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Review article

A Critical Review on Issues and Challenges of Satellite Communication

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A B S T R A C T

Global coverage, reliability, high bandwidth, scalability, mobility, security and cost-effectiveness have made satellite communication as most effective and highly preferable method of communication. It is used for a variety of applications, from emergency communication to commercial and military operations. The satellite communication offers global coverage which makes it a crucial solution for communication needs in remote areas. The high bandwidth makes it efficient for transmitting voluminous amount of data in very short time span. In this paper, we have extensively and critically discussed the major issues and challenges of satellite communication and their proposed/implemented solutions to each major challenge by different researchers.

1. INTRODUCTION

In satellite communication, electromagnetic waves behave as carrier signals that transmit information such as audio, video or data between the ground and space. The maximum range for both ground wave propagation and sky wave propagation is restricted to 2000 kilometers [1]. However, this limitation can be overcome through the use of satellite communication by leveraging satellites to an orbit at a certain altitude above the Earth. Thus the communication can be extended beyond the line of sight and over longer distances. Locating the satellites at some height from the earth can bypass the restrictions due to curvature of the earth in communication between two ground stations [2-3]. Communication satellites are particularly useful in various industries, such as telecommunications, radio, television broadcasting and internet applications. Communication satellites can be seen as repeaters in space. A repeater is an electronic circuit that amplifies the received signal before transmitting it. In the case of a communication satellite, this repeater serves as a transponder, which modifies the frequency band of the transmitted signal to match that of the received signal.

In LTE (Long-Term Evolution) networks, the uplink transmission, which occurs from the device to the cell tower, utilizes Single Carrier Frequency Division Multiple Access (SC-FDMA) modulation. This uplink transmission follows a frame structure with duration of 10 milliseconds. Conversely, LTE downlink transmission, from the tower to the device, employs Orthogonal Frequency Division Multiple Access (OFDMA) modulation. The physical resources in the LTE downlink can be visualized as a time-frequency resource grid. These resources are further organized into units known as Resource Blocks (RBs) with each RB comprising 12 subcarriers. Communication satellites can be categorized as either active or passive. An active satellite receives signals from an Earth station and using a transponder, amplifies the signal before retransmitting it back to Earth. In contrast, a passive satellite reflects signals between two Earth stations without amplifying them. A satellite transponder system consists of several components, including a receiving antenna to capture signals from ground stations, a broadband receiver, a multiplexer and a frequency converter. These components work together to reroute the received signals through a high-power amplifier for downlinking to ground stations. The primary role of a satellite is to take the received signals and retransmit them to ground stations [4]. For instance, in the case of television broadcasts, when TV programs are sent to the satellite, the satellite receives processes and responds by downlinking the signals over a broader geographical area. This allows the signals to be received by various customers equipped with compatible receiving equipment [5].

Satellite communication has numerous advantages, which include global coverage, reliability, high bandwidth, scalability, mobility, security and cost-effectiveness. The ability of satellite communication to offer global coverage, unlike terrestrial communication infrastructure, which is limited to specific geographic locations, makes it a crucial solution for communication needs in remote areas where it is difficult to build terrestrial communication infrastructure. Additionally, satellite communication is highly reliable, even in the event of natural disasters that can damage terrestrial communication infrastructure. This is due to the fact that it is not affected by such events. Satellite communication can also transmit large amounts of data quickly due to its high bandwidth, making it ideal for applications that require high data rates. It is also easily scalable, accommodating more users or higher data rates by adding more satellites or increasing the power of the existing satellites [6]. Satellite communication is ideal for mobile communication applications, such as maritime, aviation and land mobile services. Some evident reports revealed a new pattern of innovation and change in satellite communications. It includes the deployment of direct-to-the-consumer technology, bypassing traditional infrastructure [4]. It can give the early warning of geomagnetic storm [7].

Security is another advantage of satellite communication due to the difficulty in intercepting or disrupting the signal. This makes it essential for government agencies, military operations, and other critical applications that require high levels of security. Lastly, satellite communication can be a cost-effective solution, particularly in remote areas where building terrestrial communication infrastructure is not practical, even though the initial cost of launching and maintaining satellites can be high. The cost per user or data rate is often lower than that of building and maintaining terrestrial communication infrastructure in remote areas. In summary, satellite communication offers numerous advantages that make it an essential means of communication for a wide range of applications, from emergency communication to commercial and military operations to personal communication needs [8].

Satellites are mainly used for:

(a) *Traditional Communication* - The increasing demand for satellite systems is being driven by various telecommunication trends. These include the rising popularity of direct-to-home television (DTH) and direct broadcast satellite (DBS), the significant expansion of wireless handheld phone usage (such as cellular, personal communication services and paging) and the growing number of multimedia-ready personal computers worldwide that are being used to connect to the internet. Additionally, there is a surge in maritime and aeronautical telephony and fleet broadcast communication. These telecommunication trends are contributing to the interest in traditional forms of telecommunication [9].

(b) *Atmospheric Observations* - The process of gathering atmospheric data for climate forecasting involves utilizing meteorological satellites from various countries that operate within the region. These satellites, such as India's INSAT-3 series and MATSAT, China's Feng Yung-1C and the European meteorological satellite NOAA series, are used for this purpose [10].

(c) *Military Operations* - The utilization of space technology has become increasingly important in military operations, as they provide essential support for various military and security-related activities, including compliance verification with arms and control treaties. Military applications of space technology include the usage of imagery, navigation, signal intelligence, telecommunications, early warning systems and metrology. Currently, there are more than 270 military satellites, in addition to approximately 600 civil, commercial and multipurpose satellites, that serve both military and civilian purposes [10-11].

(d) *Radio and TV Broadcasting* - Satellite communication revolutionized TV and radio broadcasting by enabling the distribution of high-quality signals to remote areas. It led to the development of DTH and DBS services for television and digital radio services for radio, providing better sound quality and more channels to listeners [12].

Manmade satellites rotate around the Earth in particular positions which are known as orbits of satellites [13].

There are three main types of Earth orbit satellites:

(i) Geosynchronous Earth Orbit Satellites: Satellites placed at an altitude of about 22300miles directly above the equator of the Earth and have an orbital period synchronized with the actual time of a day (i.e., 23 hours 56 minutes) are known as Geosynchronous Earth Orbit (GEO) Satellites. These orbits may have inclination and eccentricity and can be tilted at the poles of the Earth. While they are not always circular, they appear stationary when viewed from the Earth's surface. GEO satellites are commonly used for satellite television and if their orbits are circular and in the plane of the equator, they are called Geostationary orbits. Satellites placed in Geostationary Earth Orbit (GEO) are located at an altitude of 35,900kms (same as Geosynchronous) and they rotate with the Earth's direction (west to east) at the same angular velocity as the Earth's rotation. These satellites are useful for weather forecasting, satellite TV, satellite radio, and other forms of global communication. The primary benefit of a geostationary orbit is that there is no need to track the antennas to locate the position of the satellites [14].

(ii) Medium Earth Orbit Satellites: Medium Earth orbit satellites are put at an altitude of about 1000miles to 22000miles and are often used for GPS navigation and military communications. Several studies revealed that MEO satellite constellation have greatest potential for the most cost –effective path to the high spatial, temporal and spectral resolution atmospheric data.

(iii) Low Earth Orbit Satellites: Satellites placed at an altitude between about 155miles to 1240miles are known as Low Earth Orbit (LEO) satellites. Low Earth Orbit satellites can broadly be classified into three categories. LEOs will orbit at a distance of 800Km to 1600 kilometers above the earth's surface. This satellite holds application in satellite phones and GPS, Earth observation, remote sensing, and communication purposes. They are often used for scientific research, weather observation and satellite-based internet services [15].

2. RESULT AND DISCUSSION

In this section we will discuss the major issues/challenges of satellite communications and the solution proposed/ implemented.

2.1. Latency

Latency, also known as "ping" or "ping rate," is a metric that measures the duration it takes for a particular data to reach your computer and is expressed in milliseconds. To assess latency, one can send a solitary data packet or "ping" to a remote server and measure the time it takes for the response to arrive, which can be an issue for real-time applications such as video conferencing or gaming. In many future applications, low latency is a crucial quality of service constrained the requirement on end to end latency in the fifth generation mobile network and beyond on order of 1 to 5 millisecond, is much more stringent than that in third generation and fourth generation systems [16].

Solution: Forward Error Correction (FEC) is a method used to identify and rectify errors in data transmission. It involves adding extra redundant data to original data enabling receiver to correct errors in data without requiring retransmission. This Technique reduces time for error correction, as retransmissions cause delays in communication process. The use of FEC leads to efficient and dependable data transmission, resulting in lower latency [17]. The idea of Forward Error Correction was very first put by Claude Shannon who was an American electrical engineer who invented channel coding in 1940s, which provided the groundwork for Forward Error Correction (FEC) techniques [18].

2.2 Limited bandwidth

While satellites can handle a large volume of data, their bandwidth is still limited compared to terrestrial communication networks. This can result in slower speeds or reduced quality for certain types of data-intensive applications. Satellite communication systems have a limited amount of available bandwidth due to the finite nature of the radio frequency spectrum. A restricted communication pipeline might become a resisting factor in control and distribution of robotic generated satellite systems which is an issue in current times [19]. The available frequency bands for satellite communication are limited in size and are allocated by international agreements, so to achieve optimal use of frequency resources, adaption to the variations of power constraints and frequency bandwidth availability will fulfill the purpose of applying it to Ka-band high-capacity satellite (HTS) systems [20].

Solutions - Frequency reuse is a method utilized in satellite communication to enable multiple satellites to share the same frequency band, thereby maximizing the number of channels that can be transmitted while minimizing overall bandwidth requirements. The integrated satellite and terrestrial system employs a spectrum sharing scheme, leveraging soft frequency reuse to minimize interference between satellite and ground components by focusing on temporal isolation. In this approach, the entire frequency band is partitioned into seven sub-bands and the satellite cell is further segmented into internal and external sectors. Soft frequency reuse(SFR) have become the most important system for wireless orthogonal frequency division multiplexing based once to achieve high data rate during communication. Till now, it is extensively explored under the subject of inter-cell interference coordination [21].

2.3 Weather interference

The magnetosphere is filled with particles of radiation with intensity to create problems for satellites. Thus because of the trapped radiation, the world's first telecommunication satellite stopped working just few days after its launch [7, 22]. It is very important to know the location and motion of the space objects and this is increased in present time due to the large constellations [23].

Solution - Adaptive modulation and coding is a technique used in satellite communication systems that can adjust the modulation and coding schemes of the transmitted signal in real-time. This adjustment is done to match the current signal-to-noise ratio and weather conditions. By adapting to changing weather conditions, the system can ensure reliable communication even during periods of rain attenuation. The establishment of performance limits sets the foundation for devising and refining optimal communication methods in wireless transmission. The variability of channel conditions in wireless transmission can occur unpredictably due to fluctuations in the fading environment or user mobility. However, in many real-world scenarios, the system can effectively gather valuable data about the current strength of the channel fading process based on relative dynamics [24].

2.4 Cost

Satellite communication can be expensive to implement and maintain, particularly for smaller organizations or individuals. This can limit access to satellite communication for some users. One of the primary expenditures in satellite communication is the launch of the satellite into space. Depending on the size and intricacy of the satellite, the expense of launching a satellite can vary from tens of millions to hundreds of millions of dollars [25]. Research in the field of telecommunication satellites also focuses on developing cost-effective methods for generating electricity on these satellites without adding excessive weight. The concern of weight is primarily due to the higher costs associated with launching heavier satellites using rockets. Thus, finding efficient and lightweight solutions for electricity generation is a key aspect of this area of study and which is the most important aspect [26].

Solution -Utilizing Commercial-Off-The-Shelf (COTS) Technology allows for the benefits of mass production and economies of scale, leading to cost reductions. Additionally, COTS technology is typically easily accessible, contributing to shorter lead times for satellite production. It is currently the best options for having a reduction on satellite costs [27]. The design of small satellites heavily relies on low-cost, occasionally non-space-qualified and untested off-the-shelf components and technologies. Systematic frameworks or guidelines to aid satellite designers in making informed and optimal decisions are not available which leads to potential risks and costly design.

2.5 Security

Satellite signals are broadcasted in all directions; they can be intercepted by unauthorized parties. This can be a concern for sensitive applications such as military or government communications. Security issues like interception, jamming, and spoofing pose a significant risk to satellite communication systems. Interception can result in the compromise of communication confidentiality. It is important to allot appropriate security solutions mainly as encryption, verification, and access control to tackle these security issues. Security of the satellite link is an essential and critical aspect for military and state departments. Consistent security issues arise due to attacks from intruders aiming to disrupt the link and compromise data integrity and confidentiality. The vulnerabilities in satellite communications are of utmost importance and encompass critical areas such as launch systems, communications, telemetry, tracking and command and mission completion. Throughout the satellite's lifespan, secure and resilient cyber capabilities are crucial for various other aspects of satellite communications. Given the global nature of satellite and cyberspace activities, establishing agreed legal norms through international cooperation becomes essential to safeguard satellites and their communications effectively [28].

Solution - Encryption and other security measures have been implemented to protect satellite communications from interception or hacking. Various methods of coding and algorithms have been used widely to encrypt the data. Authentication mechanisms can be deployed to verify the identity of devices or users accessing the satellite communication system. Authentication guarantees the receiver of a message that the message originates from the claimed source. Access control is a service that restricts access to host systems and applications through communication link. Access control measures, such as the implementation of firewall rules, can be applied to prevent unauthorized access to the system [29]. Encrypting the data holds a crucial role in ensuring security within open networks, particularly on the rapidly expanding internet with its multitude of multimedia applications. Encryption involves converting plain text into cipher text and is employed in cryptography for transmitting confidential messages through insecure channels. The encryption process occurs at the sender's side.

2.6 Power limitations

Satellites rely on solar panels or batteries for power, which can limit their lifetime and ability to transmit at high power levels. This can also limit the amount of data that can be transmitted [30]. Satellites have been using solar cells and batteries to generate and store the power they need. However, batteries are heavy and solar panels take up a lot of space. The growing need for extended mission durations and enhanced satellite capabilities poses a considerable challenge for satellite power management systems. An essential factor in optimizing power on satellites is the enhancement of solar panel efficiency. Since solar panels serve as the primary power source for most satellites, their efficiency significantly influences the overall power consumption of the satellite [31-32].

Solutions - Satellites can also be designed to use less power for communication, such as through the use of lower-power transmission modes or by reducing the amount of data that is transmitted. The Power-Aware Routing (PAR) protocol is designed to maximize network lifetime and minimize power consumption by selecting a route that is less congested and more stable during the process of establishing a route from the source to the destination. This allows for the efficient transfer of both real-time and non-real-time traffic, resulting in energy-efficient routes [33].The enhanced efficiency of the power supply system enables a reduction in the size and weight of critical components, such as the solar array and battery, making them pivotal considerations in satellite design. The satellite's power supply system is composed of two units: a generation unit and a storage unit. To optimize the solar arrays efficiency, a maximum power point tracker (MPPT) is utilized in the power generation unit. A novel algorithm based on the hill climbing method is proposed to further enhance the MPPT's performance. This algorithm represents a widely adopted and efficient solution in contemporary satellite design practices [34].

2.7 Orbital limitations

Satellites are typically placed in a geostationary orbit which means they remain in a fixed position relative to Earth. Geostationary orbit (GSO) satellites are located at an altitude of 35,900 km above the equator and have an almost zero inclination angle. This allows them to potentially provide latency-critical applications through satellite communication. However, the communication links between GSO satellites and ground stations are subject to high propagation losses, which mean that large antennas with higher transmitting power are necessary. Additionally, the propagation delay of GSO satellites is high due to the long distance between the satellite and the ground, making them less suitable for delay-sensitive services [35]. A GEO satellite can provide coverage to approximately one-third of the Earth's surface, excluding the Polar Regions. This extensive coverage encompasses over 99% of the world's population and economic activities. On the other hand, achieving global coverage with LEO and MEO orbits requires a larger number of satellites. Unlike GEO satellites, non-GEO satellites in LEO and MEO orbits move in relation to the Earth's surface, necessitating a higher quantity of satellites to ensure continuous service provision [36].

Solutions -Satellites can be placed in different orbits depending on the requirements of the application. When creating a satellite network, certain key decisions need to be made. These include choosing the parameters of the orbit, determining the coverage model, and establishing the network connectivity and routing model. Various deterministic models have been developed to evaluate the coverage time of low Earth orbiting satellites. These models include statistical assessments of coverage time which can be particularly useful for conducting probabilistic investigations of intersatellite handovers [37].Selecting a satellite orbit is a highly intricate process, involving the submission of an application to the ITU as a mandatory requirement. To ensure reliability, two crucial aspects must be taken into account during orbit selection: the orbit altitude and the orbit inclination [38].

2.8 Space Debris:

In the present era, space debris poses a significant concern due to the continually increasing number of objects in orbit. Various techniques have been proposed to remove space debris from its trajectory. The accumulation of space debris is surging rapidly, elevating the risk of potential damage to operational satellites. The number of satellites orbiting the Earth is increasing, which could eventually pose a serious threat to space activities. Currently, there are millions of pieces of space debris orbiting the Earth at speeds of up to several kilometers per second [39]. Objects in outer space can reach extremely high velocities, posing a threat to all operational space systems, whether they are civil or military. Even small particles, such as a drop of water, can have such an impact that they can penetrate an American Silver Dollar upon collision. Given that satellites have less compact walls, they are susceptible to being easily hit and penetrated. In response to the escalating risks, certain nations have taken proactive measures to reduce debris formation and safeguard assets from this threat. Notably, space debris becomes particularly perilous in proximity to the Earth at both Low Earth Orbit (LEO) and Geostationary Earth Orbit [40]. Currently, there are around 950 operational satellites in Earth's orbit, with three specific regions accounting for 95 percent of the deployed satellites [39].

Solutions: The last few decades have seen a significant rise in the need for and complexity of, collision avoidance activities between active spacecraft and debris or other spacecraft. This is largely due to the increasing number of satellites in orbit and significant fragmentation events, such as Fengyun-1C in 2007 and Iridium-33/Cosmos-2251 in 2009. The growing number of objects in Earth's orbit is already a critical threat to the safe and sustainable use of space. This issue is expected to escalate further due to recent advancements in the space sector [41]. According to laser orbital debris removal, a laser broom will have sufficient power to penetrate through the ionosphere and the upper parts of the atmosphere, with the remaining power being used to ablate material from debris. This ablated material will impart momentum and can alter the velocity of the debris by up to 250 meters per day [42]. By employing these innovative techniques, space agencies aim to address the ever-growing orbital population and mitigate the risks associated with space debris, ensuring a safer and more sustainable environment for space exploration and satellite operations. Fiber-based elimination strategies involve the use of fibers to remove space debris from orbit. These techniques are governed by a regulatory approach based on the exclusion methodology which has been proposed as an effective means to tackle the issue of space debris removal. By employing innovative fiber-based methods, space agencies aim to enhance their capabilities in mitigating the risks posed by space debris and maintaining a safer orbital environment for future space missions and satellite operations.

2.9 Limited payload capacity

Satellite payload refers to the on-board system within a satellite responsible for establishing communication links and facilitating the transmission of communication signals [43]. It plays a crucial role in ensuring effective communication between the satellite and ground stations or other interconnected mobile users. In the past, communication links between two ground stations were prevalent, but advancements in payload technology now allow for interconnectivity between numerous mobile users, either directly or through ground stations. The fundamental payload functions involve receiving and filtering uplink signals, along with providing frequency conversion and amplification for downlink re-transmission. Payloads can be broadly classified into two types: transparent, which does not recover original data, and regenerative, which recovers data and utilizes on-board processing (OBP). Numerous papers in the field of On-Board Processing (OBP) have focused on satellite applications, particularly in utilizing Optical Burst Switching (OBS) with asynchronous transfer mode (ATM) switching within the satellite payload. Besides enabling direct interconnection between terminals, OBS offers the advantage of selective landing, whereby the closest gateway to the destination is chosen to avoid potential network congestion in the terrestrial network. This capability enhances user access and improves overall communication efficiency [44-47].

Solution: A common reliability engineering challenge in communication satellites involves determining the most effective redundancy allocation scheme for power amplifiers within the payload transponder module [48].The function of these power amplifiers is to enhance the power levels of signals received from Earth, while simultaneously maximizing reliability against various constraints such as mass, power, and other technical limitations [49]. Addressing this problem is crucial for ensuring the satellite's performance and longevity in space, considering the importance of reliable signal amplification for successful communication operations. Innovative approaches in redundancy allocation play a vital role in optimizing the satellite's performance under real-world limitations and uncertainties [50]. Transparent payloads offer additional benefits with Optical Burst Switching (OBS), including Variable Bit Rate (VBR) services and bandwidth-on-demand capabilities. An instance of on-board switch utilization is evident in the THURAYA3 system, where it facilitates single-hop terminal-to-terminal calls. While control data continues to flow to the gateway, traffic data is switched directly on the satellite between the two users. This results in a reduced perceived delay, by minimizing the time gap between the speaker's speech initiation and its reception by the listener.

2.10 Satellite Repair and maintenance

The number of satellites orbiting Earth continues to grow, unchecked and still maintenance or repair is not possible which in turn leads to launch of new satellites which later on turns into space debris and could eventually become a significant threat to activities in near-Earth space, making it increasingly important to find effective mitigation strategies. One potential solution for the future could be to ensure new satellites are equipped with capabilities for de-orbiting and reducing orbital lifetime at the end of their service life [51]. As a result, many satellites may become obsolete, damaged or abandoned and remain in orbit for more than 25 years. These abandoned satellites and space debris may represent valuable orbital real estate and resources that could be reused, repaired or upgraded for future use. This could provide an economical solution to the problem of space debris and make use of valuable resources that would otherwise go to waste. Despite rigorous testing prior to launch, the harsh environment of space can disrupt the operation of these satellites, causing them to become inoperable. This not only results in a significant financial loss but also contributes to the problem of space debris [52-53].

Solution - Satellite service is a crucial emerging technology for the industry. The Space organizations should conduct research on servicing technology. The ability to upgrade, inspect, re-orbit and refuel spacecraft while they remain in orbit could revolutionize space operations and significantly reduce the cost and time it takes to place satellites in orbit. Satellite servicing has numerous strategic benefits and will play a vital role in maintaining space superiority over adversaries. Recently, reusable launch vehicles have been used to reduce space debris, which can damage satellites orbiting in their path. The Indian Space Research Organization (ISRO) has successfully operationalized the Polar Satellite Launch Vehicle and the Geo Synchronous Launch Vehicle. They are now developing Reusable Launch Vehicle technologies to achieve low-cost access to space and reduce the possibility of satellites getting damaged [53].

3. CONCLUSION

It can be concluded that the advantages of satellite communications in the fields of traditional communications-DTH, DBS, handheld phone usages, internet, collection of atmospheric data from different countries within the same region for forecasting and the usage of imagery, navigation, signal intelligence, telecommunications, early warning systems and metrology in military operation made satellite communication as most efficient and reliable communication systems. It has brought the revolution in the mobile communications and early weather prediction. It can give the early warning of geomagnetic storm. The satellite communications scalable technology which can accommodate a larger number of users. It is ideal for maritime, aviation and land mobile services. The government agencies, military operations, and other critical applications that require high levels of security are using satellite communication due to the difficulty in intercepting or disrupting the signals. It is a cost-effective solution for remote areas where terrestrial communication infrastructure is not practical to build. In spite of so many advantages it has some challenges like latency, limited band width, weather interference, high initial cost, possible interception of signals by unauthorized parties, challenge for satellite power management in extended missions, orbital limitations, space debris problems, limited payload capacity, repairing and maintenance of satellites which limits its efficiency. Most of these issues can be overcome by the proposed solutions and the researchers are continuously trying to mitigate these problems by changing the software and hardware of the satellites.

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