Space Communication and Satellite Technology

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by

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ABSTRACT

Space communication and satellite technology have played a crucial role in shaping the modern world by enabling seamless global communication, data transfer, and satellite-based services. These technologies rely on artificial satellites placed in Earth's orbit to transmit and receive signals, facilitating a wide range of applications, from television broadcasting and internet access to scientific research and military communication.

The principle of satellite communication involves the transmission of electromagnetic waves through space, where satellites act as intermediaries, relaying signals between ground stations or between other satellites. It also explores the different types of satellites, such as communication, weather, navigation, remote sensing, and military satellites, each serving unique purposes to address specific global needs. The technology has numerous advantages, including global coverage, high reliability, and versatility in supporting various applications. However, challenges such as high launch and maintenance costs, signal latency, limited bandwidth, and vulnerability to environmental factors like weather and space debris also persist.

In addition to examining the working principles and types of satellites, in sectors such as telecommunications, disaster management, global positioning, and environmental monitoring. As satellite technology continues to evolve with innovations like low Earth orbit (LEO) constellations and miniaturization, the potential for enhanced communication services, especially in remote or underserved regions, is immense. The continued development of satellite communication promises to revolutionize how we communicate, navigate, and interact with our environment, while also addressing future challenges in space exploration, security, and global connectivity.

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Chapter - 1
Introduction

In today's rapidly advancing world, effective communication is crucial to the functioning of societies, economies, and governments. Traditional ground-based communication systems, though effective, are limited by geographical barriers, infrastructure costs, and network congestion. To overcome these limitations, space communication, relying on satellites orbiting the Earth, has emerged as a game-changing technology. Space communication refers to the transmission of data, voice, and video signals through the use of artificial satellites placed in Earth's orbit. This technology has become an essential component of modern communication systems, enabling global connectivity in ways that were once thought impossible.

1.1. Space Communication:

This initiative named New Space has spawned a large number of innovative broadband and earth observation missions all of which require advances in Satellite Communications systems. The purpose of this survey is to describe in a structured way these technological advances and to highlight the main research challenges and open issues. In this direction, It provides details on the aforementioned developments and associated requirements that have spurred Satellite Communications innovation. Subsequently, It presents the main applications and use cases which are currently the focus of Satellite Communications research. The next four sections describe and classify the latest Satellite Communications contributions in terms of

1) System aspects
2) Air Interface
3) Medium Access Techniques
4) Networking and Upper Layers.

When needed, certain preliminaries are provided in a tutorial manner to make sure that the reader can follow the material flow without reverting to external sources. The communication testbeds which have been developed in order to practically demonstrate some of the advanced Satellite Communications concepts. The last section is reserved for highlighting open research topics that are both timely and challenging.

1.2. Satellite Technology:

Since their inception, Satellite Technology have found a plethora of applications, including media broad-casting, backhauling, news gathering etc. Nowadays, following the evolution of Internet-based applications, Satellite Communication are going through a transformation phase refocusing the system design on data services, namely broadband Satellite Communications. The main motivation is

a) the rapid adoption of media streaming instead of linear media broadcasting

b) the urgent need to extend broadband coverage to underserved areas (e.g. developing countries, aero/maritime, rural).

Furthermore, a major milestone of the 5th generation of communication systems (5G) is the integration and convergence of diverse wired and wireless technologies. In this context, Satellite Communications pave the way for seamless integration targeting specific use cases which can take advantage of their unique capabilities.

1.3. Motivation:

A New Constellation Types Traditionally, Geostationary (GEO) satellites have been mainly used for Satellite Communication. Multibeam satellite systems have been specifically developed to high-throughput broadband rates across the coverage area, not unlike their terrestrial cellular counterparts. However, new more ambitious constellation types are currently being developed, motivated by advanced communication technologies and cheaper launch costs. In this direction, there has recently been a tremendous interest in developing large Low Earth Orbit (LEO) constellations that can deliver high-throughput broadband services with low latency.

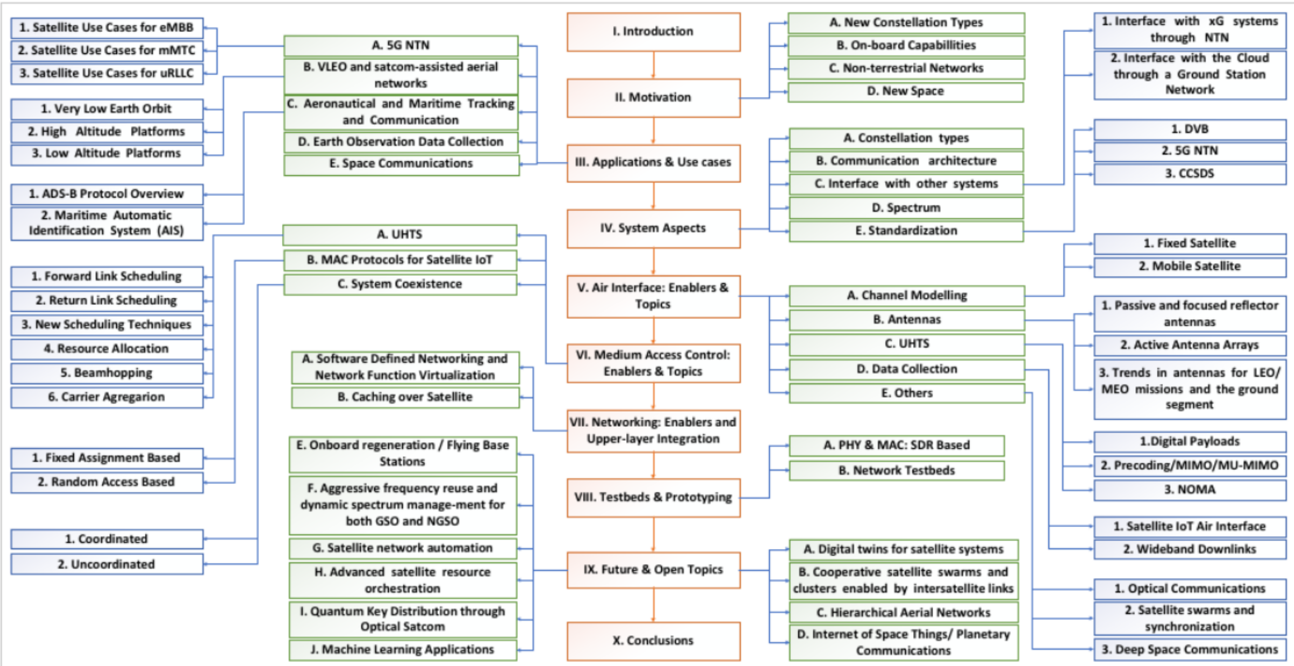

Table. 1. Constellation Types

As of January 2020, SpaceX has deployed 242 satellites to build its Starlink constellation, with the goal to reach nearly 12000 satellites by mid-2020. Moreover, we turn our focus to Medium Earth Orbit (MEO) where a constellation of 20 satellites (O3B) has been placed in a circular orbit along the equator at an altitude of 8063 km.

1.4. Communication Architecture:

The basic structure of a satellite communication system consists of a space segment that includes the satellite constellation, a ground segment including GW stations and large ground facilities for control, network operations and backhauling, and a user segment with the user terminals deployed on fixed and mobile platforms (e.g. airplanes and ships). The link between the GW station and the user terminal via intermediate satellite is named the forward link, whereas the link coming from the user through the satellite to the GW is referred to as return link. The link connecting the GW with the satellite (in both directions) is named the feeder link. The link connecting the satellite with the user terminal is referred to as user link.

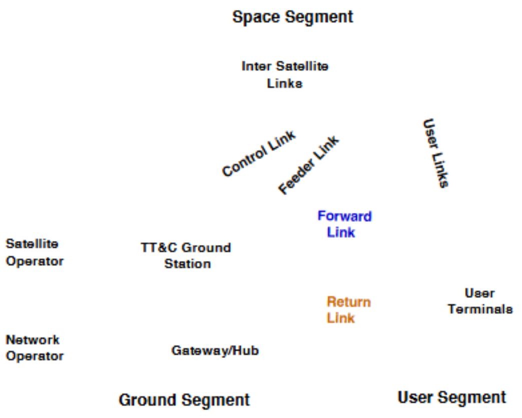

Fig. 1.1. Satellite Communication System Architecture

The control of the satellites is performed by the so-called Telemetry, Tracking and Command (TT&C) stations. The main task of TT&C stations is to monitor the status of the satellite sub-systems, run tests and update the configuration. Such control mechanisms are needed for the maintenance purposes and in order to keep the satellites on the respective orbits.

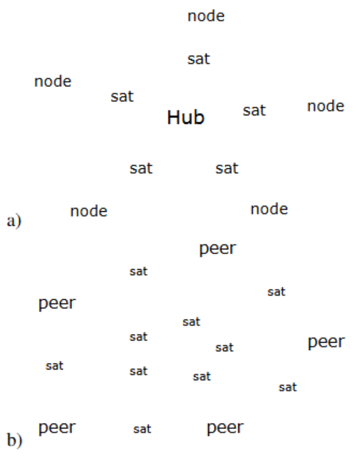

Fig. 1.2. Communication topology: a) star; b) mesh

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Principle of Operation

The operation of satellite communication is based on the principles of electromagnetic wave propagation, which allows signals to travel across vast distances through space. The fundamental idea behind satellite communication is to use satellites in Earth's orbit as relay stations to transmit and receive signals from Earth-based stations. This enables long-distance communication, overcoming the geographical constraints of traditional communication systems. The principle of operation involves several key concepts, including signal transmission, reception, amplification, and retransmission.

At the core of satellite communication is the process of electromagnetic wave transmission. Satellites work by utilizing radio frequency (RF) signals to send and receive data. These RF signals are transmitted from Earth stations to the satellite, which then amplifies and retransmits the signals back to designated ground stations or other satellites.

2.1. Steps Involved in the Principle of Operation:

1. ***Signal Transmission (Uplink):*** The process of satellite communication begins at the Earth station, which generates and sends signals to the satellite. The signal, typically in the form of electromagnetic waves (radio waves or microwaves), is directed towards the satellite. This is referred to as the uplink. The uplink is transmitted through a high-powered antenna to ensure that the signal can cover the vast distance to the satellite in orbit. The frequency used for uplink transmission is typically higher than the downlink frequency to avoid interference between the two channels.
2. ***Reception of Signal by Satellite:*** Once the signal reaches the satellite, it is received by the satellite’s receiver antenna. The satellite’s receiver is tuned to specific frequencies, allowing it to pick up the incoming signal from the Earth station. This is done using a specialized transponder onboard the satellite, which is responsible for receiving, amplifying, and converting the frequency of the received signal for retransmission.
3. ***Amplification and Frequency Conversion:*** After the signal is received, the satellite's onboard transponder amplifies the signal to compensate for any signal attenuation that occurs during transmission. This is a crucial step as signals traveling over long distances through space tend to weaken, and amplification ensures that the signal strength remains strong enough to reach its destination on Earth. The signal is then often frequency-converted to avoid interference with other signals and to ensure efficient use of the frequency spectrum. This conversion process involves shifting the signal to a different frequency range for the downlink transmission.

4. ***Signal Transmission (Downlink):*** Once the signal has been amplified and converted, it is transmitted back toward Earth. This process is referred to as the downlink. The downlink signal is broadcast at a different frequency from the uplink to prevent interference between the two signals. The signal is sent from the satellite to one or more ground stations or other designated receivers on Earth. The satellite's antenna directs the signal to the correct location, ensuring the signal reaches its intended destination.
5. ***Reception on Earth:*** The downlinked signal is received by the Earth station antenna, which is designed to pick up the incoming signal from the satellite. The ground station's receiver processes the signal, extracting the data (such as voice, video, or digital information) and converting it into a usable format for the end-user. In some systems, the data may be routed through fibre-optic cables or other terrestrial networks to ensure the efficient delivery of services such as internet, television, or telecommunications.

2.2. Key Components Involved in Satellite Communication:

1. ***Transponder:*** The transponder is one of the most critical components of a satellite's communication system. It receives the uplinked signal, amplifies it, and often changes its frequency before retransmitting it. A satellite typically has multiple transponders, each tuned to a specific frequency range to handle different communication channels.
2. ***Antennas:*** Antennas play an essential role in both transmitting and receiving signals. The satellite has antennas for receiving signals from Earth and transmitting signals back to Earth. Ground stations also utilize large parabolic dish antennas to focus the electromagnetic waves and ensure the accurate transmission and reception of signals.
3. ***Power Source:*** Satellites depend on solar panels to generate power. The solar panels convert sunlight into electrical energy, which is used to power the satellite's onboard systems, including the communication equipment and propulsion systems. The energy produced is stored in batteries to ensure continuous operation, even when the satellite is in the shadow of the Earth.
4. ***Control System:*** A satellite's onboard control system is responsible for maintaining its orientation in space. This system uses gyroscopes, reaction wheels, or momentum wheels to stabilize the satellite and ensure that its antennas and transponders are properly aligned with Earth stations. The control system also helps the satellite adjust its position in orbit if needed.

2.3. Orbits and Their Impact on Satellite Communication:

The orbit in which a satellite is placed significantly impacts its operational characteristics. There are several types of orbits that satellites can occupy, each with different operational considerations:

1. ***Geostationary Orbit (GEO):*** Satellites in geostationary orbit are positioned approximately 35,786 kilometers above the Earth's equator. These satellites orbit at the same rate as Earth’s rotation, allowing them to remain fixed over a specific point on the Earth’s surface. This makes them ideal for broadcasting and telecommunications, as they can provide continuous coverage of a large area. However, their higher distance from Earth results in higher latency and longer transmission times.
2. ***Low Earth Orbit (LEO):*** LEO satellites operate at altitudes ranging from 160 kilometers to 2,000 kilometers above Earth. These satellites are much closer to Earth, reducing latency and offering faster data transmission speeds. They are often used for Earth observation, scientific research, and remote sensing. However, their coverage area is smaller compared to GEO satellites, requiring a network of LEO satellites to provide continuous global coverage.
3. ***Medium Earth Orbit (MEO):*** MEO satellites typically orbit between 2,000 kilometers and 35,786 kilometers. These satellites strike a balance between coverage area and latency and are often used for navigation systems like GPS. MEO satellites provide more coverage than LEO satellites and less latency than GEO satellites.

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Working of Satellite Communication:

Satellite communication works through a process that involves the transmission, reception, and relay of signals via an artificial satellite orbiting Earth. The communication process relies on the transmission of electromagnetic waves (radio waves or microwaves) between ground stations and satellites, making it possible to communicate over long distances. The overall working of satellite communication involves several stages, with key components working together to ensure effective data transmission and reception.

Here's a detailed breakdown of the satellite communication process:

3.1. Uplink (Transmission from Earth to Satellite):

The communication process begins at the ground station, which generates and transmits signals to the satellite. The uplink process consists of the following steps:

- ***Signal Generation:*** The ground station generates the data to be transmitted. This could be voice, video, or digital data, which is typically encoded into a format suitable for transmission (e.g., modulated onto a carrier frequency).
- ***Signal Modulation**:* The data is modulated using a high-frequency carrier signal to ensure that the data can travel through space. The carrier frequency is typically chosen based on the communication requirements, such as avoiding interference with other signals and optimizing the use of the satellite's available bandwidth.
- ***Transmission via Antenna**:* Once the signal is modulated, it is transmitted via an antenna on the ground station. The ground station uses large parabolic dish antennas to focus the transmitted signals into a beam that will travel toward the satellite. The higher the frequency used in transmission (typically in the microwave range), the greater the distance the signal can cover, and the less susceptible it is to interference.
- ***Signal Propagation**:* The signal travels through the atmosphere and space. Atmospheric conditions (e.g., rain or fog) can sometimes impact the signal's strength, but the microwave frequency used in satellite communication generally penetrates the atmosphere effectively.

3.2. Reception by the Satellite:

Once the signal reaches the satellite, the satellite's onboard systems receive and process it. The reception process involves:

- ***Receiving Antenna**:* The satellite has a receiving antenna (often a large parabolic or phased-array antenna) that is aligned to capture the incoming signal from the ground station. Depending on the satellite's design, it may receive signals from one or more Earth stations simultaneously.

- ***Signal Reception****:* The satellite's receiver is tuned to the appropriate frequency to capture the incoming signal. Satellites are typically designed to handle multiple frequency bands, which allows for greater flexibility in managing communication with various ground stations across different regions.
- ***Signal Filtering and Conversion****:* Upon receiving the signal, the satellite's onboard systems filter out unwanted noise and interference. The signal may also undergo frequency conversion to shift it to a different frequency band that is used for retransmission. This is an essential part of the process to prevent interference between the uplink and downlink frequencies.

3.3. Signal Amplification and Processing:

The signal received by the satellite is generally weak due to the long distance it has travelled through space. To ensure the signal maintains its integrity and strength, the satellite amplifies the signal:

- ***Amplification****:* The satellite uses an amplifier (usually a traveling-wave tube amplifier, or TWT) to boost the signal strength. This amplification compensates for any attenuation (signal loss) caused by the signal's travel through space.
- ***Signal Processing****:* The signal is processed by the satellite's onboard transponder. This processing may involve demodulating the signal to extract the data, and in some cases, it may be necessary to apply error correction techniques.

3.4. Downlink (Transmission from Satellite to Earth):

After the signal is received, processed, and amplified, the satellite then retransmits the signal back to Earth through the downlink process. The downlink consists of the following:

- ***Frequency Conversion****:* The processed signal is converted to a different frequency band for transmission back to Earth, ensuring there is no interference with the uplink signal. In most satellite systems, the downlink operates at a different frequency than the uplink, using frequencies specifically allocated for communication from satellite to Earth.
- ***Signal Transmission****:* The signal is then transmitted from the satellite's onboard transmitting antenna back toward Earth. Depending on the satellite's orbit and the nature of the communication, the satellite's beam is either directed toward a specific ground station or broadcast over a wider area. This transmission is typically done in a highly focused manner, targeting specific geographic regions or areas.
- ***Signal Propagation****:* Just like the uplink signal, the downlink signal travels through space, making its way back to Earth. Due to the vast distance involved, the signal may spread out as it travels, which is why large, highly sensitive antennas are used at the ground station to ensure proper signal reception.

3.5. Reception on Earth (Downlink Reception):

Once the downlinked signal reaches Earth, it is received by a ground station or a receiving antenna. The receiving process consists of:

- ***Reception of the Signal****:* The ground station antenna (often a large parabolic dish) receives the downlink signal from the satellite. The size of the antenna determines the signal strength it can receive; larger antennas can capture weaker signals and are typically used for higher-frequency communications.
- ***Signal Demodulation****:* The received signal is demodulated by the ground station's receiver to extract the data. This step involves reversing the modulation process that occurred at the transmission end, enabling the ground station to retrieve the original information sent from the source.
- ***Data Decoding****:* After demodulation, the data is decoded and processed into the format that can be used by the end-user, such as video display, audio playback, or digital data transfer.
- ***Routing and Distribution****:* In some cases, the ground station may route the data through terrestrial networks (fibre optics, microwave links, etc.) to reach its final destination. For example, a television signal broadcast by satellite may be transmitted to homes via cable systems, or internet data may be routed to local users via Wi-Fi or Ethernet.

3.6. Communication Relays (Cross-Link Satellites):

In some advanced satellite systems, such as multi-satellite networks or constellations, the communication process involves cross-link satellites, which communicate with each other. Instead of the signal going directly from the Earth to the satellite and back, it can be passed between satellites in orbit. This system has advantages, especially for global coverage, as it reduces latency and enhances overall system flexibility. Cross-links are particularly important for Low Earth Orbit (LEO) constellations, where satellites are much closer to Earth and have smaller coverage areas.

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Types of Satellites:

1. **Communication Satellites**: These satellites facilitate telecommunications, broadcasting, and internet services. Examples include geostationary satellites used for television broadcasting and low Earth orbit (LEO) satellites used for internet connectivity.
2. **Weather Satellites**: These are used for weather observation and monitoring of Earth's atmospheric conditions. They help predict weather patterns, track storms, and provide data for climate studies.
3. **Navigation Satellites**: Used for GPS (Global Positioning System) to help with location and navigation for vehicles, ships, and aircraft.
4. **Remote Sensing Satellites**: These satellites capture images and data about the Earth's surface for environmental monitoring, resource management, and agricultural development.
5. **Spy Satellites**: Primarily used for military purposes, these satellites monitor and gather intelligence from specific regions on Earth.

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Advantages of Satellite Communication:

1. **Global Coverage**: Satellites can provide coverage over vast areas, even in remote or difficult-to-reach locations, ensuring that communication is not limited by geographical constraints.
2. **Reliable Communication**: Due to their high altitude, satellites offer stable and consistent communication, minimizing the risk of interference that ground-based systems may face.
3. **Speed**: Satellite communication allows for the quick transfer of information across great distances, facilitating near-instantaneous communication worldwide.
4. **Supports Multiple Applications**: Satellite technology supports a wide range of applications, from military and defence to entertainment, education, and scientific research.
5. **Disaster Relief**: In the event of natural disasters where ground infrastructure may be damaged, satellites provide essential communication capabilities for emergency response and relief efforts.

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Drawbacks of Satellite Communication:

1. **High Cost**: The development, launch, and maintenance of satellites require significant investment, which can be expensive for both private and governmental organizations.
2. **Latency Issues**: Particularly for communication with satellites in higher orbits, signal delay can be a concern. This is more pronounced with geostationary satellites due to their distance from Earth.
3. **Limited Bandwidth**: Satellites, especially those in geostationary orbit, have limited bandwidth, which can lead to congestion, especially during peak usage times.
4. **Weather Dependency**: Severe weather conditions like heavy rain or storms can interfere with satellite signals, especially for high-frequency communications.
5. **Vulnerability to Space Debris**: Satellites in orbit are susceptible to damage from space debris, which is an increasing concern as the number of objects in orbit grows.

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Applications of Satellite Technology:

1. **Telecommunications**: Satellites enable mobile communication, radio and television broadcasting, and broadband internet services, particularly in rural and underserved regions.
2. **Weather Forecasting**: Weather satellites monitor atmospheric conditions, track storm systems, and help in weather prediction and disaster warning.
3. **Global Positioning Systems (GPS)**: Satellites are used for navigation purposes, helping in vehicle tracking, location services, and guiding ships, airplanes, and personal devices.
4. **Military and Defence**: Satellites play a critical role in defence by providing intelligence, surveillance, reconnaissance (ISR), and secure communication for military operations.
5. **Earth Observation**: Remote sensing satellites are used for environmental monitoring, land use planning, disaster management, and agricultural applications.
6. **Scientific Research**: Satellites assist in studying the Earth's atmosphere, outer space, and planetary bodies, contributing to research in space science, geology, and climatology.

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CONCLUSION

Satellite communications have recently entered in a crucial phase of their evolution, mainly motivated by the explosive growth of various Interned-based applications and services, which have triggered an ever increasing demand for broad-band high-speed, heterogeneous, ultra-reliable and low latency communications. Due to their unique features and technical advances in the field, satellites can be a cornerstone in satisfying this demand, either as a stand-alone solution, or as an integrated satellite-terrestrial network. To the end, this paper has captured the latest technical advances in scientific, industrial and standardisation analyses in the domain of satellite communications.

In particular, the most important applications and use cases under the current focus of Satellite Communication research have been highlighted. Moreover, an in-depth literature review has been provided covering the latest Satellite Communication contributions in terms of system aspects, air interface, medium access control techniques and networking. The communication testbeds which have been developed in order to practically demonstrate some of the advanced Satellite Communication concepts are shown. Finally, some important future challenges and their respective open research topics have been described.