SATELLITE COMMUNICATIONS

WHITE PAPER

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Nostradamvs, LLC

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About Nostradamvs, LLC

We are a NY-based company that provides training and consultation services around cutting-edge technologies including 6G systems, wireless communications, artificial intelligence/machine learning, the internet of things (IoT), distributed ledger technology (DLT), network security, and more.

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We provide customized in-person and online training for businesses and organizations looking to empower their employees by enhancing their skill sets.
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Executive Summary

This white paper provides an overview of satellite communication systems, including history, architecture, orbits, frequency planning, satellite communication channels, link budgets, design trade-offs, applications, and future trends. It is intended to serve as an invaluable resource for professionals, researchers, and enthusiasts interested in satellite communications.

The paper presents a brief review of the history of satellite communication systems. There is a discussion of the early developments, such as the launch of the first artificial satellite, Sputnik, and the subsequent advancements leading to the creation of geostationary satellites. It also highlights the milestones that have shaped satellite technology throughout its evolution.

As a next step, we focus on the architecture of satellite communication systems, including an overview of the ground segment, the space segment, and the control segment. Afterwards, the satellite orbits are classified and described. The purpose of this section is to summarize the characteristics of geostationary orbit, medium Earth orbit, and low Earth orbit. Each orbit is discussed in terms of its advantages and limitations, emphasizing its suitability for a variety of applications such as telecommunications, broadcasting, and global positioning. The Lagrange points, which are mainly used by spacecraft for radioastronomy and remote sensing, are also briefly discussed.

This paper discusses the importance of frequency planning in satellite communications, and the allocation and usage of frequency bands for satellite services in accordance with international regulations and coordination efforts. In addition, challenges associated with spectrum congestion and interference mitigation are briefly discussed.

The white paper presents a detailed analysis of the satellite communication channel, which encompasses both the uplink and downlink. An overview of the key parameters affecting channel performance is provided, including signal power, modulation schemes, and error correction coding. The study emphasizes the need for efficient modulation and coding techniques to optimize bandwidth utilization and enhance data reliability.

It is crucial to analyse the link budget in order to design and evaluate satellite communication systems. The paper provides an overview of the link budget concept, which involves calculating the power budget for signal transmission and reception. The factors that contribute to link performance, including transmit power, path losses, atmospheric effects, antenna gains, noise as well as frequency, data rate, modulation and coding schemes.

Trade-offs in satellite communications are examined in light of diverse requirements and constraints. A discussion of the choices that must be made regarding satellite size, power, coverage area, data rate, and cost is provided in the paper. Providing guidance for decision-making, it discusses the trade-offs between system complexity, performance, and operational considerations.

Satellite communications have a wide range of applications and are constantly evolving. The paper examines the current and emerging applications across numerous sectors, such as telecommunications, broadcasting, remote sensing, navigation, disaster management, and Internet of Things connectivity. It highlights the role that satellite technology plays in bridging the digital divide and enabling global connectivity.

The paper discusses future trends in satellite communications, and advances such as high-throughput satellites, satellite constellations, sustainable satellite operations, and hybrid networks. A discussion of emerging technologies, such as software-defined satellites, integration of satellite communications with 5G and beyond, and optical communications, is also provided. Satellite communications have a significant role to play in supporting the growing demand for connectivity in an increasingly interconnected world.

As a valuable source of information, it enables individuals and organizations involved in the satellite communication industry to gain a deeper understanding of the underlying principles and facilitate informed decision-making.

1. Historical Background

The history of satellite communications (SATCOM) started with an article published by A. C. Clark in 1945 [1]. He stated that an object can continue to move in an orbit around the Earth as long as the gravitational force between the object and the Earth is counterbalanced by the centripetal force on the object in orbit. Satellite communications have evolved from the launch of the first satellite Sputnik-1 by the Soviet Union in 1957, marking the beginning of satellite communications. The first commercial TV broadcast across the Atlantic Ocean was made possible by the Telstar 1 satellite, which was launched in 1962.

Space exploration and telecommunications entered a new era with complex network of geostationary and low-Earth orbit satellites of today. The use of satellites for telecommunications, Internet access, radio astronomy, navigation, and remote sensing has increased exponentially over time, giving us new possibilities for accessing information.

2. Architecture of SATCOM Systems

A SATCOM system consists of ground, space and control segments. Control segment supports payload operations (user communications) by controlling the operation of the SATCOM system. Ground segment may consist of multiple satellite ground terminals (SGTs). In an SGT transmitter, baseband signals are multiplexed, encoded and modulated. Digital modulation schemes employed are mainly M-PSK (M-ary phase shift keying) and M-QAM (M-ary quadrature amplitude modulation). Then, the intermediate-frequency (IF) signals are up-converted to RF frequencies (e.g., 14 GHz for digital signals and 6 GHz for analog signals). Following band-pass filtering (BPF), they are amplified by a high-power amplifier (HPA) and transmitted by the SGT transmit antenna in the uplink. The signals transmitted by the satellite are received by an SGT receiver, which consists of a BPF, a low-noise amplifier (LNA), RF-to-IF down-convertor, demodulator, decoder and de-multiplexer [2]-[4].

The space segment (satellite) acts as a relay between transmitting and receiving SGTs. Therefore, a SATCOM system works basically as a relay network. If a satellite transponder frequency-converts and retransmits the received signals, then it is called as a bent-pipe satellite. Bent-pipe satellites operate as an amplify-and-forward (AF) relay (See [5] Section 14.1). In such systems, the dual-hop satellite link acts as a single link, and the overall SNR is determined jointly by uplink and downlink SNRs (see [5], (14.8)). In addition to the frequency conversion, if received signals undergo signal processing, such as (de)multiplexing, and (de)modulation, then the satellite is said to be regenerative.

Block diagram of a bent-pipe transponder operating in the 14/12 GHz band is shown in Figure 1. The satellite relay filters, amplifies, and frequency-converts the received uplink signals (ground-to-satellite) and transmits them back in the downlink (satellite-to-ground). The LNA onboard the satellite is usually designed to limit the power received (due to signal and/or interference) on the uplink, when the power at the receiver input exceeds a threshold level. This serves to purpose of limiting the jammer/interference power to dominate the power received by the satellite and to prevent the jammer signals from damaging the sensitive onboard receivers.

On the other hand, the high-power amplifier (HPA) (solid state HPA, traveling wave tubes, TWT, or klystron) is a major contributor of intermodulation (IM) distortion. Signals of different frequencies sharing the same transponder bandwidth interfere with each other and cause in-band as well as out-of-band interference. This wastes the very precious satellite transmit power. Therefore, non-linear amplifiers must be designed carefully and be forced to operate in the linear range to limit the IM distortion. New, e.g., semiconductor technologies are promising for the design of linear power amplifiers.

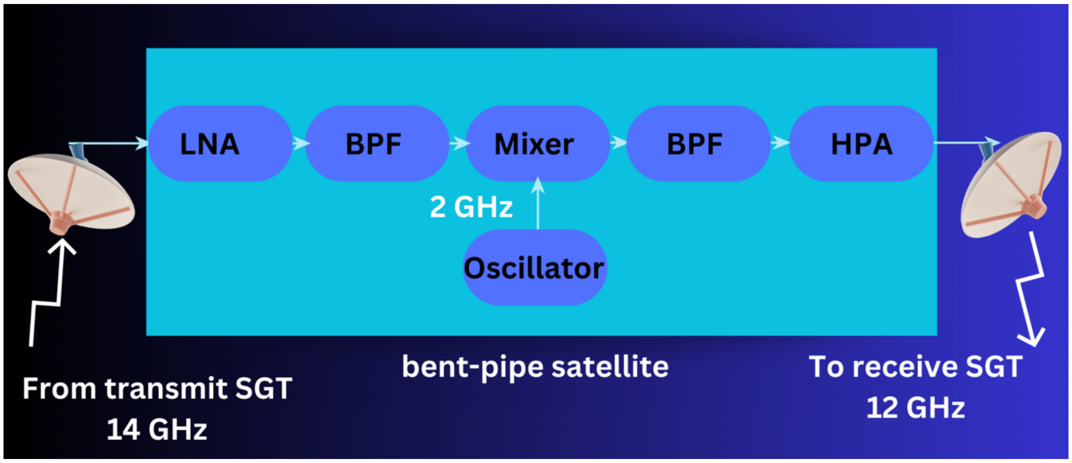

Figure 1. Block diagram of a bent-pipe transponder operating in the 14/12 GHz band.

A satellite may also be designed to operate as a decode-and-forward (DF) relay, where the uplink signals are demodulated and decoded at the satellite receiver. After re-modulation and encoding, they are forwarded to the SGT receiver via the downlink at downlink carrier frequency, which is different from the uplink carrier frequency. These, so-called regenerative, satellites are more capable compared to the bent-pipe satellites. However, the use of sensitive electronic components onboard the satellite for signal processing (demodulation, decoding, remodulation and encoding) carries a significant risk factor for the satellite life-time in a hostile nuclear radiation environment. Up- and downlinks of SATCOM systems with regenerative satellites are uncoupled from each other, that is, up- and downlink performances are not related to each other. Uplink and downlink parameters, such as modulation type, coding, multiplexing, data rate etc., may be selected separately.

The electrical power on board the satellite is commonly generated by using solar panels. Since the efficiency with which the solar energy is converted into electrical energy does not exceed a few tens of percent, large solar panels are needed to generate electrical power levels needed by the satellite. On the other hand, due to aging and nuclear radiation by the sun, the capacity of solar panels to generate electricity decreases with time. Consequently, the useful lifetime of satellites is generally limited mainly by the lifetime of the solar panels and some other sensitive electronic components. Only a fraction of the electrical power generated onboard the satellite is allocated to the communication payload, since electrical power is also needed for regulating the temperature in the satellite against wild temperature differences between day and night, as well as for satellite positioning and control, and the operation of electronic equipment. Since the weakest node of a SATCOM system is the satellite, and a malfunction onboard the satellite cannot be repaired once it is launched, reliability engineering plays an important role in the satellite design, for example, the use of redundant components, radiation shielding and hardening.

3. Satellite Orbits

Consider that a satellite of mass *m* is orbiting around the Earth of mass *M*, with a velocity *v* along a circular orbit of radius *r* centered around the Earth. For the considered orbital altitudes, the effects of gravitational forces from sun, moon, and other stars are assumed to be negligible. The satellite will continue to revolve along its orbit as long as the gravitational force is equal to the centripetal force (see Figure 2):

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \tag{1}$$

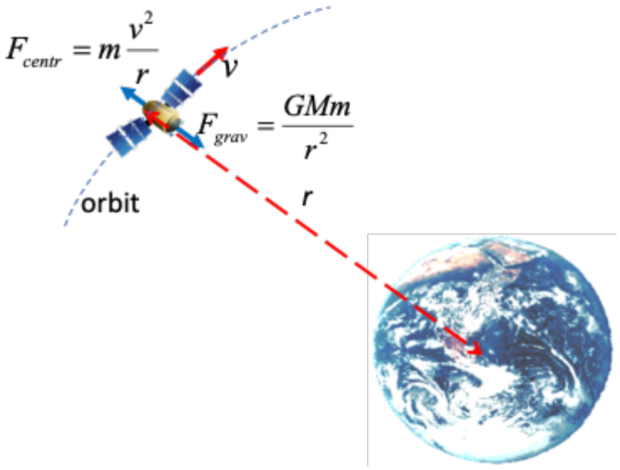

Figure 2. Centripetal and gravitational forces must be equal to each other for a satellite to remain in orbit

Note that the linear velocity *v* of the satellite along the orbit is related to its period *T*, time required to make a complete revolution around the Earth, by $v = 2\pi r/T$. Inserting *v* into the above equation, one may express the period as a function of the orbital radius:

$$T = 2\pi\sqrt{\frac{r^3}{GM}} \tag{2}$$

where $GM = 3.986 \times 10^{14}$ (m^3/s^2), and *G* denotes the gravitational constant of the Earth. Note that *r* can be written as $r = R + H$, where *R*=6371 km denotes the Earth's radius, and *H* stands for the altitude of the satellite above the Earth's surface. Table 1 shows that the time required by the satellite to make a complete revolution around the Earth increases with the satellite's altitude. The period of a satellite is 1 hour 34 minutes at an altitude of 500 km above the Earth's surface, whereas it is equal to 24 hours (one day) for a satellite at geostationary orbit, i.e., 36000 km above the Earth's surface. Also note that the linear velocity *v* of a satellite along its orbit is inversely proportional to the square root of the distance from the center of the Earth, $v = \sqrt{GM/r}$ (see (1)). This simply means that a satellite has to move faster as its altitude becomes lower.

Table 1. Dependence of the period of a satellite with its altitude above Earth's surface.

Altitude above Earth's surface, *H* (km)	Velocity *v* (km/s)	Period, *T*	No. of revolutions per day	Orbit type
500	7.617	1 hour 34 min.	16	Low-Earth orbit
1000	7.354	1 hour 45 min.	14	Low-Earth orbit
2000	6.900	2 hours 7 min.	11	Low-Earth orbit
2500	6.703	2 hours 19 min.	10	Medium-Earth orbit
20000	3.870	12 hours	2	Medium-Earth orbit
36000	3.072	24 hours	1	Geostationary orbit

Satellites may be classified by the altitude of their orbits above the surface of the Earth, as low-Earth orbit (LEO), medium-Earth orbit (MEO), and geostationary orbit (GEO).

3.1 Geostationary Orbit

The rotation period of a GEO satellite, which is located at 36,000 km altitude, is 24 hours. A GEO satellite appears stationary for users on the Earth's surface, since the angular velocities of a GEO satellite and the Earth are the same. GEO satellites are mainly used for telecommunications, and radio and TV broadcasting.

The advantages of GEO satellites may be summarized as follows [2]-[4]:

a) They remain stationary when viewed by an SGT; one does not need tracking equipment and switch-over from one satellite to the other.
b) They are available to all SGTs within their coverage area for 100% of the time.
c) A GEO satellite can have a coverage area of ~40% of the Earth's surface. Therefore, three GEO satellites with 120 degrees separation between them can cover the whole Earth, excluding polar regions with latitudes higher than 70 degrees.
d) Doppler shift is negligible

The disadvantages of GEO satellites are

a) They require sophisticated and heavy propulsion devices onboard for orbital correction.
b) They have longer propagation delay; the round-trip propagation delay between two SGTs via a GEO satellite is ~500 ms. This is unacceptably long for voice communications and live broadcasting
c) They require higher transmit powers and more sensitive repeaters to compensate for the higher free-space losses.
d) To launch a GEO satellite into orbit is expensive and orbital correction is not easy.

The coverage area of GEO satellites is determined by the beamwidth (inversely proportional to antenna electrical size) and the shape of the antennas onboard the satellite. Coverage area may be tailored by shaping the contour of an antenna. The beams may be classified as spot, regional, hemispherical and global with increasing coverage areas. A GEO satellite with a half-power beamwidth of 17.8 degrees (global beam) can cover approximately 40% of the Earth's surface. Specific regions on the Earth's surface with heavy traffic are covered by spot beams, that have narrow beamwidths.

Different transponders onboard the satellite may use the same carrier frequencies to serve different regions of the coverage zone, hence space division multiplexing (SDM). In SDM, the same frequency band is reused by directing onboard antennas into different regions in the coverage zone. These systems make best use of the available frequency spectrum by employing SDM and dual polarization. Thus, spectrum efficiency is improved by using the same downlink frequencies to serve different regions in the coverage area. Similarly, the same uplink frequencies are used to receive uplink signals from geographically different regions by using various onboard receive antennas.

Dual polarization implies that the system capacity may be doubled by transmitting and receiving signals by antennas in two orthogonal polarizations, for example, vertical and horizontal (linear) polarizations, or right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP). Slight depolarization due to the channel and/or the antennas causes interference between orthogonally polarized signals. However, techniques are available to alleviate the harmful effects of depolarization due the channel and the antennas. Dual polarized systems are widely used in civilian SATCOM systems.

3.2 Medium-Earth Orbits

The altitudes of MEO satellites vary between 2000-35800 km and they operate mainly in the 1.2-1.66 GHz band. Geo-positioning systems like GPS, GLONASS, Galileo, and BeiDou use MEO with periods in the order of 12 hours.

3.3. Low-Earth Orbits

The term LEO usually refers to orbits with altitudes not exceeding 2000 km. LEO satellites are mostly used for Internet services, remote sensing, and military applications. As LEO satellites have lower altitudes compared to GEO satellites, they have to move faster to compensate for the increase in the gravitational force (see Table 1). Therefore, received signals will experience higher Doppler frequency shifts. Therefore, LEO satellites are not synchronous and are visible to users on the Earth's surface for short durations.

These satellites are cheap because they do not have much protection and weigh only several hundred kilograms. Thousands of LEO satellites are needed for global coverage since LEO satellites can have small coverage areas. The period of rotation in LEO is shorter than 24 hours, the period for synchronous orbit. In circular orbit, the speed of rotation is constant, whereas it varies in elliptical orbits. Since LEO satellites are not stationary, and have very large speeds, they can serve an SGT during a limited time as they are visible by the SGT. However, as the satellite handling the traffic leaves the visibility region of an SGT, the traffic may be handed over to the next satellite entering into the visibility region (see Figure 3). The SGTs operating with LEO satellites require complicated and expensive tracking equipment to track the satellite as it passes overhead. However, such satellites do not need complex equipment for orbital correction.

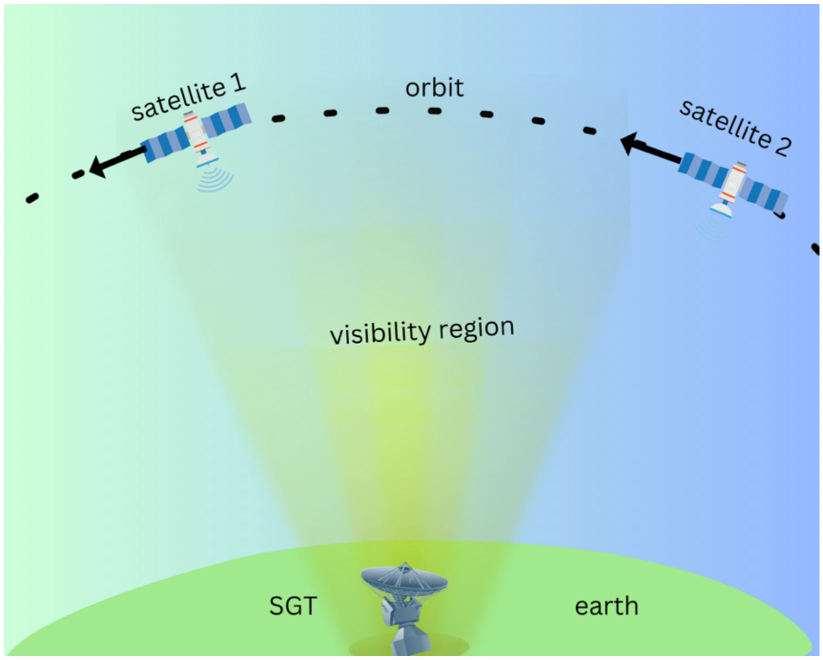

Figure 3. Visibility region of a satellite ground terminal

In non-synchronous orbits, the satellite position with respect to a fixed SGT changes continuously as it rotates around the Earth. Non-synchronous orbits in the equatorial plane, and in planes inclined with respect to the equator are shown in Figure 4. Large numbers of LEO satellites ensure continuous global coverage at all times. They are especially useful in geographic areas not covered by cellular networks, as well as during natural disasters and war when cellular networks are disabled. Constellation of LEO satellites in inclined orbits can also provide coverage for polar regions, oceans, forests, deserted areas, and mountainous regions, which are not covered by cellular systems.

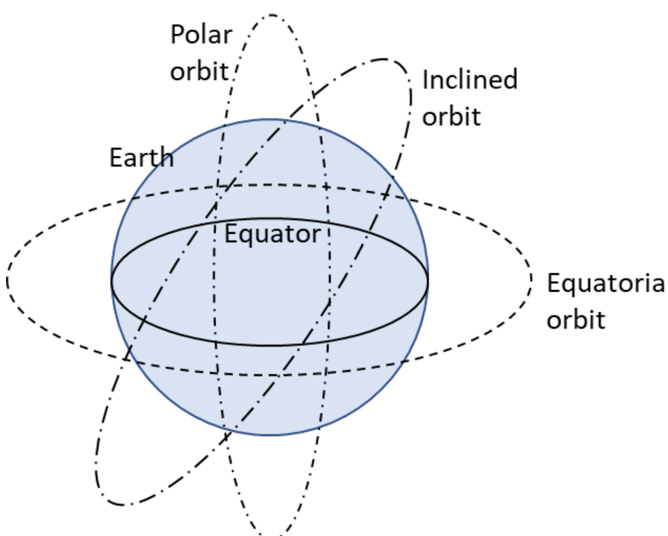

Figure 4. Equatorial (circular), inclined and polar orbits

Inclined orbits provide better coverage of the regions of higher latitudes. Angular velocity of a satellite in elliptical orbit is slowest at its apogee, i.e., when it is farther away from the Earth. However, the speed of satellite is higher at its perigee, i.e., when it is closer to Earth. Therefore, a satellite remains visible over higher latitude regions for longer durations of time if the apogee is placed above these regions. Military satellites may also use such elliptical orbits. Countries like Russia and Canada have satellite communication systems with polar elliptical (Molniya) orbit to serve their citizens living in the polar regions. The Molniya orbit has an inclination of 63.4^0, and a period of 12 hours.

LEO satellites, which generally operate in the 1.0-2.5 GHz frequency range, have lower free-space path losses compared to MEO- and GEO-satellites. This implies lower transmit power, smaller antennas and less weight. However, they need complex equipment for handover and Doppler correction.

3.4 Sub- and Super-Synchronous Orbits

The satellites may also operate at orbital heights between 30400-40000 km above Earth in so-called near-synchronous orbits. When the orbital height is slightly lower than 35680 km, the orbital period is shorter than 24 hours, Earth's rotational period, and the satellite moves slowly around Earth in a west-to-east direction. This type of orbit is called as sub-synchronous. If the satellite altitude is higher than 35680 km, the satellite's orbital period is longer than 24 hours, and the satellite will appear to move from east-to-west.

Satellites orbiting close to Earth (LEO) suffer from atmospheric drag and Earth's magnetic field. Primary disturbing forces for GEO satellites are gravitation of the sun and the stars. The orbits are normally designed assuming that the Earth is perfectly spherical and there are no external forces other than the Earth's gravitation acting on the satellite. In practice, deviations from the nominal orbits are corrected by using onboard equipment.

3.5 Lagrange Points

Lagrange points are named in honor of Italian-French mathematician Joseph-Louis Lagrange. At the Lagrange points, the gravitational pull of two large masses (like Sun and Earth, or Earth and Moon) precisely equals the centripetal force required for a small object (e.g., satellite) to orbit in a constant pattern with them. Small objects placed in orbit at Lagrange points are in equilibrium in at least two directions relative to the center of mass of the large bodies. The Lagrange points are attractive for uses in space exploration. The spacecraft located at these points reduce fuel consumption as few orbit corrections are needed to maintain the desired orbit.

There are five such points, labelled L_1 to L_5, all in the orbital plane of the two large bodies, for each given combination of two orbital bodies (see Figure 5).

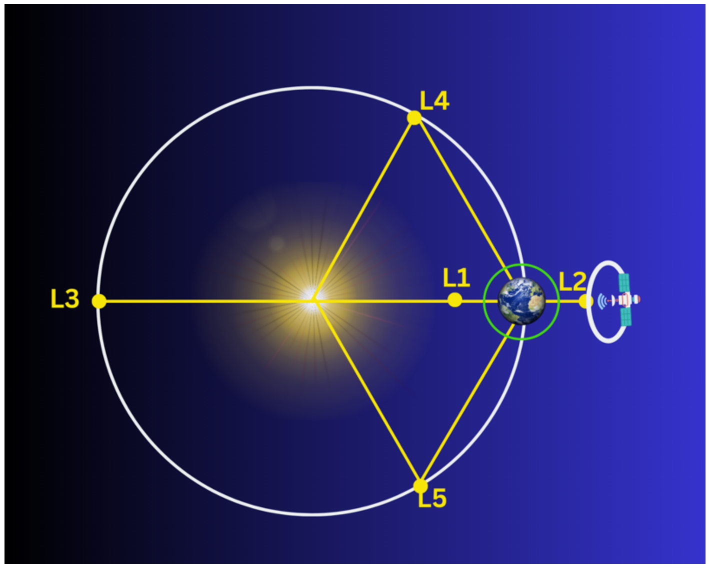

Figure 5. Lagrange points

3.5.1 L_1 Point

The L_1 point lies on the line between centers of the Sun and the Earth. For a satellite at L_1 point, Earth's gravity counteracts some of the Sun's pull on the object, and therefore increases the orbital period of the object. The closer to Earth the satellite is, the greater this effect is. At the L_1 point, the orbital period of the object becomes exactly equal to Earth's orbital period. L_1 is about 1.5 million kilometers from Earth. The L_1 point of the Earth-Sun system provides an uninterrupted view of the Sun and is currently home to the Solar and Heliospheric Observatory Satellite SOHO.

3.5.2 L_2 point

The L_2 point lies on the line through the two large masses beyond the smaller of the two. Here, the gravitational forces of the two large masses add up and balance the centrifugal effect on a body at L_2. On the opposite side of Earth from the Sun, the orbital period of an object would normally be greater than that of Earth. However, the extra pull of Earth's gravity decreases the orbital period of the object, and at the L_2 point that orbital period becomes equal to Earth's. L_2 is ideal for astronomy because a spacecraft is close enough to readily communicate with Earth, can keep Sun, Earth and Moon behind the spacecraft for solar power and (with appropriate shielding) provides a clear view of deep space for our telescopes. For example, the James Webb Telescope is designed to operate near the Earth–Sun L_2. Like L_1, L_2 is about 1.5 million kilometers away from the Earth.

4. Frequency Planning

The frequency spectrum, which is shared with terrestrial systems, is a scarce and valuable resource. Therefore, in designing SATCOM systems, care must be taken to avoid interference between terrestrial and other satellite networks. This is achieved in the international arena by careful frequency planning for different terrestrial and satellite services.

Geostationary satellites share a limited space and frequency spectrum within a given arc of the geostationary orbit. Satellites operating at or near the same frequency must be sufficiently separated in the geostationary orbit to avoid interference in both up- and downlinks. The required spatial separation is determined by the following parameters:

a) Beamwidth, and sidelobe level of both the SGT and satellite antennas.
b) RF carrier frequency
c) Acceptable interference limits
d) Transmit carrier power
e) Encoding and modulation technique used.

Generally, 1^0-4^0 spatial separations are used between GEO satellites.

Frequency allocation for SATCOM systems by the World Administrative Radio Conference (WARC) is shown Table 2 [4]:

Table 2. Frequency allocation by WARC [4]

Frequency band (GHz)				Bandwidth (GHz)
Band	Uplink	Cross-link	Downlink	
C	5.9-6.4	-	3.7-4.2	0.5
X	7.9-8.4	-	7.25-7.75	0.5
Ku	14-14.5	-	11.7-12.2	0.5
Ka	27-30	-	17-20	-
-	30-31	-	20-21	-
Q	-	-	40-41	1.0
-	-	-	41-43	2.0
V	50-51	-	-	1.0
(ISL)	-	54-58	-	3.9
-	-	59-64	-	5.0

The uplink carrier frequency is always chosen to be higher than the downlink frequency. This is to exploit higher antenna gains at the satellite with smaller antenna sizes, because of high launching costs of large and heavy satellite antennas. On the downlink, one always has the flexibility of using larger antennas. On the other hand, the separation between up- and downlink frequencies is chosen to be sufficiently far to avoid coupling of the downlink signals to the uplink receiver antenna onboard the satellite.

6/4 GHz band is allocated to analog SATCOM systems while 14/12 GHz band is for digital SATCOM systems. X band is dedicated to military SATCOM systems. Extra-high frequency (EHF) band (30 GHz-300 GHz) is to be used by next-generation commercial SATCOM systems. The SATCOM systems evolve to use higher carrier frequencies. Intersatellite links (ISLs) around 60 GHz exploit the absorption of the SATCOM signals by oxygen to avoid interference to/from ground-based systems. Optical links are actually used more for satellite control, but they offer high potential for wide-bandwidth communications. Note however that optical links may be adversely affected by atmospheric constituents.

The GEO satellite services are classified as

a) Fixed-satellite services (FSS): Between fixed or transportable SGTs located at fixed geographical points on Earth.
b) Broadcast services: For wide-area coverage by radio and TV transmitters
c) Mobile communications: Via satellites for communications with aircraft, ships and SGTs)
d) Intersatellite: In some systems, intersatellite links (ISLs) are used for coordination between satellites in orbits. The frequencies used for ISLs are chosen so that they can neither be intercepted nor be jammed from the Earth’s surface.

5. The SATCOM Channel

The SATCOM channel, basically a line-of-sight (LOS) channel, may be modelled as a function of frequency, orbital characteristics and the user mobility. The link between transmitter and receiver may be disturbed by the total electron content (TEC) of the ionosphere in lower frequency bands, the scattering from obstacles in the first Fresnel zone, and the Doppler shift due to relative speeds of satellites and SGTs. Nevertheless, the noise and interference near SGTs leads to multipath fading. In addition, the shadowing plays a dominant role in the channel modeling when the LOS between the SGTs and the satellite are obstructed by high-rise buildings, mountains, trees etc. For observation points close the ground terminal, the height of the n^{th} Fresnel zone is proportional to $f^{-1/2}$, hence the channel looks more like a free-space channel at higher carrier frequencies (see [5], (3.9)). Then, the obstructions near the SATCOM link do not affect the budget link considerably unless they are very close to the SGT. This becomes a serious issue when, for example, users are in a street with high-rise buildings in metropolitan areas.

As the carrier frequency increases, above several GHz, the TEC of the ionosphere ceases to play a significant role in signal propagation. Then, the refraction and the depolarization induced by TEC may be ignored (see [5], Section 3.2). The atmospheric attenuation of SATCOM signals is due to the absorption of the energy of electromagnetic waves by the gaseous constituents of the atmosphere and the water vapor. Then, electromagnetic waves transfer part of their energy to heat the air in the propagation path. Atmospheric attenuation changes with frequency, elevation angle (minimum in zenith direction and becomes higher as the elevation angle decreases), and altitude (due to changes in pressure, temperature, and humidity). Atmospheric absorption, which peaks at 22 GHz due to absorption by water vapor and 60 GHz due to oxygen, can be ignored below 10 GHz (see [5], Figures 3.23 and 3.24). The attenuation of SATCOM signals by precipitation (rain, snow, fog, etc.) can be ignored below 5 GHz. However, at higher frequencies, the rain attenuation may cause serious impairments in SATCOM links, especially during heavy rains and in tropical areas. The links are then required to operate with appropriate rain margins (see [5], Figure 3.26).

The receive antenna noise onboard the satellite is composed of the low noise levels collected by the antenna sidelobes from the cold space environment (~4K) and the higher noise levels collected by the satellite receive antenna looking at the warm Earth (of 290K on the average). On the other hand, the noise of the SGT receiver is collected by the sidelobes looking at the warm ground (~290K) and the main beam looking at the clear sky (~4K) (see [5], Example 4.5, and Figures 4.19 and 4.20).

The Doppler shift observed in a channel is directly proportional to the carrier frequency and the relative movements of the transmitter and receiver. Since GEO satellites look stationary to SGTs, they do not contribute to the Doppler shift; the observed Doppler shift may be due to either the time-variations in the channel and/or the mobility of the SGT. MEO and LEO satellites do not look stationary to an SGT; therefore, the Doppler shift observed in such channels may result from satellite movement, the propagation medium and/or the mobility of the SGTs. As the satellite altitude decreases, the satellite velocity increases and the Doppler shift due to satellite velocity may reach very high values and correction of the received signal frequency may be challenging.

Multipath fading in a SATCOM channel may be modelled by Rayleigh, Nakagami-m, Rice or

Gamma distributions [6]-[12]. The shadowing due to high-rise buildings, hills etc., blocking the LOS, is usually accounted for by log-normal distribution. In combined fading and shadowing channels, the mean value of the fading distribution, representing the local-mean value of the faded signal, undergoes shadowing. The channel with combined Rayleigh fading and log-normal shadowing is referred to as Loo channel [6]. Since this model is analytically difficult to analyze [6], Gamma model (see [5], Section 11.3.5) may be preferred for the sake of easiness. Shadowing in SATCOM channels is usually classified as light, or heavy. The classification is based on the mean and standard deviation of the shadowing [6].

6. Link Budget

Link budget calculations are important in the system design and to ensure satisfactory performance of operating SATCOM systems. We now formulate the link budgets for bent-pipe and regenerative satellites, assuming that both up- and downlinks suffer Rayleigh fading. Figure 6 shows the block diagram of a SATCOM system with appropriate system parameters.

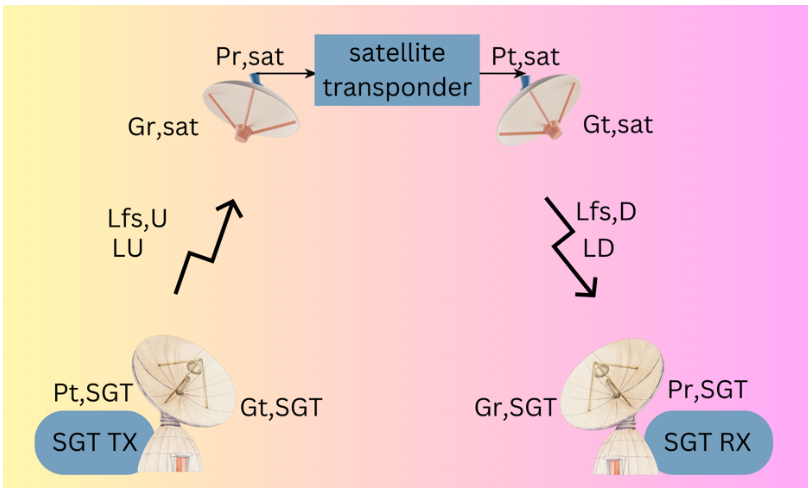

Figure 6. Block diagram of a SATCOM system with some system parameters

6.1 Bent-pipe satellites

A bent-pipe satellite basically acts an AF relay. A bent-pipe satellite band-pass filters and amplifies the received uplink signals, then frequency converts to downlink frequencies, band-pass filters, amplifies using a high-power amplifier and transmits (see Figure 1).

The E_b/N_0 at the satellite receiver (in the uplink) is given by ([5], (4.65))

$$\gamma_1 = \frac{E_{b,sat}}{N_{0,sat}} = \frac{P_{t,SGT}\, G_{t,SGT}}{k\, R_{b,U} L_U\, L_{fs,U}} \frac{G_{r,sat}}{T_{S,sat}} \tag{3}$$

where

$E_{b,sat}$	Energy per bit received by the satellite
$P_{r,sat}=E_{b,sat}\,R_{b,U}$	Signal power received by the satellite. Uplink bit rate is denoted by $R_{b,U}$
$N_{0,sat}$	Noise PSD at the satellite receiver system

$EIRP_{SGT} = P_{t,SGT}\, G_{t,SGT}$	Effective isotropic received power (EIRP) of SGT transmitter (the product of transmit power and antenna gain of the SGT transmitter)
$G_{r,sat}/T_{S,sat}$	The figure-of-merit of the satellite receiver (defined as the ratio of satellite receiver antenna gain to the satellite receiver's effective noise temperature)
$k = 1.38\times 10^{-23}\,(J/K)$	Boltzmann constant
$L_U > 1$	Uplink system losses
$L_{fs,U} = \left(4\pi d_U/\lambda_U\right)^2$	Uplink free-space loss (d_U: uplink range, $\lambda_U = c/f_U$: wavelength)

The E_b/N_0 at the SGT receiver (in the downlink) is given by ([5], (4.65))

$$\gamma_2 = \frac{E_{b,SGT}}{N_{0,SGT}} = \frac{P_{t,sat}\, G_{t,sat}}{k\, R_{b,D} L_D\, L_{fs,D}} \frac{G_{r,SGT}}{T_{S,SGT}} \tag{4}$$

where

$E_{b,SGT}$	Energy per bit received by the SGT receiver
$P_{r,SGT}=E_{b,SGT}\, R_{b,D}$	Signal power received by the SGT. Downlink bit rate is denoted by $R_{b,D}$
$N_{0,SGT}$	Noise PSD at the SGT receiver system
$EIRP_{sat} = P_{t,sat}\, G_{t,sat}$	EIRP of the satellite transmitter (the product of transmit power and antenna gain of the satellite transmitter)
$G_{r,SGT}/T_{S,SGT}$	The figure-of-merit of the SGT receiver (defined as the ratio of SGT receiver antenna gain to the SGT receiver's effective noise temperature)
$L_D > 1$	Downlink system losses
$L_{fs,D} = \left(4\pi d_D/\lambda_D\right)^2$	Downlink free-space loss (d_D: uplink range, $\lambda_D = c/f_D$: wavelength)

The equivalent E_b/N_0, γ_{eq}, of a dual-hop bent-pipe SATCOM link may be expressed as ([5], (14.8))

$$\gamma_{eq} = \frac{1}{\gamma_1^{-1} + \gamma_2^{-1}} = \frac{\gamma_1\,\gamma_2}{\gamma_1 + \gamma_2} \tag{5}$$

One may observe from (5) that γ_{eq} is symmetrical with respect to γ_1 and γ_2. Also note that γ_{eq} approaches $min(\gamma_1, \gamma_2)$, as one of them becomes much lower compared to the other. Since the weakest link determines the system performance, E_b/N_0's of uplink and downlink channels must be balanced in order to maximize γ_{eq}.

Uplink and downlink losses due to rain and/or multipath effects are random. Therefore, we assume that γ_1 and γ_2 have Rayleigh distributions:

$$f_{\gamma_i}(\gamma) = \frac{e^{-\gamma/\overline{\gamma}_i}}{\overline{\gamma}_i} \quad \gamma \geq 0, \quad i = 1,2 \tag{6}$$

where $\overline{\gamma}_i, i = 1,2$ denote the mean values of $\gamma_i, i = 1,2$.

For $\overline{\gamma}_1 = \overline{\gamma}_2$, it has been shown that $\overline{\gamma}_{eq} = \overline{\gamma}_1/3$ ([5], (14.16) and Figure 14.4). Hence, mean equivalent E_b/N_0, $\overline{\gamma}_{eq}$, of a bent-pipe satellite link with $\overline{\gamma}_1 = \overline{\gamma}_2$, is equal to 1/3 of one of the mean E_b/N_0's. This implies that the mean equivalent E_b/N_0 of a bent-pipe satellite link is 4.78 dB worse compared to a single-hop channel with mean $E_b/N_0 = \overline{\gamma}_1$. The $\overline{\gamma}_{eq}$ will be even lower if the mean E_b/N_0*'s* are not balanced; this implies further performance degradation in the considered SATCOM link. Bent-pipe SATCOM systems usually use automatic transmit power control systems to prevent impairments, for example due to heavy rain, in up- and downlink channels.

6.2 Regenerative satellites

Regenerative satellites act like DF relays. Following band-pass filtering, and amplification of the received uplink signals, a regenerative satellite demodulates them to mitigate the effects of noise, fading and interference. Later it carries out frequency down-conversion, re-modulation, band-pass filtering, and high-power amplification for downlink transmission. Regenerative satellites, with uncoupled up-and downlinks, offer significant performance improvement and operational flexibility. Then, downlinks may be designed independently from the uplinks, leading to the use of spot beams and space-division multiplexing. However, the vulnerability of onboard electronic equipment to nuclear radiations is a serious issue and requires careful shielding and hardening.

Here we consider a regenerative satellite communication system where the SGTs and the satellite are equipped with single transmit and receive antennas. As in AF relaying operating in time-division multiplexing (TDM) mode, the transmission period is divided into two-equal duration time slots. During time slot 1, transmitting SGT transmits and satellite receiver performs maximum-likelihood (ML) detection of M-PSK or M-QAM signals. The uplink bit error performance is determined only by the uplink $E_b/N_0, \gamma_1$. The detected symbols are re-modulated and subsequently transmitted during time slot 2. If the detection of an uplink signal is erroneous, then the signal transmitted in the downlink will also be in error. The signal received at the receiving SGT will then be correct only if the receiving SGT also makes an erroneous decision. If the satellite receiver makes a correct decision, then the error performance of the downlink will be determined by only γ_2.

Regenerative satellite (DF) links perform better than bent-pipe (AF) links, as expected. For $\overline{\gamma}_1 = \overline{\gamma}_2 = 10\ \mathrm{dB}$, mean equivalent E_b/N_0, $\overline{\gamma}_{eq}$, for processing satellite systems was reported to be 4.66 dB higher compared to bent-pipe relaying. Hence, the mean equivalent E_b/N_0 of a processing satellite link is only 4.78-4.66=0.12 dB worse compared to a single-hop channel with mean E_b/N_0= $\overline{\gamma}_1$. The performance difference becomes less at lower values of $\overline{\gamma}_1, \overline{\gamma}_2$, since the DF protocol suffers more errors in detecting the uplink signals ([5], Figure 14.30).

7. Design Tradeoffs

One may observe from (3) and (4) that, $\gamma_1$and γ_2 are directly proportional to the transmit power and antenna gains, but inversely proportional to the bit rate, channel losses, and received noise power, i.e., system noise temperature. Since antenna gains and the free-space loss L_{fs} are proportional to the square of the frequency (see [5], (2.101), and (2.115)), SATCOM links operating at higher carrier frequencies can use lower transmit powers, smaller antenna sizes (antenna gain is proportional to square of the product of antenna size and frequency) and/or higher bit rates. The carrier frequency plays a very important role in the design of SATCOM systems, though frequency allocation is subject to international regulations. A good design of SATCOM systems is clearly based on careful tradeoff between the operating frequency, range, antenna sizes, transmit power levels, required data rates as well as the choice of modulation techniques. The effects of fading, shadowing and receiver noise should also be carefully controlled. M-ary phase shift keying (M-PSK) and M-ary quadrature amplitude modulation (M-QAM) are commonly used for increasing the throughput in SATCOM systems, that suffer very high free-space losses. Interleaving and error-correction coding helps reducing bit errors in fading and shadowing channels at the expense of some increase in the transmission bandwidth.

In addition to technical aspects, the cost, system complexity, performance, and operational characteristics play a determining role in designing the SATCOM systems.

8. Applications

Satellite communication has revolutionized a wide range of industries through its ability to enable connectivity and deliver valuable services across the globe. The following are a few key applications that leverage the power of satellite technology:

1. Telecommunications: Satellite communications are a critical component of providing voice, data, and video services to remote and underserved areas where terrestrial infrastructure is limited. Using satellites, long-distance communication is made possible, enabling people to communicate in remote regions as well as ships at sea and aircraft in flight. During natural disasters or humanitarian emergencies, they also serve as an essential communication backbone.
2. Broadcasting and entertainment: Satellites play an important role in the distribution of television and radio signals worldwide. Thousands of viewers have access to a wide variety of channels and content via direct-to-home broadcasting (DTH). Furthermore, satellites are capable of distributing high-definition and Ultra HD content, providing viewers with a rich multimedia experience.
3. Remote Sensing and Earth Observation: Satellites equipped with sensors and imaging systems capture valuable data about Earth's surface, atmosphere, and oceans. A wide range of applications utilize this data, including weather forecasting, climate monitoring, and environmental management. Agricultural, forestry, and natural resource management rely heavily on satellite imagery to provide critical information.
4. Navigation and Positioning: Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, and Galileo use satellites to provide accurate information regarding positioning, navigation, and timing. Various sectors use these systems, including transportation, logistics, surveying, and aircraft and ship navigation. Numerous applications benefit from GNSS technology in terms of safety, efficiency, and precision.
5. Disaster Management and Emergency Services: Satellites are indispensable in disaster management, providing critical communication links and situational awareness during emergencies. In addition to enabling rapid response, they facilitate coordination among rescue teams and support disaster assessment, mapping, and recovery efforts. In order to aid in early warning systems and disaster mitigation strategies, satellites assist in monitoring and predicting natural disasters.
6. Internet of Things (IoT) Connectivity: The proliferation of IoT devices necessitates wide-ranging and reliable connectivity. In remote areas, maritime environments, and in-flight applications, satellites provide global coverage, enabling IoT connectivity. The use of satellites facilitates the seamless exchange of data between devices and systems in a wide range of IoT applications, including smart agriculture, asset tracking, environmental monitoring, and connected vehicles. Large constellations of LEO satellites offer higher potential to satisfy the requirements for versatile Internet applications of today.
7. Military and Defense: Satellite communications are vital for military and defense operations, offering secure and reliable communication channels for command, control, and intelligence gathering. Satellites allow for real-time situational awareness, battlefield communications, and remote sensing for reconnaissance and surveillance operations. They are essential to the support of military operations on land, at sea, and in the air.

Satellites are an essential technology for a wide range of sectors, including transportation and agriculture to scientific research and beyond, due to their ability to provide wide coverage, global connectivity, and reliable communication services. Continuing advances in satellite technology will lead to greater opportunities for new and innovative applications, shaping the future of connectivity and reinforcing progress across a wide range of industries.

9. Conclusions and Future Trends

Satellite communications play an important role in connecting the world, bridging the digital divide, and enabling seamless communication across vast distances. The future promises remarkable advancements in capacity, speed, and versatility for geostationary satellites, satellite constellations, and software-defined satellites.

Satellite communications have a wide range of applications, including telecommunications, broadcasting, remote sensing, navigation, and disaster management. The ability to provide ubiquitous connectivity and support emerging technologies such as the IoT and 5G integration further underscores its significance.

Satellite communications also present challenges and tradeoffs, including spectrum management, signal propagation, and design challenges. It will be crucial to address these challenges and strike the right balance among performance, cost, and sustainability in order to shape the future of satellite systems.

Satellite communications have recently witnessed significant advancements, and the field continues to grow rapidly. Satellite communication is expected to be shaped by several key trends in the future.

1.High-Throughput Satellites (HTS): These satellites are revolutionizing satellite communications by providing a much higher data rate than traditional satellites with the same amount of orbital spectrum. The capacity increase reduces the cost per bit. Through the use of advanced spot beam technology, that allows re-use of the same frequency band, these satellites are able to deliver broadband connectivity in an efficient and effective manner. Globally, HTS systems are expected to continue to be deployed, enabling enhanced broadband services and supporting the growing demand for high-speed data connectivity.

2. Satellite constellations: A network of satellites that operate in a coordinated orbit to provide global coverage. Several companies, including SpaceX and OneWeb, are attempting to deploy large constellations involving hundreds or even thousands of satellites. Among the advantages of these constellations are flexibility, reconfigurability, reduced latency, more capacity, better coverage, providing new possibilities for global connectivity, remote sensing, and IoT applications.

3. Hybrid networks combine the capabilities of satellite communications with terrestrial networks, creating an integrated network that utilizes the strengths of both technologies. Hybrid networks provide reliable, cost-effective connectivity solutions by seamlessly integrating satellite and terrestrial infrastructures. In addition to delivering ubiquitous connectivity, these networks will support emerging applications such as connected vehicles, smart cities, and industrial IoT.

4. Software-defined satellites (SDS) are an emerging technology that has considerable potential in the satellite industry. SDS provides operators with the ability to remotely program and update satellite functions and capabilities via reconfigurable and adaptable satellites in orbit. As a result of this flexibility, satellites are more efficient, scalable and long-lasting, while also being able to respond rapidly to changing market demands.

Rapid network deployment may be enabled by the central control protocol of SDSs, as well as the full use of ISLs forwarding and geospatial broadcasting. Providing a global network view and central control capability, SDS enables [13]

- the balance between flexibility and controllability of space dynamic routing algorithms,
- on-orbit upgrades and improvements,
- the rapid deployment of flexible and fine-grained network management strategies,
- significant reduction in satellite deployment costs,
- the coordination between satellites and the compatibility of heterogeneous space systems, and
- improved satellite performance.

5. Optical communications: Free-space optical communications using lasers offer high data rates and low latency compared to other communication systems. Despite its traditional use for short-range communications, advances in optical technology are making it feasible for satellites to communicate with SGTs over long distances. As a result of optical communications, satellite links can be significantly enhanced in terms of their capacity and efficiency, providing ultra-high-speed connectivity for applications such as Earth observation, deep space exploration, and inter-satellite communications.

6. Integration of satellite communications with 5G and beyond: Satellite communications are increasingly being integrated with terrestrial 5G networks in order to provide seamless and ubiquitous connectivity. As a result of this integration, a wide range of applications is possible, such as coverage of rural and remote areas, disaster recovery, maritime and aeronautical connectivity, as well as IoT connectivity in challenging environments. Satellite communications will play an increasingly important role in providing global coverage, backhauling data, and supporting advanced applications and services as the next generation of cellular networks (6G) takes shape.

Today, users need special hand terminals to connect to satellite services, since waveforms are not compatible with cellular radio, and these terminals may need higher transmit powers to transmit to the satellite, and more sensitive receivers to process potentially weaker received signals. Studies are underway to ensure direct connection between cell phones, used in cellular radio, and LEO satellites. For example, the Starlink system of SpaceX does not directly connect from its satellites to cell phones. Instead, it is linked to transportable user terminals, equipped with phased-array antennas that can track the satellites.

7. Sustainable Satellite Operations: In the wake of growing environmental concerns, satellite communications are increasingly being focused on making them more environmentally friendly. Satellite manufacturing, launch operations, and end-of-life disposal are being optimized to reduce the environmental impact. It includes such initiatives as creating reusable launch systems, utilizing electric propulsion for satellites, and implementing satellite recycling and deorbiting procedures. Satellite operations are expected to become increasingly sustainable in the future, aligning with global environmental goals.

The future of satellite communications holds tremendous promise for transformational advancements. Satellite constellations, software-defined satellites, optical communications, integration with 5G and beyond, and sustainable operations are all expected to shape the industry in the years to come Satellite communications will continue to play a key role in our global communication infrastructure as the world becomes increasingly interconnected, and will address society's evolving needs with improved performance, and wider applications. Keeping pace with technological advancements and embracing emerging trends will provide us with new opportunities, help us overcome challenges, and allow us to create a world where seamless connectivity transcends borders to connect every corner of the planet.

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