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# Wireless Optical Communication: Inter-Satellite Optical Link for Higher Data Exchange

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**Abstract**

Inter-satellite Optical wireless communication has been attracting worldwide attention because of the growing need for larger capacity and higher speed transmissions of observation data thanks to the recent improvements in the performance of Earth observation satellites and because of its features such as not needing the frequency coordination and the ease in which confidentiality is ensured compared to radio frequency (RF) communication. Satellite cross links generally require narrower bandwidths for increased power concentration. We can increase the power concentration by increasing the cross link frequency with the same size antenna. But the source technology and the modulation hardware required at these higher frequency bands are still in the development stage. Use of optical frequencies will help to overcome this problem with the availability of feasible light sources and the existence of efficient optical modulation communications links with optical beams are presently being given serious considerations in inter-satellite links. And establishing an optical cross link requires first the initial acquisition and cracking of the beacon by the transmitting satellite followed by a pointing of the LASER beam after which data can be modulated and transmitted. This paper introduces a future space system based on optical inter-satellite communication as well as the features and technologies of the laser communication terminal for satellites developed for JAXA's optical data relay and earth observation satellites.

**Keywords:** Non-Terrestrial Networks (NTN), Space-Air Ground Integrated Networks (SAGIN), Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), 5G-Advanced, 6G

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## 1. Introduction

Satellite optical communication has garnered significant interest as a promising technology for satellite communication, owing to its advantages over microwave communication, including greater bandwidth, license-free spectrum, higher data rates, enhanced security, smaller size, lower mass, and reduced power consumption. Earth observation satellites equipped with high-resolution cameras or synthetic aperture radars generate substantial data at rates of several gigabits per second (Gbps), necessitating efficient transmission to the ground with minimal latency. Conventional microwave communication, however, encounters a bottleneck due to its data transmission speed, which is limited to hundreds of megabits per second (Mbps).

Moreover, the communication link between a ground station and a low Earth orbit (LEO) satellite is established approximately 6-8 times daily for 5-15 minutes. To facilitate near real-time data transfer from LEO satellites to the ground, an optical communication link through a geostationary Earth orbit (GEO) relay satellite is required. Typically, a GEO relay system provides an optical link between LEO and GEO satellites, along with a Ka-band communication link between GEO satellites and the ground. However, an additional optical link from GEO satellites to the ground is necessary since the Ka-band downlink could become a bottleneck in the GEO relay system [1].

However, with the rapid advancement in satellite communications requiring higher data rates [2], transitioning to optical ISLs has become essential due to their significant advantages. Optical ISLs offer high data rates, large bandwidth, extended communication distances, low transmission power, improved reliability, cost-effectiveness, smaller antenna diameters, and enhanced data security. Additionally, optical systems facilitate easier multiplexing, demultiplexing, switching, and routing adaptability.

The first optical ISL using laser light was established between the European Space Agency (ESA) and the French agency, involving the Artemis satellite and the SPOT-4 Earth observation satellite. For optical ISLs, three technical parameters are crucial for establishing a connection between satellites. The first is the frequency bands, which fall within the Terahertz (THz) range to achieve high data rates. The fundamental issue in free-space signal transmission is loss due to nonalignment of the atmosphere, as there is no absorption of the signal.

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The second important aspect is the multiple access technique used to allocate satellite transponder capacity and minimize interference among incoming signals from satellites to Earth stations [3]. The station capacity is defined by the formula C = B log2 (1 + S/N), where "B" represents the bandwidth, and S/N denotes the signal-to-noise ratio.

To enhance system capacity, multiple wavelengths are employed to extend the limitations of a single optical channel as demand increases [4]. The choice of modulation method is crucial for achieving optimal modulation formats [5], which approach the theoretical maximum limits. This approach also provides exceptional security, enhancing resistance against jamming and interception [6].

This paper focuses on reviewing inter-satellite optical communication (Is-OWC), specifically its role in transferring data and collecting information among satellites. It provides a comprehensive examination of why optical transmission is chosen. The review covers various challenges faced by free space optical (FSO) communication systems for inter-satellite links.

## 2. Is-OWC SYSTEM

Wireless optical communication (WOC) uses optical carrier in the near-infrared (IR) and visible bands and is considered a viable solution for achieving high-speed and large-capacity communication links. Wireless optical communication (WOC) systems are commonly coined as wireless optical communication (WOC) systems as shown in Fig.1. The use of light in communication was ignited by the demonstration of the first working laser at Hughes Research Laboratories, California, in 1960. With the significant development in optoelectronic components and the market ecosystem over the last few years, WOC has gone through tremendous development.

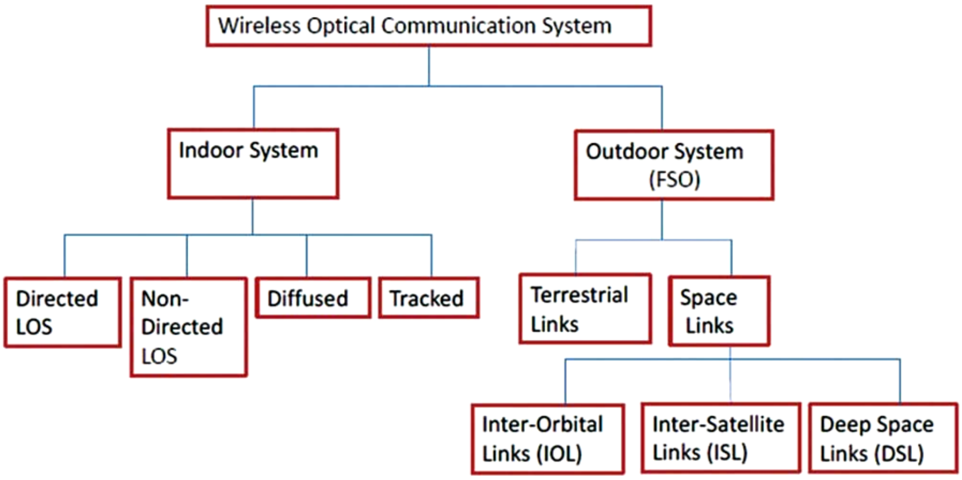

**Fig 1:** Basic Block of Wireless optical communication

## 3. OWC Signals in Atmosphere

The optical field produced at the transmitter travels only with an accompanying beam spreading loss in the fundamental wirelessly optical link [7]. Free Space Optics (FSO) is a line-of-sight technique that establishes interconnection for audio and video communication using tools like lasers. It currently supports a maximum data rate of 2.5 Gbps, however with the use of Wavelength Division Multiplexing (WDM), this rate can be extended to 10 Gbps. To accomplish full duplex communication, Free Space Optics (FSO) is reliant on connectivity between two stations each equipped with an optical transceiver. Low power lasers or light emitting diodes (LED)s are used to convey the light pulses through the atmosphere in a narrow conoid beam [8]. The performance of this kind of system can be calculated from the power flow. The transmit power $\boldsymbol{P_T}$ in watt, the receive antenna gain $\boldsymbol{G_R}$, the range loss $\boldsymbol{G_r}$, and system-dependent losses system, Link all affect the signal power received $\boldsymbol{P_R}$ in watt is denoted by Eq. 1. Since the satellites are so high above the atmosphere, atmospheric factors cannot cause any instability to affect the wireless channel; as a result, in our models, free space loss is set at 0 dB/km [9].

Therefore, in Is-OWC links, the transmitter and receiver's alignment may not be exact. In order to increase Q factor and BER at 1600 km distance, we therefore estimated that the pointing error angles value would be 0.75µrad, the transmitter and receiver efficiency would be equal to 90%, and the apertures diameter would be equal to 30 cm (or 1/10 of the aperture size necessary in case of RF signal). Totally we assumed attenuation to be 2.61 dB/Km.

$$P_R = P_T G_T G_R G_r A_{system,ink} \quad (1)$$

The transmit antenna gain $G_T$ is if a Gaussian beam fills the transmitting apertures only partially [10].

$$G_T = 32/\vartheta^2 \quad (2)$$

Where the whole angle divergence of the optical transmit beam θ is expressed in rad. The operational optical signal wavelength and link propagation distance L determine the range optical loss $G_r$, which is given by [11].

$$G_r = (/2\pi L)^2 \quad (3)$$

Additionally, the receive antenna gain is given by for telescope aperture diameter (antenna size)

$$G_R = (.D/\lambda)^2 \quad (4)$$

All of the additional optical system-dependent losses are reflected by the A system, link. It includes optical losses from telescopes, from light splitting for tracking systems, optical losses from misaligned optical links, etc. Since there are no ambient influences, the link margin M link is given in decibels by

$$M_{link} = P_{RX,Bm} - S_r \quad (5)$$

Where $P_R$ must be expressed on a logarithmic scale in decibels(dBm). $S_r$, also known as receiver sensitivity, is the amount of power needed at the receiver to deliver the desired communication quality in dBm. It is influenced by a number of limitations, including data rate and necessary bit error ratio. Sensitivity is also influenced by noise sources that interfere with detection, like background light and noise from electronics [12]. The fundamental rule of communication was that received power $P_R$ had to be lower than transmitted power $P_T$, $P_R = P_T$-Total Loss, in

$$P_R = P(comb)\text{-}L(geo)\text{-}L(sys) \qquad (6)$$

The ratio of mistakes to total bits is known as the bit error rate. Another fundamental qualitative metric of the FSO link is BER [13].

## 4. Optical Amplifier and Performance Evaluation

The rapid variation of received power brought on by atmospheric turbulences will ultimately decrease the system quality. Additionally, a bird flutter or other laser beam interruption will obstruct connection. As a result, studies have suggested methods to address the drawbacks [14]. Settlement, signal amplification is required in order to trans-port a signal over a long distance via a fiber [15]. An input optical signal can be amplified directly by a perfect optical amplifier without having to first convert it to an electrical signal. As demonstrated in Fig. 2, it may boost all WDM channels simultaneously and is typically transparent to channel count, data rate, protocol, and modulation type [16].

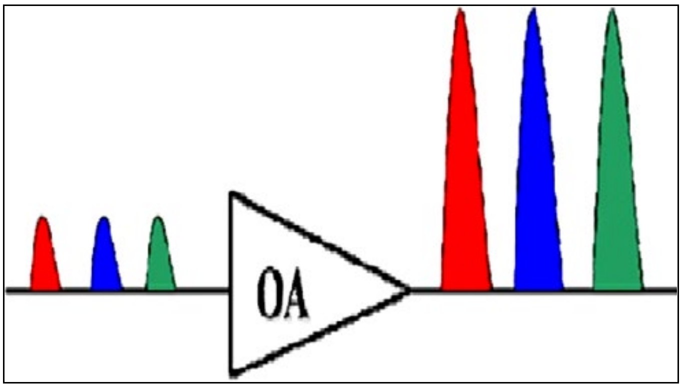

**Fig 2:** A transparent optical amplifier in which all channels are optically amplified simultaneously.

Fiber amplifiers and semiconductor optical amplifiers (SOA) are the two primary categories of optical amplifiers. There are three types of fiber amplifiers: Brillion, Raman, and Erbium doped fiber amplifiers (EDFA) [17]. Gain from EDFA can be determined by:

The total losses in an FSO communication system, pursuant to, would include all losses resulting from atmospheric occurrences, limited-angle torque motors (LATM) (dB), which can be estimated using Eq geometrical loss ($L_{GEO}$) (dB), and system loss, ($L_{SYS}$)(dB). Thus, the following is the updated equation for FSO received power [18]:

$$BER = ne/NB \qquad (7)$$

In which NB is the total number of long-distance transmission bits and ne is the number of returned mistake bits [19].

$$G_{EDFA} = G_{ma}(L, \lambda_p, \lambda_s) = exp\ [L\ \{r_p(\lambda_p)\text{-}r(\lambda_p)\}/\ \{1+rp(\lambda_p)\}\ ] \ (8)$$

In which, $\lambda_p$= pump wavelength, $\lambda_s$= signal wave-length, $r_p$ is the ratio of pump absorption and pump emission ($\sigma_{ss}/\sigma_{ss}$), r = the ratio of signal absorption and signal emission ($\sigma_{ss}/\sigma_{ss}$). The aforementioned criteria have a big impact on EDFA's gain. The EDFA is schematically represented in Fig. 3.

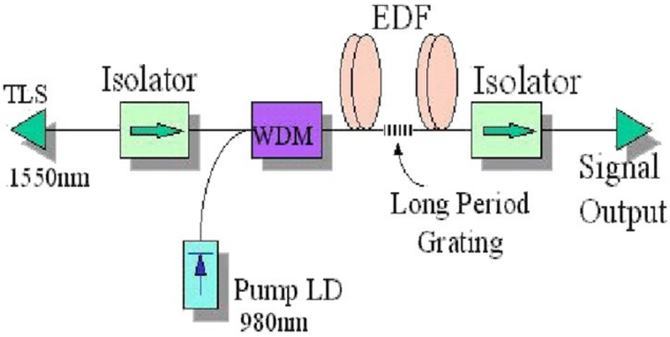

**Fig 3:** Diagram of the EDF

If the input pulse energy is considerably smaller than the saturation energy $E_{sat}$ of the semiconductor optical amplifiers (SOA), then the input pulse can be amplified without experiencing substantial distortion. Engineers who specialize in semiconductor optical amplifiers (SOA) saturation are often only a few Pico Joules in energy. When given an input pulse width ($\tau_p$), the output pulse power $P_{out}(t)$ and phase $\phi_{out}(t)$, assuming $\tau_p$is much shorter than the carrier lifetime, roughly correspond to [20].

In which $\lambda_p$= pump wavelength, $\lambda_s$= signal wave-length, $r_p$ is the ratio of pump absorption and pump emission($\sigma_{pp}/\sigma_{pp}$), r = the ratio of signal absorption and signal emission ($\sigma_{ss}/\sigma_{ss}$). The aforementioned criteria have a big impact on EDFA's gain. The EDFA is schematically represented in Fig. 3 [21]. If the input pulse energy is considerably smaller than the saturation energy $E_{sat}$ of the SOA, then the input pulse can be amplified without experiencing substantial distortion. Engineers who specialize in SOA saturation are often only a few Pico Joules in energy. When given an input pulse width ($\tau_p$), the output pulse power $P_{out}(t)$ and phase $\phi_{out}(t)$, assuming $\tau_p$ is much shorter than the carrier lifetime, roughly correspond to [22].

$$P_{out}\ (t) = P_{in}(t)\ exp\ [b(t)] \qquad (9)$$

$$\phi_{out}\ (t) = \phi_{in}(t)\text{-}(1/2)\alpha\beta\ (t) \qquad (10)$$

When

$$b(t)= [1\text{-}(1\text{-}1/G_o)exp\{\text{-}u_{in}(t)/E_{sat}\}]^{-1} \qquad (11)$$

and

$$U_i(t) = \int^{t}_{-\infty} P_{in}(\tau)\ d\tau \qquad (12)$$

$$S(w) = |\int_{-\infty}^{\infty}[Pout(t)]^2 \exp[i\varphi_{out}(t) + i(w - w_o)t]\ dt|^2 \qquad (13)$$

### 4.1. Directed LOS System

In this type of WOC system, both the beam angle of the transmitter and field of view of the receiver are very narrow, allowing point-to-point or line-of-sight (LOS) communication as shown in Fig. 4(a). The alignment of the receiver and the transmitter is very crucial to achieve the quality of service. Blocking in the LOS path breaks the communication [23].

### 4.2. Non-directed LOS System

This type of indoor system is suitable for point-to-multipoint communication. The beam angle of the transmitter and field of view of the receiver are wide enough as shown in Fig. 4(b) to avoid any stringent alignment requirement. This system allows limited user mobility [24].

### 4.3. Diffused System

In this type of system, the transmitter is faced towards the ceiling. The light is reflected from the ceiling and walls multiple times to reach the receiver having a wide field of view, as shown in Fig.4(c). Due to multiple paths from the transmitter to the receiver, this system does not suffer from blocking in the LOS path [25].

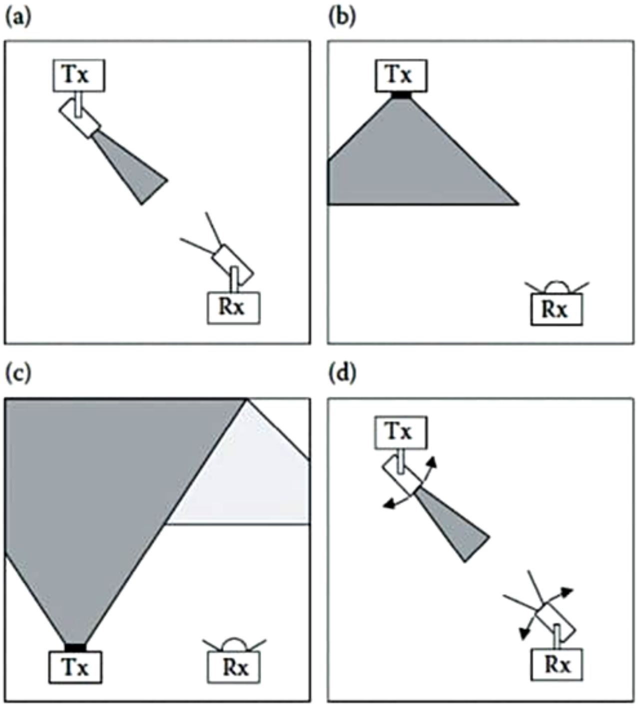

**Fig 4:** Propagation types of optical waves in WOC system

### 4.4. Tracked System

In a tracked system, the receiver and the transmitter can track each other, as shown in Fig. 4(d). Mechanical or electronic control needs to be implemented for effective tracking [26].

### 4.5. Terrestrial Links

Terrestrial free-space optical (FSO) system as shown in Fig.5 is used for building to building communication or metro area extension [27]. This is primarily an LOS communication. It has applications in disaster recovery and x-haul of 3G/4G/5G mobile communications.

### 4.6. Space Links

An inter-satellite link is a communication between two low Earth orbit (LEO) satellites. An inter-orbital link is established between LEO and geostationary Earth orbit (GEO) satellites. Tight alignment and tracking, low power consumption, and being lightweight are critical requirements for space applications [28].

**Fig 5:** Free-space optical Laser Device

## 5. Inter-Satellite Optical Wireless Communication (IS-OWC) System

The Is-OWC can be used to connect the one satellite to another satellite, whether the satellite is in the same orbit or the different orbit. The light travels at a speed of $3*10^8$ m/s. So the signals from one satellite to another satellite can be sent without much delay and with minimum distortion and attenuation because space is considered as vacuum [29].

### 5.1. Orbits for IS-OWC:

Understanding the different types of satellites and their respective roles in satellite communications is essential for analyzing and designing inter-satellite optical wireless communication (Is-OWC) systems within satellite constellations. There are many types of satellites, serving different purposes for different organizations. Based on the orbit (Shown in Fig.6), satellites fall into one of four categories: Low Earth orbit satellites (LEO), Medium Earth orbit satellites (MEO), Geostationary Earth orbit satellites (GEO), and Highly Elliptical orbit satellites (HEO). Low Earth orbit satellites orbit at altitudes ranging from a few hundred to a few thousand kilometers above the Earth's surface. LEO satellites travel at high speeds, completing multiple orbits around the Earth each day. They offer advantages such as lower latency, higher data rates, and reduced signal propagation delays compared to GEO satellites. LEO satellites are utilized for various applications, including Earth Observation, remote sensing, global internet coverage, and satellite constellations. Medium Earth orbit satellites operate at altitudes higher than LEO satellites but lower than GEO satellites, typically ranging from 8,000 to 20,000 kilometers above the Earth's surface. MEO satellites are commonly used for navigation and positioning systems, such as the global positioning system (GPS). They offer intermediate orbital characteristics, providing global coverage with a balance between coverage area and signal strength. Geostationary satellites orbit the Earth at an altitude of approximately 35,786 kilometers above the equator. Positioned directly above the Earth's equator, these satellites remain fixed relative to the planet's surface, appearing stationary when observed from the ground. GEO satellites are commonly used for applications requiring continuous coverage over specific geographic areas, such as telecommunications, broadcasting, and weather monitoring. Highly elliptical orbit (HEO) satellites orbit the Earth in a highly elongated path, with their distance from the Earth's surface varying significantly throughout their orbit [30].

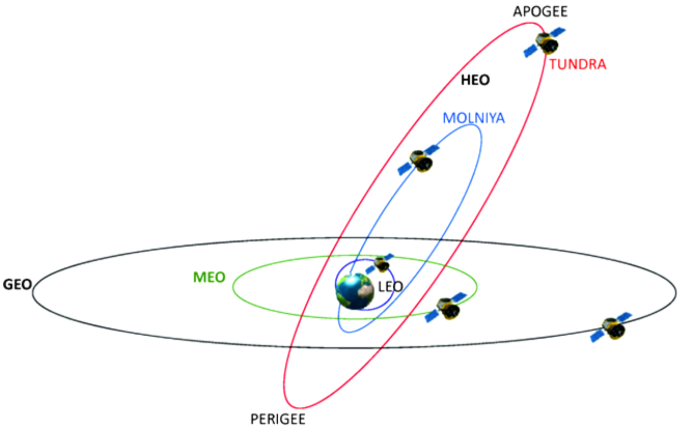

**Fig 6:** Earth's Orbit

At their highest point (apogee), HEO satellites can be several tens of thousands of kilometers above the Earth's surface, typically ranging from 10,000 to 50,000 kilometers or more. At their lowest point (perigee), they can be much closer to Earth, often within a few hundred kilometers above the surface. This highly elliptical trajectory allows HEO satellites to provide extended coverage over specific regions, especially at high latitudes, where other satellite orbits may have limitations. HEO satellites are commonly used for applications such as communication in Polar Regions, remote sensing, surveillance, and navigation augmentation systems. Inter-satellite communication (ISC) refers to the exchange of data, signals, or commands between two or more satellites in orbit around the Earth. This form of communication plays a crucial role in modern satellite systems, enabling coordination, collaboration, and data exchange between satellites within a constellation or network (shown in Fig. 7). Satellite constellations are configurations of multiple satellites working together to achieve specific communication, observation, or navigation objectives. These constellations vary in size, design, and orbital parameters based on their intended purpose. In the context of the research on "Analysis of inter-satellite optical wireless communication systems for enhanced data transmission in satellite constellations," understanding the characteristics and configurations of satellite constellations is crucial.

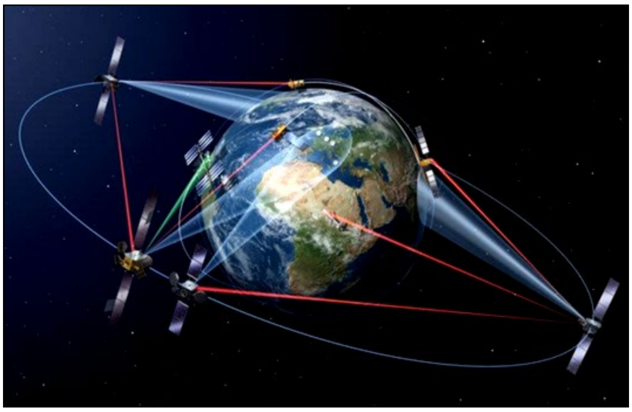

**Fig 7:** Satellites constellation for optical wireless communication

Here's an overview of some common types of satellite constellations. Low Earth orbit (LEO) constellations consist of satellites orbiting relatively close to the Earth's surface, typically at altitudes ranging from a few hundred to a few thousand kilometers. LEO constellations are known for their high data rates, lower latency, and global coverage capabilities. Satellites in LEO orbit the Earth at high speeds, completing multiple orbits per day. Examples of LEO constellations include the Starlink constellation by SpaceX, OneWeb, and the Iridium constellation. Medium Earth orbit (MEO) constellations operate at altitudes higher than LEO satellites but lower than geostationary satellites, typically ranging from 8,000 to 20,000 kilometers above the Earth's surface. MEO constellations are often used for global navigation and positioning systems, such as the global positioning system (GPS) and the European Galileo system [31]. These constellations provide intermediate orbital characteristics, offering a balance between coverage area and signal strength. Geostationary Earth orbit (GEO) constellations consist of satellites positioned in geostationary orbit, approximately 35,786 kilometers above the Earth's equator. GEO constellations are known for their continuous coverage over specific geographic areas. Satellites in GEO remain fixed relative to the Earth's surface, making them suitable for applications requiring continuous connectivity, such as telecommunications and broadcasting. While traditional GEO satellites are often deployed individually, there are emerging concepts for GEO constellations involving multiple smaller satellites. Hybrid constellations combine satellites from different orbital regimes, such as LEO, MEO, and GEO, to leverage the advantages of each orbit for specific applications. These constellations may integrate LEO satellites for global coverage and low latency with GEO or MEO satellites for continuous connectivity over specific regions. Hybrid constellations offer flexibility and scalability, catering to diverse communication, observation, and navigation requirements. In this research, we focused on low Earth orbit (LEO) constellations. The utilization of LEO constellations indicates a focus on leveraging the advantages of low latency, high data rates, and dynamic coverage offered by satellites in low Earth orbit. This choice aligns to enhance data transmission efficiency and reliability within satellite networks, particularly in the context of applications such as Earth observation, remote sensing, and global connectivity.

### 5.2. Frequency Spectrum for IS-OWC System

Since high-frequency light signal (usually 193.1THz or wavelength of 1550 nm as shown in Fig.8) is utilized as the carrier, the optical wireless connection may handle high data throughput with minimal transmission delay between two satellites or between a satellite and ground station. Since it is believed that outer space is a vacuum without an atmosphere, the impact of attenuation is negligible. Many of the drawbacks of the traditional RF connection may be solved via optical connectivity. The antenna's size is determined by the carrier's frequency. It is obvious that the RF system's transmitting and receiving antenna must be metered broad. An antenna of a few centimeters in size is necessary for an optical communication system. The biggest benefit of the optical connection is that a smaller antenna equals a smaller payload, which reduces the satellite's bulk and cost [32]. A narrower laser beam is produced when a light signal with a shorter wavelength is used [33]. As a result, compared to RF systems, signal power loss occurs less often with OWC systems. In the case of the optical system, laws and licenses governing the frequencies that may be utilized for satellite communication through RF connection do not apply [34]. A viable option is optical wireless networks, which use Wavelength Division Multiplexing (WDM) to deliver data at a high rate [35]. To ensure that the communication satellites are aligned with a precise LOS, the Is-OWC system needs a very accurate tracking system. Universities, corporations, engineers, scientists, and the military often use satellite applications, which provide various access points or nations with a cost-effective alternative. Many businesses, including Space X [36], Nano Racks [37], Terra Bella [38], Orbital Sciences Cooperation [39], Planet Labs [40], and Pumpkin [13], have created and produced advanced spacecraft. Small satellites may be launched for merely a few million dollars, compared to the $200-$1 billion cost of full-size satellites. In 2022, Boeing's Small Launch Vehicle (SLV) will launch satellites with a payload as small as 45 kg for $300,000. There have been a lot of satellites sent into orbit during the last 50 years; the figures for nano-satellites, micro-satellites, and pico-satellites, respectively, are 680, 860, and 38 [41]. Inter-satellite communications allow small satellites to control, transmit, and analyze information in real time. Multiple satellite missions that use sensor networks to monitor faraway space are becoming common. Cost-effective bulk satellite launch improves target resolution. Inter-satellite communications are needed because tiny spacecraft may be networked. Distributed Space Systems (DSSs), which will be used for the next generation of satellite communication, will consist of a large number of highly advanced, dependable, and cost-effective spacecraft that are able to communicate with one another. This could make it possible for researchers, satellite manufacturers, and scientists all over the world to access an unprecedented number of correspondence and computational capabilities [42]. With a light wave transmission speed of 3×108 m/s, Is-OWC can be used in parallel or independent circles to convey more data with fewer limitations [43]. With fewer payloads, optical links via Radio Frequency (RF) technology may send more data further. OWC systems utilize RF wavelength, which has a wider beam width than lasers and lower attenuation [44]. Is-OWC systems are incredibly easy to set up and allow compatibility to achieve secure communication with higher communication systems. The motivation behind this research is the Is-OWC system for space-based communication which can be used to cover several recent applications that can offer major significance to meet the development of the IoT concept and the upcoming 6G. This paper will demonstrate the concept of Is-OWC, the types of orbits related to satellite launching, and the significance of using the Ka-band for satellite communication. After that, their advanced modulation method along with using the dedicated techniques for achieving the optimal performance of Is-OWC will be explored. Followed by a comprehensive review of the recent techniques and hybrid schemes proposed by different literature to achieve optimal performance evaluation for Is-OWC systems. Additionally, the advantage and challenges related to Is-OWC communication will be summarized. Finally, the wide range of applications that satellite commutation can offer, and the future scope will be demonstrated at the end of the paper.

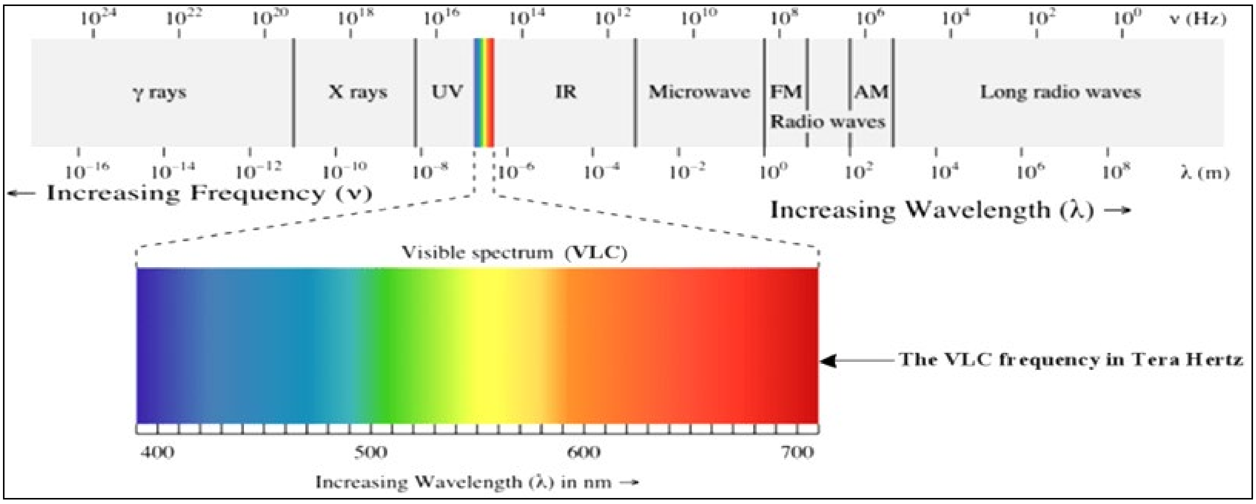

**Fig 8:** Light Spectrum

### 5.3. Transmitter

Data Source, where the data to be transmitted originates. Modulation Format is the technique used to encode the data onto the optical signal. Light Source for which typically a laser or light-emitting diode (LED) that generates the optical signal. Modulator that modulate light source with the data according to the chosen modulation format.

### 5.4. Transmission Channel

This is the medium through which the optical signal travels. Is-OWC, this channel is free space.

### 5.5. Receiver

Photodiode: This converts the received optical signal back into an electrical signal. Demodulators that decode the modulated signal to retrieve the original data. And filters are used to reduce noise and enhance the signal quality before demodulation. Each component plays a crucial role in ensuring effective communication and data integrity in the OWC system.

## 6. The Architecture of IS-WOC System

Is-WOC system consists of three major subsystems: Transmitter, channel, and receiver. The block diagram of an Is-WOC system is shown in Fig. 9. The role of transmit optics and receive optics are analogous to the antenna used in RF communication. Pointing, Acquisition, and Tracking (PAT) is a satellite protocol established to synchronize a ground station with an orbiting satellite. Because of the large distance between optical ground station (OGS) and FSO satellites and the narrow diameter of the beam that connects them, accurate and reliable pointing is a non-trivial task. Synchronization of the two end transceivers compounds.

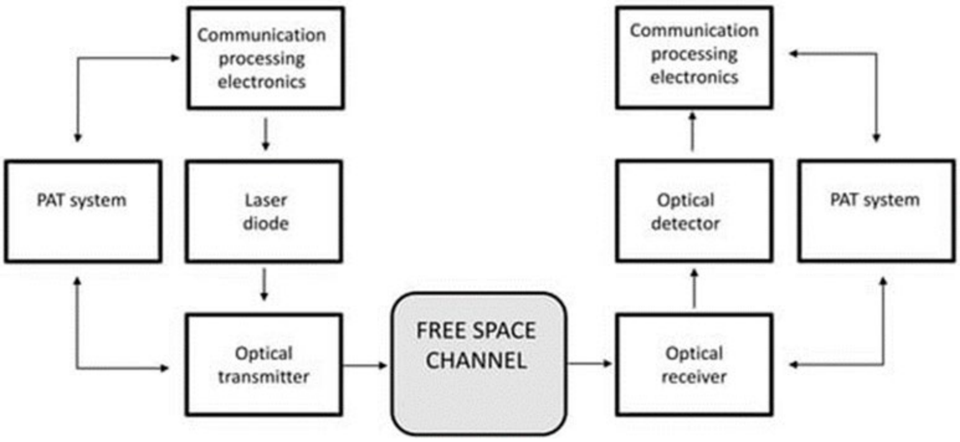

**Fig 9:** Architecture of Is-WOC system

### 6.1. Space-Air-Ground Integrated Networks (SAGIN)

Space-air-ground integrated networks (SAGIN) as shown in Fig.10 are pivotal for achieving uninterrupted in-flight connectivity (IFC). Most existing studies, however, merely treat satellites as transparent forwarding nodes, and overlook their caching capabilities in enhancing the IFC data rate. In this paper, we consider an IFC-oriented SAGIN, where the satellites collaboratively deliver the content to airborne passengers to facilitate airborne communication. Considering the cached files instantaneously accessible via satellites, this work pioneers the integration of multiple inter-satellite links (ISLs) into the IFC framework, thereby innovating the content delivery process. To minimize the average delay of content delivery, we formulate an optimization problem and propose an exact penalty-based method to derive the satellite association scheme. Our proposed framework has a low complexity and thus paves the way for high-speed Internet connectivity to aviation passengers. Finally, simulation results are presented to demonstrate the effectiveness of our proposed in-flight connectivity (IFC) framework for SAGIN. Space-air-ground integrated networks (SAGIN) make reliable internet access on airplanes a reality [45], [46]. When files requested by passengers have not been stored in the cabin, it renders content delivery to involve two main methods: air-to-ground (A2G) communications [47] and air-to-space (A2S) communications [48], where the aircraft connects directly to aircraft gateways or satellites, respectively. To simultaneously utilize the broad coverage of low-Earth orbit (LEO) satellites and the low round-trip time of aircraft gateway, it is necessary to develop an adaptive association strategy, which integrates the network topology and quality of service (QoS) requirements. Currently, the field of dual connectivity for in-flight connectivity (IFC) is relatively nascent. The work [49] and [50] begun exploring the traffic scheduling challenges in aeronautical networks within such a dual connectivity framework in SAGIN. In these works, the aircraft can obtain the services from the aircraft gateway or the satellite ground stations (GSs) via the relay satellites. However, these studies merely treated satellites as transparent forwarding nodes and assumed that all the files are obtained from ground stations, overlooking their potential capabilities for service caching. As intelligent and flexible LEO satellite networks become prevalent, LEO satellites are increasingly capable of communicating, computing, and caching simultaneously [51]. By proactively storing the popular files, satellites can share the content among the satellite network via laser inter-satellite links (ISLs) and then deliver it directly to the airplane, thus avoiding the forwarding process. Compared with traditional radio frequency (RF) links, laser inter-satellite links (ISLs) can offer a much higher speed of 10 Gb/s [52]. SpaceX indicated that each Starlink satellite can establish up to four laser inter-satellite links (ISLs) [53].

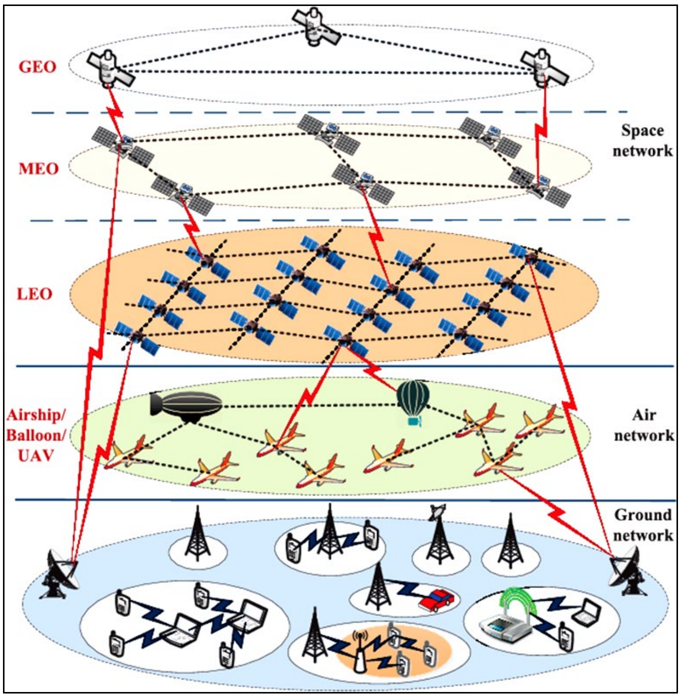

**Fig 10:** Space-air-ground integrated networks (SAGIN)

Leveraging the cache ability of satellites and high-speed laser inter-satellite links (ISLs), latency can be further reduced since the downloading latency from ground stations to satellites can be saved. Applying inter-satellite links (ISLs) can also construct a decentralized network in space and thus reduce the requirement for a large number of GSs. Yan et al. proposed an optimization method to achieve the optimal latency and throughput between satellites and GSs simultaneously when ensuring the ranging performance [54]. Qi et al. focused on the ISLs between satellites in different orbital planes and proposed an ISL scheduling method to achieve a tradeoff between the system complexity and latency performance [55]. Nonetheless, existing research has not adequately addressed the impact of multi-satellite cooperative transmission via laser inter-satellite links (ISLs) for content delivery in SAGIN. Against this background, this paper studies the content delivery strategy in SAGIN for achieving in-flight connectivity (IFC). By employing the caching capabilities of satellites, we formulate an optimization problem to minimize the average delay tailored to the inherent features of laser inter-satellite links (ISLs). To the best of our knowledge, this is the first paper to investigate cooperative transmission among multiple satellites to minimize the content delivery delay for in-flight connectivity (IFC). We first analyze the property of the optimal solution, which helps to transform the original mixed integer nonlinear programming problem into a more tractable form with only binary variables regarding satellite association. We then propose an exact penalty-based algorithm to deal with it with low complexity. Simulation results are provided to validate the effectiveness of the proposed framework as compared to several benchmarks. Moreover, we evaluate the impacts of various key parameters on the performance of the proposed algorithms. Notably, increasing the maximum number of inter-satellite links (ISLs) can significantly reduce the content delivery delay, which verifies the necessity of exploiting multiple inter-satellite links (ISLs) for in-flight connectivity (IFC).

## 7. Advantage of Inter-Satellite Optical WIRELESS Communication (IS-OWC)

Due to its numerous advantages, Inter Satellite wireless optical Communications is in this field. Some of key advantages are given as

**License Free Spectrum:** Inter satellite system are different from radio and microwave system because they do not require any licensing spectrum and frequency coronation with other clients. Therefore they do not, suffer any interference from or to other systems. In Is-OWC provides high security by using point-to-point laser signal which is extremely difficult to intercept.

**Compact Antenna Size:** Is-OWC links used very less transmitting power by reducing the antenna size with large carrier frequency which reduces the weight of the satellite.

**Wide Bandwidth:** In Is-OWC 2000 THz signals are sent over large distance. By using high information capacity these systems are different from radio frequency based communication systems. At high electromagnetic spectrum range they include infrared, visible and ultra violet frequencies, which is greater than the radio frequency [56].

**High Directionality:** Is-OWC works on extremely narrow beam, which has a diffraction limited divergence of between 0.01-0.1µrad. This is only reason for transmitted power concentrated within a very small area.

**Ultra High Bit Rates:** By using high frequency light signals Is-OWC provides very high-speed communication at high data rate signals. Beside above describe advantages, some of its benefit make it very usable due to its feature as optical transmitter and receiver size is smaller, so power consumption is less. Maintaining and installation in satellite is less costly. Satellite relays are inherently wide area broadcast i.e. point to multipoint whereas all terrestrial relays are point to point. Satellite circuits can be installed rapidly. Once satellite is in position, earth station can be installed and communication can be established in days or even hours. Terrestrial circuits require time consuming installations. Mobile communications can be easily achieved by satellite communications as it has unique degree of flexibility in inter connecting mobile vehicles. In satellite communications the quality of transmitted signal and location of stations sending and receiving information are independent of distance. Digital and analog transmissions are possible on same satellite. Earth stations can be relocated and reconfigured providing flexibility and utilisation of satellite capacity [57]. Satellite costs are independent of distance whereas terrestrial network costs are proportional to distance.

### 7.1. Addressing the LoS Requirement

A significant challenge in deploying OWC systems, particularly VLC, is the inherent LoS requirement between transmitters and receivers. This limitation limits the effectiveness of the system in environments with potential obstacles or non-direct paths, such as indoor spaces with complex layouts or urban environments with numerous obstacles. Future work should focus on innovative solutions to mitigate LoS limitations, including the development of advanced reflective materials, relay systems, and beam steering techniques to improve signal range and reliability [58].

### 7.2. Overcoming Ambient Light Interference

The performance of OWC systems, especially in outdoor or well-lit indoor environments, can be severely degraded by ambient light sources. This interference can degrade the signal-to-noise ratio (SNR), which affects the reliability and efficiency of data transmission. Research into advanced modulation schemes, filtering techniques and adaptive algorithms capable of dynamically compensating for ambient light variations is essential to mitigate these effects [59].

### 7.3. Integration with Existing Wireless Technologies

Seamless integration of OWC and optical fiber technologies with existing RF-based communication systems is a significant challenge. This integration is critical to ensuring interoperability and maximizing the coverage, reliability and efficiency of next-generation wireless networks. Future work must address the development of hybrid network architectures, standardized communication protocols, and cross-layer optimization strategies to ensure smooth coexistence with existing technologies [60].

### 7.4. Scalability and Cost-Effectiveness

As the applications of OWC and optical fiber technologies expand, ensuring the scalability and cost-effectiveness of these systems becomes imperative. Research should aim to develop cost-effective manufacturing processes for OWC and fiber optic components, as well as scalable network deployment strategies that can meet growing demands without exponential cost increases. This includes the exploration of novel materials, energy efficient devices and automated deployment methods [61].

### 7.5. Improving Sensing and Localization Accuracy

While OWC and optical fiber technologies offer significant potential for improving sensing and localization capabilities, achieving high levels of accuracy and reliability in diverse environments remains a challenge. Future research should focus on advanced algorithms and signal processing techniques that leverage AI and ML to improve the accuracy and robustness of sensing and localization functions under varying environmental conditions and in the presence of obstacles. Security and privacy concerns: The use of OWC and optical fiber technologies for communication and sensing raises pertinent security and privacy concerns. The broadcast nature of optical signals and the potential sensitivity of sensed data require robust security protocols and encryption techniques to protect against unauthorized access and data breaches. Future work must address these concerns by developing secure communication frameworks and appropriate algorithms tailored to the unique characteristics of OWC and fiber optic systems.

### 7.6. Integration of OWC with other Communication Technology

The integration of OWC and fiber technologies into future 6G wireless networks, while promising, presents a number of challenges that require concerted research and development efforts. Overcoming these challenges is critical to realizing the full potential of these technologies to enhance communication, sensing and localization capabilities in various sectors, including IoT, smart cities, healthcare and intelligent transportation systems.

## 8. Disadvantages of Satellite Communications

As beam width is narrow, so pointing, acquisition and tracking problems occur which has to be solved. It makes system complex, a major challenge with laser communications in space is keeping transmitter and receiver locked onto each other. With satellite in position the communication path between terrestrial transmitter and receiver approx. 75000 km long. Since velocity of emwaves is $3 * 10^8$ km/s, there is a delay of ¼ sec between transmission and reception of signal. Delay reduces satellite's efficiency for long distance transmission. Bandwidth is gradually becoming used up. Launching of satellite in orbit becomes costly. For proper tracking and acquisition makes the system little complex [62].

## 9. Applications of Is-OWC

Is-OWC system is explained based on its several applications. In Is-OWC links three types of satellite orbits are used, we already studied working. But based on its caparison with GEO satellite, orbit always stationary with respect to earth. But on the other hand LEO and MEO satellites orbit are not stationary with respect to earth. They do not exit constantly in earth station's view. By using inter-satellite link, information signal provided to LEO and MEO satellite at any time by using a GEO satellite as relay.

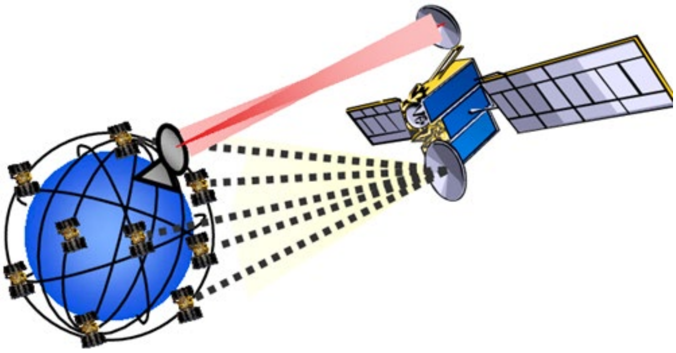

**Fig 11:** Tracking and Data Relay Satellite communications between the ground and space

Data can also be relayed from one LEO satellite to another if they have line of sight. This configuration explained in Fig 11. Side by side conventional way of relaying data is shown in Fig. 12 (a) relayed data by using inter-satellite links are shown in Fig. 12 (b).

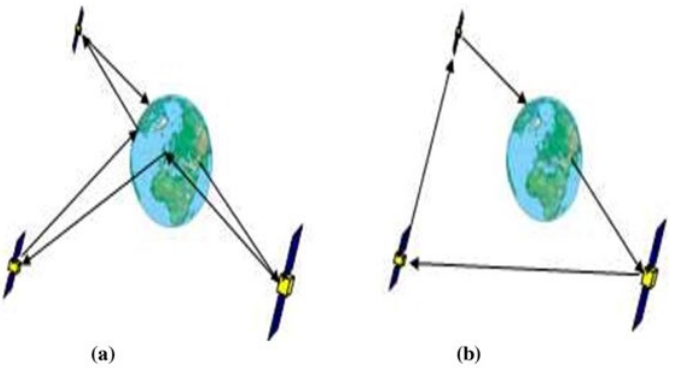

**Fig 12:** Data relay methods (a) conventional (b) using inter-satellite data relay

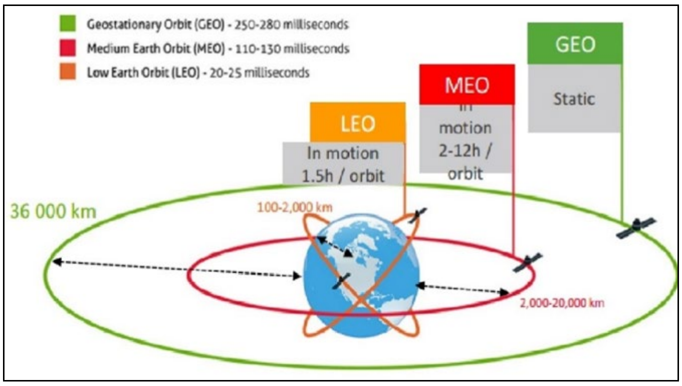

**Fig 13:** Constellation of satellites orbiting Earth

To transmit a data from earth to satellite, high time delay degrades the performance of the system which reduces by using Is-OWC links. To perform a high satellite links with other communication equipments, some missions and applications require more than one satellite such as the global tracking system (GPS) satellites and Iridium satellites. Figure 13 shows constellation of satellites orbiting Earth.

## 10. Conclusion

In this review paper, the performance of an inter satellite optical link is optimized in terms of advantages over electromagnetic wave and other factor which are affected by variation of different internal parameters of the system such as operating wavelengths, pointing errors, detector type and modulation scheme. It has been observed that the transmitter pointing error angel causes more effect on signal degradation as compared to the effect caused by error at the receiver side. Performance of the link has also been studied to evaluate the maximum possible bit rate that may be transmitted over Is-OWC giving adequate performance of the system for LEO and MEO distances. Inter-Satellite optical wireless communication is an example of innovation, empowerment, and limitless possibility in the digital era, where continuous connection drives development. Its constant development has been pushed by cutting-edge technology, changing demand environments, and the tenacious human spirit of discovery. Satellite communication has expanded from beeping satellites to complex constellations. It has connected remote parts of our planet and broken space, bringing data, information, and opportunities to unexplored locations. We see a transformational tapestry in the future. Satellites and 5G provide seamless connection, quantum communication expands security, and LEO constellations highlight the digital divide. But innovation goes beyond technology to include sustainability, cross-disciplinary cooperation, and the unrelenting desire to link the globe. Satellite communication transcends signals bouncing off satellites to demonstrate human inventiveness, perseverance, and dreaming. Is a lifeline for disaster aid, a protector of national security, a window to the stars, and a bridge between continents and civilizations. It represents progress, reflecting our constant pursuit of higher heights. In this vast story, satellite communication becomes the center of our linked universe. It's a symphony of technology, science, and knowledge. As we reflect on this trip, we stand on the brink of more incredible chapters, each written with invention, cooperation, and the infinite cosmos as our ink. Satellite communication has shown us how far we can go if we try.

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