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1. INTRODUCTION

Data communication refers to the exchange of data between two devices through a transmission medium (Forouzan, 2013).

Data communication plays a vital role in modern society by enabling the efficient exchange of information between devices like computers and systems across different locations (WAN, LAN) etc,

Data communication enables fast and reliable transfer of information over long distances, it can also support global connectivity through the Internet and telecommunication networks.

Satellite has become an important thing in the establishment of long range of telecommunications for a couple of years now and it will also have an impact in the future as it stands now, because it has helped in fast communication even in long distances. One satellite can even serve a huge country even some continents, which tells you that distances does not matter in Data communication (transmitting and receiving Data), Communication depends on where the satellite will reach not ground distance.

In the modern systems of broadband satellite, which can give a high amount of speed during data transmission, receiving and connectivity to the terrestrial data networks. These systems are really improving when it comes to this new generation, can be send very quick and can easily connect with normal network based like fiber optic cables and the internet.

Because of this changes in our generation, it will have a major impact in the future as i mentioned earlier, this will include important areas like the Internet, online services and electronic commerce (buying and selling goods).

They are studying how future satellite networks will work and how well they can connect and function together with some existing based networks, such as wireless (mobile networks, Bluetooth, Hotspot) and wired systems like (fiber optic cables). A. Jamalipour University of Sydney, Australia

A communication Satellite is a microwave repeater station that permits two or more users with appropriate earth stations to deliver or exchange information in various forms, it works like a signal relay station in space that receives signals from maybe Earth, it will strengthen it and then send it back to its locations. This allows people with ground stations like earth equipment to exchange information in different forms like voice, data, or video.

A satellite in geostationary Earth orbit (GEO) moves around the Earth above the equator and completes one full rotation in 24hours, because it moves at the same rate as the Earth spins, it appears to stay fixed over one position on the planet. This makes it very useful or important for continuous communication. There are different types of 24-hour orbits, meaning different

ways satellites can stay synchronized with Earth's rotation, but your sentence cuts off before explaining them.

2. TECHNICAL PRINCIPLES OF SATELLITE COMMUNICATION

2.1 ORBITAL MECHANICS

Low Earth Orbit (LEO)

LEO means Low Earth Orbit which is the region of space located closest to the Earth, where satellites operate at altitudes ranging from approximately 160 km to 2,000 km. Satellites in LEO orbit are mostly used for communication because Earth allows fast transmission of data.

CubeSats are very small satellites that are built to operate in Low Earth Orbit (LEO). Their purpose is that universities and students around the world can use them for space research.

CubeSats are very tiny satellites usually around 1.33kg, they are also built in standard cube shape. They use standard electronic modules for their internal circuits and initially supported by California Polytechnic State University (Cal Poly) and Stanford University.

A CubeSat with dimensions 10 cm x 10 cm x 10 cm is called 1U (one unit). CubeSats are formed by extending this unit in only one direction to support additional components and other mission requirements. CubeSats like 2U and 3U are also there (it has been created) and they are used for some specific missions (huge or complex ones than 1U). CubeSats are no longer just for students, they are now used for serious, complex missions. It was launched using a standard system, this system was developed by California Polytechnic State University, it is called Poly-Picosatellite Orbital Deployer (P-POD) which helps release CubeSats into space. It is like a specific container used to launch CubeSats into orbit.

There are different types of CubeSats, each has been built for a specific purpose including research and development, Earth observation (remote sensing) and experimental missions (like space tether systems), it shows that CubeSats are designed differently depending on what they are meant to do.

Examples of the Earth observation CubeSats include Quake Sat, Swiss Cube, PLUME and Firefly which are real satellites used for monitoring Earth.

LEO satellite (Low Earth Orbit) is mainly used for communication, Earth imaging that is (taking pictures of the Earth), they carry a payload which is the main working part of the satellite, some of these payloads are signal processing modules (equipment that receives, processes, and sends

signals). When designing a LEO satellite engineer carefully choose materials that are lightweight, that have high strength compared to their weight and be suitable for use in space (space-qualified).

In addition, when designing the shape and structure (geometry) of a satellite, engineers consider many factors like Heat distribution and dissipation which talks about how heat spreads and removed, Weight of fasteners (bolts, screws, joints (must be light)), Accessibility & maintainability (easy to assemble or fix), Accommodation of subsystems-there must be enough space for components (power, sensors, etc.), Center of gravity that talks of balance and stability and

Manufacturing cost. Research also shows that aluminium alloy is commonly used to build satellites, The satellite structure is often cube-shaped, this is because of the factors mentioned earlier (lightweight, strength, heat control, etc.).

The Swiss Cube is a real example of a satellite that demonstrates good design and material selection, it is used as a reference model for building CubeSats too. Monoblock structure also in satellites, it is like the main central frame (backbone) of the satellite, It also supports and connects all parts of the satellite. The Monoblock is the main support structure that holds everything together and makes the satellite strong and stable. It has three main functions which are:

Keeps the satellite structure properly aligned (shape stays correct).

Holds important components like attitude thrusters (used for control and movement).

Provides a base to attach all other parts (subsystems).

Sedighi and Mohammadi analysed a small satellite, they performed Static analysis - checks strength under constant force, Dynamic analysis - checks behaviour under vibrations (like during launch). What they did is they ensured safety factor greater than 5, meaning the structure is 5 times stronger than required load. They adjusted it to stringer height (support beams in the structure) and tray thickness (platforms holding components).

Medium Earth Orbit (MEO)

The MEO is identical to the LEO except that the satellite is in a higher circular orbit - between 1,600 and 4,200 km above the surface of the earth. This altitude range places MEO satellites in a strategically intermediate zone in the orbital environment of the Earth and places them far above the densely populated low earth orbital shell and much closer to the surface of the Earth compared to the much higher geostationary orbital arc. Such

between-the-world positioning gives MEO satellites a unique and operationally beneficial combination of coverage area, signal propagation characteristics, and orbital stability that make them especially well-suited to a wide variety of specialized and mission-critical communication and navigation applications.

The Medium Earth Orbit is a well-known orbital region of navigation constellations to provide global positioning and provide constant coverage of the Earth. As a result of gravitational effects of the Moon and Sun, MEO satellites experience gravitational influences affecting orbital stability as a design consideration to long-term performance. These third-body gravitational perturbations, - exerted by both the lunar and solar gravitational fields - cause observable and progressive changes in the orbital elements of MEO satellites over time, including changes in orbital inclination, orbital eccentricity, and the orientation of the orbital plane. Mission designers and satellite engineers should then take into consideration these cumulative perturbation effects during the early design phase and provide appropriate station-keeping maneuver budgets and propulsion reserves to keep the satellite within its designated orbital slot and ensure consistent, predictable performance throughout the desired operational lifespan of the spacecraft.

The Medium Earth Orbit (MEO) provides a larger breadth of satellite view than the Low Earth Orbit (LEO) yet it is also closer to the surface of the earth than the geostationary earth orbit (GEO). This wider field of view than LEO implies that fewer MEO satellites are needed to provide continuous and overlapping coverage of the globe as compared to the much larger constellations required at lower orbital altitudes to achieve the same type of continuous and overlapping globe coverage. MEO has already found applications in GPS and navigation systems, atmospheric studies, and it can be used in Earth observation, communication, positioning, as well as scientific research. The most well-known and globally-established examples of MEO-based navigation systems include the United States Global Positioning System (GPS), the European Galileo constellation, the Russian GLONASS system and the Chinese Bei Dou Navigation Satellite System - all of which operate their core satellite components within the MEO altitude regime and collectively form the backbone of the global navigation satellite system (GNSS) infrastructure throughout the world.

There is a special type of MEO called Sun-Synchronous MEO (SS-MEO). Sun-Synchronous aids satellites in tracking the surface of the Earth at regular intervals and with a clear view of the surface every day. Sun-Synchronous MEO satellites orbit the Earth approximately at the same local solar time each time they pass over any given location on the surface of the earth. This desirable property is critical in ensuring that ground-based imaging sensors onboard these satellites will always be able to encounter relatively similar angles of solar illumination and other related lighting conditions during one observation cycle to the next. This renders SS-MEO particularly useful in applications requiring consistency of observational conditions, such as environmental monitoring, detecting land-use changes, agricultural assessment, and long-term climate studies, where consistency of observational conditions is mandatory to the integrity and comparability of the collected data.

But the Medium Earth orbit (MEO) and Sun-Synchronous MEO (SS-MEO) satellites are exposed to intense radiation through the Van Allen belts and limitations by launch and orbital direction. Passing through the segments of the MEO altitude regime, the Van Allen radiation belts, which

are composed of two concentric belts of energetically charged particles trapped in the magnetosphere of Earth, expose satellites in this orbital region to very high levels of ionizing radiation. In designing satellite platforms in the MEO band, this highly and sustained radiation environment presents serious hazards on onboard electronic components, solar power generation systems and sensitive optical or scientific instrumentation. The paper evaluates the orbital parameters, the capability to observe the earth, the viability of construction and the deployment of such satellites. Trishchenko, A. P., Garand, L., & Tishchenko, L. D. (2019).

Geostationary Earth Orbit (GEO)

The Geostationary Satellite Orbit is one of the most popular orbit formats. The satellite remains at a single point with respect to the earth, and no movement of the ground antennas is necessary, so there is no reorientation of the direction. This operationally convenient and unique feature inherently makes GEO the choice of a wide and diverse array of commercial, governmental and military communication applications demanding constant, uninterrupted and geographically fixed satellite visibility at a specified ground location.

One of the greatest advantages of the Geostationary Satellite Orbit (GEO) is that the satellite is in a fixed position relative to the earth throughout the day, thus ground antennas can be constantly pointed towards the satellite without the necessity of reorientation. This is especially important in applications like direct broadcast television since it would not be practicable, cost-effective or technologically viable to change the directions of the antenna to serve mass market consumer installations. The removal of the requirement of mechanically steerable or electronically adaptive antenna systems at the ground terminal level radically reduces the cost, complexity and maintenance demands associated with the deployment of large-scale satellite-based broadcasting and communication infrastructure, and makes GEO-based services accessible and economically viable to hundreds of millions of users worldwide. Beyond direct broadcast television, this fixed-pointing advantage is also important to very small aperture terminal (VSAT) networks, satellite-based internet service provision, weather observation platforms, and government communication relay systems, all of which are beneficiaries of this fixed-pointing advantage to a considerable extent.

The concept of a geostationary orbit has been theorized and debated long, and the theoretical basis of the concept dates back to the visionary work of pioneering aerospace thinkers of the mid-twentieth century. It was determined that satellites at an altitude of about 35,900km above the surface of the earth with a corresponding 24 hour orbital period that is perfectly synchronized with the rotation period of the earth as viewed by the earth surface. This theoretical starting point formed the intellectual and scientific basis of what would come in a few decades to be one of the most commercially significant and strategically important technological developments in the entire history of telecommunications and has been the backbone of international broadcasting and data communications over several decades.

The longer the height or altitude of a satellite, the longer the time which the satellite will take to complete a complete orbital revolution around the earth. A satellite at an altitude of about 35,790 km takes a full 24 hours to completely orbit the Earth, an orbit that

coincidentally takes exactly the same time that it would take the Earth to complete a full rotation. Due to this very perfect synchronization between orbital period and planetary rotation, the satellite will appear to be completely stationary when viewed through any fixed point on the surface of the Earth below - a condition technically known as geosynchronous orbit, wherein the satellite will remain entirely synchronized with the rotational movement of the Earth. When this geosynchronous state is further coupled with a circular orbit that is in the plane of the equator of the Earth, then the satellite attains true geostationary status, in the sense that it seems to be suspended motionlessly in the air directly above a fixed equatorial longitude point throughout the entirety of its operational life, making it continuously and reliably accessible by ground stations and end-user terminals located across an immense geographic footprint spanning the length of one-third of the Earth.

Though geostationary satellites seem to remain stationary in the eyes of observers on the ground and those at the user terminals, they are constantly subjected to an array of external forces and environmental perturbations which otherwise, had to be compensated, they would slowly drift out of their specified orbital position with time. These perturbing forces are the gravitational effects due to the non-uniform distribution of the mass of the Earth, especially the equatorial bulge as a result of the oblate spheroidal shape of the Earth, as well as the third-body gravitational influence of the Moon and the Sun, whose gravitational fields exert cyclically varying forces on GEO satellites that also tend to change their orbital inclination and introduce a slow but progressive north south drift component into their apparent motion. Also, there is the pressure of solar radiation - the small, yet cumulatively important, force exerted on the physical surface area of the satellite by the photons emitted by the Sun. To overcome these combined perturbation effects and keep the satellite accurately within its allocated geostationary orbital slot (that is typically defined within a tolerance of plus or minus 0.05 degrees in both the north-south direction and the east-west direction) the satellite operators must carry out regular and carefully computed station-keeping manoeuvres using onboard thruster systems throughout the operational life of the spacecraft. The propellant budget spent on these station-keeping manoeuvres is one of the main factors that determine the ultimate operational lifespan of a geostationary satellite since the exhaust of onboard propellant reserves marks the effective end of the controlled operational life of a geostationary satellite. (Roddy, 2006)

2.2 Frequency Spectrum Management

C BAND

C band frequencies have not been in used in earlier satellite (European Galileo satellite) systems but are being considered for future satellite navigation applications.

For some reasons, a specific part or a portion of the C band as been allocated for satellite communication applications which has a 20 MHz bandwidth around 5 GHz.

C-band has both advantages and disadvantages and one advantage is less ionospheric delay which is it has better signal accuracy and some disadvantages are signal loss in space (free space

loss) rain attenuation (weather affects signal). It is therefore necessary to see the performance of the C band frequencies to know if they are suitable to use for satellite communication. This shows the overall system performance within this frequency band.

C band performance is affected by several signal issues like:

Atmospheric effects.

Signals loss.

Interference and noise.

It is compared with GPS (L-band) systems and the results help in designing satellite systems and receivers.

KU BAND

Ku-band is a band of satellite communication frequencies that operates within the 12-18 GHz frequency range, offering a better bandwidth and enhanced data transmission rates than the lower frequency bands such as the L-band. It is common and increasingly popular in high capacity uses which require fast and efficient transfer of large amounts of data, such as direct-to-home (DTH) television broadcasting, broadband satellite internet services, and maritime and aeronautical communication systems. The Ku-band is a more desirable and cost-effective choice among consumer-facing deployments of satellite communications since it permits the use of smaller and more compact Ku-band antenna dishes at the ground terminal level.

However, Ku-band signals are even more susceptible to poor weather conditions, most of all rain fade, a phenomenon whereby heavy rainfall absorbs and scatters the signal energy, leading to measurable degradation of the link quality and, in extreme cases, the temporary loss of service. This vulnerability is such that proper planning of link budget and inclusion of sufficient fade margin in the system design is necessary to achieve acceptable level of service availability under varying meteorological conditions. Also, Ku-band systems need to maintain accuracy and precision in the alignment of the antennas to maintain stable and reliable communication with the target satellite. In addition, the spread spectrum methods may be utilized to improve the overall performance of the Ku-band transmitters and receivers in terms of effectively avoiding interference and enhancing the reliability of signals under problematic and congested operating conditions. (Bostani, n.d.)

KA BAND

The Ka-band is a high frequency band of satellite communications with significantly higher bandwidth and data transfer rates than the low frequency bands such as C-band and Ku-band. It can facilitate high-capacity satellite communication technologies like multiple spot-beam systems and high-efficiency frequency reuse which complements system performance. Smaller and compact user terminals can also be used in Ka-band systems which makes them appropriate to the current mobile and broadband applications.

Ka-band has many applications in broadband internet services, Very Small Aperture Terminal (VSAT) networks, rural and remote area connections, satellite news gathering, military and defence communications, and disaster management systems. These applications take advantage of its capability of transmitting high speed and volume of data.

Recent Ka-band satellite systems are sometimes termed as High Throughput Satellites (HTS), where the system performance is gauged in terms of overall data throughput, not transporter count. This change indicates the increasing interest in digital communication services where one can consider capacity as the number of gigabits per second. Consequently, the Ka-band technology is important in facilitating adaptable internet-based communication systems and coordinated satellite network service. (Venugopal, Chandrasekhar, Mohanavelu, & Narayanan, n.d.)

2.3 Signal Modulation

The type of modulation of a signal managed by a receiver can be determined by examining the envelope properties of the signal, despite the noise. Different modulation schemes may be classified based on a distinguishing parameter, which is the ratio of the variance of the signal envelope to the square of its mean. Using this ratio of a received signal and comparing it with the known values, it is possible to identify the type of modulation. This method has demonstrated to be effective in simulating cases of signal classification in noisy conditions.

3. SATELLITE ZOOMING AND PRECISION TECHNOLOGY

3.1 High Throughput Satellites

High Throughput Satellites (HTS) are designed to deliver high data rates and improved communication capacity. (Ben Yahia et al., 2023)

The growing world need to have data communication with individuals, businesses and governments has led to the constant evolution of communication systems. Terrestrial networks are constantly being enhanced in terms of capacity and efficiency but satellite systems are also forced to evolve and compete. The next-generation satellite systems thus have new technologies like the use of Ka band, better antenna systems and better payload processing that enable high-capacity communication services (Hasan & Bianchi, 2015).

3.2 Fractional Frequency reuse (FFR)

Fractional Frequency Reuse (FFR) is a method of interference management in communication systems to enhance the use of a spectrum. It operates by allocating the available frequency band to different areas and allocating identical frequency to different areas under controlled conditions. This will contribute to minimizing signal interference and maximizing the overall system capacity. Moreover, FFR enhances the quality of signals and coverage, especially in users at the outer periphery of a coverage area, where signal interference tends to be the greatest. Through effective control of frequency distribution, FFR is significant in improving the performance and reliability of the modern communication systems. (Novlan et al., n.d.)

Under more advanced communication systems, FFR may be applied with the other approaches such as frequency planning and spatial reuse approaches to further improve the network efficiency. By dynamically controlling the frequency allocation in various regions, systems will be capable of accommodating the various amounts of traffic, and remove the congestion. This makes FFR particularly applicable in the modern high-capacity networks where spectro-efficient spectrum usage is supreme.

In High Throughput Satellite (HTS) systems, the principle of frequency reuse is similar, and is used in the coverage areas of spot beams to maximize capacity and minimize interference between beams.

3.3 Satellite Spot Beam Delivery

In a modern satellite system, targeted spot beam delivery is a technology that divides the area of satellite coverage into multiple small and focused beams in place of a wide beam. Every spot beam is focused on a particular geographic area and this enables more effective utilization of power and frequency resources. This focused methodology enhances the signal strength, data transmission rates and overall capacity of the system. Moreover, it allows efficient frequency reuse among the various beams which helps in minimizing the interference and also provides the high-performance communication services.

Spot beam technology has been very important in facilitating the high throughput communication in a practical satellite system. With satellites able to concentrate power into smaller coverage areas, the satellites are able to deliver stronger signals with reduced transmission losses compared to wide-beam systems. This renders spot beams especially useful in areas with a high density of people or areas with high data rates and where efficient use of bandwidth is an absolute must.

The other crucial benefit of spot beam technology is that it can enable aggressive frequency reuse. The overlapping beams can be used to reuse the same frequency bands within the non-overlapping beams without causing any major interference. This greatly enhances the overall

capacity of the system and enables the satellite operators to accommodate more users at the same time.

Also, the flexibility in design of spot beam systems can be taken into consideration and operators can use the flexibility to allocate capacity to the regional need. Regions that experience heavier traffic may have more beams or higher power levels and less demanding areas may receive fewer resources. Such dynamic allocation enhances the overall efficiency of the network, and the quality of the service is better.

Nevertheless, although it has its benefits, there are also several challenges associated with spot beam technology. The management and design of the various beams involves the use of sophisticated antenna systems together with highly accurate control mechanisms. Moreover, keeping the beam straight and reducing the interference of the neighboring beams may be technically challenging. However, spot beam technology is one of the main elements of a modern high-throughput satellite system because of its capacity to greatly increase the capacity and performance. (Schneider, Hartwanger, & Wolf, n.d.)

4. COMPARATIVE ANALYSIS: SATELLITE VS TERRESTRIAL COMMUNICATION

The radical increase in the number of different services enhances innovation and development of terrestrial communication systems to be used in the implementation of next-generation mobile communication networks. Nonetheless, merely using scarce resources in land-based communication systems makes it hard to support huge quality of service (QoS)-aware demands and it is difficult to guarantee a smooth coverage even in very remote areas.

(Wang et al., n.d.)

With the inherent benefits of high altitude and the capability to multicast or broadcast, the system of satellite communication offers a chance of new mobile communication networks through close interaction and complementary nature with the existing terrestrial networks.

It is thought that, the merging of the satellite and the terrestrial network may resolve the issues that are present in the current mobile communication systems and has a serious influence on the information dissemination in the world. Satellite-terrestrial integration in this context helps in the enhancement of coverage, better service delivery as well as enhanced network performance in future communication systems.

Terrestrial communication systems have various benefits including low latency, high rates of data transmission and cost efficiency in densely populated urban areas where infrastructure is highly developed. But the geographical constraints limit them and extensive physical infrastructures are needed which are costly and cumbersome to put in place in remote or rural areas.

Conversely, satellite communication systems are also widely-area and global, and thus are appropriate with remote locations, maritime communication, aviation, and disaster recovery applications. Nonetheless, satellite systems tend to have greater latency because of long distances of signal propagation and may be impacted by atmospheric conditions such as attenuation of rain signal propagation and may be affected by atmospheric conditions such as rain attenuation, particularly at higher frequencies.

5. CHALLENGES IN SATELLITE COMMUNICATION

5.1 Atmospheric Attenuation

The primary aim of this technology assessment project will be to determine robust and affordable solutions to achieving high system availability through rain fade compensation. In the satellite communication systems, particularly those that are operating in higher frequency bands like the Ka-band, atmospheric conditions contribute significantly in signal degradation. The Advanced Communications Technology Satellite (ACTS) is a Ka-band system which isolates spot beams by using spatial separation and cross-polarization techniques. Moreover, ACTS has been applied with adaptive rain fade compensation in its VSAT network to aid in maintaining the quality of communication in case of bad weather conditions. There are also experiments of adaptive power augmentation using ACTS, where transmission power is dynamically adjusted to overcome the effects of signal attenuation by rain.

Up to this day no major research work has been conducted in which the findings of the ACTS operations and experiments have been fully used to show the most appropriate and standardized methods of mitigating the effects of rain fade. This means that despite the fact that there are practical applications and experiments, there is still a gap in terms of translating these results into generally accepted solutions. Future Ka-band commercial systems such as Astrolink, CyberStar, and Spaceway are thus demanded to maximize system capacity, by minimizing the link margins required by user terminals. This matters as large link margins, though good at ensuring reliability, can result in an in-efficient utilization of system resources.

The Ka-band communication satellites have to be designed in such a way that they can offer high-quality services despite their uplinks and downlinks suffering heavy rain fade. As an example, even relatively small signal outages may demand very high levels of margin in individual communication links, perhaps well above 10 dB. What this shows is that the rain attenuation is a crucial limiting factor in the performance of Ka-band systems, especially in areas where there is heavy rainfall or adverse weather conditions. It is also hard to ensure the same signal strength due to variability of atmospheric conditions, thus impacting overall system reliability and quality of service.

The alternative to using huge fixed link margins across all communication lines, which would be the easiest response to providing adequate service delivery, is to apply the adaptive fade

compensation techniques that would only target those users who would be affected by rain. This scheme means that the system resources are used more efficiently since it dynamically varies transmission power or other link parameters only when signal degradation is observed. In doing so, the system will eliminate the unnecessary usage of power, will also maintain the optimal levels of performance of the system by unaffected users, thus enhancing the overall system efficiency and reliability. (Acosta, n.d.)

5.2 Latency

Benefiting from the development of satellite on-board processing capability, orbital computing can be realized by deploying edge computing servers on satellites to reduce task processing latency. However, edge computing based on geostationary Earth orbit (GEO) or low Earth orbit (LEO) alone can hardly meet the latency requirements of Satellite-assisted Internet of Things (SIoT) services. This implies that despite having advanced satellite computing capabilities, latency is an important issue in the contemporary satellite networks.

In addition, the load imbalance among various satellites can also be caused by uneven distribution of tasks created by the SIoT devices. This asymmetry also helps to generate the inefficiencies in the task processing and enhance the total delay of communication within the network.

In this regard, hybrid GEO-LEO SIoT networks are explored that jointly allocates computing and communication resources. In order to solve the problem of unbalancing loads, the tasks created by the SIoT devices may be processed by the collaborative LEO satellites or may be transferred to the ground gateways through GEO satellites. This mixed solution brings flexibility to the way the computational tasks are handled at various levels of the satellite network.

Accordingly, the joint offloading of tasks, communication, and resource allocation of the hybrid SIoT network can be formulated into a mixed integer dynamic programming problem that involves both the satellite-ground cooperation and inter-satellite cooperation via inter-satellite links. To address this, a smart task offloading and multidimensional resource allocation algorithm (TOMRA) is suggested to reduce latency in offloading tasks and processing them.

To solve the subproblem of task offloading and channel allocation, a method based on deep reinforcement learning is used. Subsequently, convex optimization is used to solve the subproblem of computing the resource allocation when the offloading and channel allocation choices are fixed. The simulation results have indicated that the proposed TOMRA algorithm provides better performance than reference schemes, with lower latency reduction and system efficiency. (Cui et al., n.d.)

5.3 Orbital Debris

Taking advantage of the introduction of satellite on-board processing capability, orbital computing can be achieved by deploying edge computing servers on satellites to reduce task processing latency. However, edge computing based on geostationary Earth orbit (GEO) or low Earth orbit (LEO) alone can hardly meet the latency requirements of Satellite-assisted Internet of Things (SIoT) services. This implies that despite the state-of-the-art satellite computing technology, latency is a major issue in the contemporary satellite networks.

In addition, the unbalanced distribution of tasks generated by SIoT devices may also result in the unbalanced distribution of loads among various satellites. This asymmetry also adds to inefficiencies in how tasks are processed, and adds to the overall delay in communication in the network.

Here, joint computing and allocation of computing and communication resources are explored in the context of hybrid GEOLEO SIoT networks. To overcome the load unbalancing issue, the jobs created by SIoT devices can be calculated by collaborative LEO satellites or be sent to ground gateways via GEO satellites. This composite system brings flexibility in the management of the computational functions at the various levels of the satellite network.

In this way, the joint task offloading, communication, and computing resource allocation to the hybrid SIoT network can be formulated as a mixed integer dynamic programming problem, which includes satellite-ground cooperation and inter-satellite cooperation via inter-satellite links. In order to address this, an intelligent task offloading and multidimensional resource allocation algorithm (TOMRA) is proposed that minimizes latency in task offloading and processing.

To address the subproblem of task offloading and channel allocation, a method based on deep reinforcement learning is used to solve the subproblem. Next, a convex optimization is used to solve the subproblem of calculating resource allocation at given offloading and channel allocation decisions. Simulation results indicate that the proposed TOMRA algorithm has a better performance than the reference schemes, showing a better latency reduction and system efficiency.

5.4 Cyber Security

Satellite communication (Satcom) systems have emerged as an inseparable part of the contemporary society offering lifeblood infrastructure to a plethora of applications such as communication, navigation, broadcasting, and emergency response. Nevertheless, as the dependency on Satcom systems continues to grow, cyber attacks targeting the systems have become a major issue, which can result in a considerable amount of service outage, loss of money, and even human safety.

The typical Satcom system has three main segments: space segment, which includes satellites; ground segment, which includes terrestrial ground stations, end users; and link segment, which represents the channels of communication between space and ground. The vulnerabilities presented

by each of these segments are unique and can be utilized by attackers.

According to this segmented architecture, it is possible to divide cyberattacks based on the particular components that they are aimed at attacking. They are attacks specific to Satcoms like jamming on signals, spoofing, unauthorized access, and data interception. The threats can be further discussed in terms of the known models of cybersecurity, such as the STRIDE framework that will be used to classify the threats.

To overcome these threats, a number of cybersecurity measures and systems are introduced to every layer of Satcom systems. These are encryption measures, authentication measures, intrusion detection measures and secure communication measures. The major challenge, however, is to strike a balance between the implementation of stringent security measures and cost-effectiveness and efficiency of the system.

Although, there are still current developments in security technologies, Satcom systems are still subject to the changing cyber threats. As such, ongoing research and development must occur to respond to the current vulnerabilities, as well as to enhance the resilience and reliability of the satellite communication systems to the emerging cyber risks. (Salim et al., n.d.)

6. FUTURE TRENDS IN SATELLITE COMMUNICATION

6.1 Artificial Intelligence in Satellite Systems

This recent surge of building an interconnected world via satellites has brought back a high level of interest in satellite communications both in the public sector and within the private sector. To both government-funded space agencies and private enterprises alike, there is a continuously growing and ever more significant advancement in the design, creation and large-scale deployment of satellite constellations, pushing the boundaries of what is technologically achievable in orbital infrastructure. At the same time, the introduction and rapid deployment of 5G networks globally has only served to further highlight and underscore the pressing need to have a fully connected, seamless global communication system capable of supporting unprecedented amounts of data traffic, and different user demands.

Satellites are also being proposed and recognized as highly effective solutions to establishing high-throughput and low-latency communication links between locations, in particular in remote, rural, and hard-to-reach locations where terrestrial communication infrastructure is severely limited, prohibitively expensive to deploy, or entirely unavailable. The space-based systems provide a special edge in overcoming the digital divide by bringing reliable connectivity to underserved populations and areas that the more traditional ground-based networks simply can not reach. But the rapid and accelerating growth in the number of satellites being launched into the orbit of the earth has both simultaneously given rise to a series of significant challenges and discrepancies within the overall system which include increased complexity of operation,

increased risk of signal interference, the possibility of collision due to the growing orbital congestion and mounting difficulties in the coordinated management and control of these large-scale constellations.

This is because, directly as a result of these compounding issues, there is an immediate and increasingly pressing need to develop highly adaptive, resilient and flexible satellite communication systems that are fully capable of overcoming these challenges and efficiently managing the ever-increasing global demand of quality and reliable connectivity. Within this changing and challenging arena, the use of Machine Learning (ML) and Deep Learning (DL) has become especially popular and significant in the wider realm of communication systems due to their shown capacities to substantially enhance the performance of a system, to enhance its adaptability to various circumstances, to enable real-time decision-making, and to support autonomous system control without the need to constantly monitor and make decisions in the system.

This review is a rich and comprehensive information on how the powerful and versatile methodologies of ML and DL can be strategically implemented in a broad spectrum of diverse satellite communication subsystems and applications in a wide variety of different satellite system applications. By the careful and systematic introduction of Artificial Intelligence (AI) into satellite architectures, these advanced space-based systems can be able to achieve more efficient and optimized operation, better spectral use, better signal processing, and overall better performance under different and unpredictable environmental conditions.

Along with seeking out these promising opportunities, this review also critically examines, analyzes, and discusses the current open challenges and unresolved technical barriers related to the practical implementation of AI in satellite communication systems. Also, it identifies and discusses potential future research directions with a specific focus on developing the capabilities, robustness, scalability and long-term effectiveness of these intelligent and autonomous technologies in the constantly changing environment of space-based communication networks. (Bhattacharyya et al., 2023)

6.2 Integration with 6G Network

The dire need to create strong and multi-layered Aerospace Integrated Networks (AINs) has become so acute with the ever-increasing and rapidly escalating global demand in creating ubiquitous, reliable and highly differentiated communication services accessible at any given time, and under virtually any other location on the Earth. These advanced and architecturally sophisticated networks are designed around multiple interconnected levels, including high-altitude platforms (HAPs), unmanned aerial vehicles (UAVs) and low earth orbit (LEO) satellites among other aerial and space-based nodes, all operating in coordinated tandem to provide wide-area coverage and substantially high network capacity. Each level of the AIN is uniquely and complementarily valuable to the system as a whole, with LEO satellites particularly serving as a backbone layer with significant value in the entire system.

Nevertheless, although the potential of AINs to revolutionize the world communication process is astounding, the fact that they have yet to be practically implemented and smoothly introduced into the world economy remains under the narrowing influence of a complex of carefully-rooted and technically-formidable challenges. The natural heterogeneity of the network components, the high time-variability of the channel conditions and the availability of links, and the highly differentiated mobility properties displayed by the various levels of terrestrial and aerial nodes together present severe constraints to the complete realisation of the AINs expected capabilities. The fairly stable and predictable nature of terrestrial networks needs to be intelligently and dynamically reconciled to the highly mobile, highly changing and highly environmental nature of aerial and satellite-based network segments. This fundamental incompatibility of the operating environments and the behavioral characteristics of these network layers presents major technical obstacles which must be systematically addressed through advanced modeling, adaptive protocols, and intelligent network management strategies.

It is thus of the utmost importance and of the most critical technical need that a comprehensive and thorough knowledge of the multifaceted effects that AINs have on the enabling technologies of sixth-generation (6G) wireless communication systems should be developed. Developing such an understanding would offer a highly critical and essential technical reference to the larger research and engineering community, helping to guide the informed development of AIN-empowered 6G architectures that are both practically implementable and capable of meeting the rigorous performance criteria required of next-gen global communication infrastructure. The merging of satellite systems with 6G networks is not just a simple technological developmental step but instead a paradigm shift in terms of the conceptualization, design, and delivery of global connectivity.

To fully capture and systematize the most recent developments in this fast developing and highly important research domain, scholars have begun to produce pioneer survey works, which serve as systematic and methodologically rigorous overviews of the AIN-related research, including both single-tier operational scenarios and more complex multi-tier combining scenarios. These background surveys start their analysis with a thorough substantive discussion of the state-of-the-art methodologies and architecturally promising models that are emerging in the era of AINs empowering 6G, approached on one hand, by the system architecture and networking design, and on the other hand, by the technology enabling AINs. This two-viewpoint analytical method is critical in facilitating the dynamic, scalable, and dynamically responsive management and control over AINs in varied operational environments and at the same time ensuring long-term stability, reliability and dynamical responsiveness of the integrated network as a whole.

Moreover, these academic research studies further extend their analytical levels to include a comprehensive and in-depth literature analysis frameworks and multi-objective system optimization frameworks. This is a cross-domain analysis that is guided towards the overall objective of improving overall system performance, spectral efficiency, latency, and ensuring the consistency of user on demand delivery of user-on-demand services that meet the highly personalized and context sensitive needs of future 6G subscribers. The ability to integrate satellite communication systems - and especially High-Throughput Satellites (HTS) with advanced spot beam technologies - into these AIN-based 6G frameworks further increases the capacity and precision with which differentiated services can be targeted and delivered to specific geographic regions and user groups.

Also, and of special interest to the future direction of satellite communication research, these all-encompassing studies conspicuously go on to point out the most pressing of the current research issues, as well as indicate promising future research directions with a concentrated focus on the accelerating development trend of ultra-dense satellite constellations within the 6G ecosystem. The biggest opportunity, as well as the hardest engineering challenge on the horizon of satellite-integrated 6G networks is the deployment of ultra-dense constellations, which are composed of hundreds or even thousands of coordinated, LEO satellites, operating in carefully coordinated orbital shells. The further development of AI-based autonomous network management, adaptive beamforming, and intelligent resource allocation - which will sit squarely at the intersection of the innovative capabilities of satellite communications and the transformative capabilities of sixth-generation wireless technology - will be required.

(Zhou et al., 2023)

7. CONCLUSION

The satellite communication has unambiguously transformed into one of the most invaluable and transformative factors of the modern global data communication infrastructure that fundamentally redefines the borders of the connectivity in ways that were previously unthinkable and technically impossible. During the course of this essay, the key foundational and advanced concepts underlying satellite communication have been carefully studied and critically analyzed, including the complex physical principles that govern signal transmission and propagation, the complex architectural design of satellite systems, and the complex application of orbital mechanics in determining and optimizing the performance of satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) configurations. The analysis also expanded to the strategic use of different frequency bands - such as C, Ku and Ka bands - and the implementation of multiple access methods as key mechanisms to ensure efficient and fair use of the already limited radiofrequency spectrum. The detailed discussion of High-Throughput Satellites (HTS) and the precision-based technology of satellite zooming via high-resolution spot beam delivery has shown, with compelling clarity, the extraordinary level to which satellite systems have technologically matured and adapted directly in response to the exponentially growing global demand of high-capacity data services, broadband connectivity, and increasingly sophisticated communications applications. These accumulated findings all cumulatively affirm and reinforce the fundamental conclusion that satellite communication is not just an auxiliary or peripheral support technology within the overall communication framework, but is one of the most essential and structurally vital building blocks of the modern global communication infrastructure upon which modern society relies.

The quantifiable and multidimensional effect of satellite communication on the communication systems of the world is not only deep but also multidimensional. By overcoming the natural geographic and topographic constraints that still continue to restrict the deployment of terrestrial networks to populations that in turn would remain wholly beyond their reach, satellite systems have made it realistically possible to have the populations living in the most distant, geographically isolated, and long-term underserved areas of the world to avail

themselves of reliable communications services which would otherwise remain entirely beyond their reach. This ability to bypass the physical and infrastructural boundaries has been groundbreaking not just on an individual scale but also on a whole national and regional economy. It has been known to support an unusually diverse and broad portfolio of services, including direct broadcast television and broadband internet delivery, as well as precision global navigation, maritime and aeronautical communications, coordination of disaster response, and life-critical emergency communications. Their applications cut across and enhance many strategic sectors, among them education - through the provision of remote learning platforms and e-learning content to communities with limited access to hospital infrastructure - healthcare, through telemedicine and transmission of medical data in real-time in areas where hospital infrastructure is limited - as well as business operations, governmental administration, military communications, and environmental monitoring. Importantly, satellite communication is a central and quantifiable aspect of the global development agenda as it actively contributes to the narrowing of the digital divide, democratizing access to information and communication technologies on a truly planetary scale, and is supportive of the United Nations Sustainable Development Goals associated with universal connectivity and universal access to digital information and communication technologies on a truly planetary scale.

Still, it is imperative to recognize with intellectual honesty and technical rigor that, within the winding-up and dedicated research efforts, the field still faces a number of long-standing, complicated and technically challenging issues that require ongoing and intensive research attention. Atmospheric attenuation - which is also caused by rain fade, tropospheric scintillation and ionospheric disturbances continues to impair signal quality and link reliability especially in the higher frequency Ka-band systems most commonly associated with High-Throughput Satellite operations. The latency caused by the geostationary satellite communications as a result of the vast distances through which the signals have to travel is a fundamental constraint to real-time and delay-sensitive applications, but the rapidly increasing deployment of LEO constellation networks is actively, and progressively, alleviating this constraint. Moreover, the rapid increase in the number of satellites in Earth orbital environment has heightened the concerns with regard to orbital debris formation, conjunction hazards and sustainability of major orbital regimes. At the same time, due to the increasing strategic value of satellite infrastructure, satellite-transmitted data has become an increasingly attractive target of advanced, multi-layered security architecture and encryption frameworks to ensure the integrity and confidentiality of data transmitted by satellites.

Despite these obstacles, the course of the evolution of technologies in the sphere of satellite communication is highly and undoubtedly positive. The continuing and accelerating convergence of satellite systems with next-generation terrestrial networks, most immediately with the infrastructure of fifth-generation (5G) networks and potentially in the future with the infrastructure of the emerging sixth-generation (6G) ecosystem, are expected to yield a powerfully synergistic convergence that dramatically extends network reach, increases aggregate throughput, and enables the seamless delivery of ultra-low-latency services across both terrestrial and non-terrestrial network segments. The integration of Aerospace Integrated Networks (AINs), including multi-tier architectures of the coordination of LEO satellites, High-Altitude Platforms (HAPs) and Unmanned Aerial Vehicle (UAV) relays in a single and intelligently managed network fabric, is a particularly promising and consequential frontier in this integration process. In addition, the incremental integration of Artificial Intelligence (AI) and Machine Learning (ML) functionality directly into the satellite operational systems is

fundamentally changing how satellite networks are monitored, managed and optimized. Autonomous operations of satellites based on AI make it possible to allocate resources in real-time in an adaptive fashion and to do so in a manner that is responsive and resilient, previously unattainable through traditional deterministic network management schemes.

Going forward, it is possible to promote several highly focused and strategically valuable suggestions that will help develop, streamline and responsibly govern satellite communication systems further. To begin with, long-term and heavily invested research and development, specifically the further miniaturization of satellite hardware, further expansion of onboard data processing bandwidth, lowering overall end-to-end communication latency, and the eventual development of more energy-efficient satellite propulsion and power systems, will have to be maintained and indeed accelerated, with a particular emphasis on advancing the miniaturization of satellite hardware, increasing the onboard data processing bandwidth, further reducing end-to-end communication latency, and the ultimate development of more energy-efficient satellite propulsion and power systems, in next-generation satellite platforms. Second, an even more complex, internationally coordinated and technologically responsive approach to radiofrequency spectrum regulation is urgently needed so that the equitable, efficient and interference free management of the ever-growing volume of frequency resources on which all satellite communication relies can be achieved. Third, detailed, active cybersecurity systems should be developed, standardized and executed across all levels of the satellite communication system - between the ground station infrastructure and the onboard satellite systems - to protect the entire and dynamic bound of cyber threats and unauthorized intrusion attempts. Fourth, and probably most importantly in terms of its implications to governance and equity are sustained and meaningful collaboration between national governments, satellite communication technology satellite operators, international regulatory bodies such as the International Telecommunication Union (ITU) and multilateral development organizations are completely necessary to ensuring that the further development of the satellite communication technology is translated into real, equitable, and universally accessible benefits to all regions and populations of the globe, including those of the least developed countries.

Overall, the field of satellite communication has been one of the most vibrant, technically advanced and socially influential in the whole terrain of contemporary data communication. It stands in a distinctively strong position of the intersections of aerospace engineering, wireless communication theory, network architecture and global development policy. With the ongoing accelerating pace of technological innovation, driven by improvements in the precision of HTS spot beams, autonomous network management via AI, deployment of LEO mega-constellations, and deep integration with 6G terrestrial infrastructure, satellite systems will become increasingly more capable, more efficient, more intelligent, and more universally accessible. They will remain the indispensable backbone of the global connectivity system, the pioneering application of a new communication medium, pushing the boundaries of the technologically possible beyond its limits, and making a lasting and transformative contribution to the development of the human communication system on an international scale.

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