COMMUNICATION SATELLITES – TECHNOLOGIES AND SYSTEMS

Lillian L. Dai, Jihwan (Patrick) Choi, and **Vincent W. S. Chan**
Massachusetts Institute of Technology, Cambridge, MA, USA

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Contents

Summary

Since the middle of the 20th century, satellites have evolved from being technical marvels to essential components of industrialized societies. Currently, satellites are used for a diverse range of applications, including telecommunication, navigation, weather prediction, military intelligence, space exploration, and scientific studies. Of the operational satellites in space today, more than half are dedicated to telecommunication uses. These satellites complement the terrestrial communication network, enabling people across the globe to communicate. Due to their unique advantage of large coverage range and independence from most terrestrial network failures, satellites are strategic assets for ensuring continuous information flow among people, businesses, and governments when terrestrial network connections are disrupted. This chapter provides an overview of the history, evolution, and current developments of commercial communication satellite systems and technologies.

1. Introduction

Satellites are man-made systems that operate in space (*the broadest definition of "satellite" includes celestial bodies (such as the moon) orbiting around planets. In this chapter, the definition of "satellite" is limited to man-made spacecrafts only*). Since the launch of the first satellite in 1957, people have found diverse applications for these systems and have made significant technical advances and innovations to improve their efficiency. Currently, millions of people around the world rely on satellites for telecommunication, navigation, weather forecast, military intelligence, space exploration, and scientific studies of the atmosphere and beyond. As of March 2006, there are approximately 800 operational satellites orbiting Earth, of which about half are operated by the United States and the remaining half operated by forty other countries and several multinational organizations.

Of the operational satellites, more than half are dedicated to telecommunication purposes. These satellites are used around the globe for telephone calls, fax, e-mail, internet, financial transactions, television (TV), radio broadcasts, and much more. Compared to terrestrial communication systems, satellites have the unique advantage of being able to provide coverage to large geographical areas. A single satellite can connect users on different continents across the Atlantic or Pacific Ocean. Moreover, satellites can provide communication services to mobile users anywhere in the coverage region, including land, ocean, and air. Figure 1 depicts a satellite system providing communication services to a diverse range of users on Earth.

Figure 1: Communication Satellite Serving a Diverse Range of Users

Although satellite services are not available to the same extent to every individual in the world, many rely on satellites as the only economically feasible mode of communication. Currently, many communities in developing countries and remote areas are not within the reach of any terrestrial communication network but all are within the coverage of at least one satellite. In addition, during periods of natural disaster or war when terrestrial communication facilities are either destroyed or unavailable, disaster relief workers, military personnel, and newscast agencies depend on satellites to provide continuous information flow among each other and with the rest of the world. For nearly half a century, satellite technologies and applications have continuously evolved in response to our ever changing way of life; in turn, many people have come to depend on satellites in their daily lives.

This chapter provides an overview of the history, evolution, and current developments of commercial communication satellite systems and technologies. Chapter 2 provides an introduction to the fundamental principles of satellite operations. Chapter 3 provides a brief history of commercial satellites over the past 50 years. In Chapter 4, some of the important satellite communication technologies are explained. In Chapter 5, we present some future outlooks and impacts of communication satellites.

2. Satellite Fundamentals

A communication satellite system consists of a *space segment* and a *ground segment*. The space segment includes satellites in space, while the ground segment includes user communication devices, ground stations that connect to the terrestrial network, and control facilities that control and monitor the satellites. To make a telephone call, send an e-mail, broadcast TV programs, or exchange other information, a user on the ground generates the information and sends it to a satellite through a communication device either directly or via a ground station. The satellite then relays the information back down to the intended receiving user(s), possibly via another ground station. As shown in Figure 2, by relaying information through a satellite, users located far apart (possibly on different continents), can communicate without the need to connect them with cables. Although most satellites are custom designed and optimized for an intended application, they all operate under the same fundamental principles. In this section, we provide a brief overview of basic satellite subsystems, orbital mechanics, launch vehicles, and ground facilities.

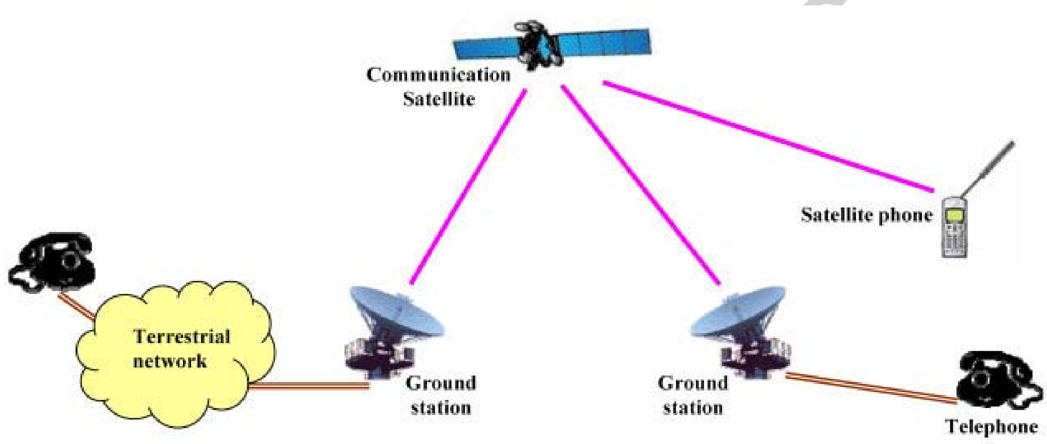


Figure 2: An Example Communication Satellite System

2.1. Space Segment

A typical communication satellite consists of a *bus* and a communication *payload*. The payload is the essential subsystem for providing communication services and the bus consists of all other subsystems needed for the proper operation of the payload. Figure 3 shows a modern satellite bus, which consists of structural, thermal, power, attitude control, propulsion, and telemetry, tracking, and command (TT&C) subsystems. We will provide a brief description of each of the main subsystems in a satellite.

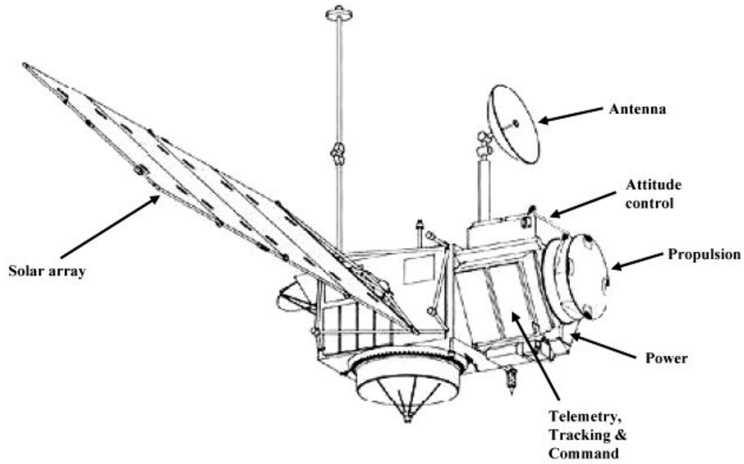


Figure 3: Satellite Subsystems

2.1.1. Satellite Bus

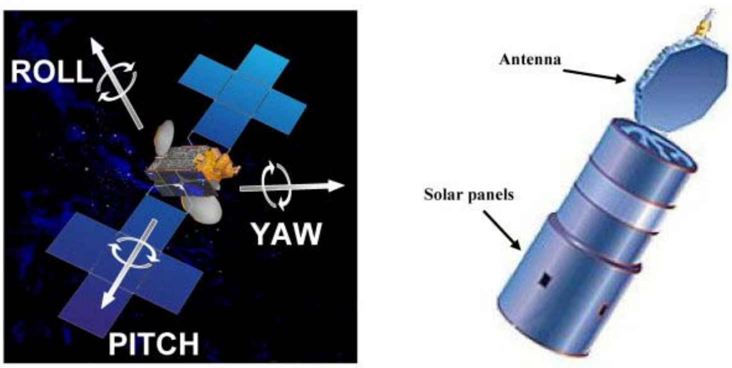
The exterior of a satellite is typically made from a lightweight material such as aluminum, titanium, and more frequently, graphite epoxy that provides the necessary structural support for the satellite. Internal structures of graphite epoxy include central support panels or cylinders, struts, and brackets that support internal and external equipments during satellite launch and help maintain precise alignment between elements of the payload, especially the antennas.

Integrated with the structural components are thermal and radiation control modules. When operating in space, excessive radiation from the sun can cause temporary electronic malfunction and possibly physical damages to a satellite's electronic circuits. Furthermore, Earth and sun facing sides of a satellite can experience very difference temperatures that range from -100 to +100 degrees Celsius. To maintain the sensitive electronics inside satellites within an acceptable temperature range under varying sun angles, the external surfaces of equipment-carrying panels use special mirrors and coatings that maximize heat rejection by radiation and minimize heat absorption from the incident sunlight. In addition, heat pipes are used to spread the equipment-generated heat over the panel area and to carry heat from some interior components to the surface or to deployable radiators. Panels with heavy sun exposure are often covered with thermal blankets to minimize thermal input. External structures such as antenna supports are heavily blanketed to minimize dimensional changes that could affect communication performance.

The electricity needed to power all on-board electronics comes from two sources. The primary source is from solar arrays that convert sunlight to electricity. The secondary source is from on-board batteries, which are recharged when the solar arrays are facing the sun. During periods of eclipse when Earth blocks the sun, batteries are used to power on-board electronics. For some satellite systems, an eclipse can last for more than an hour. Hence, these batteries must store enough energy to power the satellite when no other energy source is available. Currently, batteries constitute a large percentage of the total weight of most satellites (~15-20% for many). Much research effort is geared towards improving the efficiency of batteries.

The attitude (or orientation) control subsystem is responsible for maintaining a satellite's orientation in terms of its local coordinate system: yaw, pitch, and roll, as shown in Figure 4a. Without attitude control, a satellite will not be able to point its communication antennas towards Earth at all times. First generation satellites are cylindrically shaped (Figure 4b) with solar panels covering the exterior of the satellite body. These satellites are spin-stabilized such that the spacecraft rotates around a vertical axis. Since spinning objects are not easily perturbed by minor disturbances, the orientation of a spinning satellite can be well maintained. The disadvantage of spin-stabilization is that not all solar cells face the sun at any given time; therefore, power levels are low (typically 2 kW or less). Furthermore, the communication antennas need to be "de-spun" to maintain its pointed direction. Due to these disadvantages, most satellites in operation are three-axis stabilized (Figure 4a) using inertia wheels (also called reaction wheels or momentum wheels) and thrusters. Inertia wheels are instruments that can rotate about an axis to generate stabilizing force and thrusters are instruments that expel on-board propellant to produce a linear force. Three-axis stabilization using these instruments ensures that the communication antennas are pointed towards Earth and the solar arrays are pointed towards the sun most of the time, permitting power levels well above 10 kW.

Even with active stabilization, the orientation of a satellite may be disturbed by several external forces, including solar radiation pressure, Earth's magnetic field, and atmospheric drag in the case of low altitude spacecraft. To determine a satellite's orientation, on-board sensors use Earth, sun, and stars as reference points. If an attitude adjustment is necessary, a satellite must generate either a linear force or a rotational force (termed *torque*) to maneuver itself into the desired orientation. Since there is little counterbalancing force acting upon a satellite in space, the attitude adjustments are usually minute and carefully controlled. To correct a satellite's orientation, several techniques can be used by the attitude control and propulsion subsystems: with inertia wheels that generate torque, with thrusters that produce a linear force, with magnetic coils that generate torque by interacting with Earth's magnetic field, and with solar sails that generate torque by letting solar radiation push the satellite in a particular direction.



4a. Three-axis Stabilized Satellite and Orientation   4b. Spin Stabilized Satellite

Figure 4: Satellite Orientation and Stabilization
a) Three-axis Stabilized Satellite and Orientation; b) Spin Stabilized Satellite\

A satellite's propulsion subsystem is not only used for attitude control but also for getting the satellite into the desired orbit. As will be explained in Section 2.2, many satellites are not placed directly into the desired orbit. Often, for energy efficiency, satellites are placed into an intermediate orbit first. A satellite's own propulsion system will then generate forces to change its trajectory, gradually moving the satellite into the desired orbit. For this reason, satellites that use chemical propellants usually need to carry a lot of fuel, which adds to their weight and cost. Once the fuel is spent, a satellite can no longer effectively maintain its orientation. The service life span of a satellite is typically limited by this factor alone, ranging from 3 to more than 15 years depending on the type of satellite. New technologies based on electric propulsion, including plasma and ionic propulsion systems, have been developed to relieve some of the demands on the chemical propulsion system.

As with all physical systems, satellite components may malfunction or break down. Since it is highly impractical to send technicians into space to fix any anomalies in the satellite, all of the diagnostic and control functions must be done on the ground. Various on-board sensors are used to monitor satellite health information for diagnostic purposes. This information is transmitted to the ground control center via a telemetry, tracking, and command communication link (TT&C). Based on the received information, the ground controller may then take appropriate actions such as command a satellite to switch to backup modules, reset certain parameters, or load new software.

2.1.2. Communication Payload

The communication payload is responsible for establishing connections between communication devices, which may be located on Earth, in the air, or in space as shown in Figure 1. In general, the communication payload is custom designed for the particular application a satellite is intended to serve. Here, we briefly describe the principle of satellite communication and some of the essential components of a satellite communication payload, including antennas, receivers, and transmitters. A more detailed description of communication payloads is provided in Section 4.

The physical principle of establishing communication connections between remote communication devices dates back to the late 1800s when scientists were beginning to understand electromagnetism and discovered that electromagnetic (EM) radiation (also called *EM waves*) generated by one device can be detected by another located at some distance away. By controlling certain aspects of the radiation (through a process called *modulation*, explained in Section 4.4), useful information can be embedded in the EM waves and transmitted from one device to another. These discoveries served as the foundation for all modes of wireless communication we are familiar with today, including cellphones, walkie-talkies, wireless LANs (local area networks), and satellite systems.

EM waves are characterized by frequency in cycles per second (unit in Hz). Theoretically, EM waves can take on any frequency in the spectrum between zero and infinity. Practically, communication systems utilize two sections of the spectrum (*frequency bands*) termed radio frequency (RF) and optical bands. The RF band spans a frequency range between 3 kHz (3×10^3 Hz) to 300 GHz (300×10^9 Hz), whereas the optical band spans the visible light spectrum, which has much higher frequency. Since the RF band is used for a diverse range of applications, subsections of the band are allocated for specific uses. Some of these allocations are shown in Figure 5. Currently, only a portion of the RF band is used for commercial satellites. There are some experimental and military satellites that utilize sections of the optical band. For communication purposes, the larger the allocated frequency band (or *bandwidth*), the higher the communication capacity on a link (measured in bits per second (bps)). Only devices operating at the same frequency can communicate with one another. Without coordination, two nearby devices operating simultaneously at the same frequency can interfere with one another, making information reconstruction more error prone at the receiver. See Section 4.1 for more information about the technical impacts of different frequency bands.

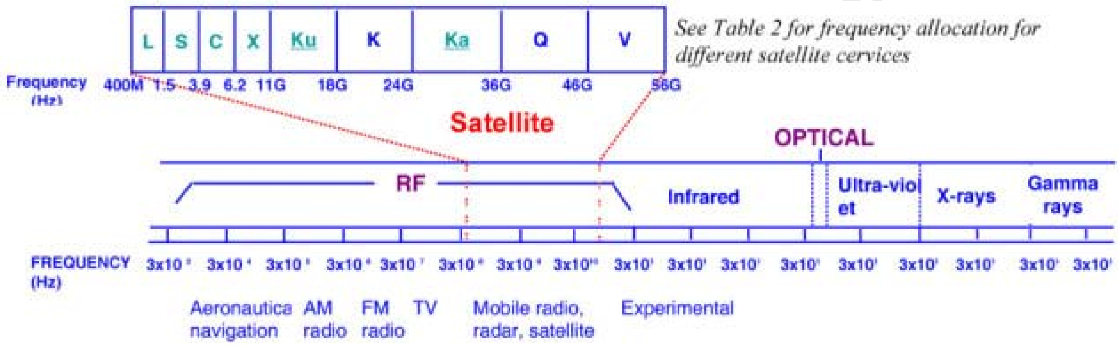


Figure 5: Frequency Spectrum and Allocations (also see Table 2)

By convention, signals (information-carrying EM waves) sent towards a satellite from the ground are called *uplink signals*, while signals sent by a satellite towards the ground are called *downlink signals*. Typically, non-overlapping frequency bands are allocated to the satellite uplink and downlink to allow non-interfering two-way communication. Signals transmitted between two satellites and between a satellite and another spacecraft do not have specialized terminology. Usually, these signals are said to be carried on *space links* or, in the case of communication between two satellites, on intersatellite links (also called *crosslinks*). As signals propagate through space, they weaken and become distorted (these effects are known as *channel effects*) to different extents such that the received signals become approximations of the transmitted signals (see Section 4.1). The satellite communication payload receives the uplink signals, appropriately enhances and/or processes these signals to counter the channel effects, and then forwards them on the downlink. The type of enhancement or processing depends on the type of satellite. Typically, the payload consists of either *transparent repeaters* (also referred to as non-regenerative or "bent-pipe" repeaters), which amplify the uplink signals without processing, or *regenerative repeaters* with on-board processing capabilities. A much simplified schematic diagram of a communication payload, consisting of antennas, a receiver, and a transmitter, is shown in Figure 6.

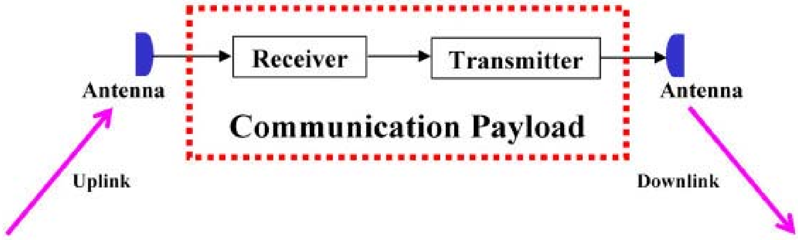


Figure 6: Simplified Schematic Diagram of the Communication Payload

Antennas serve as interfaces between transmitted/received signals and transmitters/receivers. Depending on the type, shape, and size of the transmit antenna, the transmitted signal will have directionality and polarization properties. A receive antenna is designed to match this directionality and polarization so that the transmitted signal can be received. Earth-facing antennas are usually designed to provide a coverage region with a particular contour shape as shown in Figure 7. Typically, horn antennas and parabolic reflector antennas are used for this purpose. In some satellites, multiple transmit antennas (lens antennas and antenna arrays) are used to generate multiple "spot beams" for higher signal directionality and gain. The coverage region and the spot beams may be fixed or dynamically formed depending on the application. Some advanced experimental satellites also use free-space optical lasers for high speed transmissions between satellites.

Figure 7: Antenna Coverage Contour of Intelsat 10-02

Receivers amplify the weak received signals and filter out unwanted signals. Satellites with transparent repeaters simply transmit the amplified signals on the downlink without looking at the information contained in the signals. In contrast, satellites with regenerative repeaters not only perform amplification and filtering but also regenerate the information contained in the signals. The regenerated signals are then transmitted on the downlink. Section 4 describes the amplification, decoding, and other communication payload functionalities in greater detail.

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Biographical Sketches

Lillian L. Dai is a Ph.D. candidate in the Laboratory for Information and Decision Systems at Massachusetts Institute of Technology (MIT). She received a B.Sc. degree in electrical engineering and computer science with distinction from University of Calgary, Canada, in 2000, and a M.S. degree in electrical engineering and computer science from Massachusetts Institute of Technology (MIT), in 2002. Her research interests include wireless, satellite, and hybrid network architectures as well as the application of communication, probability, and optimization techniques to improve network efficiency and to enable new application frontiers. Her current research is on a novel architecture for wireless networks that incorporates mobility and quality of service management.

Ms. Dai is a student member of IEEE, IEEE Communications Society, and Sigma Xi – The Scientific Research Society.

Jihwan P. Choi received the B.S. degree from Seoul National University, Seoul, Korea in 1998, and the S.M. and Ph.D. degrees from Massachusetts Institute of Technology, Cambridge, USA in 2000 and 2006 all in electrical engineering.

From 1999 to 2006, he participated in next-generation- Internet (NGI) satellite network projects at MIT. In 2006, he joined Marvell Semiconductor Inc., Santa Clara, CA, where he is currently a senior DSP engineer. His research interests are in space, wireless communications and network theory.

Dr. Choi is a member of IEEE and a recipient of KFAS (the Korea Foundation for Advanced Studies) fellowships.

Vincent W. S. Chan is the Joan and Irwin Jacobs Professor of Electrical Engineering & Computer Science and Aeronautics & Astronautics, and Director of the Laboratory for Information and Decision Systems (LIDS) at MIT. He received his BS(71), MS(71), EE(72), and Ph.D.(74) degrees in electrical engineering from MIT in the area of communications.

From 1974 to 1977, he was an assistant professor with the School of Electrical Engineering at Cornell University. He joined Lincoln Laboratory in 1977 as a staff member of the Satellite Communication System Engineering Group working on military communications and networking. In January 1981, he became the Assistant Leader of the Communication Technology Group starting a research and development program on optical space communications. In July 1983, he formed and became Leader of the Optical Communication Technology Group and Manager of the LITE (Laser Intersatellite Transmission Experiment) Program. He became the Head of the Communications and Information Technology Division of Lincoln Laboratory until joining LIDS in 1999. In 1989, he formed the AON (All-optical-network Consortium) among MIT, AT&T and DEC. He has also served as the principal investigator of a Next Generation Internet Consortium (ONRAMP) formed among AT&T, Cabletron, MIT, and JDS, and a Satellite Networking Research Consortium formed between MIT, Motorola, Teledesic and Globalstar. He is a member of the Board of Directors of Vitesse Semiconductor Corporation and the Chairman of its Technical Advisory Board. He also serves as a Member of the Corporation of Draper Laboratory and is currently serving as the Editor-in-Chief of the IEEE Optical Communications and Networking Series (as Journal of Selected Area in Communications, Part II), an incubator for a new IEEE journal in the area. His research interests are in optical communications, wireless communications, space communication and networks.

Prof. Chan is a Fellow of the IEEE and the Optical Society of America.