guide to satellite communication principles and engineering with inclusion of recent developments enabling digital information transmission and delivery via satellite. Satellite communication is one of the most impressive spin-offs from the space programs, and has made a major contribution to the pattern of international communications. The engineering aspect of satellite communications combines such diverse topics as antennas, radiowave propagation, signal processing, data communication, modulation, detection, coding, filtering, orbital mechanics, and electronics. Each of these is a major field of study, and each has its own extensive literature. Satellite Communication Engineering emphasizes the relevant material from these areas that is important to the book's subject matter and derives equations that the reader can follow and understand. The aim of this book is to present in a simple and concise manner the fundamental principles common to the majority of information communications systems. Mastering the basic principles permits moving on to concrete realizations without great difficulty. Throughout, concepts are developed mostly on an intuitive, physical basis, with further insight provided by means of a combination of applications and performance curves. Problem sets are provided for those seeking additional training. Starred sections containing basic mathematical development may be skipped with no loss of continuity by those seeking only a qualitative understanding. The book is addressed to electrical, electronics, and communication engineering students, as well as practicing engineers wishing to familiarize themselves with the broad field of information transmission, particularly satellite communications. The first of the book's eight chapters covers the basic principles of satellite communications, including message security (cryptology). Chapter 2 discusses the technical fundamentals for satellite communications services, which do not change rapidly as technology, and provides the reader with the tools necessary for calculation of basic orbit characteristics such as period, dwell time, and coverage area; antenna system specifications such as type, size, beamwidth, and aperture-frequency product; and power system design. The system building blocks comprising satellite transponder and system design procedures are also described. While acknowledging that systems engineering is a discipline on its own, it is my belief that the reader will gain a broad understanding of the system engineering design procedure, accumulated from my experience in large, complex turnkey projects. Earth station, which forms the vital part of the overall satellite system, is the central theme of Chapter 3. The basic intent of data transmission is to provide quality transfer of information from the source to the receiver with xi K21636_Book.indb 11 10/22/13 4:09 PM xii Preface minimum error due to noise in the transmission channel. To ensure quality information requires smart signal processing technique (modulation) and efficient use of system bandwidth (coding, which is discussed extensively in Chapter 6). The most popular forms of modulation employed in digital communications, such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), offset-quadrature phase shift keying (OQPSK), and 8-ary phase shift keying (8-PSK), are discussed together with their performance criteria (bit error rate [BER]). An overview of information theory is given to enhance the reader's understanding of how maximum data can be transmitted reliably over the communication medium. Chapter 3 concludes by describing (1) a method for calculating system noise temperature, (2) elements of earth station design, and (3) antenna tracking and the items that facilitate primary terrestrial links to and from the earth stations. Chapter 4 discusses the process of designing and calculating the carrierto-noise ratio as a measure of the system performance standard. The quality of signals received by the satellite transponder and that retransmitted and received by the receiving earth station is important if successful information transfer via the satellite is to be achieved. Within constraints of transmitter power and information channel bandwidth, a communication system must be designed to meet certain minimum performance standards. The most important performance standard is the energy bit per noise density in the information channel, which carries the signals in a format in which they are delivered to the end users. To broadcast video, data, or audio signals over a wide area to many users, a single transmission to the satellite is repeated and received by multiple receivers. While this might be a common application of satellites, there are others that may attempt to exploit the unique capacity of a satellite medium to create an instant network and connectivity between any points within its view. To exploit this geometric advantage, it is necessary to create a system of multiple accesses in which many transmitters can use the same satellite transponder simultaneously. Chapter 5 discusses the sharing techniques called multiple access. Sharing can be in many formats, such as sharing the transponder bandwidth in separate frequency slots (frequency division multiple access [FDMA]), sharing the transponder availability in time slots (time division multiple access [TDMA]), or allowing coded signals to overlap in time and frequency (code division multiple access [CDMA]). The relative performance of these sharing techniques is discussed. Chapter 6 explores the use of error-correcting codes in a noisy communication environment, and how transmission error can be detected and correction effected using the forward error correction (FEC) methods, namely, the linear block and convolutional coding techniques. Examples are sparingly used as illustrative tools to explain the FEC techniques. The regulation that covers satellite networks occurs on three levels: international, regional, and national. Chapter 7 discusses the interaction among these three regulatory levels. K21636_Book.indb 12 10/22/13 4:09 PM Preface xiii Customer's demands for personalized services and mobility, as well as provision of standardized system solutions, have caused the proliferation of telecommunications systems. Chapter 8 examines basic mobile satellite systems services and their interaction with land-based backbone networks—in particular the integrated services digital network (ISDN). Since the services covered by ISDN should also, in principle, be provided by a digital satellite network, it is necessary to discuss in some detail the basic architecture of ISDN as well as its principal functional groups in terms of reference configurations, applications, and protocols. Chapter 8 concludes by briefly looking at the cellular mobile system, including cell assignment and internetworking principles, as well as technological obstacles to providing efficient Internet access over satellite links. Michael Olorunfunmi Kolawole K21636_Book.indb 13 10/22/13 4:09 PM Acknowledgments The inspiration for writing Satellite Communication Engineering comes partly from my students who have wanted me to share the wealth of my experience acquired over the years and to ease students' burden in understanding the fundamental principles of satellite communications. Very special thanks go to my darling wife, Dr. Marjorie Helen Kolawole, who actively reminds me about my promise to my students, and more importantly to transfer knowledge to a wider audience. I am eternally grateful for their vision and support. I also thank Professor Patrick Leung of Victoria University, Melbourne, Australia, for his review of the first edition and for his constructive criticisms, and acknowledge the anonymous reviewers for their helpful comments. Finally, I thank my family for sparing me the time, which I would have otherwise spent with them, and their unconditional love that keeps me going. xv K21636_Book.indb 15 10/22/13 4:09 PM The Author Dr. Michael O. Kolawole is a distinguished educator and practitioner. He is the director of Jolade Consulting Company, Melbourne, and has held adjunct and visiting professorial appointments in Australia and Nigeria, including the Federal University of Technology, Akure. He has published more than 50 papers in technical journals and 25 industry-based technical reports covering design, performance evaluation, and developmental algorithms. He has overseen a number of operational innovations and holds two patents. He is the author of Satellite Communication Engineering (New York: Marcel Dekker, 2002), Radar Systems, Peak Detection and Tracking (Oxford: Elsevier, 2003), and A Course in Telecommunication Engineering (New Delhi: S Chand, 2009), and co-author of Basic Electrical Engineering (Akure: Aoge Publishers, 2012). Dr. Kolawole received a B.Eng. (1986) degree from Victoria University, Melbourne, and Ph.D. (2000) degree from the University of New South Wales, Sydney, both in electrical engineering. He also received an M.S. (1989) degree from the University of Adelaide in environmental studies. Dr. Kolawole is a chartered professional engineer in Australia, and a member of the New York Academy of Sciences. He plays clarinet and saxophone, and composes and arranges music. xvii K21636_Book.indb 17 10/22/13 4:09 PM 1 Basic Principles of Satellite Communications Satellite communication is one of the most impressive spin-offs from the space programs, and has made a major contribution to the pattern of international communications. A communication satellite is basically an electronic communication package placed in orbit whose prime objective is to initiate or assist communication transmission of information or messages from one point to another through space. The information transferred most often corresponds to voice (telephone), video (television), and digital data. Communication involves the transfer of information between a source and a user. An obvious example of information transfer is through terrestrial media, through the use of wire lines, coaxial cables, optical fibers, or a combination of these media. Communication satellites may involve other important communication subsystems as well. In this instance, the satellites need to be monitored for position location in order to instantaneously return an upwardly transmitting (uplink) ranging waveform for tracking from an earth terminal (or station). The term earth terminal refers collectively to the terrestrial equipment complex concerned with transmitting signals to and receiving signals from the satellite. The earth terminal configurations vary widely with various types of systems and terminal sizes. An earth terminal can be fixed and mobile land based, sea based, or airborne. Fixed terminals, used in military and commercial systems, are large and may incorporate network control center functions. Transportable terminals are movable but are intended to operate from a fixed location, that is, a spot that does not move. Mobile terminals operate while in motion; examples are those on commercial and navy ships as well as those on aircraft. Chapter 3 addresses a basic earth terminal configuration. Vast literature has been published on the subject of satellite communications. However, the available literature appears to deal specifically with specialized topics related to communications techniques, design or part thereof, or satellite systems as a whole. This chapter looks briefly at the development and principles of satellite communication and its characteristic features. 1 K21636_Book.indb 1 10/22/13 4:09 PM 2 Satellite Communication Engineering, Second Edition 1.1 The Origin of Satellites The space age began in 1957 with the USSR's launch of the first artificial satellite, called Sputnik, which transmitted telemetry information for 21 days. This achievement was followed in 1958 by the American artificial satellite, Score, which was used to broadcast President Eisenhower's Christmas message. Two satellites were deployed in 1960: a reflector satellite, called Echo, and Courier. The Courier was particularly significant because it recorded a message that could be played back later. In 1962 active communication satellites (repeaters), called Telstar and Relay, were deployed, and the first geostationary satellite, called Syncom, was launched in 1963. The race for space exploitation for commercial and civil purposes truly started. A satellite is geostationary if it remains relatively fixed (stationary) in an apparent position relative to the earth. This position is typically about 35,784 km away from the earth. Its elevation angle is orthogonal (i.e., 90°) to the equator, and its period of revolution is synchronized with that of the earth in inertial space. A geostationary satellite has also been called a geosynchronous or synchronous orbit, or simply geosatellite. The first series of commercial geostationary satellites (Intelsat and Molnya) was inaugurated in 1965. These satellites provided video (television) and voice (telephone) communications for their audiences. Intelsat was the first commercial global satellite system owned and operated by a consortium of more than 100 nations, hence its name, which stands for International Telecommunications Satellite Organization. The first organization to provide global satellite coverage and connectivity, it continues to be the major communications provider with the broadest reach and the most comprehensive range of services. Other providers for industrial and domestic markets include Westar in 1974, Satcom in 1975, Comstar in 1976, SBS in 1980, Galaxy and Telstar in 1983, Spacenet and Anik in 1984, Gstar in 1985, Aussat in 1985–1986, Optus A2 in 1985, Hughes-Ku in 1987, NASA ACTS in 1993, Optus A3 in 1997, Iridium and Intelsat VIIIA in 1998, and Optus C in 2003. With technology for communication satellites improving with time, competition among nations has increased to provide and meet domestic communication as well as security needs, for example, Sina-1 in 2005, NigeriaSat-2 and NigeriaSat-X in 2011, Zhongxing-1A in 2011, GSAT-10 in 2012, Zenit-3SL in 2006, and SATCOM-4 in 2012. Even more are planned. Some of these satellites host dedicated military communication channels. The need to have market domination and a competitive edge in military surveillance and tactical fields results in more sophisticated developments in the satellite field. K21636_Book.indb 2 10/22/13 4:09 PM 3 Basic Principles of Satellite Communications 1.2 Communications via Satellite Radiowaves, suitable as carriers of information with a large bandwidth, are found in frequency ranges where the electromagnetic waves are propagated through space almost in conformity with the law of optics, so that only line-of-sight radiocommunication is possible [1]. As a result, topographical conditions and the curvature of the earth limit the length of the radio path. Relay stations, or repeaters, must be inserted to allow the bridging of greater distances (see Figure 1.1). Skywave radar uses the ionosphere, at a height of 70 to 300 km, to transmit information beyond the horizon and may not require repeaters. However, transmission suffers from ionospheric distortions and fading [16]. To ensure that appropriate frequencies are optimally selected, additional monitoring equipment is required to sample the ionospheric conditions instantaneously. A communication satellite in orbit around the earth exceeds the latter requirement. Depending on the orbit's diameter, satellites can span large distances almost half the earth's circumference. However, a communication link between two subsystems—for instance, earth stations or terminals—via Satellite Satellite orbit Ionosphere Continental shelf Skywave radar Ocean or sea surface Microwave radar Figure 1.1 Intercontinental communication paths. K21636_Book.indb 3 10/22/13 4:09 PM 4 Satellite Communication Engineering, Second Edition Satellite Home register Terrestrial link (e.g., data, phone, video) Earth Station A Terrestrial link Home register (e.g., data, phone, video) Earth Station B Figure 1.2 Communication between two earth stations via a satellite. the satellite may be considered a special case of radio relay, as shown in Figure 1.2, with a number of favorable characteristics: A desired link between two terminals in the illumination zone can be established. The investment for a link in the illumination zone is independent of the distance between the terminals. A provision for wide-area coverage for remote or inaccessible territories or for new services is made. This is ideally suited to medium, point-to-multiunit (broadcast) operations. A practical satellite comprises several individual chains of equipment called a transponder—a term derived from transmitter and responder. Trans ponders can channel the satellite capacity both in frequency and in power. A transponder may be accessed by one or by several carriers. Transponders exhibit strong nonlinear characteristics and multicarrier operations, unless properly balanced, which may result in unacceptable interference. The structure and operation of a transponder are addressed in Chapter 2, and the techniques used to access the transponder are examined in Chapter 5. 1.3 Characteristic Features of Communication Satellites Satellite communication circuits have several characteristic features. These include: 1. Circuits that traverse essentially the same radiofrequency (RF) pathlength regardless of the terrestrial distance between the terminals. K21636_Book.indb 4 10/22/13 4:09 PM 5 Basic Principles of Satellite Communications 2. Circuits positioned in geosynchronous orbits may suffer a transmission delay, td, of about 119 ms between an earth terminal and the satellite, resulting in a user-to-user delay of 238 ms and an echo delay of 476 ms. For completeness, transmission delay is calculated using td = h0 c (1.1) where h0 is the altitude above the subsatellite point on the earth terminal and c is the speed of light (c = 3 × 108 m/s). For example, consider a geostationary satellite whose altitude h0 above the subsatellite point on the equator is 35,784 km. This gives a one-way transmission delay of 119 ms, or a round-trip transmission delay of 238 ms. It should be noted that an earth terminal not located at the subsatellite point would have greater transmission delays. 3. Satellite circuits in a common coverage area pass through a single RF repeater for each satellite link (more is said of the coverage area, repeater, and satellite links in Chapters 2 and 4). This ensures that earth terminals, which are positioned at any suitable location within the coverage area, are illuminated by the satellite antenna(s). The terminal equipment could be fixed or mobile on land or mobile on ship and aircraft. 4. Although the uplink power level is generally high, the signal strength or power level of the received downlink signal is considerably low because of: High signal attenuation due to free-space loss Limited available downlink power Finite satellite downlink antenna gain, which is dictated by the required coverage area For these reasons, the earth terminal receivers must be designed to work at significantly low RF signal levels. This leads to the use of the largest antennas possible for a given type of earth terminal (discussed in Chapter 3) and the provision of low-noise amplifiers (LNAs) located in close proximity to the antenna feed. 5. Messages transmitted via the circuits are to be secured, rendering them inaccessible to unauthorized users of the system. Message security is a commerce closely monitored by the security system designers and users alike. For example, Pretty Good Privacy (PGP), invented by Philip Zimmerman, is an effective encryption tool [2]. The U.S. government sued Zimmerman for releasing PGP to the public, alleging that making PGP available to enemies of the United States could endanger national security. Although the lawsuit was later dropped, the use of PGP in many other countries is still illegal. K21636_Book.indb 5 10/22/13 4:09 PM 6 Satellite Communication Engineering, Second Edition 1.4 Message Security Customers' (private and government) increasing demand to protect satellite message transmission against passive eavesdropping or active tampering has prompted system designers to make encryption an essential part of satellite communications system design. Message security can be provided through cryptographic techniques. Cryptology is the theory of cryptography (i.e., the art of writing in or deciphering secret code) and cryptanalysis (i.e., the art of interpreting or uncovering the deciphered codes without the sender's consent or authorization). Cryptology is an area of special difficulty for readers and students because many good techniques and analyses are available but remain the property of the organizations whose main business is secrecy. As such, we discuss the fundamental technique of cryptography in this section without making any specific recommendation. 1.4.1 Basic Cryptographic Functions Basic cryptography comprises encryption, decryption, and key management unit, as shown in Figure 1.3. Encryption (enciphering) is the process of converting messages, information, or data into a form unreadable by anyone except the intended recipient. The encrypted (enciphered) text is called a cryptogram. Encrypted data must be deciphered (unlocked, or decrypted) before the recipient can read it. Decryption is the unlocking of the locked message—that is, the reverse of encryption. Key simply means "password." Key management refers to the generation, distribution, recognition, and reception of the cryptographic keys. Cryptographic key management is the most important element of any cryptographic system (simply called cryptosystem) design. Encryption uses a special system called an algorithm to convert the text of the original message (plaintext) into an encrypted form of the message (ciphertext or cryptogram). Algorithms are step-by-step procedures for solving problems in the case of encryption, for enciphering and deciphering a Transmitted message, MT Encryption, Ey Cryptogram, Cy Decryption, Dy Received message, MR KD KE Key management, K Figure 1.3 General cryptographic functions. K21636_Book.indb 6 10/22/13 4:09 PM Basic Principles of Satellite Communications 7 plaintext message. Cryptographic algorithms (like key and transformation functions) equate individual characters in the plaintext with one or more different keys, numbers, or strings of characters. In Figure 1.3, the encryption algorithm Ey transforms the transmitted message MT into a cryptogram Cy by the cryptographic key KE algorithm. The received message MR is obtained through the decryption algorithm Dy with the corresponding decryption key KD algorithm. These cryptographic functions are concisely written as follows. Encryption: Cy = Ey (MT , KE) (1.2) Decryption: MR = Dy (Cy , K D) = Dy (Ey (MT , KE), K D) (1.3) 1.4.2 Ciphering in Satellite Communication Systems New-generation equipment aboard satellites and earth stations is extraordinarily sophisticated. It acts as a series of massive electronic vacuum cleaners, sweeping up every kind of communication with embedded security devices. Message security in a satellite network can be achieved by placing the ciphering equipment either at the earth station or in the satellite. Figure 1.4 shows the block diagrams of messages MTi transmitted between earth stations via the satellite. Each earth station has a number of cryptographic keys Kti (where i = 1, 2, ..., n) shared between the communicating earth stations while the satellite remains transparent, meaning the satellite has no role in the ciphering process. A cryptosystem that may work for the scenario depicted by Figure 1.4 is described as follows. All the earth stations TS(i) and RS(j) are assumed capable of generating random numbers RDN(i) and RDN(j), respectively. Each transmitting earth station TS(i) generates and stores the random numbers RDN(i). It then encrypts RDN(i), that is, Ey[RDN(i)], and transmits the encrypted random number Ey[RDN(i)] to RS(j). The receiving earth station RS(j) generates RDN(j) and performs a modulo-2 (simply, mod-2) addition with RDN(i), that is, RDN (j) ⊕ RDN (i), to obtain the session key Kr(j), where ⊕ denotes mod-2 addition. It should be noted that mod-2 addition is implemented with exclusive-OR gates and obeys the ordinary rules of addition, except that 1⊕1 = 0. The transmitting earth station retrieves RDN(i) and performs mod-2 addition with RDN(j), that is, RDN (i) ⊕ RDN (j), to obtain the session key Kt(i). This process is reversed if RS(j) transmits messages and TS(i) receives. K21636_Book.indb 7 10/22/13 4:09 PM 8 Satellite Communication Engineering, Second Edition Encryption MT1 Decryption TS1 TS1 Kt1 MT2 Transparency Ktj E1[RDN(1)] TSl TS2 Kt2 . E2[RDN(2)] . . MRj MRl Krl Satellite channel . . . En[RDN(n)] MTn TSn Ktn TS = transmitting station RS = receiving station K = cryptographic key M = message TSz MRlz Krz Figure 1.4 Earth station-to-earth station ciphering. Figure 1.5 demonstrates the case where the satellite plays an active ciphering role. In it the keys K Ei (where i = 1, 2, ..., n) the satellite receives from the transmitting uplink stations TSi are recognized by the onboard processor, which in turn arranges, ciphers, and distributes to the downlink earth stations, RS(j) (more is said about onboard processing in Chapter 2). Each receiving earth station has matching cryptographic keys K Dj (where j = l, m, ..., z) to be able to decipher the received messages M Rj. The cryptosystem that may work for the scenario depicted by Figure 1.5 is described as follows. It is assumed that the satellite onboard processor is capable of working the cryptographic procedures of the satellite network. It is also assumed that all the earth stations TS(i) and RS(j) play passive roles and only respond to the requests of the satellite onboard processor. The key session of the onboard processor is encrypted under the station master key. The onboard processor's cryptographic procedure provides the key session for recognizing the key session of each earth station. Thus, when an earth station receives encrypted messages from the satellite, the earth station's master key is retrieved from storage. Using the relevant working key to recognize the session key activates the decryption procedure. The earth station is ready to retrieve the original (plaintext) message using the recognized session key. K21636_Book.indb 8 10/22/13 4:09 PM 9 Basic Principles of Satellite Communications Encryption MT1 Ciphering Decryption RS1 TS1 KDl KE1 MT2 . . . MTn RSm TS2 KE2 TSn KEn MRl Satellite on-board processor with key functions TS = transmitting station RS = receiving station K = cryptographic key M = message MRm KDm . . . MRz RSz KDz Figure 1.5 Ciphering with keyed satellite onboard processor. The European Telecommunication Satellite (EUTELSAT) has implemented encryption algorithms, for example, the Data Encryption Standard (DES), as a way of providing security for their satellite link (more is said about DES in Section 1.4.3). Having discussed the session key functions K, the next item to discuss is the basic functionality of ciphering techniques and transformation functions. 1.4.3 Ciphering Techniques Two basic ciphering techniques fundamental to secret system design are discussed in this section: block ciphering and feedback ciphering. 1.4.3.1 Block Ciphering Block ciphering is a process by which messages are encrypted and decrypted in blocks of information digits. Block ciphering has the same fundamental structure as block coding for error correction (block coding is further discussed in Chapter 6). Comparatively, a ciphering system consists of an encipher and a decipher, while a coding system consists of an encoder and a decoder. The major difference between the two systems (ciphering and block coding) is that block ciphering is achieved by ciphering keys while coding K21636_Book.indb 9 10/22/13 4:09 PM 10 Satellite Communication Engineering, Second Edition Input data X Initial Permutation Permuted Input L(0) K(1) R(0) f L(1) = R(0) . . . R(1) = L(0)+f[R(0),K(1)] K(n–1) f . . . L(n) = R(n–1) Pre-output R(n) = L(n–1)+f[R(n–1),k(n–1)] Inverse Initial Permutation Output data Y Figure 1.6 Block ciphering technique with partition and iteration. relies on parity checking. A generalized description of the block ciphering technique is shown in Figure 1.6. In block ciphering, system security is achieved by: 1. Partitioning the message into subblocks, then encrypting (e.g., by simple bit permutation and bit inversion) and decrypting (i.e., the reverse of encryption) each subblock separately. 2. Repeating the encryption procedure several times. Often in practice, the ensuing pattern may be asymmetric, making it difficult for the cryptanalyst to break. 3. Combining parts 1 and 2. The security system designer might use a combination of these procedures to ensure a reasonably secured transmission channel. In 1977 the U.S. government adopted the preceding partition and iteration procedure as the DES for use in unclassified applications [3]. As of this writing, a new encryption system called the Advanced Encryption Standard (AES)—a block cipher standardization process—is being revalidated by the U.S. National Institute of Standards and Technology [4]. AES replaced the DES, as it uses a more complex algorithm based on a 256-bit key K K21636_Book.indb 10 10/22/13 4:09 PM Basic Principles of Satellite Communications 11 encryption standard instead of the DES 64-bit standards. The European Electronic Signature Standardization Initiative [5] also adopted the AES. GOST—another encryption system and the official encryption standard of the Russian Federation—uses a 256-bit key K block cipher and encryption standardization process [6]. GOST is an acronym for gosudarstvennyy standart, which means state standard. The DES system uses public-key encryption [3, 4]. In a DES system, each person gets two keys: a public key and a private key. The keys allow a person to either lock (encrypt) a message or unlock (decipher) an enciphered message. Each person's public key is published, and the private key is kept secret. Messages are encrypted using the intended recipient's public key and can only be decrypted using the private key, which is never shared. It is virtually impossible to determine the private key even if you know the public key. In addition to encryption, public-key cryptography can be used for authentication, that is, providing a digital signature that proves a sender or the identity of the recipient. There are other public-key cryptosystems, such as trapdoor [7], the Rivest-Shamir-Adleman (RSA) system [8], McEliece's system [9], elliptic curve cryptography [10, 11], discrete logarithm cryptosystems [12], quantum cryptography [13], and keys with auxiliary inputs [14]. The basic algorithm for block ciphering is shown in Figure 1.6 and described as follows. Suppose there are n + 1 iterations to be performed. Denote the input and output data by X = x1 , x2 , x3 , , xm and Y = y1 , y 2 , y 3 , , y m , respectively. Since the input data to be transformed iteratively is n + 1 times, the block of data is divided equally into left and right halves, denoted by L(j) and R(j), respectively, where j = 0, 1, 2, ..., n. The key of the jth iteration is denoted by K(j). The symbol f denotes a transformation function. There are many processes within Figure 1.6 that require further clarification. The next few subsections attempt to explain these processes, complemented with examples. If we take a segment of the arrangement in Figure 1.6 and reproduce it as Figure 1.7, where the main functions (i.e., encryption, keying, and decryption) are clearly identified, we can write the iteration j + 1 from the jth iteration for the encryption function as L(j + 1) = R(j) R(j + 1) = L(j) ⊕ f [K (j + 1), R(j)] (1.4) Also, we can write the decryption function as L(j) = R(j + 1) R(j) = L(j + 1) ⊕ f [K (j + 1), R(j + 1)] (1.5) where ⊕ denotes mod-2 addition. K21636_Book.indb 11 10/22/13 4:09 PM 12 Satellite Communication Engineering, Second Edition Encryption Keying L(j) L(j+1) R(j) K(j+1) f L(j+1) Decryption R(j+1) f L(j) R(j+1) R(j) f = transformation function L(j) = left half of message j R(j) = right half of message j K(j+1) = set of iteration dependent keys Figure 1.7 Part of block ciphering with partition and iteration. 1.4.3.1.1 Transformation Function The transformation function f [K (j + 1), R(j)] consists of bit expansion, key mod-2 addition, and selection (or substitution) and permutation operations. Figure 1.8 shows the processes involved in transforming a block of data R(j). The transformation function's operation is a bit mathematically involved. Instead of mathematical representation, each of the functions comprising Figure 1.8 is discussed separately with numerical examples. 1.4.3.1.2 Bit Expansion Function The function of the bit expansion function is to convert an n-bit block into an (n + p)-bit block in accordance with the ordering sequence Ef. The ordering sequence Ef assigns and expands the n-bit block into an extended (n + p)-bit block Ex; that is, Ex (j) = E f [R(j)] (1.6) The extended function Ex must match the number of bits of the key function K(j + 1). Example 1.1 As an illustration, define R(j) as a 32-bit block given by R(j) = 10011001110110110101010000111101 (1.7a) The bit expansion function can be solved by partitioning R(j) into eight segments (columns) with 4 bits in each segment. Ensure that each of the K21636_Book.indb 12 10/22/13 4:09 PM 13 Basic Principles of Satellite Communications R(j) Bit Expansion Function Ef Ex K(j+1) Sin Selection function Sf Sop Permutation function Pf z Figure 1.8 Sequence of transformation function. end bits of the segment is assigned to two positions, with the exception of the first and last bits, thus ensuring the ordering sequence of a 48-bit block: Ef = 32 4 8 12 16 20 24 28 1 5 9 13 17 21 25 29 2 6 10 14 18 22 26 30 3 7 11 15 19 23 27 31 4 8 12 16 20 24 28 32 5 9 13 17 21 25 29 1 (1.7b) Based on the ordering sequence of (1.7b), the bit expansion function of (1.6) becomes ⎛ ⎜ ⎜ ⎜ ⎜ Ex (j) = E f [R(j)] = ⎜ ⎜ ⎜ ⎜ ⎜ ⎝ 1 1 1 1 0 0 0 1 1 1 1 0 1 1 0 1 0 0 0 1 0 0 1 0 0 0 1 1 1 0 1 1 1 1 0 0 0 1 1 1 1 0 1 1 0 1 0 ⎞ ⎟ ⎟ ⎟ ⎟ ⎟ ⎟ ⎟ ⎟ ⎟ ⎠ (1.8) which equates to 48 bits, matching the number of bits of key function K(j + 1). K21636_Book.indb 13 10/22/13 4:09 PM 14 Satellite Communication Engineering, Second Edition 1.4.3.1.3 Selection Function For simplicity, consider an 8-bit selection function Sfj, where j = 1, 2, ..., 8. Each function has l rows and (m + 1) columns. The elements of selection function Sfj have a specific arrangement of any set of integers from 0 to m. From Example 1.1, each function Sfj takes a 6-bit block as its input, Sin, denoted by Sin = x1 , x2 , x3 , x4 , x5 , x6 (1.9) Suppose rj and cj correspond to a particular row and column of selection function Sfj. Row rj is determined by the first and last digits of Sin; that is, (x1 , x6). Since x1 and x6 are binary digits, it follows that there can be only four possible outcomes to indicate the four rows (l = 4) of Sfj, while the other four binary digits (x2 , x3 , x4 , x5) will provide numbers between 0 and m, thereby determining cj. The intersection of rj and cj in Sfj produces a specific integer between 0 and m, which, when converted to its binary digits, gives the output Sop = y1 , y 2 , y 3 , y 4 (1.10) In practice, the elements of the selection functions Sfj are tabulated like a lookup table. In the case of DES, l = 4 and m = 15; these elements are shown in Table 1.1. As seen in Table 1.1, each selection function Sfj has 4-bit output, giving a total of 32 bits for all selection functions. Example 1.2 demonstrates how the selection function's algorithm is implemented. Example 1.2 Take a row from (1.8), say the first row, as input data; that is, Sin = 110011. It follows that rj = (x1, x6) = 11 and cj = 1001 = 9. Our task now is to provide the output Sop due to Sin using the previous transformation process on the basis of the selection functions given by Table 1.1. If we let j = 8, the element of S8 in the fourth row and ninth column is 15, which equates to the digital output Sop = y1 , y 2 , y 3 , y 4 = 1111 . 1.4.3.1.4 Permutation Function The purpose of permutation function Pf of Figure 1.8 is to take all the selection function's 32 bits and permute the digits to produce a 32-bit block output. The permutation function Pf simply performs Z = Pf (Y) K21636_Book.indb 14 (1.11) 10/22/13 4:09 PM 15 Basic Principles of Satellite Communications Table 1.1 DES Selection Functions S1 14 0 4 15 4 15 1 12 13 7 14 8 1 4 8 2 2 14 13 4 15 2 6 9 11 13 2 1 8 1 11 7 15 3 0 13 1 13 14 8 8 4 7 10 14 7 11 1 6 15 10 3 11 2 4 15 3 8 13 4 4 14 1 2 3 10 15 5 10 6 12 11 6 12 9 3 12 11 7 14 5 9 3 10 9 5 10 0 0 3 5 6 7 8 0 13 9 12 5 11 7 0 8 6 2 1 12 7 13 10 6 12 12 6 9 0 0 9 3 5 5 11 2 14 10 5 15 9 1 2 11 4 13 8 1 15 12 5 2 14 7 14 12 3 11 12 5 11 4 11 10 5 2 15 14 2 8 1 7 12 1 4 15 9 2 7 1 4 8 2 3 5 5 12 14 11 11 1 5 12 12 10 2 7 4 14 8 2 15 9 4 14 8 5 15 6 5 0 9 15 3 15 12 0 15 10 5 9 13 3 6 10 0 9 3 4 14 8 0 5 9 6 14 3 0 6 7 11 13 1 0 14 3 13 4 1 4 14 10 7 14 0 1 6 7 11 13 0 5 3 11 8 11 8 6 13 3 14 10 9 12 3 15 5 9 5 6 0 7 12 8 15 5 2 0 14 10 15 5 2 6 8 9 3 1 6 2 12 10 12 0 15 9 5 6 12 3 6 10 9 14 11 13 0 5 0 15 3 0 14 3 5 12 9 5 6 7 2 8 11 S2 S3 10 13 13 1 0 7 6 10 9 0 4 13 14 9 9 0 6 3 8 6 3 4 15 9 15 6 3 8 7 13 10 3 13 8 6 15 14 11 9 0 3 5 0 6 0 6 12 10 6 15 11 1 9 0 7 13 5 10 0 7 S4 10 3 13 8 2 14 4 11 12 11 2 8 4 2 1 12 1 12 11 7 7 4 10 1 10 7 13 14 11 13 7 2 6 1 8 13 12 10 9 4 1 15 14 3 10 4 15 2 15 2 5 12 9 7 2 9 2 12 8 5 6 9 12 15 8 5 3 10 S5 S6 S7 4 13 1 6 11 0 4 11 2 11 11 13 14 7 13 8 15 4 12 1 0 9 3 4 8 1 7 10 13 10 14 7 S8 13 1 7 2 K21636_Book.indb 15 2 15 1 1 8 13 4 14 4 8 1 7 6 10 9 4 15 3 12 10 11 7 14 8 1 4 2 13 10/22/13 4:09 PM 16 Satellite Communication Engineering, Second Edition where the permutation is like the ordering sequence of the expansion function: Pf = 16 29 1 5 2 32 19 22 7 12 15 18 8 27 13 11 20 28 23 31 24 3 30 4 21 17 26 10 14 9 6 25 (1.12a) and the 32-bit block input is Y = y1 , y 2 , y 3 , , y 32 (1.12b) Hence, on the basis of (1.12), the permutation function can be written as Z = Pf (Y) = y16 , y7 , y 20 , y 21 , y 29 , , y 4 , y 25 (1.13) which suggests that the 32-bit block input (1.12b) is rearranged (permuted) according to the ordered permutation function given by (1.12a). Example 1.3 Suppose Y = 10011001110110110101010000111101 If we rearrange Y according to (1.12a), the output of the permutation function is Z = 10101110110011010100110101101010 In summary, Section 1.4.3.1.2 has demonstrated the process by which an input block data R(j) is transformed to produce an output function, z(j). 1.4.3.2 Feedback Ciphering A general feedback arrangement is shown in Figure 1.9. Within the mappers G contain the ciphering and deciphering algorithms. The mapping of keys G(Ki) is used for encryption, while G(Kj) is used for decryption. K21636_Book.indb 16 10/22/13 4:09 PM 17 Basic Principles of Satellite Communications Encryption Decryption Function, F Function, F x * ± Mapper, G Z ...... * ± Mapper, G x kj ki Figure 1.9 Feedback ciphering. For an uncoded message x and the feedback function F, the encrypted message z can be written as z = [x ± zF] G (K i) (1.14) Rearranging (1.14) in terms of z, we have z[1 FG(K i)] = xG(K i) (1.15a) or z= G(K i) x 1 FG(K i) (1.15b) For the decryption circuit, the expression for the decrypted message x can be written as x = [z ± xF] G(K j) (1.16a) Alternately, in terms of encrypted message z, z= 1 FG(K j) x G(K j) (1.16b) For the same transmission sequence, (1.15b) and (1.16b) must be equal; that is, 1 FG(K j) G(K i) = G(K j) 1 FG(K i) K21636_Book.indb 17 (1.17) 10/22/13 4:09 PM 18 Satellite Communication Engineering, Second Edition which turns to G(K i) = 1 FG(K j) G(K j) = 1 FG(K i) (1.18) It can be seen in (1.18) that the key functions relate to the feedback functions. If for argument's sake we let the feedback F equate to unity, then the key functions become an additive inverse of each other. This shows that the feedback function and the mapping function are linear functions in this type of ciphering. In general, a feedback mechanism enhances the strength of a cryptosystem [15]. 1.5 Summary This chapter has briefly introduced the genesis and characteristic features of communication satellites. A communication satellite is basically an electronic communication package placed in orbit whose prime objective is to initiate or assist communication transmission of information or messages from one point to another through space. The information being transferred most often corresponds to voice (telephone), video (television), and digital data. As electronic forms of communication, commerce, and information storage and processing have developed, the opportunities to intercept and read confidential information have grown, and the need for sophisticated encryption has increased. This chapter has also explained basic cryptographic techniques. Many newer cryptography techniques being introduced to the market are highly complex and nearly unbreakable, but their designers and users alike carefully guard their secrets. The use of satellites for communication has been steadily increasing, and more frontiers will be broken as advances in technology make system production costs economical. Problems 1. The role of telecommunications networks has changed over the last decade. a. Discuss the role of telecommunications networks in modern society. b. How has this changed your perception in terms of security, social cohesion, and commerce? K21636_Book.indb 18 10/22/13 4:09 PM Basic Principles of Satellite Communications 19 2. Your task is to develop a communication network covering some inhospitable terrain. What sort of telecommunication infrastructure would you suggest? Discuss the social, legal, and political implications of the recommended telecommunications network(s). 3. A packet-switched network is to be designed with onboard processing capability. Design a suitable cryptosystem for securing the information flow and message contents. References 1. Dressler, W. (1987). Satellite communications. In Siemens Telecom Report, vol. 10. 2. Meyer, C., and Matyas, S. (1982). Cryptography: a new dimension in computer data security. New York: John Wiley. 3. National Bureau of Standards. (1977). Data encryption standard. Federal Information Processing Standards, Publication 46. U.S. Department of Commerce. 4. National Institute of Standards and Technology. (2012). Advanced encryption standard (AES). Federal Information Processing Standards, Publication 197. U.S. Department of Commerce. 5. New European Schemes for Signatures, Integrity, and Encryption (NESSIE). (2004). . 6. Poschmann, A., Ling, S., and Wang, H. (2010). 256 bit standardized crypto for 650 GE GOST revisited. In Lecture Notes in Computer Science, LNCS 6225, 219–233. 7. Diffie, W., and Hellman, M. (1976). New directions in cryptography. IEEE Transactions on Communications Technology, 29(11), 644–654. 8. Rivest, R., Shamir, A., and Adleman, L. (1978). A method for obtaining digital signatures and public-key cryptosystems. Communications for the ACM, 21(2), 120–126. 9. McEliece, R. (1977). The theory of information and coding. In Encyclopedia of mathematics and its applications. Reading, MA: Addison-Wesley. 10. Koblitz, N. (1987). Elliptic curve cryptosystems. Mathematics of Computation, 48, 203–209. 11. Miller, V. (1986). Uses of elliptic curves in cryptography. Advances in Cryptology— CRYPTO '85, Lecture Notes in Computer Science, 218, 417–426. 12. Proos, J., and Zalka, C. (2003). Shor's discrete logarithm quantum algorithm for elliptic curves. Quantum Information and Computation, 3, 317–344. 13. Shor, P.W. (1997). Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. SIAM Journal on Computing, 26, 1484–1509. 14. Dodis, Y., Goldwasser, S., Kalai, Y., Peikert, C., and Vaikuntanathan, V. (2010). Public-key encryption schemes with auxiliary inputs. Proceedings of Theory of Cryptography Conference, 361–381. 15. Wu, W.W. (1985). Elements of digital satellite communication. Rockville, MD: Computer Science Press. 16. Kolawole, M.O. (2003). Radar systems, peak detection and tracking. Oxford: Elsevier Science. K21636_Book.indb 19 10/22/13 4:09 PM 2 Satellites 2.1 Overview A satellite is a radiofrequency repeater. New-generation satellites are regenerative; that is, they have onboard processing capability making them more of an intelligent unit than a mere repeater (more is said of onboard processing in Section 2.9). This capability enables the satellite to condition, amplify, or reformat received uplink data and route the data to specified locations, or actually regenerate data onboard the spacecraft as opposed to simply acting as a relay station between two or more ground stations. A typical satellite with onboard processors is the NASA Advanced Communications Technology Satellite (ACTS) shown in Figure 2.1. It was part of the payload on the Space Shuttle Discovery launched on September 12, 1993. According to NASA, its satellite weighs 3250 lb (1477.3 kg) and measures 47.1 ft (14.36 m) from tip to tip of the solar arrays and 29.9 ft (9.11 m) across the main receiving and transmitting antenna reflectors, with a height of 15.2 ft (4.63 m) from the spacecraft separation plane to the tip of the highest antenna. The solar arrays provide approximately 1.4 kW. The main communication antennas are a 7.2-ft (2.19-m) receiving antenna and a 10.8-ft (3.29-m) transmitting antenna. We describe more about the satellite components' design later in this chapter, particularly overall system design procedure, availability, and reliability in Section 2.6; antennas in Section 2.7; power systems in Section 2.8; onboard processing and switching systems in Section 2.9; and antenna control and tracking in Chapter 3, Section 3.4.2. Other characteristics of satellites are discussed in the next five sections. As stated in Chapter 1, a satellite comprises several individual chains of equipment called a transponder, a term derived from transmitter and responder. The block diagram shown in Figure 2.2 may represent a transponder unit. As seen in the figure, a transponder may be described as a system composed basically of a bandpass filter required to select the particular channel's band frequencies, a frequency translator that changes frequencies from one level to another, and an output amplifier. Once amplified, the channels are recombined in an output multiplexer for the return transmission. All these devices must be stable over their operating temperature range to maintain 21 K21636_Book.indb 21 10/22/13 4:09 PM 22 Satellite Communication Engineering, Second Edition (Nadr) 15.2 ft West z (North) y (East) x C-band omni antenna Dual subreflectors South 29.9 ft Solar array Ka-band command, ranging, and telemetry antenna 10.8 ft, 20-GHz transmitting antenna Beam-forming networks 7.2 ft, 30-GHz receiving antenna 3.3 ft steerable antenna Solar array 47.1 ft Figure 2.1 Geometry of a satellite. (Courtesy of NASA.) the desired rejection characteristics. The functionality of these devices (each component block in Figure 2.2) is addressed later in this chapter. A transponder may channel the satellite capacity both in frequency and in power and may be accessed by one or by several carriers. In most system applications, one satellite serves many earth stations. With the assistance of earth stations, fixed or transportable, satellites Receiver Matrix switch Translator Input channel filter LPA Antenna LO Output multiplexer Antenna HPA Channel filter Transmitter Figure 2.2 Basic transponder arrangement. K21636_Book.indb 22 10/22/13 4:09 PM Satellites 23 have opened a new era for global satellite multiaccess channels' data transmission and broadcast of major news events, live, from anywhere in the world. Commercial and operational needs dictate the design and complexity of satellites. The most common expected satellite attributes include the following: 1. Improved coverage areas and quality services, and frequency reusability 2. Compatibility of satellite system with other systems and expandability of current system that enhances future operations 3. High-gain, multiple hopping beam antenna systems that permit smaller-aperture earth stations 4. Increased capacity requirements that allow several G/s (gigabits per second) communication between users 5. Competitive pricing Future trends in satellite antennas (concerning design and complexity) are likely to be dictated from the status of the satellite technology, traffic growth, emerging technology, and commercial activities. The next two sections examine the type of satellites and the major characteristics that determine the satellite path relative to the earth. These characteristics are as follows: 1. Orbital eccentricity of the selected orbit 2. Period of the orbit 3. Elevation angle; the inclination of the orbital plane relative to the reference axis 2.1.1 Type of Satellites There are, in general, four types of satellite: Geostationary satellite (GEO) High elliptical orbiting satellite (HEO) Middle-earth orbiting satellite (MEO) Low-earth orbiting satellite (LEO) An HEO is a specialized orbit in which a satellite continuously swings very close to the earth, loops out into space, and then repeats its swing by the earth. It is an elliptical orbit approximately 18,000 to 35,000 km above the earth's surface, not necessarily above the equator. HEOs are designed to give better coverage to countries with higher northern or southern latitudes. Systems can be designed so that the apogee is arranged to provide continuous coverage in a particular area. By definition, an apogee is the highest-altitude point K21636_Book.indb 23 10/22/13 4:09 PM 24 Satellite Communication Engineering, Second Edition Sm Focus Sp Sf Apogee Perigee θ r Elliptical orbit Semi-major axis, a Figure 2.3 Geometric properties of an elliptical orbit (Sf = semifocal length, Sp = semiparameter, Sm = semiminor axis, r = radius distance, focus to orbit path, θ = position angle). of the orbit, that is, the point in the orbit where the satellite is farthest from the earth. To clarify some of the terminology, we provide Figure 2.3, which shows the geometric properties of an elliptical orbit. By geometry, Sm = a 1 − e 2 Sp = S2m = a 1 − e2 a ((2.1)) (2.2) where the eccentricity, or the amount by which the ellipse departs from a circle, is e= Sf a (2.3) The general equation of an ellipse can thus be written as r= (a 1 − e2) 1 + e cos θ (2.4) It is apparent from (2.4) that if e = 0, the resulting locus is a circle. An MEO is a circular orbit, orbiting approximately 8000 to 18,000 km above the earth's surface, again not necessarily above the equator. An MEO is a compromise between the lower orbits and the geosynchronous orbits. MEO system design involves more delays and higher power levels than satellites in the lower orbits. However, it requires fewer satellites to achieve the same coverage. K21636_Book.indb 24 10/22/13 4:09 PM 25 Satellites Table 2.1 Frequency Classification of LEOs Type Frequency Big LEO Little LEO >10 GHz 40 Messaging Military, navigation mobile Mobile, audio broadcast radiolocation Mobile navigation Fixed Military Fixed video broadcast Fixed Fixed, audio broadcast, intersatellite Intersatellite VHF UHF L S C X Ku K Ka Millimeter waves elliptical orbit becomes lower, and as a consequence, the orbit gradually becomes circular. The longer the influence on the orbit, the slower the satellite becomes, and it eventually falls from orbit. Aerodynamic drag is more significant at low altitude (200 to 400 km) and negligible at about 3000 km because, in spite of the low value of atmospheric density encountered at the altitudes of satellites, their high orbital velocity, which is high, implies that perturbations due to drag are very significant. A geostationary orbit is a nonretrograde circular orbit in the equatorial plane with zero eccentricity and zero inclination. The satellite remains fixed (stationary) in an apparent position relative to the earth, about 35,784 km away from the earth if its elevation angle is orthogonal (90°) to the equator. Its period of revolution is synchronized with that of the earth in inertial space. The geometric considerations for a geostationary satellite communication system will be discussed later in the text. Commercial GEOs provide fixed satellite service (FSS) in the C- and Ku-bands of the radio spectrum. Some GEOs use the Ku-band to provide certain mobile services. The International Telecommunication Union (ITU) (see Chapter 7) has allocated satellite bands in various parts of the radio spectrum from very high frequency (VHF) to 275 GHz. Table 2.2 shows satellite communications frequency bands and the services they perform, while Table 2.3 shows typical link frequency bands. Table 2.3 Typical Link Frequency Band Allocation Band C Ku Ka K21636_Book.indb 26 Uplink Frequency (GHz) Downlink Frequency (GHz) 5.925–7.075 3.7–4.2 14.0–14.5 27.5–31.0 11.7–12.2 17.7–21.2 10/22/13 4:09 PM 27 Satellites Frequency bands in the ultra-high frequency (UHF) are suitable for communicating with small or mobile terminals, for television broadcasting, and for military fleet communication. The band of frequencies suitable for an earth-space-earth radio link is between 450 MHz and 20 GHz. Frequencies between 20 and 50 GHz can be used but would be subject to precipitation attenuation. However, if an availability greater than 99.5% is required, a special provision such as diversity reception and adaptive power control would need to be employed. Higher frequencies are more suitable for intersatellite links (ISLs) and may become usable as the orbital congestion arises at the lower frequencies. Another benefit of higher-frequency communication systems is that system components generally become smaller. For satellites, this translates to lighter weight, lower power, and reduced cost, and more importantly, it means increased mobility and flexibility. 2.2 Satellite Orbits and Orbital Errors For geometric consideration, a satellite can also be explained as a body that moves around another body (of greater mass) under the influence of the gravitational force between them. The force F required to keep a satellite in a circular orbit can be expressed as F = msω2r N (Newton) (2.7) where ms = mass of the satellite, g; ω = angular velocity of the satellite, rad/s;

and r = radius of the orbit, m, = Re + h0, m. This is the distance of a synchronous satellite from the center of the earth. h0 is the orbit altitude, that is, the height above the subsatellite point on the earth terminal (m). The gravitational force Fg acting on the satellite of mass ms at distance r from the center of the earth is Fg = ms g Re2 r2 N (2.8) where g = acceleration due to gravity at the surface of the earth = 9.807 m/s2, and Re = radius of the earth. The value varies with location. For example, Re at the equator = 6378.39 km (≈ 6378 km) Re at the pole = 6356.91 km (≈ 6357 km) K21636_Book.indb 27 10/22/13 4:09 PM 28 Satellite Communication Engineering, Second Edition Consequently, for a satellite in a stable circular orbit round the earth, F = Fg (2.9) In view of (2.7) and (2.8) in (2.9), r3 = g Re2 ω2 (2.10) The period of the orbit, ts, that is, the time taken for one complete revolution (360° or 2π radians), can be expressed as ts = 2π 2π = ω Re r3 g s (2.11) If we assume a spherical homogeneous earth, a satellite will have an orbital velocity represented by v = Re g r m/s (2.12) For elliptical orbits, Equations (2.11) and (2.12) are also valid by equating the ellipse semimajor axis a with the orbit radius, r (i.e., r = a). In terms of the orbit parameters, r is replaced with the average of the apogee to the focus and the perigee to the focus. By definition, a perigee is the lowestaltitude point of the orbit, whereas an apogee is the highest-altitude point of the orbit. In a circular orbit, with variable altitude and upon substitution of empirical values in (2.11) and (2.12), Figure 2.4, which relates period 30 8 Period (h) 25 7 Time 20 6 5 15 4 10 3 Velocity 2 5 0 1 0 10 20 30 Orbit Altitude × 103 (km) 40 Orbital Velocity (km/s) 9 0 Figure 2.4 Satellite period and orbital speed vs. altitude. K21636_Book.indb 28 10/22/13 4:09 PM Satellites 29 and velocity for circular orbits, assuming a spherical homogeneous earth, is plotted. For a circular orbit at an altitude of 35,784 km, Figure 2.4 shows that a geosatellite orbit takes a period of rotation of the earth relative to the fixed star (called sidereal day) in 86,163.9001 s, or 23 h 56 min 4 s. In some books and papers, an approximate value of 36,000 km is frequently cited for the altitude of the satellite in geosynchronous orbit. The geosynchronous orbit in the equatorial plane is called the geostationary orbit. Although a satellite in the geostationary orbit does not appear to be moving when seen from the earth, its velocity, from Figure 2.4, in space equals 3.076 km/s (11,071.9 km/h). Low-altitude satellites, which have orbits of less than nominally 24 h, have other applications in addition to those earlier tabulated in Table 2.1. The applications include reconnaissance purposes, provision for communications at extreme north and south latitudes when in a polar orbit, and numerous business opportunities in producing remotely located monitoring and data acquisition devices that could be accessed by satellite. 2.2.1 Orbital Errors It is not possible to put a satellite into a perfect geostationary orbit because any practical orbit is slightly inclined to the equatorial plane. In addition, it is not exactly circular; it does not have exactly the same period as that of the earth’s rotation, and it is constantly bombarded by disturbing forces (such as the attraction of the sun and moon) that try to change the orbit. These disturbing forces cause satellites to drift slowly in longitude. Their effects are counteracted from time to time by operating thrusters on the satellite. It is logical to suggest that these forces introduce orbital errors outside the intended nominal longitudes. Advances in space technology have enabled minimization of the orbital errors. For example, INTELSAT V satellites were kept within ±0.1° of the equator and of their nominal longitudes, whereas INTELSAT VI satellites are kept within ±0.02° of the equator and ±0.06° of their nominal longitudes. 2.3 Coverage Area and Satellite Networks 2.3.1 Geometric Coverage Area Clarke [2] foresaw in his article that it would be possible to provide complete radio coverage of the world from just three satellites, provided they could be precisely placed in geosynchronous orbit. Figure 2.5 demonstrates this. K21636_Book.indb 29 10/22/13 4:09 PM 30 Satellite Communication Engineering, Second Edition Geosynchronous orbit Satellite Earth Figure 2.5 Complete coverage of the earth’s surface from three satellites. The amount of coverage is an important feature in the design of earth observation satellites. Coverage depends on altitude and look angles of the equipment, among several factors. To establish the geometric relationship of the coverage, we take a section of the satellites in Figure 2.5 as an illustration. This section is redrawn as shown in Figure 2.6. The maximum geometric coverage can then be defined as the portion of the earth within a cone of the satellite at its apex, which is tangential to the earth’s surface. Consider the angle of view from the satellite to the earth terminal as α; then the apex angle is 2α. The view angle has a mathematical physical function given by ⎛ Re ⎞⎛R ⎞α = sin −1 ⎜ = sin −1 ⎜ e ⎟⎝ r ⎠⎝ ho + Re ⎟⎠ (2.13) Using empirical values (Re = 6378 km, r = 42,162 km), the apex angle 2α equals 17.33°, the planar angle beamwidth. It follows that an “earth coverage” satellite antenna must have a minimum beamwidth θBW of 17.33°. In practice, an antenna of 18° or 19° beamwidth is used to allow for directional misalignment. Thus, for a single geostationary satellite to illuminate in excess of a third of the earth’s surface, the antenna minimum beamwidth must be at least 2α. The beamwidth of the satellite antennas determines the area of the earth serviced or covered. The beamwidth required directly determines the antenna gain and, for a given operating frequency, the physical size of the antenna aperture (see a further discussion on antennas in Section 2.7). K21636_Book.indb 30 10/22/13 4:09 PM 31 Satellites Satellite h0 Orbit 2α Rs M θ Coverage area G Re γ Equator o Figure 2.6 An illustration of coverage area and apex angle. Using the notations in Figure 2.6 as a guide, the coverage area, Acov, from which the satellite is visible with an elevation angle of at least θ can be established as Acov = 2 πRe2 (1 − cos γ) (2.14) where γ is the central angle. It is a spherical trigonometric relation that relates to the earth and satellite coordinates (to be discussed in detail in Section 2.4). The apex angle required at the satellite to produce a given coverage Acov must satisfy 2 π{1 − cos α} = Acov h02 (2.15) However, for small angles, that is, α

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