Analysis of Possibility of New Generation Satellite Communications for Navigation

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Satellite communication has become an indispensable technology for modern society, providing global connectivity and enabling a wide range of applications such as navigation, weather forecasting, and data transmission. However, the efficiency and security of satellite communication channels are still challenging issues that require continuous improvement. This article presents recent advances and the state of art in satellite communication technology. Specifically, we discuss the RF power flux density, received power and received signal power. Using the RF PROP application, we compared the link characteristics of the leading satellite service providers depending on whether they broadcast from geostationary, medium, or low Earth orbit.

KEY WORDS

~ Satellite communications
~ Navigation
~ RF prop
~ Friis transmission equation
~ Intelsat,
~ Iridium
~ Globalstar
~ Navic
~ GPS

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1. INTRODUCTION

The importance of satellite communications is growing rapidly, and there are a number of ways to improve its performance and reliability. One such way is to improve the redundancy of satellite communication channels by using multiple satellites simultaneously. This would enable more reliable communication as signals from multiple satellites would be received more often than if only one satellite system were used. Satellite communication is a vital part of our modern life and it is important to ensure that it is reliable and secure (Malarić, 2018).

Satellite communication for ship navigation is primarily achieved using global navigation satellite systems (GNSS), such as the US Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), and the Chinese BeiDou Navigation Satellite System (BDS) (Kumar *et al*., 2021). These systems provide accurate position, speed, and weather information to ships at sea, enabling precise navigation and route planning. The current state of satellite communication for shipboard navigation is quite advanced (Ceruzzi, 2018), with a range of technologies and systems available to improve navigation accuracy and reliability. In recent years, there have been several advances in the field of satellite navigation, including the deployment of new satellite constellations, improvements in ground infrastructure, and the development of new receiver technologies.

For example, in addition to the traditional GPS, GLONASS, and BDS systems, there are now several other GNSS systems that ships can use for navigation. These include Europe's Galileo system, India's NavIC system, and Japan's QZSS system. In addition to GNSS, there are other satellite technologies that can be used for ship navigation, such as the Automatic Identification System (AIS) which uses satellite communications to track the position of ships and exchange information between vessels. Satellite communication systems, such as Inmarsat, also provide reliable voice and data communication for ships at sea.

The Global Navigation Satellite System (GNSS) has several drawbacks, including weak signal strength and high costs. However, Signals of Opportunity (SOPs) can effectively address these limitations. Non-GNSS satellite SOPs provide notable advantages, such as higher signal strength and lower costs compared to ground-based SOPs, as well as offering superior coverage.

In this paper, the five most commonly used satellite communication systems are compared. In general, commercial satellites are key to today's communications needs, with Intelsat, Iridium, GPS, and Globalstar being the four most common in use today. The NaViC satellite system, which represents a satellite system of great regional importance for India and neighboring countries, was also analyzed.

Most of the above-mentioned satellites can be used for navigation, and most of the research on the signals of the Iridium, e.g.,Tan *et al*. (2019), Kassas *et al.* (2023), and Orabi *et al*. (2021) as well as Globalstar satellite systems, e.g., Zhang *et al*. (2023), Neinavaie *et al*. (2021), and Iskandar *et al*. (2016.), which can also be used for navigation with the help of the so-called signals of opportunity and the Doppler shift.

The quality of satellite reception largely depends on the composition of the layers it passes through, the temperature of the medium, the emitted energy, the gain of the antenna, the width of the frequency range, the distance, and many other parameters (Ya'acob *et al*. (2017); Cakaj and Malarić (2006). We included most of these parameters in the RF PROP application and tried to use it to calculate the elements of the satellite link budget. Each satellite has its advantages and disadvantages, so it is important to consider the level of coverage and required bandwidth before choosing. The research was conducted in the areas of reliability, reception quality, bandwidth, coverage area, and global reach.

2. THE MOST COMMON SATELLITE COMMUNICATION SYSTEM

2.1. Intelsat satellite communications

Intelsat is a global leader in satellite communications, providing connectivity solutions to customers worldwide (Gunter's Space Page, 2023). With over 50 satellites in orbits, Intelsat's network covers virtually every part of the globe, enabling reliable and secure communication services for a wide range of applications. Intelsat satellite services include broadband connectivity, video distribution, mobile and maritime communications, and government and military applications. These services are critical for industries such as media and entertainment, aviation, and emergency response, enabling businesses and organizations to operate more efficiently and effectively. Intelsat has a long history of innovation in satellite communications, including the development of high-throughput satellite (HTS) technology for increased capacity and efficiency. This technology enables faster data transfer rates, higher-quality video streaming, and more reliable connectivity for users in remote and underserved areas. In addition to its technological advancements, Intelsat is committed to sustainability, including efforts to reduce the environmental impact of its operations and to support initiatives that promote access to education and healthcare in underserved communities. This commitment aligns with Intelsat broader mission to connect the world and create a more inclusive and sustainable future for all.

Technically, Intelsat satellites operate on a variety of frequency bands, including the C-band, Ku-band, and Ka-band. These bands are crucial for different types of services: C-band is highly valued for its reliability and minimal rain-fade interference, making it ideal for television broadcasting and data services in the tropical regions. Ku-band is predominantly used for broadcasting direct-to-home (DTH) television services and backhauling, and it has a smaller antenna size requirement. Ka-band offers higher bandwidth capabilities, which makes it suitable for high-throughput data services and expanding broadband coverage.

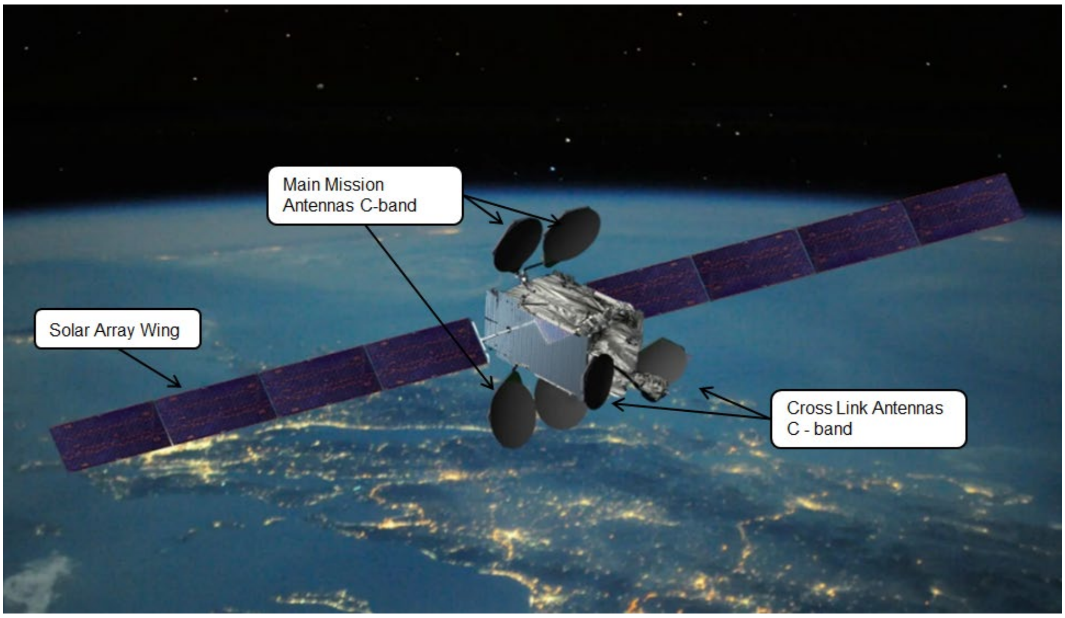

Figure 1. Intelsat 22 (Satnews, 2020)

Galaxy 31, Galaxy 32, Galaxy 35, Galaxy 36 and Galaxy 37 (Fig.1.) are five C-band-only communications satellites owned by Intelsat. The Intelsat 22 uplink frequency of the C-band varies from 5,850MHz to 6,425MHz, while the downlink frequency ranges between 3,625MHz and 4,200MHz (Aerospace, 2022).

2.2. Iridium satellite system

Iridium satellite system (Fig. 2.) stands out as a remarkable feat of engineering in global telecommunications, renowned for providing voice and data coverage to every corner of the planet, including poles, oceans, and airways (Iridium, 2023). This unique capability is especially crucial for industries and services that operate in remote and otherwise inaccessible regions where traditional communication systems fail to reach.

Iridium's constellation consists of 66 active satellites in Low Earth Orbit (LEO), positioned approximately 780 kilometers above the Earth. This strategic deployment not only ensures lower latency in the signal transmission compared to geostationary satellites but also provides comprehensive global coverage. Each Iridium satellite is equipped with a mesh network of cross-linked payloads that facilitate seamless handovers and continuous service, a distinctive feature that enables Iridium to deliver uninterrupted communication capabilities across the globe.

Operating primarily in the L-band spectrum, specifically between 1,616 and 1,626.5 MHz, Iridium's satellites handle both voice and data communication. This range is particularly chosen for its reliability in different environmental conditions, ensuring consistent service quality regardless of location.

Iridium's service offerings are diverse, catering to a wide range of needs. The system supports voice calls, SMS messaging, and data services that are critical for maritime, aviation, military, and emergency response operations. Notably, Iridium provides vital communications for disaster relief efforts, where traditional networks are often compromised or entirely down.

One of Iridium's notable advancements is the Iridium NEXT, a satellite upgrade initiative that began deployments in 2017. This next-generation satellite technology has enhanced Iridium's overall network capabilities, including higher data throughput rates and improved service delivery. Alongside its traditional services, Iridium NEXT supports Iridium Certus, a multi-service platform offering a suite of advanced communications solutions. These include safety services, mobile office functionality, and IoT applications, catering to the evolving demands of global connectivity.

Figure 2. Image of Iridium satellites in LEO orbit (Ground control, 2023)

Overall, the Iridium satellite system is pivotal for modern global communications, ensuring that no area is too remote or too challenging to reach. Its robust network architecture and broad spectrum of services make it an indispensable resource for critical communications worldwide.

2.3. Globalstar satellite system

Globalstar satellite system with large coverage (Fig. 3) is a vital component of today's global communications infrastructure, providing mobile satellite services (MSS) that include voice and data communications. Developed to cater to the needs of mobile users in regions where traditional networks are unreliable or nonexistent, Globalstar serves a diverse clientele, including travelers, maritime and aeronautical sectors, remote workers, and emergency services (Globalstar, 2023).

Globalstar's satellite constellation is designed to support low-latency voice and data services, a notable feature that distinguishes it from many other satellite systems which often have higher latency due to their geostationary orbits. Globalstar satellites operate in Low Earth Orbit (LEO) at an altitude of approximately 1,414 kilometers, facilitating faster, more efficient signal transmission and reception. The constellation consists of 48 satellites, organized so as to ensure extensive coverage and continuous service availability across much of the Earth surface.

Technologically, Globalstar satellites operate primarily on the L-band frequency, specifically using the 1,610 to 1,626.5 MHz range for satellite-to-user segment communications. This frequency band is particularly effective for penetrating atmospheric interference and delivering clear voice and data signals.

Globalstar offers a variety of functionalities tailored to the needs of its users. Its primary service includes duplex voice and data communication, which allows for two-way transmission, enabling users not only to receive data but also to send it from even the most remote areas. The system also supports an efficient simplex data service, ideal for messaging and telemetry, which helps in tracking assets and monitoring data remotely. These capabilities make Globalstar especially useful for industries such as oil and gas, mining, forestry, and wildlife conservation, where operations are often conducted far from established communication networks.

In addition to these services, Globalstar also provides a critical safety feature through its SPOT product line, which offers GPS location-based messaging and emergency notification services for individual users. These devices are widely used by adventurers, hikers, and anyone needing reliable emergency communication when off the grid.

Globalstar continues to evolve, pushing the envelope with new technologies and services to improve connectivity and expand the reach of mobile satellite communications. Its commitment to maintaining a robust, reliable, and efficient service underscores its importance in the landscape of global communications.

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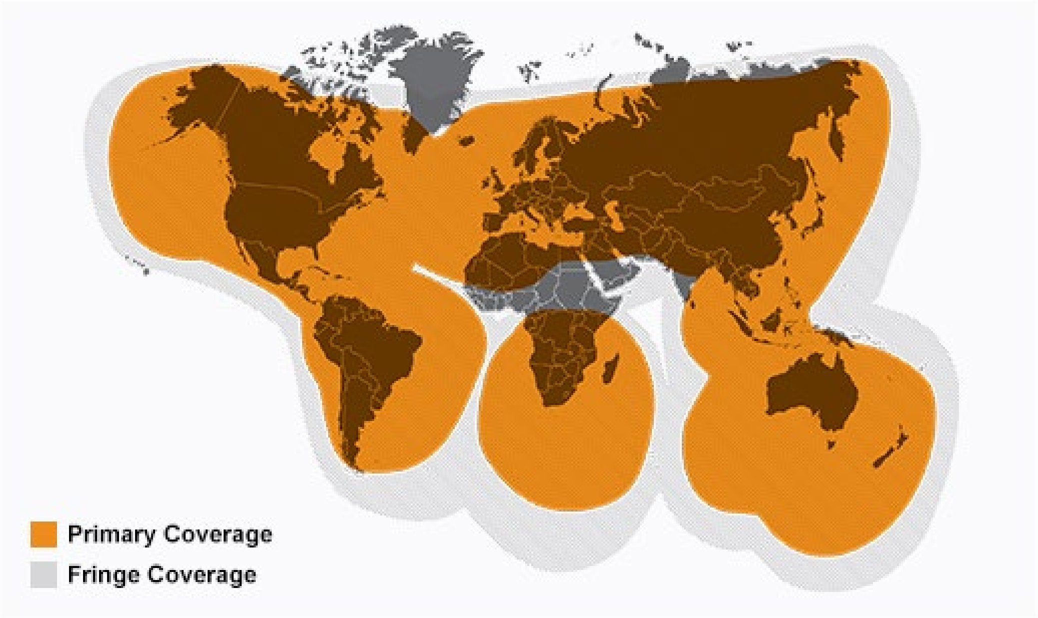

Figure 3. Globalstar global mobile communications network coverage (Traksat, 2023)

2.4. Navigation with Indian Constellation - NAVIC

The NAVIC (Navigation with Indian Constellation) satellite system, developed by the Indian Space Research Organisation (ISRO), represents a significant stride in autonomous regional satellite-based navigation. Originally known as IRNSS (Indian Regional Navigation Satellite System), NAVIC provides accurate position information services to users in India and the surrounding region, extending up to 1,500 km from its boundary (IRNSS, 2024). NAVIC consists of a constellation of 8 satellites, positioned in geosynchronous and geostationary orbits. These include 3 satellites in geostationary orbit (GEO) at approximately 35,786 kilometers above the Earth and 5 satellites in inclined geosynchronous orbits (GSO), which maintain an altitude similar to the GEO but travel in an ellipse across the Equator and the Indian Ocean region. This configuration ensures the complete coverage and optimized service quality over the Indian subcontinent.

Operating on two main frequencies, the L5-band (1,176.45 MHz) and S-band (2,492.028 MHz), NAVIC provides two types of services: the Standard Positioning Service (SPS), which is open for civilian use, and the Restricted Service (RS), an encrypted service available only to authorized users for governmental and military applications. These dual frequencies help in reducing the error caused by atmospheric interference, thus enhancing accuracy.

Technically, NAVIC is capable of providing positional accuracy of better than 20 meters in the primary service area. Additional functionalities offered by NAVIC include highly accurate time synchronization, and applications tailored for terrestrial, aerial, and marine navigation. Furthermore, it assists in disaster management through prompt and precise position and timing information, which is crucial during emergencies. The system also supports mobile phone integration, providing directions for drivers and aiding in fleet management for logistics and transportation businesses.

By bolstering local technological infrastructure and reducing dependency on foreign satellite navigation systems like the American GPS, Russian GLONASS, or European Galileo, NAVIC serves as a cornerstone in India's strategic autonomy in space-based navigation and tracking. The system not only enhances national security but also propels the development of indigenous technologies and applications in various sectors, significantly contributing to the regional economy and safety.

In comparison, the Galileo system, developed by the European Union, consists of 24 operational satellites at an altitude of about 23,222 kilometers in Medium Earth Orbit (MEO) (Galileo, 2024). Galileo operates on multiple frequency bands, including E1 (1.575 GHz), E5a (1.176 GHz), and E5b (1.207 GHz). It offers global coverage and delivers high accuracy, particularly within Europe, where it provides position accuracy of up to 1 meter for public users.

The Japanese Quasi-Zenith Satellite System (QZSS), on the other hand, comprises four satellites in highly elliptical and geostationary orbits at an altitude similar to NavIC's. The QZSS operates primarily on the L-band frequencies (such as L1, L2, L5), enhancing GPS signals over Japan and the Asia-Oceania region (QZSS, 2024). The QZSS is particularly significant for urban areas with many tall buildings, as its inclined orbit allows for better signal reception where traditional GNSS signals are often obstructed.

In summary, while NavIC focuses on the regional coverage with a robust frequency strategy to ensure accuracy over India, Galileo provides global coverage with extensive satellite numbers and superior accuracy in Europe. The QZSS enhances the GPS signal availability in urban and mountainous regions of Japan. Each system is tailored to the specific needs of its region, reflecting the unique geographical and operational demands.

2.5. Global Positioning System (GPS)

The Global Positioning System (GPS) is a satellite-based navigation system managed by the United States Space Force. It provides users worldwide with reliable positioning, navigation, and timing (PNT) services under all weather conditions (NASA, 2024). GPS is a critical component in global transportation, emergency response, and countless commercial and personal applications. The GPS constellation is designed to ensure that at least four satellites are visible from virtually any point on the planet at any given time. This design includes a network of roughly 31 operational satellites in Medium Earth Orbit, approximately 20,000 kilometers (12,427 miles) above the Earth. These satellites are distributed among 6 orbital planes with an inclination of 55 degrees to the Equatorial plane, which facilitates global coverage.

The GPS satellites transmit signals on several frequencies, primarily the L1 (1,575.42 MHz) and L2 (1,227.60 MHz) bands for civilian use, and additional frequencies like L5 (1,176.45 MHz) for more advanced applications. These signals carry a precise time code synchronized with onboard atomic clocks, essential for determining the user's exact position by calculating the time it takes for the signals to travel from the satellite to the receiver.

The functionalities of the GPS system include providing accurate positioning services with a standard accuracy of about 5 to 10 meters for civilian use and more precise capabilities for military users through encrypted signals. The GPS also offers highly precise time signals crucial for operations like power grid management, synchronization of financial transactions, and scientific experiments. Moreover, the GPS supports enhanced services like the Differential GPS (DGPS), which improves accuracy, and the Assisted GPS (AGPS) utilized in mobile phones for faster and more accurate location determination, especially in environments where satellite signals might be weak.

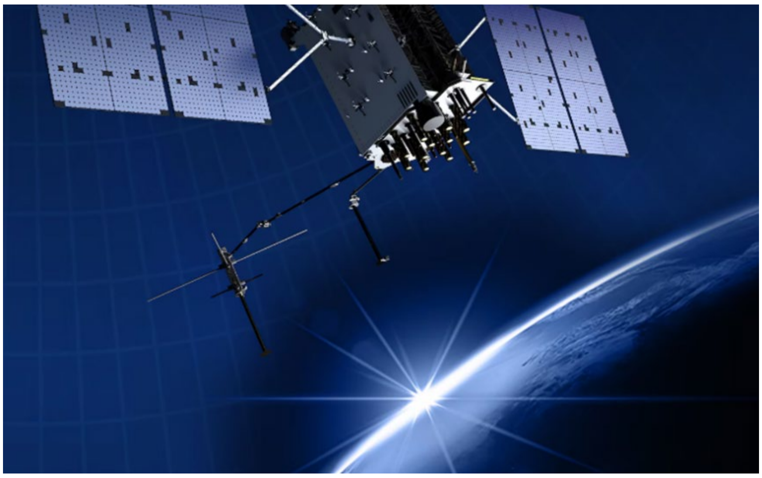

Figure 4. Global Positioning System (GPS) Satellite (NASA, 2024)

In summary, the GPS system exemplifies a comprehensive global navigation satellite system (GNSS) that has become indispensable in modern society. Its extensive satellite coverage, high-accuracy timing and positioning capabilities, and robust service delivery across various frequencies underscore its role as a foundational technology in contemporary geolocation, navigation, and time-sensitive operations worldwide.

3. THEORETICAL BACKGROUND

The RF prop, or radio frequency propagation, is the study and modeling of how radio waves propagate through different media such as air, water, and various types of terrain (Colin, 2021). The RF propagation plays an important role in the design, implementation, and optimization of wireless communication systems including radio and television broadcasting, satellite communication, cellular networks, and other wireless communication technologies.

The application of the RF propagation can help engineers and designers to optimize the coverage and capacity of wireless communication systems by predicting how radio waves will propagate through different environments (Linshu H. *et al*., 2022). For example, in cellular networks, the RF propagation models can be used to determine the best locations for cell towers and base stations to ensure that the network provides reliable coverage and capacity to users.

Received signal power (P_r) can be found from (Ellingson, 2020):

$$P_r = P_t \cdot \frac{\lambda^2 G_t G_r}{16\pi^2 d^2} \tag{1}$$

where P_t is the transmitted power from the satellite, G_t and G_r are the transmitting and the receiving antenna gains, d is the distance from the transmitter and the receiver, and λ depends on the frequency of the signal as (David, 2002):

$$\lambda = \frac{c}{f} \tag{2}$$

where c is the speed of light, that is 3x10^8 m/s and f is the frequency in Hz. The above equations can be expressed as the so-called Friis transmission equation (Pierce, 1956) shown in Fig. 5.

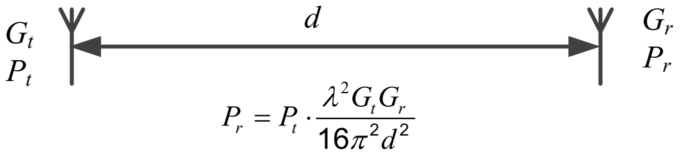

Figure 5. Friis transmission equation

Figure 5 shows the Friis transmission equation that the RF prop application contains and by which it calculates radio signal propagation. The RF propagation modeling can also be used to predict the behavior of radio waves in specific locations or scenarios, such as in urban environments with high-rise buildings, in tunnels or underground structures, or over long distances in open spaces. By understanding how radio waves behave in different environments, designers can optimize the placement of antennas, select appropriate transmission frequencies and power levels, and employ other techniques to improve communication performance.

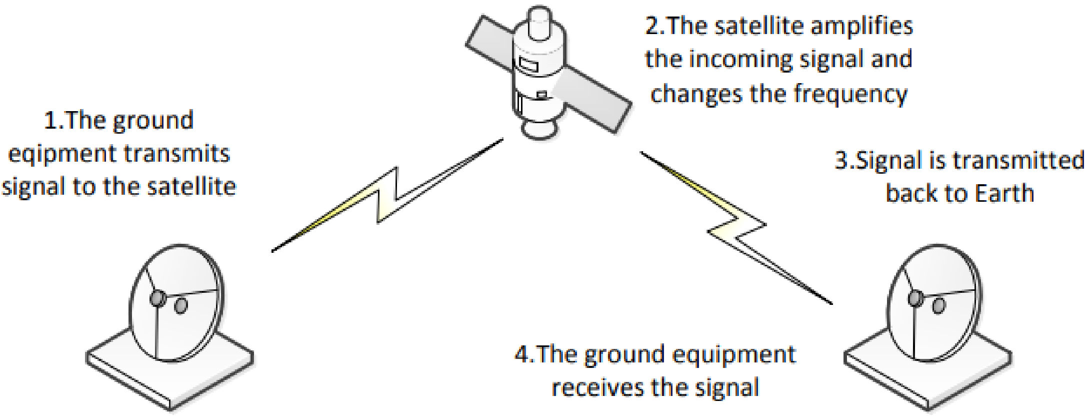

Figure 6. Basic communication scheme of the satellite system

In Figure 6, we can see the basic communication scheme of the satellite system. We establish the uplink from a ground station or some other device that emits a signal to the satellite. The satellite amplifies the incoming signal, changes the frequency, and transmits the signal back to the Earth. In our simulation, the uplink was tested by comparing the most represented providers of such satellite connections in terms of connection quality, minimum requirements for connection establishment, connection availability, and the amount of data transmitted by the system.

Thermal or channel noise depends on the temperature and the frequency bandwidth according to:

$$P_{rerm} = k \cdot T \cdot B \tag{3}$$

where *k* = 1.38x10-38 J/K, the Boltzmann constant, *T* is the temperature in (K), and *B* is the bandwidth in (Hz). Thermal noise exists in every communication system and cannot be avoided. The larger the bandwidth and the higher the temperature in (K), the higher the thermal noise in the communication link.

4. RESULTS

The parameters shown in Table 1 were used to compare satellite systems with the RFProp application (Colin, 2023). For example, the height of the satellite is taken as the height when the satellite is farthest from the Earth, and the reception point is vertically below it. Globalstar satellites as well as the satellites from the Iridium system are in Low Earth Orbit. Their heights are 1,414 km and 780 km respectively. Intelsat satellites are in geostationary orbit, and their height is 35,786 km (Prol, 2022: Iridium, 2023; Globalstar, 2023; Gunter's, 2023; 2j antennas, 2023). The article also deals with the NavIC satellite system, a part of which is located in inclined geosynchronous orbits at an altitude of 29,200 km. One of the more famous satellite systems for geo-positioning and navigation, GPS (US) is located in the Medium Earth Orbit and its satellites are positioned at an altitude of 20,200 km. The following literature was used for the analysis of existing communication links: Gunter's Space Page (2023); Aerospace (2022); Iridium (2023); Tan *et al*. (2019); Orabi *et al*. (2021); Zhang *et al*. (2023); Neinavaie *et al*. (2021); Globalstar (2023); IRNSS (2024); Galileo (2024); QZSS (2024); NASA (2024).

	Intelsat (GEO)	**Iridium (LEO)**	**Globalstar (LEO)**	**NavIC (GSO)**	**GPS(MEO)**
Specified Range [km]	35,786	780	1414	29,200	20,200
Frequency [MHz]	4,000	1,616	1610	2,498	1,575
Frequency band width [MHz]	35	10.5	16.5	16,5	15.35
Number of satellites	52	66	48	8 (+2 on the ground)	31
Transmit Power [dBW]	50	7	8	27	27
Transmit Antenna Gain [dBi]	40	3	12	14	13
Receive Antenna Gain [dBi]	2,15 dBi handheld u. to 40 dBi fixed installations	2,15 dBi handheld u. to 15 dBi fixed installations	2,15 dBi handheld u. to 15 dBi fixed installations	2,15 to 5 dBi for handheld units	2,15 to 5 dBi for handheld units
Receive Noise Figure [dB]	4	4	4	3	3
Fading Margin [dB]	15	15	15	20	20
Det. S/N for modulation used [dB]	9	10	10	6	6

Table 1. Parameters entered into the calculation via RF PROP application (Satellite System technical parameters)

The quality of communication satellite systems that are most often used for navigation can be compared using several parameters that ensure quality reception on the receiving side. The analyzed parameters are: minimum received signal power and power flux density on the receiving side. An analysis of the ratio of the receiver power and the propagation range power was also made. The appearance of the interface of the RFProp program after entering the parameters from Table 1 set the variables needed for the calculation.

4.1. Received signal power

The results are obtained as the actual results of the minimal received signal power without obstacles in the way. A 2.5 dBi handheld mobile device antenna was used as the receiving antenna. Table 2 shows the values of the received signal power (min) (dBm)

T(K)	Iridium	Globalstar	Intelsat	NavIC	GPS
260	-90,24	-88,28	-92,28	-93,32	-92,59
270	-90,08	-88,11	-92,11	-93,15	-92,43
280	-89,92	-87,95	-91,95	-92,99	-92,27
290	-89,77	-87,80	-91,80	-92,84	-92,12
300	-89,62	-87,66	-91,66	-92,69	-91,97
310	-89,48	-87,51	-91,51	-92,55	-91,83
320	-89,34	-87,37	-91,37	-92,41	-91,69

Table 2. Propagation results – minimum receivable signal (dBm)

This table presents a comparison of the received signal power (min) in dBm across different temperature conditions for the five satellite systems: Iridium, Globalstar, Intelsat, NavIC, and GPS. Across all the temperatures ranging from 260K to 320K, NavIC consistently exhibits the lowest received signal power. GPS generally follows, with slightly higher signal power values than NavIC. Intelsat maintains a marginally better signal power compared to GPS and NavIC. Globalstar and Iridium consistently exhibit the highest received signal power across all the temperature ranges. As the temperature increases, there is a trend of decreasing signal power across all the satellite systems. Globalstar and Iridium demonstrate the lowest sensitivity to temperature variations, maintaining relatively higher signal power even at higher temperatures compared to the other systems. Overall, Globalstar and Iridium appear to be more resilient to temperature effects compared to Intelsat, GPS, and NavIC. Thus, we have received signal power vs. temperature shown in Figure 7:

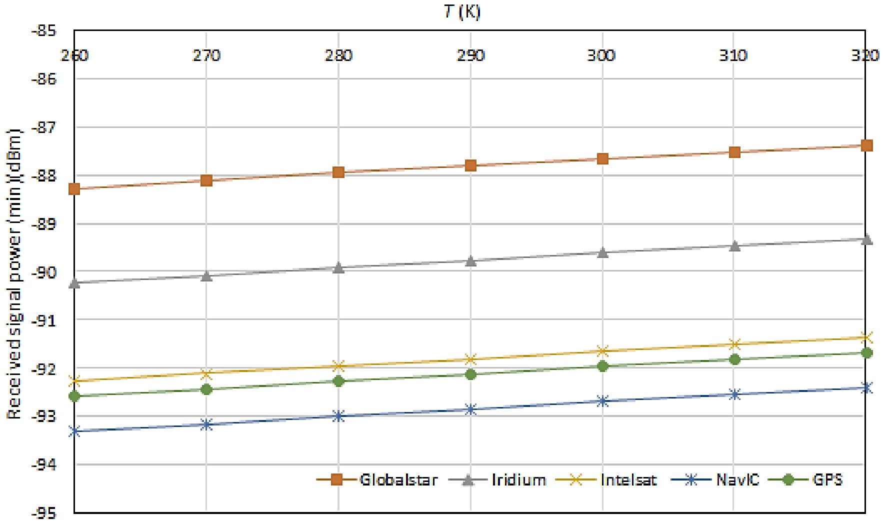

Figure 7. Comparison of the received signal power

Figure 7 shows a comparison of the received signal power for the Intelsat, Iridium, NavIC, GPS, and Globalstar systems calculated using the RF PROP application. The specified values refer to the minimum signal strength required for communication. The average measured values of the power of the received signal, without diffraction are: for Iridium -187.31 dBm, for Globalstar -122.44 dBm, for Intelsat - 88 dBm, for NavIC - 136.565 dBm, and for the GPS -130.35 dBm.

4.2. Power flux density

In the area of high-frequency radiation, the power flux density is the measure of the strength of the radiation in the far field. Its unit of measurement is Watt per square meter (W/m²). It characterizes the energy flowing per time unit through an area vertical to the distribution direction of the radiation.

Figure 8 shows a comparison of the minimum received power density (in units of 10^{-10} W/m²) for different satellite systems at various temperatures. Intelsat consistently demonstrates the highest minimum received power density, followed by Globalstar and NavIC. Iridium consistently exhibits the lowest minimum received power density among the satellite systems listed. As the temperature increases, there is a general trend of increasing minimum received power density for all satellite systems. NavIC and the GPS show a slightly steeper increase in the minimum received power density compared to the other systems as temperature rises.

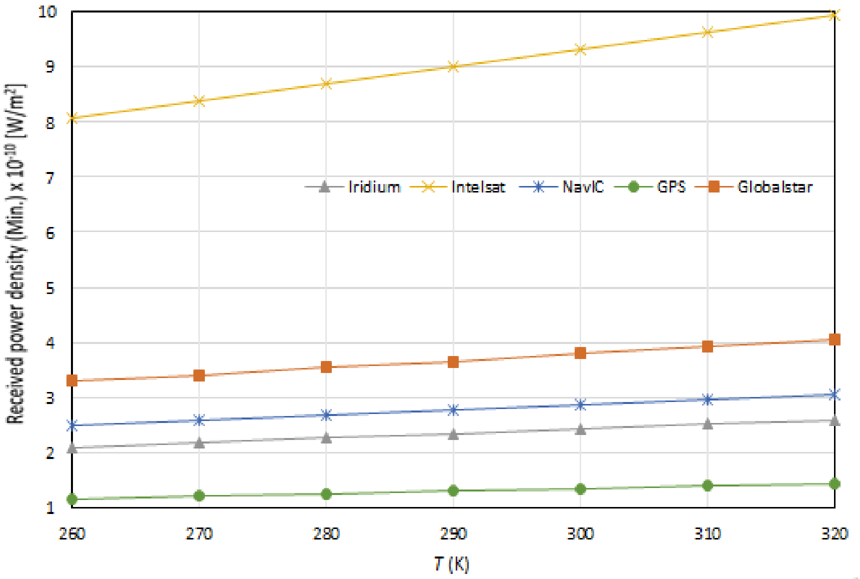

Figure 8. Comparison of the received signal power density

Despite fluctuations, there is a noticeable consistency in the hierarchy of power density among the satellite systems across different temperatures. Overall, Intelsat consistently exhibits the highest power density, while Iridium consistently shows the lowest, regardless of the temperature variations.

4.3. Receiver power vs. propagation range power

Since there is an occurrence of higher losses in urban areas as well as in areas with obstacles to the distribution of electromagnetic waves, a calculation was made of the current signal application without diffraction in urban areas. An approximation of additional distributed losses in certain urban/indoor environments can be made by changing the law of the propagation range - on a mostly empirical basis basically.

Environmental factors such as weather conditions and physical obstacles can significantly impact satellite communication, affecting signal strength, quality, and reliability. Heavy rain or snow can cause signal attenuation, a phenomenon known as "rain fade," where the satellite signal weakens as it passes through the moisture-laden atmosphere. This is particularly problematic for higher frequency bands like Ka-band. Dense cloud cover and fog can also contribute to signal degradation, though to a lesser extent than rain. These conditions scatter the satellite signals, leading to potential loss of clarity and strength. Strong winds can misalign satellite dishes or antennas, disrupting the connection between the satellite and the receiver. Severe storms, especially those with lightning, can create electromagnetic interference, further compromising communication. Solar flares and geomagnetic storms can induce electromagnetic interference in satellite signals, causing disruptions in communication. These disturbances can temporarily degrade signal quality or cause a complete loss of the signal.

Physical obstacles can also cause problems with satellite connections. Structures like tall buildings or dense forests can obstruct the line of sight between a satellite and the ground-based receiver. This blockage can result in signal reflection, refraction, or even complete signal loss, known as *signal shadowing*. In areas with rugged terrain, such as mountains or deep valleys, satellite signals can be blocked or deflected, making it challenging to establish a reliable communication link. In cities, signals can bounce off buildings and other structures, creating multipath interference, where multiple reflected signals reach the receiver at slightly different times. This can cause signal distortion and reduce communication quality.

Depending on the degree of signal interference, in the RFprop application itself, the propagation range-power law parameter p is adjusted, which varies in the range from 2 to 4, the value of p which is 2 is used for free open space, while p = 4 is used for urban areas with lots of reflection and obstacles. Figure 9 shows the changes in the power of the received signal for certain values of the propagation range law variable, going from around -80 dBm in open area or free space to less than -250 dBm for urban areas.

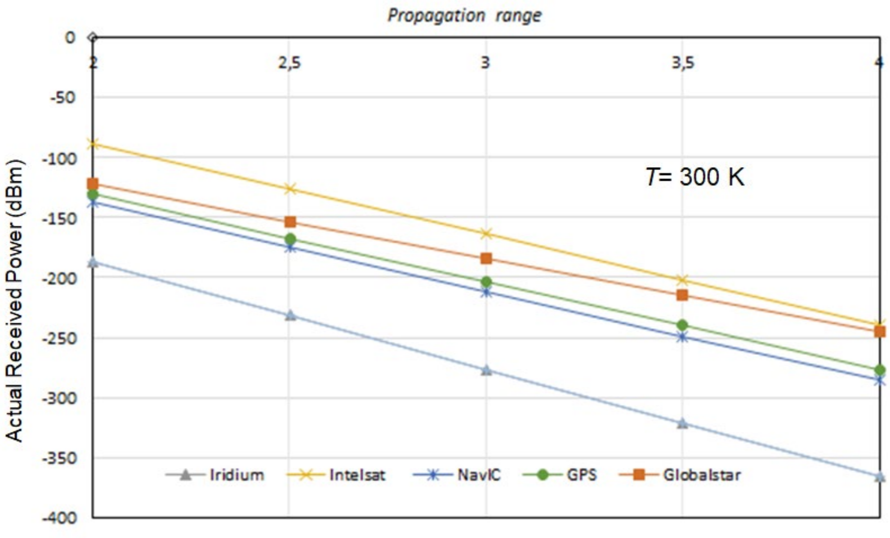

Figure 9. Receiver power (dBm) vs propagation range power p

Figure 9 presents the propagation results without diffraction, specifically focusing on actual received signal power (in dBm) at a temperature of 300K, across different propagation ranges governed by the power law. Across all propagation ranges, Intelsat consistently exhibits the highest received signal power among the listed satellite systems, followed by Intelsat and Globalstar. Iridium consistently demonstrates the lowest received signal power across all the propagation ranges. As the propagation range increases, there is a trend of decreasing received signal power for all the satellite systems, indicating signal attenuation over distance. Intelsat exhibits the least attenuation, maintaining relatively higher received signal power even at longer propagation ranges compared to the other systems. Globalstar shows moderate attenuation, while GPS demonstrates slightly higher attenuation. Overall, Intelsat appears to be more resilient to signal attenuation over distance compared to Iridium, Globalstar, GPS, and Intelsat.

5. CONCLUSIONS

In conclusion, satellite communication has significantly transformed global communication and information access, yet it is not without challenges. Issues such as high bandwidth requirements, interference, latency, and security threats persist. Future efforts should focus on enhancing the redundancy of satellite communication channels by employing multiple satellites simultaneously to bolster reliability. This would mitigate the risk of signal loss due to atmospheric conditions or technical issues, which is crucial for navigation and high-reliability applications like emergency response and military operations.

If we compare the five most commonly used satellite communication systems, we come to the following conclusions. Each of the five satellite systems offers advantages and disadvantages. Intelsat is the most common commercial satellite in use today. It offers a high bandwidth, large coverage area, and global reach. However, it is also expensive to purchase bandwidth and operate. Iridium offers a small size, relatively low-cost and global coverage. However, it limits the bandwidth and data rate. Globalstar has a low-cost and medium-sized coverage area, but also has limited bandwidth and data rate. For companies that need reliable and fast communication, particularly in remote areas of the world, Intelsat remains the best choice. The extra cost is often worthwhile for a better coverage and larger bandwidth. Iridium is a good option for those who need global coverage but can make it with reduced bandwidth. Globalstar is the least expensive option and is reasonable for companies that need limited coverage at a lower cost. GPS is today the most famous satellite system for geo-positioning and covers almost the entire surface of the Earth.

Our analysis using the RFprop application reveals that the received signal power and its density fluctuate based on the medium's temperature and the level of interference. These variations are influenced by parameters of the ground station, satellite characteristics, signal frequency, and the distance of the radar station. For instance, geostationary satellites, such as Intelsat, cover larger areas but require higher gain antennas and greater power compared to low-orbit satellites.

Examining the minimum received signal strength needed for effective communication, NavIC consistently shows the lowest strength, followed by the GPS, Intelsat, Globalstar, and Iridium, with the latter two being the least affected by temperature changes. In terms of minimum received power density, Intelsat performs the best, followed by Globalstar and NavIC, indicating robust signal maintenance despite temperature variations. Conversely, Iridium shows the lowest power density but maintains relative consistency across temperature increases.

Interference factors also play a crucial role, especially in urban areas with significant reflection and obstructions. Intelsat again shows the highest received signal strength, followed by Globalstar, with Iridium showing the least. All systems experience signal attenuation over greater distances, but Intelsat is the least affected, demonstrating superior resistance to signal loss compared to Iridium, Globalstar, and GPS.

Overall, while satellite communication is a formidable technology facilitating global connectivity, improving its efficiency and security remains essential. Enhancing redundancy, data compression, ship-to-satellite communication algorithms, and secure encryption protocols are vital steps forward. This study contributes to understanding signal quality among leading satellite service providers, aiming to inspire further innovation in satellite communications and enhance our global communication capabilities.

CONFLICT OF INTEREST

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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