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Inter-satellite optical wireless communication (Is-OWC) trends: a review, challenges and opportunities

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Abstract

Satellite communication has been achieving high-speed transmission for over 50 years. However, alongside these advancements, other IT and telecommunications systems have also improved their performance. As a result, these significant gains are less apparent to the public compared to if this surge in performance had occurred in isolation. Satellite communications serve various purposes, including civilian and military surveillance, telecommunications, object tracking, and space exploration missions. Bulk production of small satellites in clusters can prove beneficial for activities such as wildfire monitoring, research missions, gravity mapping, and water-based investigations due to their size, capacity, and durability limitations. Additionally, communications satellites, enabled by multi-satellite systems, can help study the near-earth environment and facilitate more efficient and cost-effective space exploration. Inter-satellite links have recently gained considerable attention due to their advantages over conventional microwave links in satellite communications. These advantages include the utilization of underutilized and unregulated spectrum availability, large channel bandwidth, lightweight equipment, reduced power and mass requirements, secure transmission, high-speed long-reach links, and cost-effectiveness. After providing a background on satellite communication, we present a brief overview of Inter-Satellite Optical Wireless Communication (Is-OWC) satellite communication systems for various applications. Furthermore, an important aspect in determining satellite applications is the allocation of satellites utilizing Is-OWC links in different orbits. We also explore and compare different orbits based on various aspects. The study highlights the significance of employing advanced modulation techniques to improve the satellite field and achieve higher performance. Additionally, the research explains the importance of utilizing the Ka-band and addresses limitations associated with Is-OWC, such as the Doppler impact, pointing errors between satellites, tracking, and different sources of noise. It emphasizes that Is-OWC links are crucial for providing global coverage for communication purposes.

1. Introduction

The last-mile connection systems with connectivity between end clients, contemporary fiber optic communications, and inter-space laser connections are examples of the complex indoor and outdoor broadband remote applications that optical remote communication is considered to be well suited for [1,2]. Indoor optical remote communication is frequently referred to as remote infrared communication. This is in contrast to outside optical wireless connectivity, which is known as Free Space Optical (FSO) communication. The Inter-Satellite Optical Wireless Communication (Is-OWC) system is one of the most significant applications of free-space optics (FSO). This technology allows for the rapid transmission of data between satellite and space exchanges. Applications for wireless infrared communication need networks that are not directed and do not require any alignment of the transmitter and receiver. There are two different kinds of connections that these are, and they are called Line-of-Sight (LOS) and diffuse relationships. For hassle-free communication, LOS linkages need a specific route, while diffuse links need several optical channels from surface reflections. Directed LOS and point-to-point laser connections that go through the atmosphere are necessary for is-OWC. With unlicensed optical wavelengths, OWC technology offers possibilities for broadband communication capacity. However, variations in temperature and air pressure lead to changes in the transmission line's refractive index, which further affect the optical intensity on the receiver and cause it to fade [3]. The fading connections may also have a negative impact on the system's performance, increasing the Bit Error Rate (BER) and transmission delays [4].

Since high-frequency light signal (usually 193.1THz or wavelength of 1550nm) 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 [5]. A narrower laser beam is produced when a light signal with a shorter wavelength is used [6]. 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 [7]. A viable option is optical wireless networks, which use Wavelength Division Multiplexing (WDM) to deliver data at a high rate [8]. 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 [9], Nano Racks [10], Terra Bella [11], Orbital Sciences Cooperation [6], Planet Labs [12], 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-, micro-, and pico-satellites, respectively, are 680, 860, and 38 [14–16]. The satellite size following each type can be clarified in Table 1. 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 [17].

Table 1. Satellite classification based on size.

Satellite type	size (kg)
Femto, Pico	<1
Nano	<10
Micro	<100
Mini	<500
Medium	<1000
Large	>1000

With a light wave transmission speed of 3×10^8 m/s, Is-OWC can be used in parallel or independent circles to convey more data with fewer limitations [18].

With fewer payloads, optical links via Radio Frequency (RF) technology may send more data further. OWC systems utilize RF wavelength, which has a wider beamwidth than lasers and lower attenuation [19]. 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.

2. Inter Satellite Optical Wireless Communication (Is-OWC)

Expanding networking in space may be made possible by the use of optical wireless communications (OWC), which offers high-speed transmission without human interference by exchanging approach and position knowledge and maintaining point-time harmonisation between spacecraft. The OWC exchanges approach and positional data to provide high-speed information delivery without human interference.

However, more research is necessary in order to get an in-depth comprehension of the communication architecture of a network of microscopic satellites that are entirely autonomous and display a wide range of characteristics [20-22]. A sophisticated network architecture may be generated by several movable nodes inside a compact satellite structure. On the other hand, these devices have limitations on both the transmitting and receiving ends, such as the size of the antenna, the mass, the capacity limits, the onboard resources, the intermittent and processing capabilities, and the communication connections, to name a few [23]. This will make it possible for internetworking to spread into outer space while also reducing operational expenses.

Is-OWC technology connects satellites in various orbits. Iridium and NASA's Tracking Data Relay Satellite System (TDRSS) utilize RF to connect satellites. ESA's Artemis and Japan's Kirari satellites have OWC inter-satellite connectivity [24]. Artemis and French satellite SPOT-4 established the first inter-satellite optical contact in March 2003. Artemis was in GEO while SPOT-4 was in LEO at 832 km [25,26]. Hybrid systems require faster ISL connectivity.

In the future, missions will be aided by developments in communication and navigation technology, which will make it possible to establish communication lines with high bandwidth. In recent years, there has been a resurgence in interest in communication techniques known as OWC and FSO. FSO is generally considered to be a practicable alternative to already existing technology such as radio frequency. In certain instances [27–31], FSO is also seen as a feasible alternative to and integration with the technologies of the next generation, such as 5G wireless network technology. As a consequence of this, Is-OWC joins satellites that are either in the same orbit or in a different orbit. Is-OWC uses LASER as its light source, and the speed of light is about 3×10^8 meters per second [32–34]. Is-OWC system consists basically of three parts, which are the transmitter, the transmission channel, and the receiver as seen in Figure 1. For the transmitter side, it should include the data source, dedicated modulation format, light source, and modulator. Meanwhile, the receiver side includes the photodiode, demodulators, and appropriate filters.

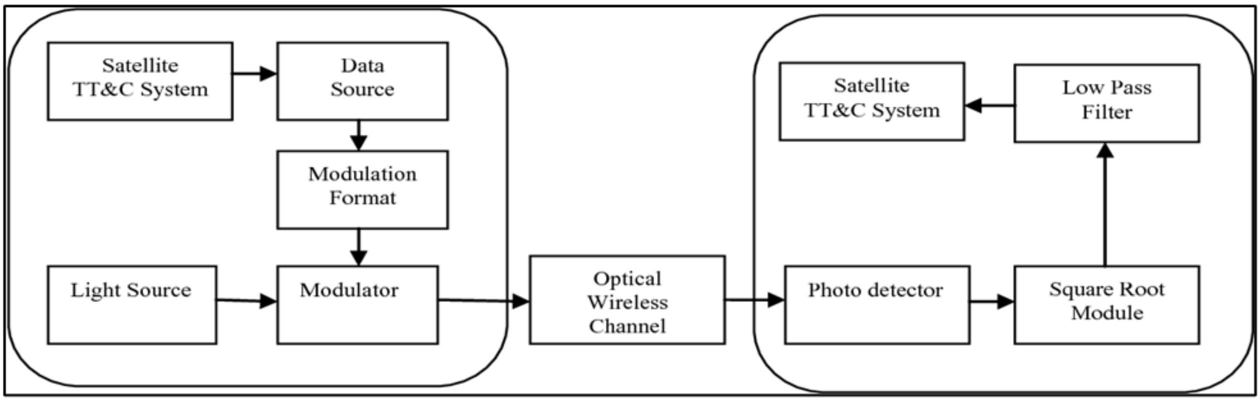

Figure 1. General Is-OWC system [23].

3. Orbits for Is-OWC

The orbit of a satellite or planet refers to the axis around which it revolves as seen from another point in space. The path that the planets take as they orbit the sun is the same one that satellites in orbit around the earth follow.

The principle that governs them all is known as the law of motion [35]. In general, the shape of a satellite orbit is that of an ellipse, and the position of the planet should fall between the two foci of the ellipse. Satellite orbits are divided into several categories depending on their altitude. There are three main orbits specified around the earth as seen in Figure 2.

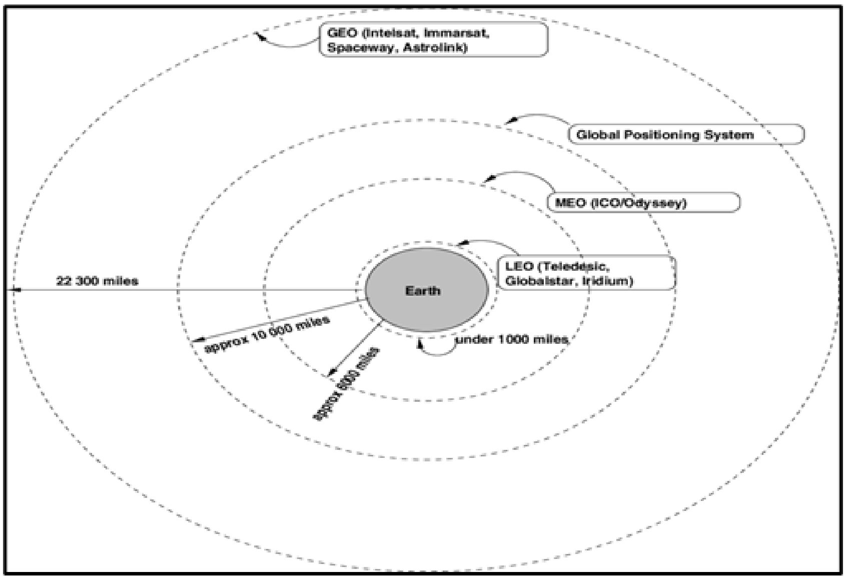

Figure 2. Satellite orbits [36].

1- Low Earth orbit, often known as (LEO), refers to satellites that orbit at an altitude that is between 500 and 1000 kilometers above the surface of the earth. The shape of LEO satellites often takes the form of a circle. The location of LEO satellites does not remain constant throughout time [23]. LEO satellites take between two and four hours to complete one rotation around the planet. The launching of LEO can be seen in Figure 3.

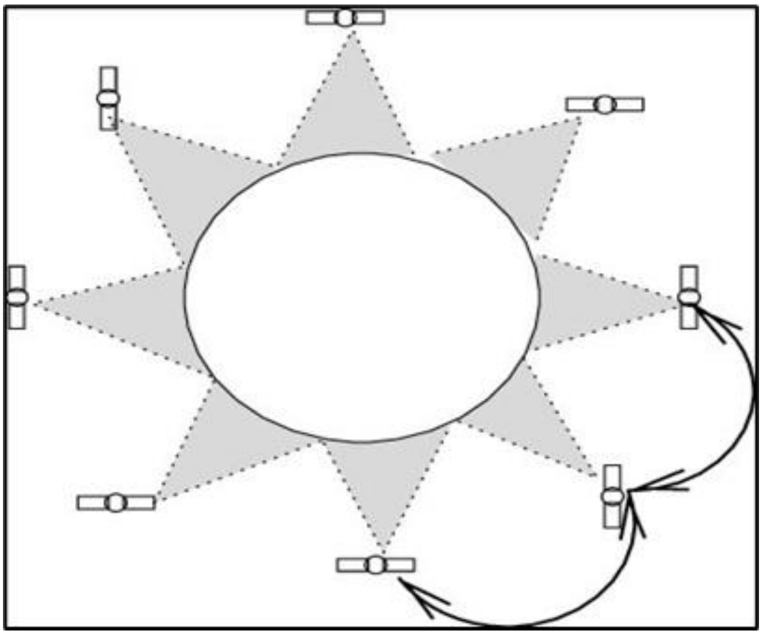

Figure 3. LEO satellite launching [36].

2- Satellites in medium earth orbit, or (MEO) for short, are those that travel between 5,000 and 25,000 kilometers above the surface of the Earth. Functionally, MEO and LEO satellites are similar [23].
3- Geostationary Earth orbit (GEO): The speed of rotation of objects in geosynchronous Earth Orbit is the same as the pace at which the earth itself rotates. The satellites that are in geosynchronous Planet orbit have a more consistent placement when compared to the surface of the earth. The satellite is traveling at an altitude of 35,786 kilometers and is currently in an equatorial circular orbit. Satellites in GEO go around the planet once every 24 hours. For communication, three satellites in geosynchronous orbit around the earth, spaced 120 degrees apart above the equator, can cover the whole planet. Figure 2 is a representation of the satellites that go around the Earth in orbit [23]. GEO launching in orbit can be seen in Figure 4.

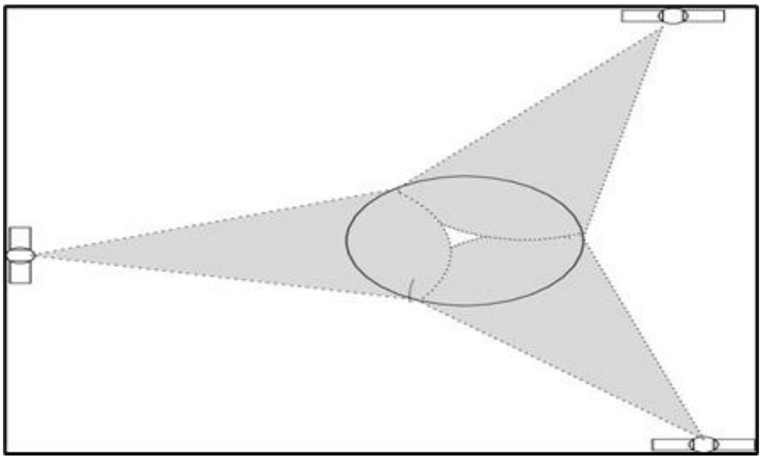

Figure 4. GEO satellite launching [36].

1- The Molniya orbit is one that Russia has been employing for several years now. When the satellite is in a Molniya orbit, it maintains a fixed position around the earth. The Molniya satellite travels in an elliptical path because of its orbit. The duration of a Molniya orbit satellite is about eight hours on average [23]. If you line up three Molniya spacecraft in a row, they can simulate a satellite in GEO. This type of orbit can be seen in Figure 5.

2- Platforms located at a great height (also known as HAPs): One of the most cutting-edge ideas in terms of communication via satellite is the HAPs. A blimp may function as a satellite by flying around 20 kilometers above the surface of the planet. HAPs have coverage that is rather restricted when measured with respect to the area it covers, but they send out a pretty big signal when measured in terms of signal power. Table 2 provides information regarding several aspects of satellite and HAPS target deployments, including their degrees of deployment and operational complexity, total system capacities, and latency performances [23].

When it comes to spectrum, a large number of next-generation satellites are transitioning toward the use of mmWave to improve their capacity performance in long-distance scenarios. While HAPS has an advantage due to its closer proximity to the earth, which enables it to deliver mobile services to normal mobile devices through the use of licensed bands operating at lower frequencies (below 6 GHz). The characteristics of different satellite orbits lists in Table 2 [37]. It is essential to find a way for HAPS and terrestrial networks to coexist in a solution. The utilization of different bands for satellite communication can be seen in Figure 6 [38]. A comparison between different orbits from the prospects of latency and bandwidth is summarized in Table 3 [38,39].

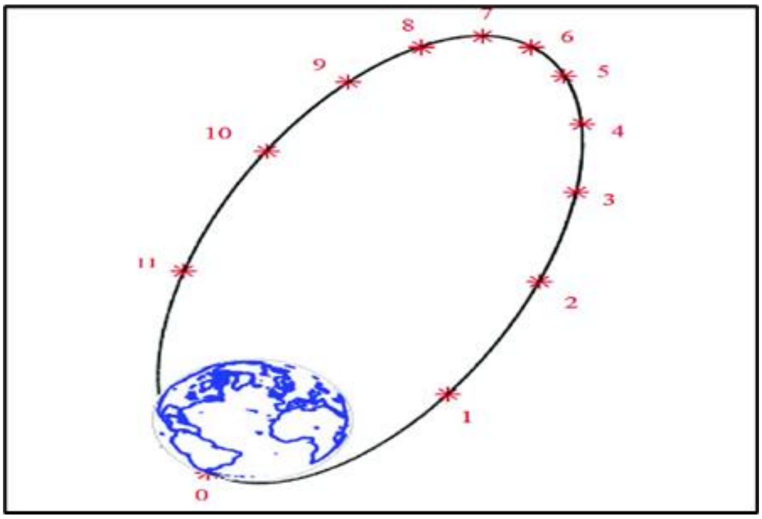

Figure 5. Positions for launching satellites from the Molniya orbit [36].

Table 2. Different satellite orbital characteristics [37].

Orbits	Satellite number for Full Coverage	Orbit time (hour)	Latency (ms)	Lifetime (years)
GEO	3	24	(600 to 700)	15
MEO	(10 to 30)	(5 to 12)	< 150	12
LEO	more than 100	1.5	<50	(5 to 7)
HAPS	1 aircraft	varied	< 10	> 5 for Balloon and >8 for aircraft

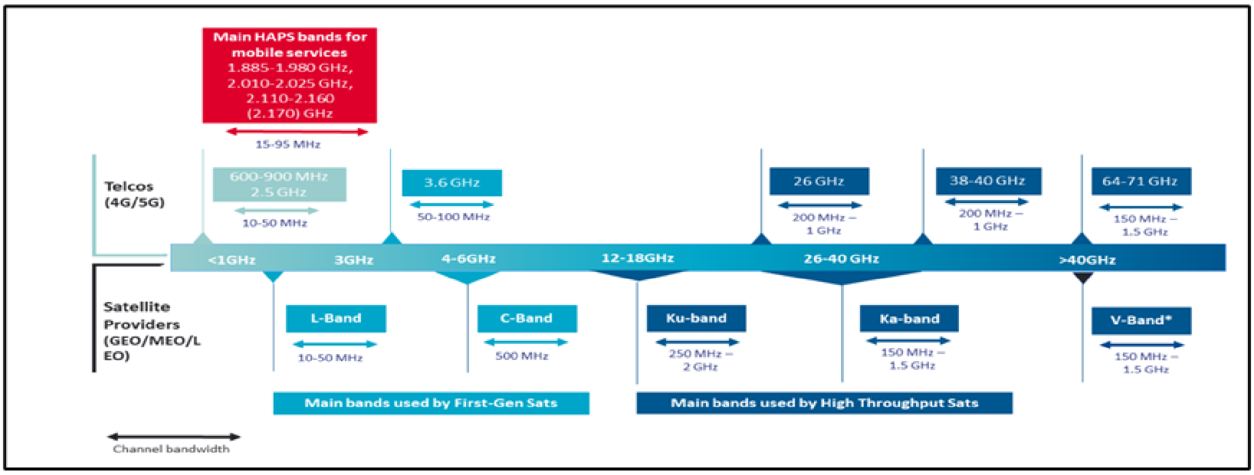

Figure 6. Different band utilization for different satellite orbits [38].

Table 3. A comparison of several orbits in terms of bandwidth and delay [38].

Characteristics	GEO	LEO	Wired	Wireless
Latency/ Variability	Fixed	Fixed	Traffic dependent	Fixed
Latency/ Milliseconds	500 ms	< 50 ms	medium	<10 ms
Bandwidth/ Total	over 100 Mbps	over 100 Mbps	High - Fiber unlimited	Low (WLAN)
Bandwidth/ Multicasting	Very high	Very high	High	Low
Bandwidth/ User incremental	Low	Low	High	Low
Bandwidth/ Coverage	Global	Global	wide	Local

4. Ka-band

As early as the 1970s, scientists from the United States, Europe, and Japan started looking into the Ka-band spectrum, which runs from 26.5 GHz to 40 GHz. Although at that time just the fundamental technology for transparent "bent-pipe" transponders was available, Japan was the first nation in the world to provide services using the Ka-band frequency range. Over the last two decades, a variety of exploratory satellites have been sent into orbit to investigate the use of the Ka-band frequency [40]. The demonstration of different satellite launching using the Ka-band for different coverage areas can be seen in Table 4 [40-44].

Because of its associated significance, the Ka-band is used for satellite communication. The following [40–44] provides an illustration of this significance:

1- High bandwidth: The primary driver behind the development of Ka-band satellite systems is the bands' abundant bandwidth. This is due to the fact that lower frequency bands have become congested, making it challenging to locate open bandwidth in such channels.
2- Smaller dimensions for the antenna: As the frequency increases, the dimensions of the antenna will get smaller while maintaining the same gain and beamwidth. This will result in a large reduction in interference from neighboring satellite systems when applied to an antenna of a constant size. The price of the more compact antenna will, of course, be cheaper, which will make it possible for millions of businesses and household end-users to pay for broadband satellite service without breaking the bank.
3- Ka-band satellites provide smaller spot beams to boost the satellite power density and allow extensive frequency reuses, which will lead to enhanced spectrum occupancy. This results in a larger system capacity. This may be accomplished by increasing the satellite's utilization rate. It is possible to service a large number of user terminals all at once.
4- Ubiquitous access refers to the fact that services may be accessed from any point within the satellite's footprint. This is particularly useful in areas where the installation of terrestrial wired networks is either not viable or would be prohibitively expensive.
5- The capacity for flexible bandwidth-on-demand is a feature that, when combined, enhances the usage of both bandwidth and resources while simultaneously reducing the cost to end users.

However, satellite links in the Ka-band suffer from atmospheric propagation effects, which are more severe at this frequency than they are at lower bands. This is because the effects of atmospheric propagation on Ka-band connections are more severe. The most important factors that have an impact on propagation include attenuation brought on by precipitation, losses brought on by wet antennas, depolarization brought on by atmospheric noise, tropospheric scintillation, gaseous absorption, cloud attenuation, precipitation, and ice. Attenuation caused by rain is the most difficult challenge that Ka-band systems must overcome among these elements.

Numerous Ka-band satellites have shown that the signal strength suffers a significant decline during periods of heavy rain; nevertheless, there are a variety of ways and methods available to reduce the impact of rain fade. For instance, the ACTS program developed extremely tiny hopping spot beams to concentrate the strength of the satellite signal on a localized region to transmit signals that can pass through the rain. Coding is another method that may be used by satellite systems to circumvent transmission limitations. Reduced bit rates during periods of precipitation are another tactic that might be used. This strategy would not be appropriate for a great number of applications, but it would be adequate for others, such as access to the internet. Uplink power regulation is a further strategy that may be used to reduce the amount of signal degradation caused by persistent rain [43, 44].

Table 4. Examples of launched satellite that uses Ka Band with different orbits and coverage.

Company	Satellites	Type	Coverage
NASA	ACTS	GEO	Americas
Alenia Spazio	ITALSAT 1 (1991) and ITALSAT 2 (1996)	GEO	Europe
National Space Development Agency of Japan	Sakura CS, CS-2A, CS-2B, CS-3A, and CS-3B	GEO	Japan
Amos	AMOS-3, AMOS-4, AMOS-17 (2019)	GEO	Europe, Middle
Apstar	Apstar-5C, Apstar-6C, Apstar-6D (2019)	GEO	Middle East
Arabsat	BADR5, BADR7, Arabsat-5A, Arabsat-5C	GEO	Middle East,
AsiaSat	AsiaSat 7, 8, and 9	GEO	Asia Pacific
Astro Digital US	Landmapper-BC	LEO	Americas
Audacy Zero	Audacy 0	LEO	Americas
Avanti	Hylas 1, 2, Hylas 2B & 4 with 3 (2019)	GEO	Europe, Middle
Chinasatcom	Chinasat	GEO	Asia Pacific
DirecTV	SKY-B1, Spaceway-1, Spaceway-2, DirecTV-11,8,10,9s.	GEO	Americas
Eutelsat	KA-SAT, KONNECT (2019), KONNECT-VHTS (2021)	GEO	Europe, Africa, the Americas, Russia
Hispasat	H30W-5, H30W-6, H36W-1,	GEO	Europe, North Africa, Americas
Echostar/	Echostar-9, Jupiter 1, Jupiter 2, future Jupiter 3.	GEO	Americas
Inmarsat	Inmarsat-5 F1, F2, F3, F4, GX-5 (2019),	GEO	Global
Intelsat	EuropeStar, IS-33e, IS-37e, IS-36, IS-20, Galaxy	GEO	Global
Kacific	Kacific-1 (2019)	GEO	South Asia,
LEO SAT	Next Gen Constellation (2021)	LEO	Global
Measat	Measat-3D	GEO	Asia
New DBSD	ICO G1 / DBSD G1	GEO	Americas
NBNCo	Sky Muster 1,2	GEO	Australia
One Web	6 in orbit; 30 more (Q4 2019); over 600 by Q4	LEO	Global
OHB	Future H2Sat, Astra 2E, 2F, 2G, 3B, 4A, 5B, Twenty O3B satellites, AMC-15, AMC-16, SES-11, SES-12, SES-14, SES-15, SES-17 (2020), 7 mPOWER	GEO	Global
Star One	Star One D1, Star One D2 (in construction)	GEO	Americas
Telesat	Anik F2, T12V, T18V, T19V, Next Gen	GEO/	Global
Thaicom	THAICOM 4 (IPSTAR)	GEO	Asia Pacific
CASC	Chinasat-16, Chinasat-18 and Chinasat-26.	GEO	China
ISRO/Antrix	HYLAS 1,2,2B,3 and 4		
Inmarsat	Inmarsat-5 F1 (GX-1), (GX-2), (GX-3), (GX-4), (GX-5), and (GX-6) recently.	GEO	Global
SpaceX	Starlink	LEO	Global

5. Advanced Modulation for Is-OWC system

The modulation technique may have a significant impact on the transmission's dependability, energy efficiency, and spectrum efficiency. In recent years, it has come to light that the propagation medium dependency of Is-OWC systems has a significant impact on the selection of other parameters. This discovery came about as a result of observations made in recent years. As a consequence of this, approaches of bandwidth-efficient modulation play a vital part in the design of the various components of the system. Visible Light Communication (VLC) has been the subject of several experiments and simulations that have been published in academic journals. These experiments and simulations make use of a variety of line coding and modulation techniques, and On-Off Keying (OOK) has been taken into consideration on numerous occasions because of its straightforward architecture, high level of power efficiency, and cost-effective character. On the other hand, OOK is only capable of supporting modest data rates and is particularly susceptible to pulse width widening effects. Pulse Amplitude Modulation (PAM) is being researched as PAM-4 and PAM-8 to increase the spectrum efficiency of the carrier; however, this results in a large reduction in receiver sensitivity [45–47]. The LED dimming technology known as pulse width modulation (PWM) has been extensively demonstrated but only supports a modest data rate. Both OOK and PPM employ single-carrier pulsed modulation techniques [48]. Time-domain equalisation is another criterion for PPM, which may be challenging for FSO lines with severe channel impairments if they do not match the standards. Researchers were urged to look forward to advanced modulation as a solution to the inefficiency and complexity of PPMs regarding bandwidth use. In addition, the usage of advanced modulation formats such as Carrier Suppressed Return-To-Zero (CSRZ), Duobinary Return-To-Zero (RZ), and modified DRZ is becoming more common; nevertheless, these formats can only sustain data speeds of up to 40 Gbps [49–52]. The ever-increasing need for data necessitates the use of FSO systems with a very high capacity. Both Differential Phase Shift Keying (DPSK) and Differential Quadrature Phase Shift Keying (DQPSK) are types of modulations that contain FSO many times. DPSK and DQPSK each have two (0 and) and four (0, +/2, /2) phase shifts, respectively. The most significant limitation of DPSK is that its reception is dependent on the use of two bits in succession. Consequently, an error in the first bit will induce an error in the second bit, and so on. On the other hand, there is a significant amount of interference from background noise while using DQPSK. There is a possibility that multi-level modulations might allow high speeds while also extending FSO distances. FSO systems that are based on orthogonal frequency division multiplexing (OFDM) have the advantage of an ultra-narrow spectrum and the resistance to inter-symbol interference (ISI), but they also have the disadvantage of nonlinear distortions due to a high Peak-To-Average-Power Ratio (PAPR) [53, 54]. FSO systems that are based on quadrature amplitude modulation (QPSK) have immunity to disturbances and have operations that are efficient in terms of bandwidth. In comparison to quadrature amplitude modulation, the most significant drawback of QPSK is that it is a power-inefficient kind of modulation (QAM). Many various variations of QAM may be used, ranging from 8-QAM up to 256-QAM. Because each symbol uses 8 bits, the 256-QAM variation of QAM has the narrowest carrier spectrum of the QAM types previously described. To obtain high speed, it is possible to study a number of different dimensions, such as space, time, frequency, polarisation, and modulation quadrature. The polarization dimension is a feasible parameter in FSO systems; hence, polarization division multiplexing, commonly known as PDM, may be employed to increase spectral efficiency while simultaneously doubling the user capacity. Combining PDM with other modulations, such as OFDM, QAM, QPSK, and others, may result in an improvement in the capacity of optical transmission. When compared to transmission using a single polarization mode, the effective symbol rate in PDM may be reduced by up to half. This makes it possible to use electronics designed for lower speeds inside a transmission system designed for higher speeds [23].

6. Previous Studies related to Is-OWC

A review of previous literature will be listed as seen in Table 5 to demonstrate the improvement carried for the aspect of Is-OWC and the related drawbacks.

7. Advantage of Satellite Communications

Is-OWC has seen significant growth in popularity over the last several years as a direct consequence of the following benefits [23, 67-69]:

1- It is feasible to enhance rapid inter-satellite communications by using light as a carrier frequency. This makes it possible to raise the speed of the links. Communication between satellites that use optics is capable of effortlessly handling data speeds of several gigabits per second.
2- Unlicensed spectrum: Unlike RF, FSO does not require licensing because LOS links are utilised. Point-to-point laser transmissions are extremely stable and protected, and interference from or to equipment is not a major concern. It's also very challenging to interrupt.
3- Less extensive wavelengths: the wavelength of light is one thousand times shorter than that of microwaves. As a direct consequence of this, the difference in signal wavelength between Is-OWC and RF systems is made much worse. The wavelength of RF and microwave radiation is quite a bit longer than the wavelength of light emitted by a LASER. The beam width of the signal will be significantly narrowed as a consequence of the transition from radio frequency to microwave to light wave transmission. Because the beam width is reduced, there is a rise in the intensity on the receiver side, and there is a reduction in the amount of crosstalk between the closer functioning connections [68-75].
4- Huge Bandwidth: The modulated carrier bandwidth determines how much data may be delivered using certain communication technology. A bandwidth of about 2000 THz may be accomplished by the use of a high-frequency optical carrier. When compared to RF communication methods, optical inter-satellite communication offers an unrivaled advantage in terms of its capacity to transmit and receive information. The frequency that is functional in the RF/microwave region has a relatively modest bandwidth, but it has a high Is-OWC value [66-75].

5- Decrease the size of the antenna If an RF or microwave gadget is to be used, both the transmitter and reception antennas will need to be somewhat large and cumbersome. The antenna size, on the other hand, could be reduced to just a few millimeters thanks to the very high carrier frequency of optical inter-satellite communication. This would result in a reduction in both the weight of the satellite and the amount of power that would be needed. By reducing the size of the satellite, resources may be used more effectively.
6- Diffraction-restricted divergence of 0.01–0.1 rad in a conventional laser beam and a narrow beam size are both characteristics of the narrow beam size [60-65].

Table 5. Demonstration of previous literature.

Ref.	Year	Methodology	Pros.	Cons.
[55]	2016	Using Co-(8 and 16) AOM, Co-(8 and 16) PSK	1 Tbps data rate and a distance of 45,000 kilometers using 16 PSK.	Higher-order modulation methods can make a drawback for the proposed system. Also, the data rate needs further increment.
[56]	2016	64 channel DWDM with different modulation methods of (CSRZ-DRZ-MDRZ)	Using a Modified Duobinary modulation scheme gives better results	The data rate of 2.56 Tbps needs to be improved. Also, the distance of 1250 km needs to raise, and consider optimization approach for the performance of CSRZ and DRZ
[57]	2016	6-channel WDM Polarization Interleaving (PI)	using the technique of PI	the data rate of 120 Gbps and distance of 1000 km does not satisfy with satellite recent applications.
[58]	2018	64 channel using advanced modulation methods of (CRZ, AMI, and DPSK)	AMI gives an optimum performance with a data rate of 2.56 Tbps	Distance needs to improve to satisfy different orbit allocation
[59]	2018	4 channel QPSK with CO and DSP	Mitigating nonlinearity impact and achieving a data rate of 100 Gbps per channel with a distance of 42,500 km	Overall capacity needs to be improved by reducing the complexity due to using the DSP
[60]	2019	DPSK OFDM system with 850 nm and 1550 nm of bandwidth	transfer 10 Gbps for a distance of up to 20,000 km	Using DPSK can be improved via using the dual polarization with differential QAM to raise the transmitted data rate
[61]	2019	10-channel OCDMA NRZ	transfer 100 Gbps over 25,000 km	Improving the data rate and distance is required
[62]	2019	64 channels using different advanced modulations of (Manchester, DPSK, and DQPSK)	Using DQPSK gives the best results and achieves 2.56 Tbps	The overall weakness of using the single polarization which can be further improved
[63]	2020	OFDM PDM CO	powerful of PDM to reach 400 Gbps of data rate and a distance of 60,000 km	improving the data rate for higher distances is required
[64]	2020	PDM-QPSK-Co DSP	160 Gbps transfer for 40,000 km	performance to raise distance is needed
[65]	2021	2 channel Is-OWC using MDM NRZ coding scheme	spectral intensity via using MDM	low data rate and distance needs to raise for recent satellite requirements
[66]	2022	4 channel OFDM MDM with the hybrid medium of FSO RoF	Powerful of using MDM with different profiles to improve the spectral intensity	data rate and the distance does not satisfy with recent Is-OWC-based applications
[67]	2022	10-channel DP-QPSK MDM	powerful of MDM with dual polarization technique to reach 4 Tbps and a distance of 40,000 km	using lower pointing error values for performance evaluation which will raise due to the dual polarization method

8. Challenges of Is-OWC

The result of satellite interaction with the ground and ground interaction with satellites may be affected by the atmosphere. FSO engineering uses the environmental window to get beyond restrictions imposed by arbitrary features like time and location. One of the many factors that could limit inter-satellite FSO connectivity is link availability. In this study, a range of challenges associated with Is-OWC communication downstream and upstream are discussed. These challenges are faced by data designers. Satellite orbits are devoid of air and have the characteristics of a vacuum, making them immune to the effects of erratic weather. The Is-OWC had difficulties due to several issues, which will be listed in Table 6 [23,70].

Table 6. Challenges facing the Is-OWC system from different prospects.

Technical Feature	Description	Challenge and opportunity
Delay of communication	would be high for GEO and medium for LEO-MEO.	Selecting the optimum network topology plays a major role in reducing the delay. Additionally, the selection of dedicated applications to be used would also help in reducing the delay in transmission.
Network Topology	depending on the satellite specification whether single, hybrid, or integrated.	complete integration to handle the same payload layers and protocols across network segments.
Throughput	The utilization of a higher frequency band with fiber link to satisfy the high data throughput.	By adopting a focused beam or dedicated ground stations, processing diversity-based solutions significantly contribute to reducing the fading effects caused by rain. Some IoT applications, however, may not necessitate increased throughput.
Availability of link	Higher availability has a reverse relation with the frequency band, which depends on the tracking and switching systems. Meanwhile, higher frequency achieves higher throughput over availability reduction. As a result, a tradeoff must be considered when handling the availability of satellite communication links.	In order to reduce the effects of fading effects and the latency in data transfer while the satellite establishes links, diversity, and tracking system plays a vital issue.
Pricing	such an issue depends on the satellite's purpose and mission to be used for. And the amount of bandwidth to be utilized for that.	Integration of hybrid schemes for satellite communication is the key factor that minimizes the overall pricing.
Spectral efficiency	using the dedicated modulation and coding schemes with recent division techniques is the key cause to increase the spectral efficiency.	Flexible frequency allocation and software-defined carriers are essential for maximising satellite efficiency in the future while taking new applications into account.
Pointing error	It is necessary for the arrival signal to be offset from the location of the beacon in order for it to arrive at the receiver in the correct geographical and temporal position. This is because the transmitter terminal and the reception terminal are both subject to a relative rotational motion relative to one another.	In a cross-linking system, the relative speeds of the two satellites determine how long it takes to travel over long distances. this is brought on by an incompatibility between the laser beam's and the beacon's directions.
Satellite vibration	The LOS signal is generated by the satellite, and it is then captured and tracked.	The satellite generates a variety of disruptive external pressures as a result of a number of different variables, including but not limited to, packages, wheels, velocity, thrusters, and solar panels. Different types of noise can come from a variety of sources, such as thermal noise, dark current, signal shot noise, and relative intensity background noise.
Doppler shift	The Doppler effect is a phenomenon that occurs when there is relative motion and a shift in the reception. The transmitter and receiver move in different directions as a result. Because satellites in lower orbits move more quickly than those in higher orbits, this occurs in the context of inter-orbit satellite links.	Lasers and filters used in Local Oscillator (LO) systems are required to have a wide range of optical links if coherent optical communication is to be achieved. The magnitude of the Doppler shift is at its highest point when the radial component of the relative speed has reached its maximum value. Carelessness with the Doppler effect on the part of the beneficiary end might result in knowledge loss and problems with recurrence simultaneity. In combination with the LO laser, the adoption of a protocol for an optical phase lock loop is required to minimize Doppler shift.
Background noises	The inter-satellite link may be used to identify the source of the interference in received signals, which is determined by the detection process. Massive dark current is used to identify noise sources directly at the receiver's end, which ultimately leads to the production of noise. Massive dark current serves as both a detector and an amplifier for the receiver.	The impact of noise in the preamplifier, noise in the thermal circuit, and eventually noise in the signal circuit, is commonly known as shot noise. The coherent detection is impacted by noise caused by LO. On the other side, sources of background noise are produced by stellar and cosmic radiation fluxes.
Acquiring, Tracking, and Pointing	is a major limitation problem with satellite communication. Several studies consider this aspect by considering fixed beam dimensions to achieve control over beam transmission.	The satellite needs to perform communication with angular accuracy that is better than a few micro radians, even while the host satellite is experiencing vibrational disturbances.

9. Applications of Is-OWC

Several applications were built and improved due to the utilization of satellite communication. Their applications will be listed based on the category that they are used to covering or working with and as listed [71]:

1. Weather forecasting: which predicts the weather. Weather satellites predict the weather. Weather satellites track Earth's climate. Radiometers measure ground surface heat energy. Hurricanes are forecast by weather satellites.
2. Navigation: This usually involves locating an item. Navigation satellites locate airplanes, ships, vehicles, trains, and other objects. Navigation systems include GPS. It locates users worldwide.
3. Astronomy: studies stars, planets, galaxies, natural satellites, comets, and more. Astronomical satellites examine faraway stars, galaxies, planets, etc. They mostly locate new stars, planets, and galaxies. Astronomical satellites include Hubble. High-resolution photos of faraway stars, galaxies, planets, etc.
4. Satellite phone: Cell towers only function in their coverage areas.
5. Satellite television: it is a wireless method that employs communication satellites to distribute television programming to viewers. TV typically employs geostationary satellites since they seem stationary from Earth.
6. Military satellites spy on enemies, communicate and navigate. Military satellites steal adversary secrets. These satellites also detect foreign missiles in orbit.
7. Satellite internet: which sends internet signals to people wirelessly. Satellite internet is best for speed. Satellite internet utilizes satellites to transfer data.
8. Satellite radio: which employs orbiting satellites to transmit radio waves to users. Mostly in vehicles. The satellite collects signals from the base station, amplifies them, and sends them back to earth.

10. Future scope of Is-OWC

Artificial satellites have grown due to internet connection. 35 billion IoT devices link humans more than ever. IoT devices will exceed 50 billion by 2030. Satellites offer data, research, telecommunications, safety and weather predictions, navigation, corporate insights, environmental monitoring, military, and more. Satellite launches have skyrocketed in the previous two years [23].

Multilevel modulations enable Is-OWC systems to reach larger distances due to spectral efficiency. Coherent receiver terminal detection improves sensitivity. A receiver DSP module can reduce nonlinearity effects and estimate carrier phase. Is-OWC communication is needed for ultra-long-distance, high-data-rate communication. Is-OWC system reach is being extended by 3D modulation. Future systems may address [23]:

1. Is-OWC capacity employing dual-polarization multilevel modulations and using the dedicated method of division multiplexing.
2. an expanded distance of the Is-OWC systems to meet the requirements of different orbits.
3. BER reduction via using different hardware equipment.

11. Conclusion

With developments in satellite communications, a huge number of satellites are already functioning in orbit, and constant progress is being witnessed to make satellite communication more cost-effective. In the field of Is-OWC, significant research efforts have been put forth, and the purpose of this article is to discuss several aspects of Is-OWC, such as the fundamental structure of satellite communication, the different kinds of satellite communication, the history of their development, laser communication, problems, and applications. Based on the literature analysis, it is possible to infer that utilizing the methods based on QPSK and DQPSK might increase the dependability of the suggested systems. However, one of the most important criteria for satellite communication is the transmission distance. Thus, current publications begin employing the OFDM approach in conjunction with other coding schemes to attain large data rates. Furthermore, the OFDM approach has recently been applied with PDM, which may further enhance the performance of the Is-OWC systems. Another factor to consider while showing the satellite system is the effect of the aiming mistake and its influence on the proposed system's reaction. As a consequence, the feature of the satellite system may provide numerous prospects for development and improvement via the use of widely established methods.

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Author contributions

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Conflicts of interest

The authors declare no conflicts of interest.

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