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MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

LOW EARTH ORBIT (LEO) SATELLITE TELECOMMUNICATIONS PLATFORMS:

FEASIBILITY AND APPLICATIONS IN THE ELECTRIC UTILITY

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Madrid

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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

"Low Earth Orbit (LEO) satellite telecommunications platforms:

Feasibility and applications in the electric utility."

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2023/24 es de mi autoría, original e inédito y

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tomada de otros documentos está debidamente referenciada.

Fdo.: Javier Rodriguez Silva Fecha: 30/08/2024

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Ignacio Martín Díaz de Cerio Fecha: 30/08/2024

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LOW EARTH ORBIT (LEO) SATELLITE TELECOMMUNICATIONS PLATFORMS: FEASIBILITY AND APPLICATIONS IN THE ELECTRIC UTILITY."

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PROJECT OVERVIEW

This Master's Thesis aims to identify potential applications within the energy sector for the implementation of the new ultra-dense low-orbit (LEO) constellations dedicated to high-speed internet, and to carry out an analysis of their feasibility.

Keywords: Smart Grid, Satellite, Telecommunication, Utilities, Commercial solutions, LEO (Low Earth Orbit), Digitalization, Mbps, Jitter, Latency, Packet loss, Availability.

1. Introduction

The integration of LEO (Low Earth Orbit) high-speed internet constellations, such as Starlink and OneWeb, represents one of the most promising technologies for improving global connectivity in a safe and environmentally sustainable way. Without geographical barriers, with global, fast, competitive coverage and enhancement of economic and social development, these constellations are pioneers in the democratization of internet access.

Thanks to advances in reusable rocket technology, such as those from SpaceX, and improvements in satellite manufacturing, which are now smaller and cheaper, the cost of launch has been drastically reduced by being able to launch multiple satellites simultaneously. This has significantly lowered the barriers to entry into the telecommunications space segment creating a new environment. It is in this where these constellations have emerged, opening up competition and allowing the participation of numerous agents in the sector, who continuously propose new solutions.

The advanced capabilities offered by LEO constellations have great potential to be integrated into the *utilities* sector, improving the digitalization of the network and facilitating communication in remote areas. The ability to provide high-speed connectivity in rural and hard-to-reach areas is critical for the efficient monitoring and management of energy infrastructure, as well as for the implementation of smart technologies on the grid. This interest is reflected in this project by Iberdrola, Spain's largest electricity company with an international presence, which seeks to assess whether it can take advantage of these new technologies across its many and dispersed assets.

2. Project definition

- The project consists of the identification and evaluation of potential use cases where the integration of LEO telecommunication platforms is viable and provides advantages over the current ones.
- The project is divided into 3 phases:
  1. **Contextualization**: In this phase, everything related to the space sector and its relationship with the energy sector is studied; space technology, the different commercial solutions available currently and in the near future, the space environment and its effects on technology, electricity grids and their evolution, the current digitalization of the grid and transformation of the electricity sector, and finally, the challenges and needs of telecommunications within it.
  2. **Commercial Technology Study and Evaluation:** This phase is subdivided into three tasks:
     - 2.1. Study of the characteristics of the commercial telecommunications technologies identified in the previous phase and the preparation of technical data sheets for them.
     - 2.2. Categorization of the solutions studied. This is done with the aim of segmenting and facilitating the evaluation of technologies.
     - 2.3. Identification of the different use cases within Iberdrola's assets and the assessment of the viability of the different technologies. This provides a deep insight into the reasons for using the technologies they currently have integrated, as well as identifying where the new LEO constellations fit.
  3. **In-depth study and testing of LEO constellations**: The technological study is carried out for both constellations, OneWeb and Starlink. In this study, research is carried out on their operating models, technology, business orientation, etc. Once their integration with the remaining use cases has been carried out and evaluated, a series of tests are carried out where it is verified that the technologies that have been potentially viable are really in line with what they have offered.

3. Results

This section covers the results of the different phases.

First, the **first phase** succeeds in establishing a solid contextual framework for the project and documents it in the initial chapters of the document.

The **second phase** has managed to delimit and categorise the different technological solutions available. First, detailed technical data sheets have been developed for each commercial telecommunication solution in the space segment.

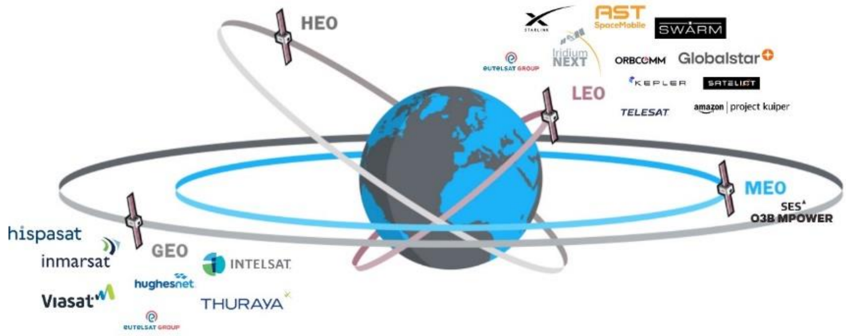

Figure 1: Commercial Telecommunication Satellite Technologies

Then, in order to facilitate the evaluation of the technologies, a segmentation has been carried out based on their orbit, service, cost and type of antenna used.

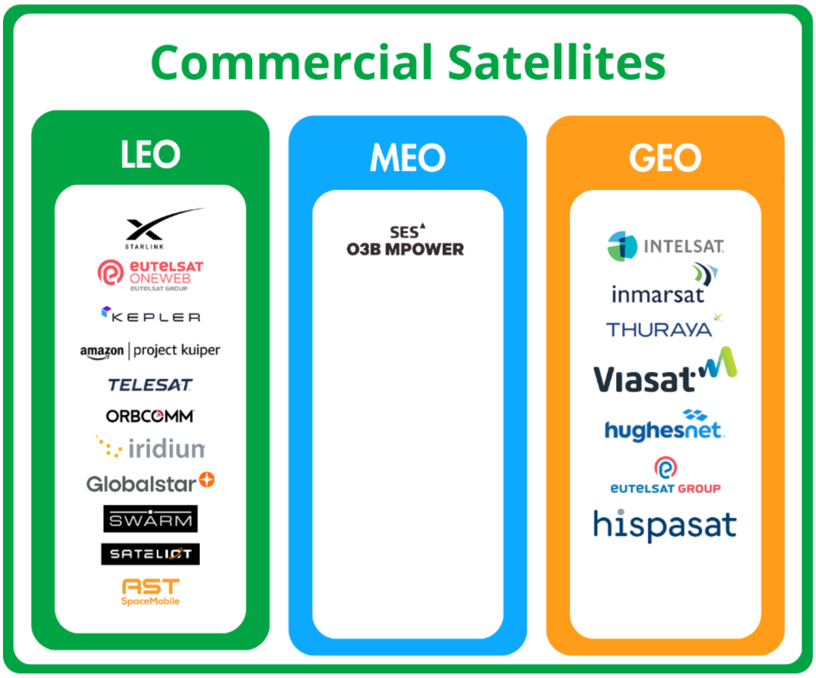

Figure 2: Categorization by Orbit

Orbit is related to latency and relative position relative to the observer on Earth. GEO satellites have latencies of approximately 600 ms and remain static relative to the observer, while LEO satellites have much lower latencies, between 30 ms and 75 ms, and move relative to the observer. This movement forces the antennas to dynamically follow the satellites to maintain the connection, as well as requiring jumps between satellites when they leave the field of view. The altitude of the LEO orbit influences how long satellites remain in the field of view, although this is usually less than an hour. Satellites in MEO orbits also suffer from this, but their viewing times are longer. Dynamic positioning complicates constellation operation and antenna orientation, although the new digitally oriented phased array antennas have mitigated this challenge considerably.

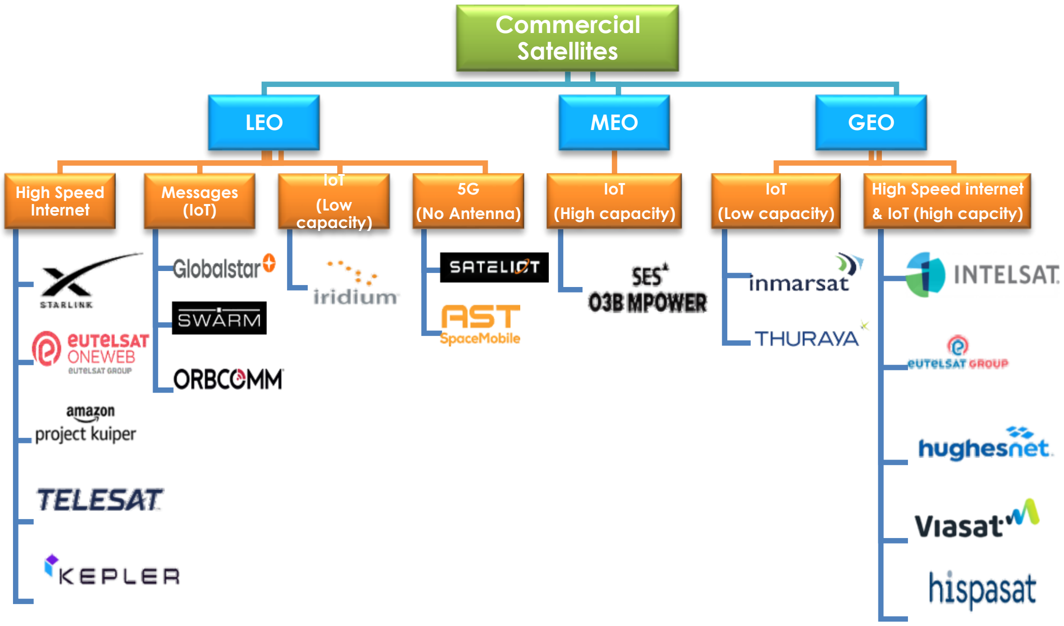

Figure 3: Service Categorization

Regardless of the orbit, three types of service have been identified: **IoT messages, low-capacity IoT, and high-speed internet.** There are other services such as 5G, which are not yet available. An additional comment should be made on IoT message technologies. As these are not really a data transmission technology, they cannot be considered in the study, as they do not fit Iberdrola's needs.

The study identifies the key characteristics that differentiate technologies according to their capacity. Depending on the service, higher or lower frequency bands are used. High frequencies provide greater bandwidth and, therefore, more transmission capacity, but they are more susceptible to environmental factors, such as heavy rain, which causes the phenomenon known as "rain fade", and can cause a total loss of communication. Therefore, **a higher frequency implies greater capacity but with more vulnerable communications, and vice versa.**

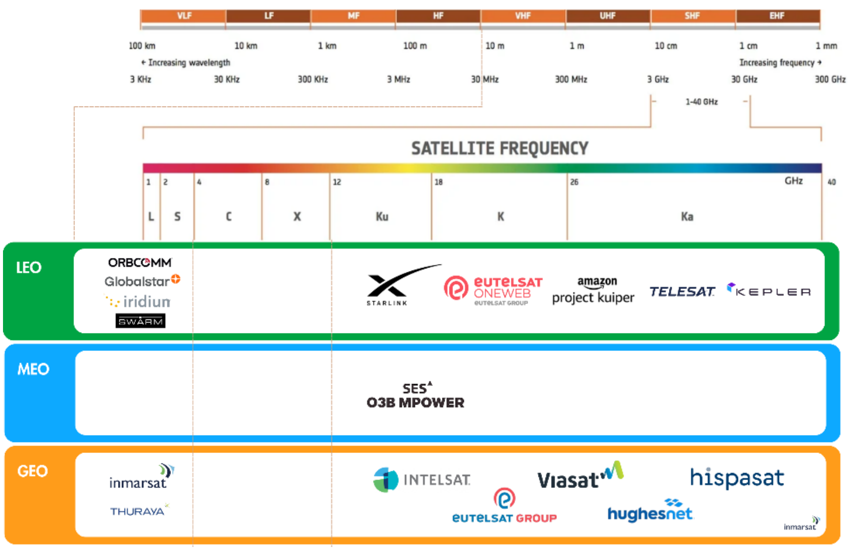

Figure 4: Categorization by frequency

The frequency used also affects the type of antenna required. Robust low-frequency, low-capacity telecommunications services require small antennas (patch), while high-frequency telecommunications services require larger antennas, such as VSATs (Very Small Aperture Terminals) or phase antennas. However, the market for the latter is focused on the development of more powerful and smaller antennas.

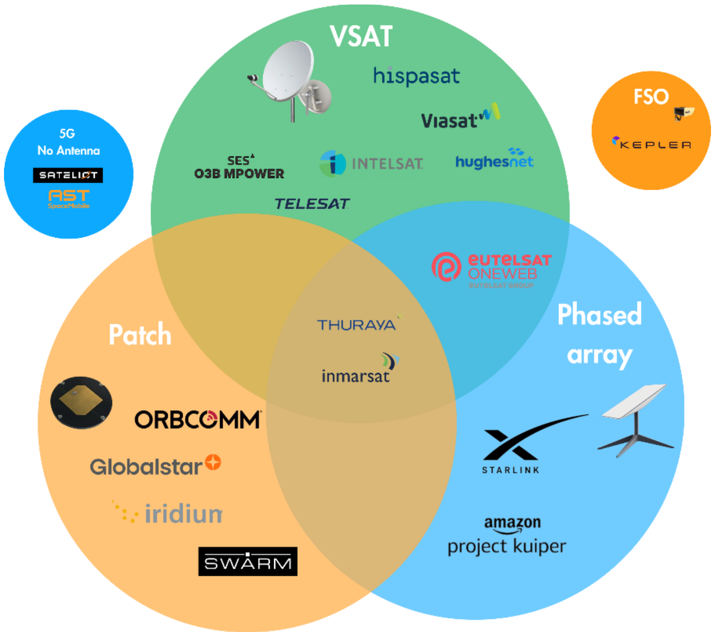

Figure 5: Categorization by antenna type

Finally, a categorization of the cost of traffic has been made. The costs have been estimated based on the tariffs of the main distributors. Given the difficulty of making direct cost comparisons, it has been approximated using the cost per MB. This calculation is complex because low-capacity technologies offer a base price for an initial range of data traffic and then charge higher additional fees for overage usage. In contrast, high-capacity technologies typically have a minimum supply that far exceeds the traffic needs of the telecommunications system. Therefore, the classification presented should be considered as a rough guide.

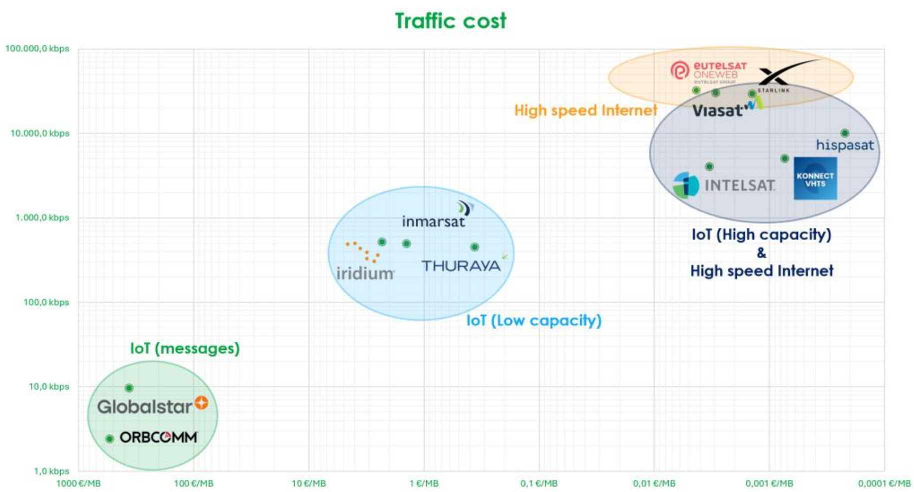

Figure 6: Categorization by Cost

The last task of the second phase is the identification of potential use cases. In this case, three have been identified:

- **Renewable generation parks and substations**
- **Remote secondary substations (transformer stations, CTs) and remote reclosers (OCRs)**
- **Corporate Office Communications**

With the following telecommunication needs and requirements:

Subestation/Windfarm			SS/Reclosers			Corporate office	
Traffic	8 GB/month		Traffic	300 MB/month		Traffic	1 TB/month
Capacity	25 kbps		Capacity	1 kbps		Capacity	10 Mbps
Latency	< 1s		Latency	< 1s		Latency	150 ms
Packet Loss	Critical		Packet Loss	Critical		Packet Loss	Not critical
Availability	> 99%		Availability	> 99%		Availability	> 99%
Reference cost	100 €/month		Reference cost	10 €/month		Reference cost	1000 €/month
Antenna Size	Not critical		Antenna Size	Critical		Antenna Size	Not critical

Table 1: Telecommunication requirements of the different use cases

Adjusting the categories to the requirements, it has been determined that for the first use case (Substations and renewable parks), high-speed internet technologies present a theoretical viability in both LEO and GEO orbit. This result was expected, as this use case is currently covered by GEO high-speed internet technologies, or as they are commonly known, VSATs:

In the second case (CT and OCR), no space telecommunications technology is feasible due to the limitations of size (for high-capacity technologies) and cost (for low-capacity technologies).

For the third case (Office Services), only LEO high-speed internet constellations are theoretically viable, while GEO constellations are ruled out due to their high latency. To confirm the actual feasibility, it is necessary to carry out tests that verify the practical operation of the network in these scenarios.

In the **Third phase** the study on LEO constellations (technology, business orientation, equipment, rates, operating model, etc.) was deepened, Tabla 2. Firstly, although OneWeb's technology is better aligned with Iberdrola's needs due to its ability to dedicate telecommunications segments and offer availability guarantees with SLAs, it has been found to be unfeasible due to the high cost of its equipment, specifically the antenna. The market price of this antenna is around €20,000, far from the budget of around €1,000 per installation.

	Starlink	OneWeb	VSAT
Orbit	LEO	LEO	GEO
Altitude	500 km	1200 km	36570 km
Latency	30 ms	70 ms	600 ms
Uplink Speed	~ 22 Mbps	~ 32 Mbps	~ 10 Mbps
Downlink Speed	~ 190 Mbps	~ 190 Mbps	~ 200 Mbps
Phased array antennas	Yes	Yes	No (some options)
Size	57cm x 51cm	56cm x 45cm	100cm x 100 cm
Price	2.000 €	20.000 €	2.000 € + 1.000€ (installation)
Installation	Easy	Easy	Difficult
SLA (Guaranteed channel)	No	Yes	Yes
Availability	95%	99%	99%

Table 2: Technology Comparison

Therefore, only Starlink technology has been considered. Obtaining the following:

	Uplink Speed	Downlink Speed	Latency	Availability	Packet loss
Avarage	24,19 Mbps	97 Mbps	153,63 ms	97,31%	2,69%
Variability (Std.)	7,96 Mbps	12,3 Mbps	29,94 ms	2,64%	

Table 3: Starlink test results

The results of the tests that have been carried out place starlink with average telecommunication parameters comparable to the networks of 4G operators. But its high variability has a major drawback. In addition, this variability is aggravated by temporality. In the tests there have been periods of poor results and others of excellent results:

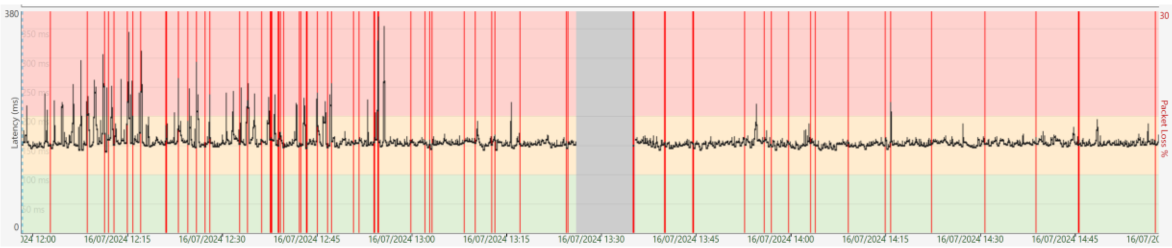

Figure 7: Result of latency (black line) and packet loss (red bars) tests

4. Conclusions

Based on the results obtained, it is concluded that the possible uses of Starlink are mainly as **a backup technology, or specifically dedicated to corporate services**. Iberdrola uses SDN (Software Defined Networking) devices to seamlessly integrate two or more telecommunications infrastructures into a single installation. These devices allow total control of telecommunications, making it feasible to dedicate a specific service to a certain technology.

The first potential use case is renewable generation parks, currently served exclusively by VSAT with two antennas. Starlink could be integrated by replacing one of the technologies to create a GEO-LEO service. This would not only maintain redundancy with other technology, but also allow for improved corporate services by running them on the LEO segment.

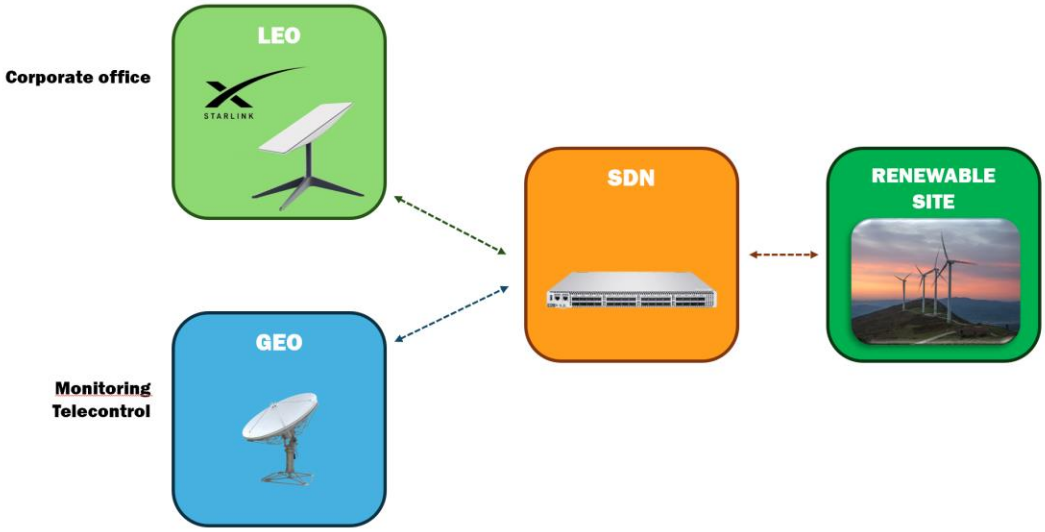

Figure 8: Architecture with Starlink integration (renewable generation park)

Another scenario where Starlink has potential utility is as a backup technology for infrastructures currently connected via optic fiber (O.F.) or radio (P2P or P2M) networks. Currently, Iberdrola uses operator networks as a backup to its own network (fibre optics, point-to-point radio (PP), point-to-multipoint radio (PMP)) in substations. While 4G can be used as a backup where there is coverage, in areas without coverage, VSAT GEO or LEO could be employed. The main advantage of Starlink as a backup would be its self-sufficiency with respect to electricity supply, since Starlink satellites do not depend on terrestrial electricity supplies, unlike traditional mobile and radio networks. This autonomy is particularly advantageous compared to 4G operator networks, as private networks are already designed independently of the electricity supply.

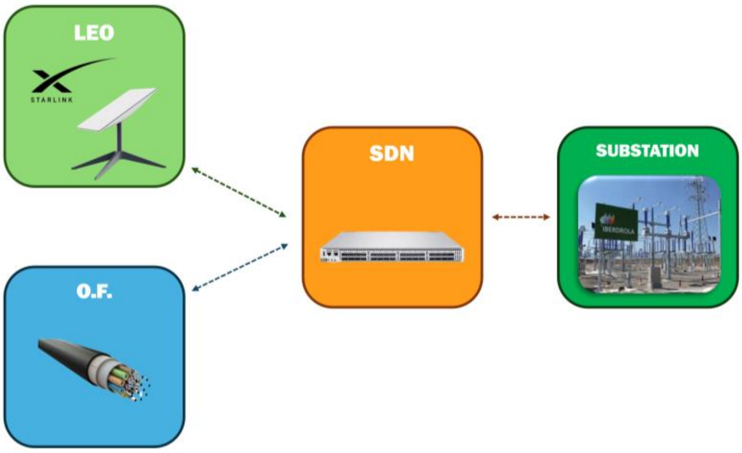

Figure 9: Architecture with Starlink integration (Substation, OF)

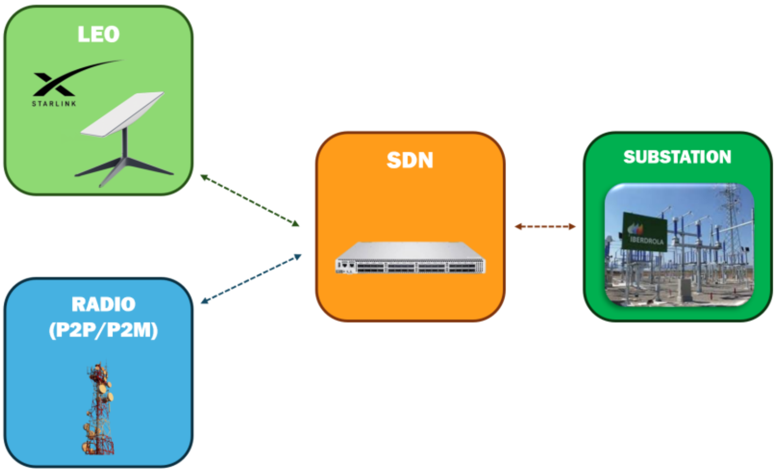

Figure 10: Architecture with Starlink integration (Substation, Radio)

In short, Starlink already has certain applications where it can be implemented effectively. In addition, as technologies evolve, the range of uses for Starlink will expand. In two years, the arrival of Amazon Kuiper, which promises to vastly surpass Starlink services with more powerful and smaller antennas, will bring real competition to the Starlink market. Additionally, as the cost of antennas decreases, OneWeb will become a very attractive technology. And finally, Starlink's business customers are known to be continuously requesting dedicated IP services. Who knows if they will respond to this demand and become a much more reliable service?

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RESUMEN DEL PROYECTO

Este Trabajo de Fin de Máster tiene como objetivo identificar potenciales aplicaciones dentro del sector energético para la implantación de las nuevas constelaciones ultra densas de baja orbita (LEO) dedicadas al internet de alta velocidad, y realizar un análisis de su viabilidad.

Palabras clave: Smart Grid, Satellite, Telecommunication, Utilities, Commercial solutions, LEO (Low Earth Orbit), Digitalization, Mbps, Jitter, Latency, Packet loss, Availability.

1. Introducción

La integración de las constelaciones LEO (Low Earth Orbit) de internet de alta velocidad, como Starlink y OneWeb, representa una de las tecnologías más prometedoras para mejorar la conectividad global de manera segura y ambientalmente sostenible. Sin barreras geográficas, con una cobertura global, rápida, competitiva y potenciadora de desarrollo económico y social, estas constelaciones son pioneras en la democratización del acceso a internet.

Gracias a los avances en la tecnología de cohetes reutilizables, como los de SpaceX, y a las mejoras en la fabricación de satélites, que ahora son más pequeños y económicos, el coste de lanzamiento se ha reducido drásticamente al poder lanzar múltiples satélites simultáneamente. Esto ha reducido significativamente las barreras de entrada en el segmento espacial de las telecomunicaciones creando un nuevo entorno. Es en este donde han surgido estas constelaciones, abriendo la competencia y permitiendo la participación de numerosos agentes en el sector, quienes proponen continuamente nuevas soluciones.

Las capacidades avanzadas que ofrecen las constelaciones LEO tienen un gran potencial para integrarse en el sector de las *utilities*, mejorando la digitalización de la red y facilitando la comunicación en zonas remotas. La posibilidad de brindar conectividad de alta velocidad en áreas rurales y de difícil acceso es fundamental para la supervisión y gestión eficiente de la infraestructura energética, así como para la implementación de tecnologías inteligentes en la red. Este interés se refleja en este proyecto de Iberdrola, la empresa eléctrica más grande de España con presencia internacional, que busca evaluar si puede aprovechar estas nuevas tecnologías en sus numerosos y dispersos activos.

2. Definición del proyecto

- El proyecto consiste en la identificación y evaluación de potenciales casos de uso donde la integración de las plataformas de telecomunicación LEO sean viables y aporten ventajas sobre las actuales.
- El proyecto se divide en 3 fases:
    1. **Contextualización**: Em esta fase se estudia todo lo relacionado con sector espacial y su relación con el sector energético; la tecnología espacial, las diferentes soluciones comerciales disponibles actualmente y en un futuro próximo, el entorno espacial y sus efectos sobre la tecnología, las redes eléctricas y su evolución, la actual digitalización de la red y transformación del sector eléctrico, y finalmente, los retos y necesidades de las telecomunicaciones dentro de él.
    2. **Estudio de tecnologías comerciales y evaluación:** Esta fase se subdivide en tres tareas:
        - 2.1. Estudio de características de las tecnologías de telecomunicación comerciales identificadas en la fase anterior y la elaboración de fichas técnicas de las mismas.
        - 2.2. Categorización de las soluciones estudiadas. Esto se realiza con el objetivo de segmentar y facilitar la evaluación de las tecnologías.
        - 2.3. Identificación de los distintos casos de uso dentro de los activos de Iberdrola y la evaluación de la viabilidad de las distintas tecnologías. Con esto se consigue una percepción profunda de los motivos del uso de las tecnologías que tienen actualmente integradas, además de identificar en qué casos encajan las nuevas constelaciones LEO.
    3. **Estudio en profundidad y prueba de las constelaciones LEO**: El estudio tecnológico se realiza para ambas constelaciones, OneWeb y Starlink. En este se investiga sobre sus modelos de operación, tecnología, orientación de negocio, etc. una vez realizado y evaluada su integración a los casos de uso restantes, se realizan una serie de prueba donde se comprueba que las tecnologías que hayan resultado potencialmente viables realmente están en línea con lo que han ofertado.

3. Resultados

Este apartado recorre los resultados de las diferentes fases.

En primer lugar, la **primera fase** consigue establecer un marco contextual sólido para el proyecto y lo documenta en los capítulos iniciales del documento.

La **segunda fase** ha logrado delimitar y categorizar las distintas soluciones tecnológicas disponibles. Primero, se han elaborado fichas técnicas detalladas para cada solución comercial de telecomunicación del segmento espacial.

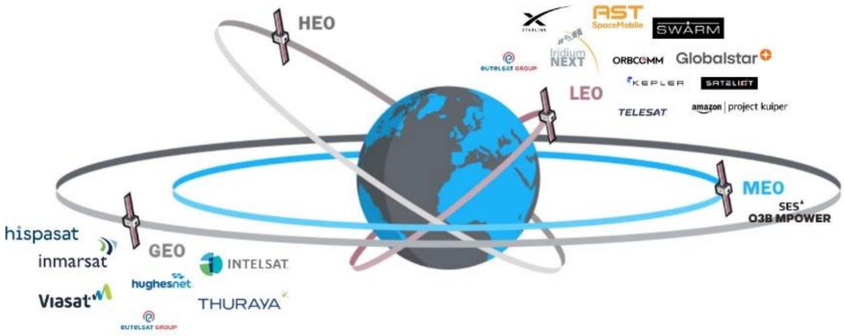

Figura 11: Tecnologías satélite comerciales de telecomunicación

Seguidamente, con el objetivo de facilitar la evaluación de las tecnologías, se ha realizado una segmentación basada en su órbita, servicio, coste y tipo de antena utilizada.

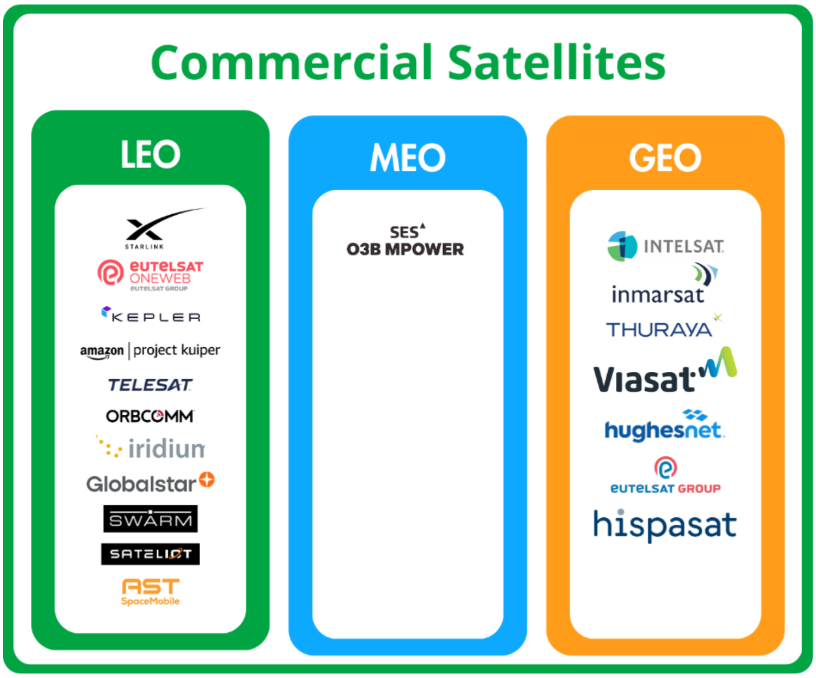

Figura 12: Categorización por órbita

La órbita está relacionada con la latencia y la posición relativa respecto al observador en la Tierra. Los satélites GEO tienen latencias de aproximadamente 600 ms y se mantienen estáticos respecto al observador, mientras que los satélites LEO tienen latencias mucho menores, entre 30 ms y 75 ms, y se mueven respecto al observador. Este movimiento obliga a las antenas a seguir dinámicamente a los satélites para mantener la conexión, además de requerir saltos entre satélites cuando estos salen del campo de visión. La altitud de la órbita LEO influye en el tiempo que los satélites permanecen en el campo de visión, aunque esta siempre suele ser inferior a una hora. Los satélites en orbitas MEO también sufren esto, pero sus tiempos de visión son mayores. La posición dinámica complica la operación de la constelación y la orientación de las antenas, aunque las nuevas antenas planas de fase ("phased array") con orientación digital han mitigado este desafío considerablemente.

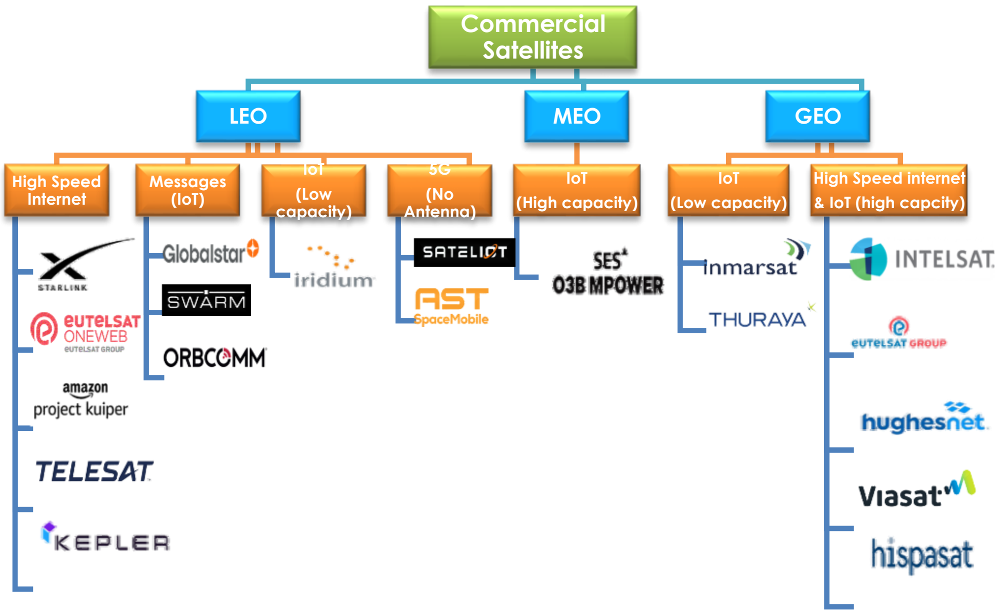

Figura 13: Categorización por servicio

Independientemente de la órbita, se han identificado tres tipos de servicio: **mensajes IoT, IoT de baja capacidad e internet de alta velocidad.** Existen otros servicios como el 5G, que aún no están disponibles. Se ha de hacer un comentario adicional sobre las tecnologías de mensajes IoT. Como estas no son realmente una tecnología de transmisión de datos no se pueden considerar en el estudio, ya que no encajan con las necesidades de Iberdrola.

Del estudio se identifican las características clave que diferencian las tecnologías según su capacidad. En función del servicio, se utilizan bandas de frecuencia más altas o más bajas. Las frecuencias altas proporcionan un mayor ancho de banda y, por ende, más capacidad de transmisión, pero son más susceptibles a factores medioambientales, como la lluvia intensa, que provoca el fenómeno conocido como “rain fade” o Desvanecimiento por lluvia en español, y puede llegar causar la pérdida total de comunicación. Por tanto, **una mayor frecuencia implica mayor capacidad pero con comunicaciones más vulnerables, y viceversa.**

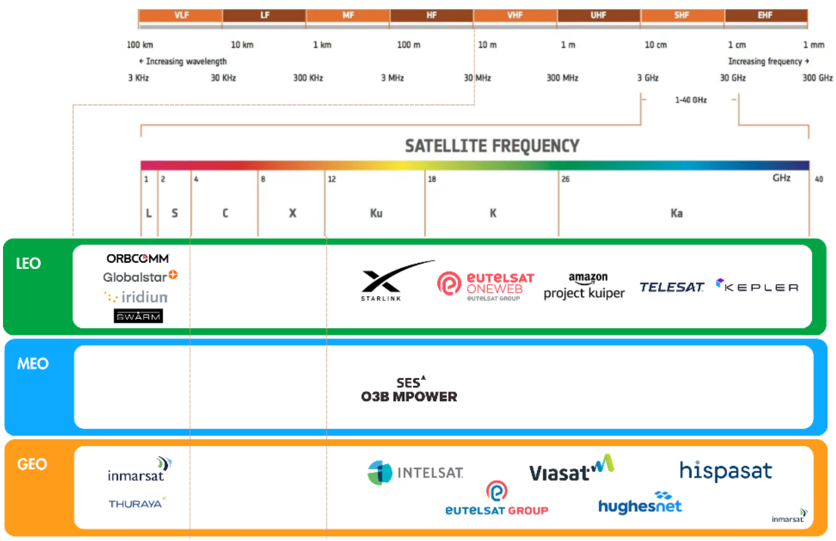

Figura 14: Categorización por frecuencia

La frecuencia utilizada también afecta al tipo de antena requerida. Los servicios de telecomunicaciones robustas de baja frecuencia y baja capacidad requieren antenas pequeñas (parche), mientras que las de altas frecuencias necesitan antenas más grandes, como las VSAT (Very Small Aperture Terminal) o las de fase. Sin embargo, el mercado de las últimas está centrado en el desarrollo de más potentes y más pequeñas antenas.

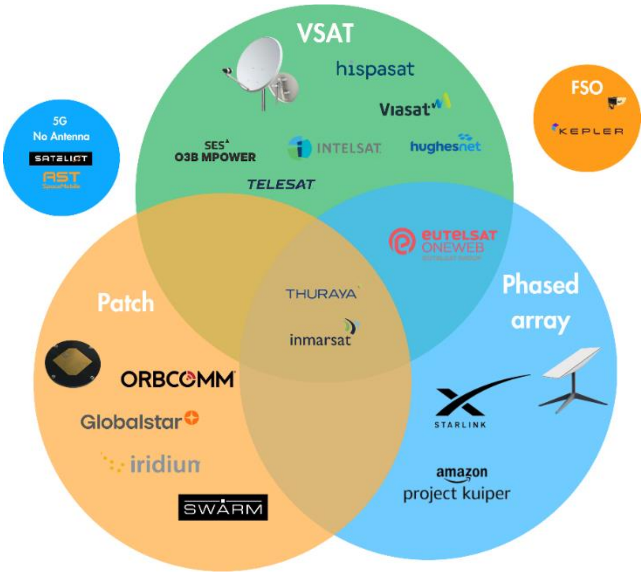

Figura 15: Categorización por tipo de antena

Finalmente, se ha realizado una categorización del coste del tráfico. Los costes se han estimado basándose en las tarifas de los principales distribuidores. Dada la dificultad de hacer comparaciones directas de costos, se ha aproximado utilizando el coste por MB. Este cálculo es complejo porque las tecnologías de baja capacidad ofrecen un precio base para un rango inicial de tráfico de datos y luego cobran tarifas adicionales más altas por el uso excedente. En contraste, las tecnologías de alta capacidad suelen tener una oferta mínima que supera con creces las necesidades de tráfico del sistema de telecomunicaciones. Por lo tanto, la clasificación presentada debe considerarse como una guía aproximada.

Figura 16: Categorización por coste

La última tarea de la segunda fase es la identificación de potenciales casos de uso. En este cas se han identificado tres:

- **Parques de generación renovables y subestaciones**
- **Subestaciones secundarias (centros de transformación, CT) remotas y reconectadores (OCR) remotos**
- **Comunicaciones de Oficina Corporativa**

Con las siguientes necesidades de telecomunicación y requisitos:

(Subestación/P.Eólico)			**CT/OCR**			**Oficina**	
Tráfico	8 GB/mes		Tráfico	300 MB/mes		Tráfico	1 TB/mes
Capacidad	25 kbps		Capacidad	1 kbps		Capacidad	10 Mbps
Latencia	< 1s		Latencia	< 1s		Latencia	150 ms
Pérdida de paquetes	Crítico		Pérdida de paquetes	Crítico		Pérdida de paquetes	No crítico
Disponibilidad	> 99%		Disponibilidad	> 99%		Disponibilidad	> 99%
Coste Referencia	100 €/mes		Coste Referencia	10 €/mes		Coste Referencia	1000 €/mes
Tamaño de antena	No crítico		Tamaño de antena	Crítico		Tamaño de antena	No crítico

Tabla 1: Requerimientos de telecomunicación de los distintos casos de uso

Ajustando las categorías a los requerimientos, se ha determinado que para el primer caso de uso (Subestaciones y parques renovables), las tecnologías de internet de alta velocidad presentan una viabilidad teórica tanto en órbita LEO como en GEO. Este resultado era esperable, ya que actualmente este caso de uso esta cubierto por las tecnologías de internet de alta velocidad GEO, o como se conocen normalmente, las VSAT:

En el segundo caso (CT y OCR), ninguna tecnología de telecomunicaciones espacial resulta viable debido a las limitaciones de tamaño (para las tecnologías de alta capacidad) y coste (para las tecnologías de baja capacidad).

Para el tercer caso (Servicios de oficina), únicamente las constelaciones LEO de internet de alta velocidad son teóricamente viables, mientras que las GEO quedan descartadas por su alta latencia. Para confirmar la viabilidad real, es necesario llevar a cabo pruebas que verifiquen el funcionamiento práctico de la red en estos escenarios.

En la **tercera fase** se profundizado el estudio sobre las constelaciones LEO (tecnología, orientación de negocio, equipamiento, tarifas, modelo de operación, etc), Tabla 2. En primer lugar, aunque la tecnología de OneWeb está mejor alineada con las necesidades de Iberdrola debido a su capacidad de dedicar segmentos de telecomunicaciones y ofrecer garantías de disponibilidad con SLAs, se ha descubierto que resulta inviable debido al elevado coste de su equipamiento, específicamente la antena. El precio de mercado de esta antena ronda los 20.000€, muy alejado del presupuesto de alrededor de 1.000€ por instalación,

	Starlink	OneWeb	VSAT
Orbit	LEO	LEO	GEO
Altitude	500 km	1200 km	36570 km
Latency	30 ms	70 ms	600 ms
Uplink Speed	~ 22 Mbps	~ 32 Mbps	~ 10 Mbps
Downlink Speed	~ 190 Mbps	~ 190 Mbps	~ 200 Mbps
Phased array antennas	Yes	Yes	No (some options)
Size	57cm x 51cm	56cm x 45cm	100cm x 100 cm
Price	2.000 €	20.000 €	2.000 € + 1.000€ (installation)
Installation	Easy	Easy	Difficult
SLA (Guaranteed channel)	No	Yes	Yes
Availability	95%	99%	99%

Tabla 2: Comparación de tecnologías

Por lo que solo se ha considerado realizar pruebas a la tecnología Starlink. Obteniendo lo siguiente:

	Uplink Speed	Downlink Speed	Latency	Availability	Packet loss
Avarage	24,19 Mbps	97 Mbps	153,63 ms	97,31%	2,69%
Variability (Std.)	7,96 Mbps	12,3 Mbps	29,94 ms	2,64%	

Tabla 3: Starlink test results

Los resultados de las pruebas que se han podido realizar, sitúan a starlink con parámetros medios de telecomunicación comparables a las redes de operadores de 4G. Pero su alta variabilidad presenta una gran pega. Además, esta variabilidad se ve agravada por la temporalidad. En las pruebas se han tenido periodos de malos resultados y otros de resultados excelentes:

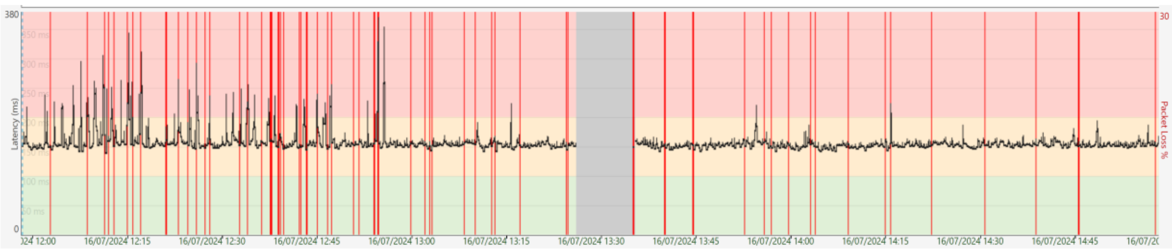

Figura 17: Resultado de pruebas de latencia(línea negra) y perdida de paquetes(barras rojas)

4. Conclusiones

Se concluye en función de los resultados obtenidos que los posibles usos de Starlink son principalmente como **tecnología de respaldo, o dedicada específicamente a servicios corporativos**. Iberdrola utiliza dispositivos SDN (Software Defined Networking) para integrar sin problemas dos o más infraestructuras de telecomunicaciones en una sola instalación. Estos dispositivos permiten el control total de las telecomunicaciones, haciendo factible la dedicación de un servicio específico a una cierta tecnología.

El primer caso de uso potencial son los parques de generación renovables, actualmente servidos exclusivamente por VSAT con dos antenas. Starlink podría integrarse reemplazando una de las tecnologías para crear un servicio GEO-LEO. Esto no solo mantendría la redundancia con otra tecnología, sino que también permitiría mejorar los servicios corporativos al ejecutarlos sobre el segmento LEO.

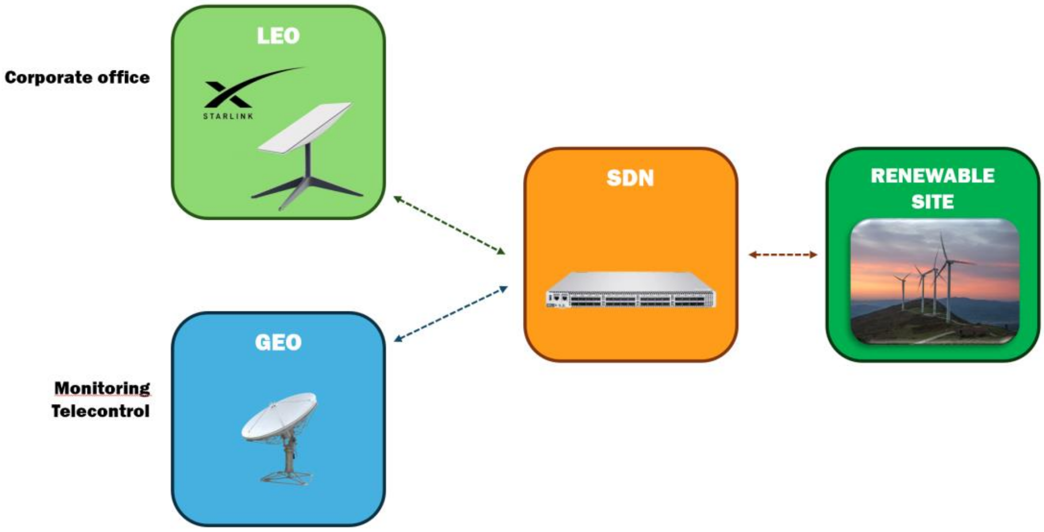

Figura 18: Arquitectura con integración de Starlink (parque de generación renovable)

Otro escenario donde Starlink tiene potencial utilidad es como tecnología de respaldo para infraestructuras conectadas actualmente a través de fibra óptica (F.O.) o radio (P2P o P2M). Actualmente, Iberdrola utiliza las redes de operadores como respaldo a su propia red (fibra óptica, radio punto a punto (PP), radio punto a multipunto (PMP)) en subestaciones. Mientras que el 4G puede usarse como respaldo donde hay cobertura, en áreas sin cobertura, se podrían emplear VSAT GEO o LEO. La principal ventaja de Starlink como respaldo sería su autosuficiencia con respecto al suministro eléctrico, ya que los satélites de Starlink no dependen de suministros eléctricos terrestres, a diferencia de las redes móviles y de radio tradicionales. Esta autonomía es particularmente ventajosa en comparación con las redes de operadores 4G, ya que las redes privadas ya están diseñadas con independencia del suministro eléctrico.

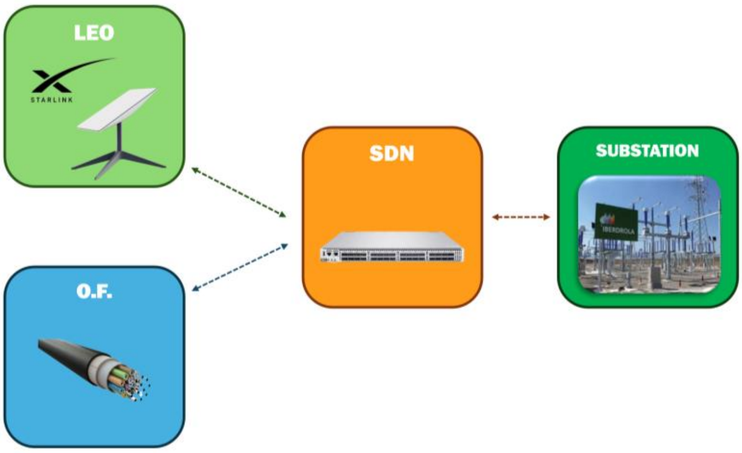

Figura 19: Arquitectura con integración Starlink (Subestación, FO)

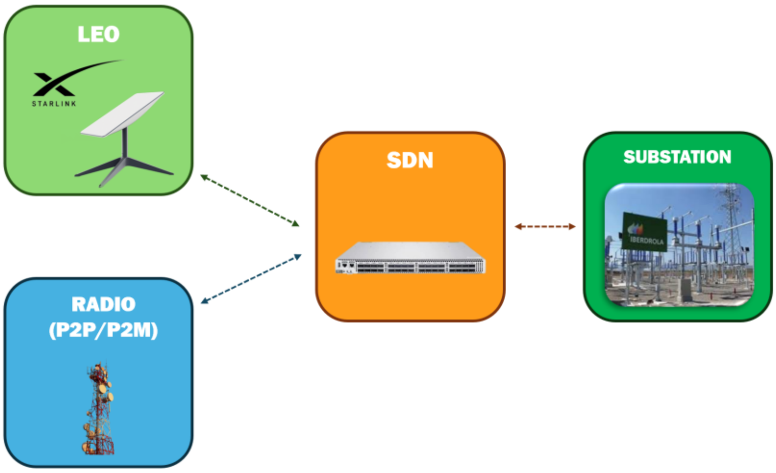

Figura 20: Arquitectura con integración Starlink (Subestación, Radio)

En resumen, Starlink ya tiene ciertas aplicaciones donde puede implementarse eficazmente. Además, a medida que las tecnologías evolucionen, el rango de usos para Starlink se expandirá. En dos años, la llegada de Amazon Kuiper, que promete superar ampliamente los servicios de Starlink con antenas más potentes y pequeñas, aparecerá una competencia real al mercado de starlink. Adicionalmente, a medida que el costo de las antenas disminuya, OneWeb se convertirá en una tecnología muy atractiva. Y finalmente, se sabe que los clientes comerciales de Starlink están solicitando continuamente servicios IP dedicados. ¿Quién sabe si responderán a esta demanda y se convertirán en un servicio mucho más fiable?

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Chapter 1. INTRODUCTION

This study aims to represent a further step on the path towards the digitalization of the grid, towards the Smart Grid. More specifically, a step in Iberdrola's, one of the main actors in the Spanish distribution grid, plans of grid modernization and greater management capacity (monitoring, control and action) for a more efficient use of its resources.

This project will first study satellite telecommunication technologies, its state of the art and the commercial solutions available. Then, based on the information of this first stage of the study, an analysis will be carried out on the opportunities of incorporating satellite telecommunications in different assets of the electric grid. And finally, the feasibility of this use cases will be assessed and tested.

Following up in the goal of this project, the digitalization of the grid, the deeper purpose is to change the paradigm through the new capabilities that the integration of IoT and telecommunications enable. The paradigm's most significant change is bidirectional flows of energy. This, while enhancing energy efficiency, promotes the proliferation of DERs (Distributed Energy Resources) such as DG (Distributed Generation), BESS (Battery energy storage systems) and the EV (electric vehicle) fleet among others, which are key elements in the transition towards clean, renewable and sustainable energy. Furthermore, the new capabilities of the system will change the status of the consumer as a new active agent, a "prosumer", with decision-making power that embodies the well-known demand response (DR). Other benefits of the modernization of the grid include further developments in dynamic pricing, as well as a greater management ability to optimize the grid operations, further improving the quality of service (QoS), stability and resilience of the grid. [1]

In order to put the project in context, a brief introduction of the evolution of the system from its origins, up to the current situation will be made, specifically with the Spanish system on the focus of the study. The precedents and evolution of the system is of greater importance in the electric industry than in other industries, since its technologic cycles are longer due to the high economic intensity of investments and their extended amortization times, the strategic background of the energy sector within countries and the condition of energy of being a basic service, a human right. [2]

Chapter 2. THE EVOLUTION OF THE GRID

The use of energy by humans dates back to prehistoric times. Millions of years ago, humans already knew how to handle fire. As they evolved, they perfected their techniques and discovered how to harness it, as well as how to make good use of other forms of energy in their environment, both those contained in natural resources like wind or water, and those provided by animals. In the end, the management of energy has always been the cornerstone of how humans simplify their tasks.

Leaping into more recent history, more complex systems were developed, and new energy sources were discovered. A huge milestone in human history was the development of the steam engine in the late 18th century, which enabled **the mechanization of the industry**, driving the **first industrial revolution**. Also in the late 18th century the concepts of the second industrial revolution were beginning to take shape. Important advances were being made in the fields of electricity and magnetism by renowned scientists such as Franklin, Volta, Faraday and Ohm among others. However, it was with the formulation of Maxwell equations in mid-19th century that both fields were related, describing the electromagnetic phenomena completely, and marking the origin of electricity. [3], [4]

It was not long before the first electric devices appeared, electromagnets, motors and even electric cars were fabricated. However, it was the lightbulb what truly drove the industry. After obtaining the patent in 1879, Edison founded the Edison Illuminating Company to mass produce lightbulbs and in 1882, he inaugurated the first power plant to sell electric energy to his clients.

In the early days of power plants, the primary energy generation technologies were steam turbines and hydroelectric power. As demand increased, it was small hydroelectric power plants the technology that gained importance in the supply of electricity to the main urban centers. However, these plants were small and operated on direct current (DC), which, due to voltage limitations at the time, prevented energy from being transported over long distances, thus limiting the areas that could be electrified.[5]

Tesla's AC technology then proved to be the solution to this issue. After the competition to demonstrate which technologic model was superior ("the War of Currents"), Tesla, with the support of Westinghouse, emerged as the winner. It was with the construction of the Niagara Falls hydroelectric power plant, capable of transporting electricity up to 40 kilometers away, that they marked the beginning of the **second industrial revolution**, **the electrification of the world.** [6], [7]

Further advances were made in the raising of voltages to allow longer distances transport, as well as the development in new sources of energy. Over the 20th century, technologies such as nuclear, fossil fuels and renewables appear, as they were no longer constraint by the proximity to consumption due to the parallel development of the **electric grid**.

The electrical grid is as important, if not more important, than any power plant technology because it connects energy generation and consumption. Since energy must be produced and consumed simultaneously, the **grid serves as the cornerstone of the entire system**. The grid can therefore, be represented as the rivers of a system that operates on a cascade model: energy is generated at a power plant at the top, then transported and distributed downstream to customers. The model evolved from an initial zonal coverage, where energy was consumed from the nearest power plant as it was the only one available. A line was used to transmit the power from the power plant to the consumption zone and then was ramified to reach individual consumers. To the current complex system. Over time, the system expanded and isolated zones were interconnected, developing into complex, meshed network with extensive reach, including remote areas. The current power grid represents one of the major achievements of the 20th century, it is one of the most complicated systems ever created by humans and it will be even more complex as the grid continues to evolve. As it must continue to adapt to new technological advances and to integrate growing energy demands.[8], [9]

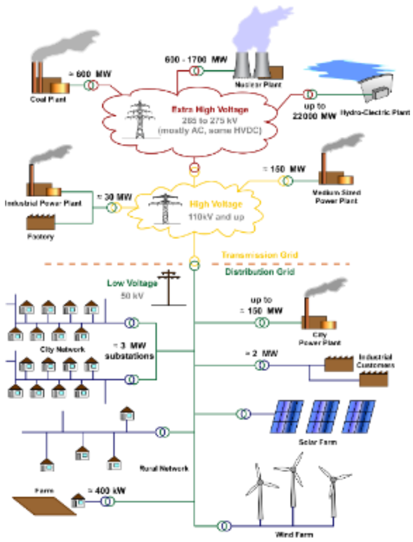


Figure 1: Traditional electric system (Source: Renewable energy plant for distribution grid)

Some of the mentioned technological advances include the integration of devices that marked **the third industrial revolution**. In the mid-20th century, with development of the first computers and the integrated circuit board (the chip), and the parallel to the expansion of electric systems, the digital revolution began. This revolution was characterized by the transition of industry and the global economy to digital technology. Or what is the same, **the integration of computational (information) and communications technologies (ICTs)**.[10]

The integration of computation and communication technologies was a huge step forward in the industry. This new capacities enabled generation of great amounts of data for monitoring for instance, and most importantly, they enabled the **automation of the industry**.

Within the developed technologies, the personal computers, mobile phones and the internet stand out. They, alongside the advances in transportation, strongly promote the globalization of the world. Globalization eased the transmission of knowledge, which fasten the technological advances and the technological competition. In the energy sector, this drove the development of asset automation and of renewable energy generation technologies. The latter, as the technology matured, gave rise to a social movement toward sustainability and decarbonization, that is still at the center of attention.

This revolution laid the foundation for **the Fourth Industrial Revolution, the bringing of intelligence to the industry.** This revolution focuses its efforts on the processing of data generated by the third revolution devices (ICT) in search of patterns, relationships and insights that allow a better understanding of industry processes. Some of these approaches include Big Data, Deep learning, Artificial Intelligence, advanced robotics, IoT, cloud services, nanotechnology, virtual reality and cybersecurity among others.[11]

Nevertheless, the fact that there is an industrial revolution does not mean that its advances are integrated immediately to the industry. Just as with a new technology or a new product, there is a cycle with different phases through which it passes from its appearance to its maturity.[12]

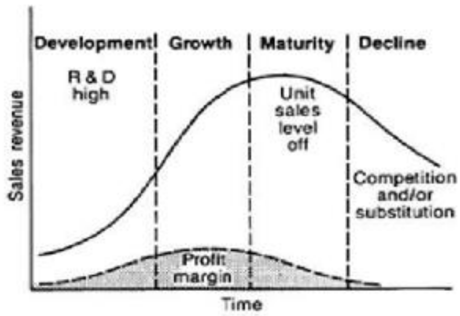


Figure 2: Technology life cycle (source: Pere Condom-Vilà)

Both, the third and fourth industrial revolutions are relatively recent and very close together. In fact, they are quite overlapping. The third is only approaching maturity when there is already a lot of progress in the fourth. In fact, this is the case of the electric utility. In advanced energy systems, the industry is still are facing the challenges of the third industrial revolution, integrating ICTs to the different assets. While, in parallel, integrating intelligence applications as soon as the information is available.

The concept of "*Smart Grid*" is actually the name given to this process. The integration of ICT devices with assets and the use of data to create new capabilities that improve visibility and management of the network and service, as well as the ability to integrate new technologies such as electric vehicles, distributed generation or the evolution of the customers from consumer to prosumer, from passive agent to an active one.[2]

Many of the challenges associated with the new model are related to the paradigm shift from unidirectional cascade model energy flows to bidirectional flows. However, this study does not focus on them. It is more focused in the conclusion of the previous challenge of monitoring the whole grid.

Several years have passed since the start of the digitalization of the electricity grid. Almost all assets are now equipped with meters that allow them to be monitored. However, there is a gap in this process related to the communication of these devices. Telecommunication is commonly done through PLC, fiber optic or cellular networks. However, in places where these technologies are not available, it is still necessary for an operator to travel periodically to take the necessary readings. It is this challenge that this study seeks to address.[2]

2.1 SOLUTIONS

In the field of communications, there are currently 3 technologies; fiber optics, wireless communications and satellite communications. These technologies have evolved over the years and each has a set of characteristics, capabilities and limitations. From highest to lowest, the capacity of the technologies goes in the order they have been mentioned. First and foremost, capacity is directly related to bandwidth. In terms of spectrum handled, fiber has the highest capacity, followed by cellular and satellite.

The limitation of fiber is that it is a physical medium. That is, it requires the deployment of a dedicated infrastructure to provide the service. It is therefore logical that this infrastructure should only be present where it is feasible to deploy it. The same is true for mobile networks. They consist of a series of antennas that act as relays to transmit signals. The advantage is that their transmission medium, the air, is available everywhere. The problem is that they are dependent on the terrain. Therefore, multiple antennas are needed to provide good coverage, and a meshed infrastructure is needed to avoid obstacles and ensure a clear LoS (Line of Sight).[2]

Lastly, there are satellite communications, which, like cellular networks, transmit in the electromagnetic spectrum and their antennas act relays. However, they have the advantage of largely eliminating the problem of terrain orography, being limited only by overhead obstructions and, like cellular networks, by the weather.

In developed countries, the coverage of the first two technologies is extremely high, covering high percentages of the population, as can be seen from the coverage maps in Figure 3 and Figure 4. However, there are municipalities where this coverage does not reach. This is mainly because the deployment of infrastructure is not attractive to telecommunications companies. As with every industry, the systems are developed according to the needs of the market. In this case, it is not worth the investment to connect rural areas with traditional networks.[13]

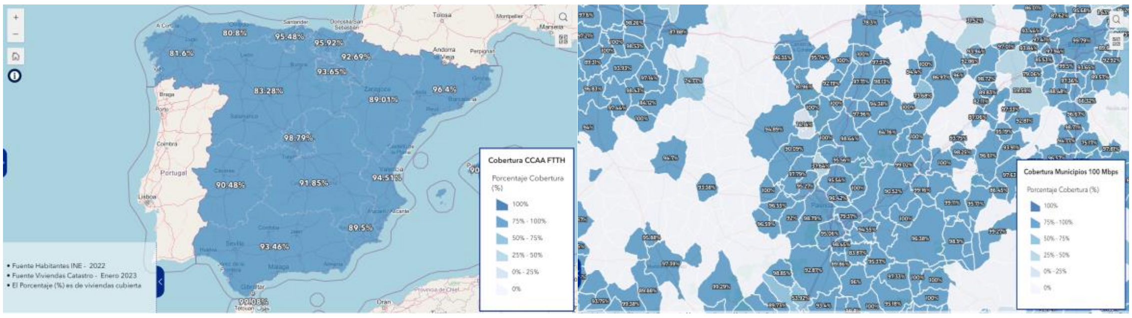


Figure 3: Optic fiber network coverage (Source: Ministry of Industry, Government of Spain)

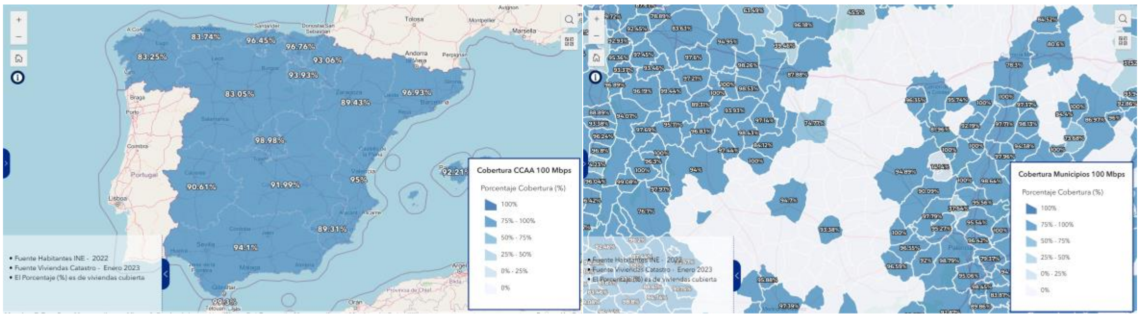


Figure 4: Cellular network coverage (Source: Ministry of Industry, Government of Spain)

Therefore, the only option in these areas is satellite communications (Figure 5). The problem with satellite technology is its cost. Traditionally, launching and manufacturing satellites was a very expensive, thus its pace of development was slow. In addition, due to the small number of satellites compared to terrestrial networks, the available capacity is very limited and therefore very expensive. However, satellite technology has recently made a breakthrough. Because of its close relationship with rockets, its attractiveness has increased with the development of reusable rockets. These have drastically reduced launch costs. Furthermore, satellite manufacture costs have also been reduced, which has opened the window for new constellations of massive numbers of satellites to explore and/or dominate new telecommunications sectors, having a lot more capacity available at competitive prices.[13]

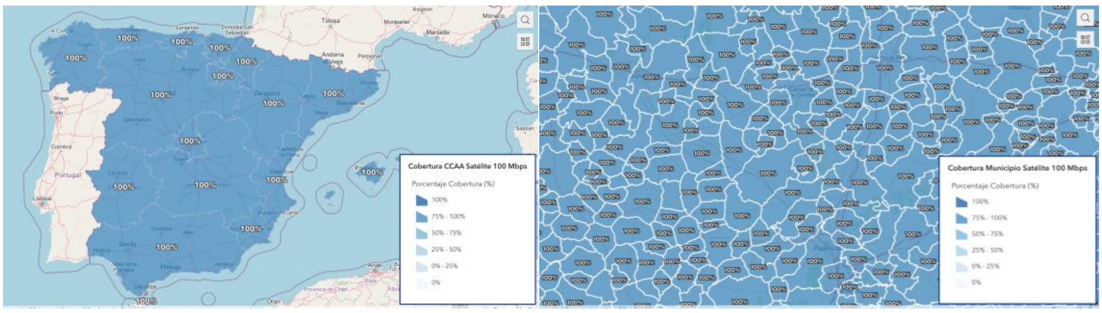


Figure 5: Satellite network coverage (Source: Ministry of Industry, Government of Spain)

Chapter 3. HISTORY OF SATELLITE TECHNOLOGIES

It is important to understand the political context of the time in order to fully appreciate the history of satellites. During the Cold War, the United States and the Soviet Union competed for technological and scientific supremacy, which significantly boosted advances in rocket and satellite technology. However, there were some key precedents that paved the way for these technologies. The most significant were Tsiolkovsky's first description of the geosynchronous orbit in 1895, Noordung's 1929 concept of radio communications with a space station in geosynchronous orbit using large antennas and solar power, and Arthur C. Clarke's 1945 proposal of global coverage with three interconnected satellites in his article "Extra-Terrestrial Relays" in Wireless World. Furthermore, within the technological advances, there were two that laid the groundwork for the feasibility of artificial communication satellites. The invention of the transistor, that enabled the development of unattended, long-endurance satellites. And advances in rocketry and rocket guidance systems, developed by military interests of both superpowers (USA and USSR), that made the deployment of satellites at high altitudes possible.[14]

3.1 ORIGIN AND SPACE RACE KEY MILESTONES

The event that is widely recognized as the origin of satellite communications was the launch of the Sputnik 1 in 1957 by the Soviet Union (USSR). It was the first artificial satellite to orbit the Earth that transmitted a simple radio signal back to the planet. The achievement occurred at a time when communism and capitalism were in fierce competition, right in the apex of the cold war that followed WWII, and served as a significant demonstration of Soviet model superiority over that of the United States. [15]

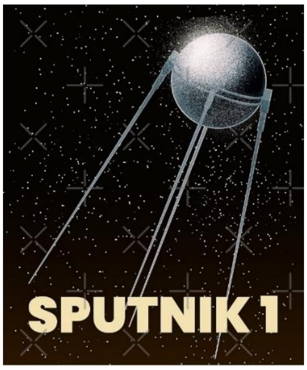


Figure 6: Sputnik 1, the first artificial satellite launched by the Soviet Union in 1957. (Redbubble)

The impact on the United States was profound, and did not passed without a response. The first measure of the US government was to upgrade the priority level of its three military satellite program to very high priority. And only two months after Sputnik I launch, the US

Navy was ready to attempt their first launch which failed due to an explosion in the fuselage. However, soon, another two months later (4 months after Sputnik I), the US Army successfully launched the first US artificial satellite, the Explorer I. [16]

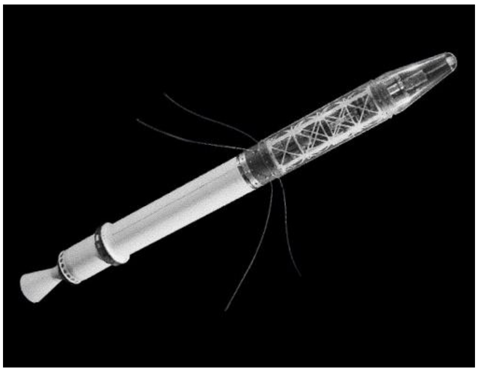


Figure 7: Explorer I (NASA)

Further in the United States' response and marking the start of the *Space Race*, in 1958, the National Aeronautics and Space Administration (NASA) was established to pursue a civil space program. The American satellite industry thus, diverged into two groups, later three with commercial. On the one hand was the civil/scientific, led by NASA. While on the other hand, there was the military, led by the U.S. Department of Defense (DOD). The military was split further and specialized among communications, reconnaissance, and navigation/ RDSS (Radio Determination Satellite Services) which include between other technologies the GPS (global positioning system).[14], [16]

Figure 8: NASA's first logo (NASA)

In late 1958, the U.S. army launched the first communication satellite with an active system, Project SCORE (Signal Communications by Orbiting Relay Equipment). It featured a very high frequency (VHF) radio receiver/transmitter and a tape recorder to receive, store, and broadcast, making it capable of both delayed and real-time voice message broadcasts from space. Both where useful, but the first mentioned was considered an important tactical asset, as it enabled a communication channel between the Pentagon and commanders in distant remote locations. The satellite only lasted 12 days, but marked a milestone in the space industry as it demonstrated that telecommunications via Satellite were possible. This success opened the doors to the DOD to assume responsibility for satellite programs, establishing the DOD's Advanced Research Projects Agency (DARPA).

Figure 9: Project SCORE components (National Air and Space Museum)

DARPA achieved its next milestone with the launch of the Courier satellite in 1960. This 500-pound satellite demonstrated the use of solar cells to supply electric power for an active repeater satellite. This innovation was crucial as it marked a transformative shift in the operational life of satellites, which power previously depended on batteries. By harnessing solar energy, satellites were no longer constrained by the limited lifespan of their onboard batteries, and satellites were no able to remain functional for extended periods.[16]

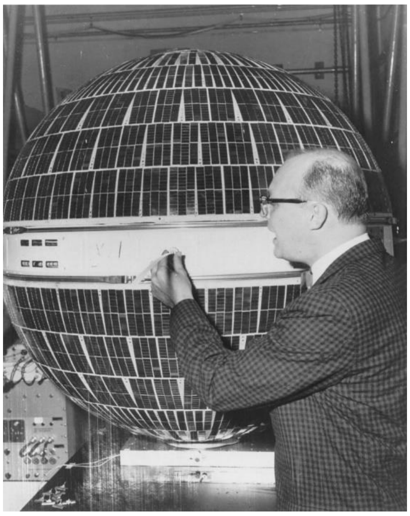


Figure 10: Courier satellite (National Air and Space Museum)

As mentioned before, NASA assumed federal responsibility for developing civil communications satellites. In the early 1960s, NASA collaborated with companies like AT&T, Radio Corporation of America (RCA), and Hughes Aircraft Company to advance communications satellite technologies. Initially, efforts focused on passive satellites, which were simpler and less complex than active ones. In 1960, NASA launched the first Echo satellites, a 30 meter diameter balloon in a 1,600 km orbit. This technology was thought to bounce **VHF and UHF** (Ultra-High Frequency) signals off the balloon's aluminum skin of ground transmitters to receivers at distant locations.

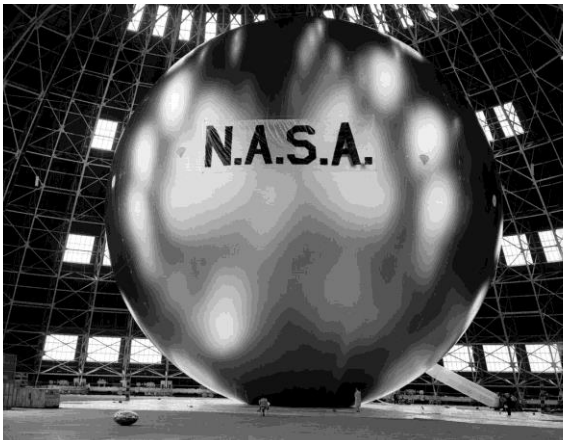


Figure 11: Echo satellite (NASA)

The next and most famous satellite experiment involved the Telstar satellites, developed by NASA in collaboration with AT&T's Bell Laboratories in 1962/1963. This project marked a shift to active satellites, incorporating advancements from military projects SCORE and Courier. Telstar was a solar-powered, active satellite capable of carrying live television and multiple voice channels, which significantly heightened public interest in satellite technology due to its ability to provide live international television transmissions. It was placed in an inclined elliptical orbit, with its perigee at about 960 km and its apogee at 5,600 km. Telstar, roughly the size of a large beach ball, circled the Earth every 3 hours, providing a live **C-band [6 and 4 GHz]** communications link for about 10 minutes each pass.

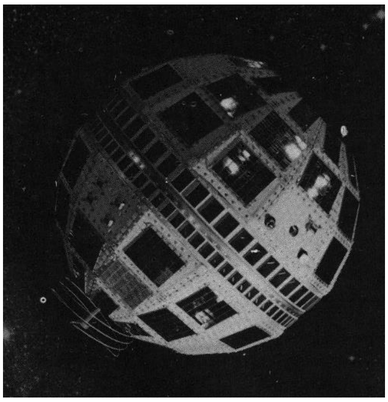


Figure 12: Telstar (NASA)

Relay was the third of the early NASA experimental satellites. It was built by RCA and launched in 1964. These elliptically orbiting satellite tested redundant systems and demonstrated that satellites could **operate at the C-band** without interfering with terrestrial microwave systems.

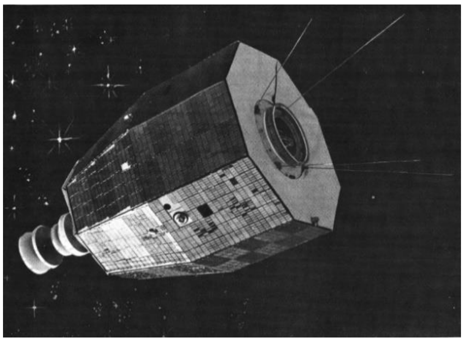


Figure 13: Relay 1 (Wikipedia)

None of these early experimental communications satellites led directly to an operational system, but they provided essential engineering data. Telstar and Relay had a common limitation: their orbits caused them to move eastward across the sky faster than Earth's rotation, resulting in brief visibility. These medium earth-orbiting (MEO) satellites were visible for only about 10 minutes and took hours to reappear, making continuous communication impossible without a costly and technically challenging ring of MEO satellites, which was unfeasible in the early 1960s.

While NASA initially focused on low and medium altitude communications satellite technologies, DARPA and the Army pursued a large geostationary (GEO) communications satellite called Advent. However, due to developmental challenges and increasing demands from various military services, Advent was canceled because no rocket was powerful enough to launch it in the early 1960s. Meanwhile, Hughes Aircraft Company proposed a smaller geostationary communications satellite called Syncom, which would spin for stability. Despite initial resistance, NASA and the DOD supported the development of three Syncom satellites, which operated **military frequencies of 7.36 GHz uplink and 1.815 GHz downlink**. Launched in early 1963, the Syncom series became the first geostationary communications satellites, proving the feasibility of geostationary communications.

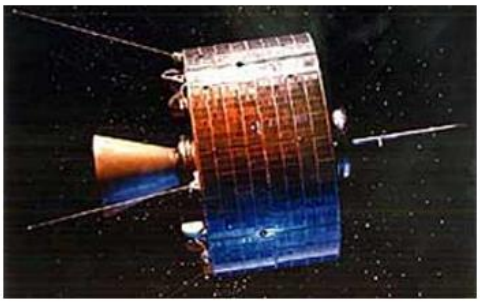


Figure 14: Syncom Satellite (Gunter's Space Page)

3.2 COMMERCIAL SATELLITES

The space industry experienced significant growth, which resulted in the emergence of the commercial sector as a new area of focus. This led to the necessity for the development and implementation of policies. Thus, in 1960, President Eisenhower established a national policy to create a commercial communications satellite system. However, with President Kennedy's administration, the focus shifted towards an international effort. In his 1961 State of the Union address, Kennedy invited other countries to join the U.S. in developing a communications satellite program, emphasizing its foreign policy significance as the nature of this new technology required. This shift led to a debate in Congress about the future use of government-developed satellite communications technology. In the end, Congress decided in 1962 to create a new organization to commercialize this technology through American international collaboration. This organization, the Communications Satellite Corporation (COMSAT), was a shareholder-owned company operating under the oversight of the State Department, the Commerce Department, and the FCC (Federal Communications Commission). COMSAT was designed to be the US part of and lead a multinational effort to develop satellites for international communications. The multinational effort came to be known as INTELSAT (International Telecommunications Satellite Organization).[14]

After INTELSAT was established, it launched its first satellite, Early Bird (INTELSAT I), built by Hughes. This geostationary satellite was placed 35,900 km over the Atlantic Ocean. INTELSAT, aimed to deploy **GEO, C-band satellites** over the three main oceans. For its operation, its member countries designated operating organizations, usually their national telephone network operators, known as PTTs (as countries tend to integrate Posts, Telegraph, and Telephone services under the same agency), to invest in and manage the satellite system's usage. These organizations, called *Signatories*, were responsible for handling INTELSAT satellite circuits domestically.[17]

Figure 15: INTELSAT 1964 (INTELSAT)

In response to INTELSAT and also due to its own civil and military needs, the Soviet Union developed its own communications satellites. However, due to the northern location of Soviet territory, the geostationary orbits above the equator were impractical for the soviets. Instead, they used elliptical orbits (Molniya orbit), for their communications satellites. Molniya satellites launches started in 1964, and orbited from about 40,000 km at apogee to 500-900 km at perigee. The drawback was that these satellites required complex ground stations with tracking antennas to maintain continuous communication links.

The success of this elliptical satellites led to the creation of INTERSPUTNIK in 1971, a smaller counterpart to INTELSAT, providing international communications services mainly among Soviet-aligned countries. In 1975, the Soviets added a significant number of geostationary satellites, including the Statsionar series: Raduga, Ekran, Gorizont, and Louch. Further in time, after the Soviet Union's collapse, the Russian Federation took over, and by 2013, INTERSPUTNIK included 26 countries, offering access to fixed users from 16 GEO satellites.[17]

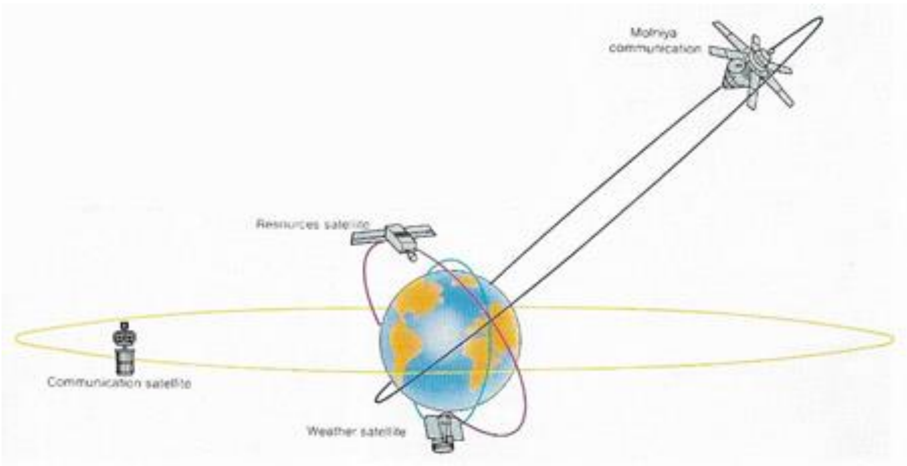


Figure 16: Molniya orbit vs other orbits (The worlds of D.D.)

INTELSAT had some uncertainty during its establishment. The United States advocated for INTELSAT to have a virtual monopoly on international satellite communications among member countries to maintain economic integrity and Western alliance interests, while European countries preferred a looser arrangement. The negotiations resulted in a system where non-INTELSAT satellite international services were allowed but had to be coordinated with INTELSAT to avoid economic harm. Ground stations linking to international satellite systems were therefore, regulated by their host countries.[14]

For satellites which only provided domestic service, there was no need to coordinate with INTELSAT. However, important parameters such as satellite frequency and orbital slot assignments were needed to be managed in coordination. This responsibility was laid upon the UN's International Telecommunications Union (ITU). This flexibility was crucial, alongside the decrease of deployment cost, for the proliferation of domestic satellites during the 1970s and 1980s for cable TV, remote TV transmission, and voice/data networks (DBS-Direct Broadcast Satellites).

Afterwards, under President Ronald Reagan, the U.S. government shifted its stance and began promoting competition in international satellite systems by encouraging the development of privately-owned satellite systems to compete with INTELSAT. This policy gained support in Europe and beyond, leading to the deployment of international communications satellites by Luxembourg-based SES and U.S.-based PanAmSat. Both companies eventually became major global providers of communications satellite services until PanAmSat was acquired by Intelsat, Ltd. in 2006. Another company that had a significant participation in the commercialization of satellite technology in the 1980s was Inmarsat, which launched fleets of satellites to provide global communication services.[14]

By the late 1980s, international communications satellite systems, including INTELSAT, faced increasing competition from efficient, high-speed fiber optic cables. In the 1990s, the push for competition intensified, with critics arguing that INTELSAT's intergovernmental status hindered fair competition and its own competitiveness. In response, INTELSAT announced plans to privatize in 1999, leading to the U.S. Congress passing the ORBIT Act in 2000, which aimed to transform INTELSAT into a private, for-profit corporation.[14], [17]

In 2001, INTELSAT transferred its assets to Intelsat, Ltd., a Bermuda-registered holding company that established several subsidiaries, including U.S.-based Intelsat, LLC. By 2006, Intelsat, Ltd. had acquired ground stations to offer end-to-end satellite links, merged with PanAmSat, and acquired the Telstar communications satellites of Loral Skynet. Subsequently, Intelsat, Ltd. was acquired by private investors and, in 2009, changed its domicile to Luxembourg, becoming Intelsat, S.A. During this period, other governmental entities such as EUTELSAT (European treaty-organization) established in 1977, also privatized. [15]

Advancements in technology, triggered in the 2000s the start of satellite constellations, such as Iridium and Globalstar, which utilized low Earth orbit (LEO) to offer global mobile communication services. These systems revolutionized the industry by providing coverage in remote and underserved areas, highlighting the versatility and reach of satellite technology.

The latest trend is the deployment of ultra-dense LEO constellations that provide high-speed internet. Since 2019, SpaceX and Oneweb have been deploying their satellite constellation. This satellites operate in the Ku-band (12-18 GHz) and Ka-band (26.5-40 GHz) to provide broadband access to underserved and remote areas worldwide.

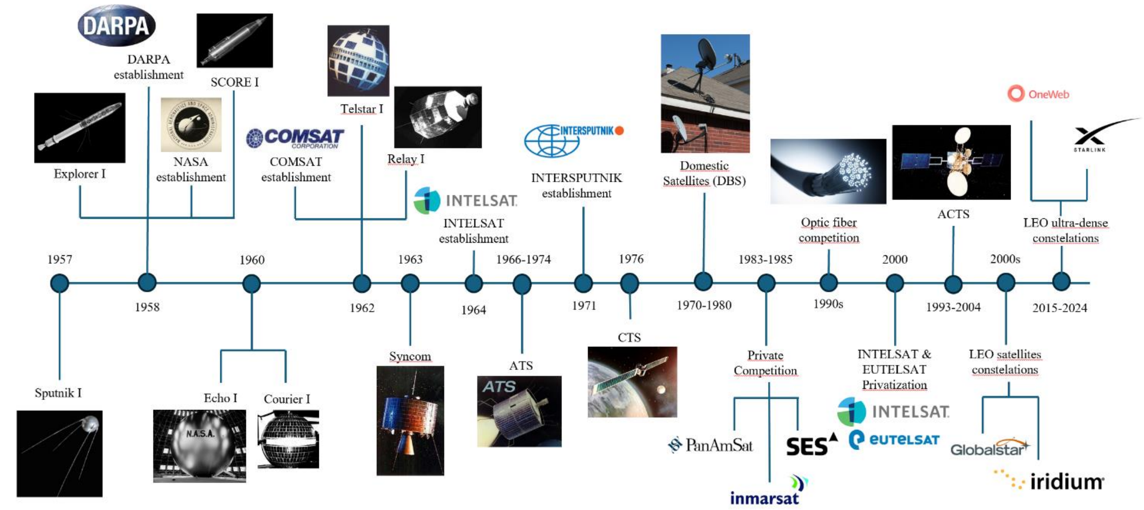


Figure 17: Timeline

3.2.1 COMMERCIAL SATELLITES FREQUENCIES

As mentioned, domestic and international communications satellites where built on NASA and US military foundations, which at the time were based on Geostationary orbits. Building on its latest successful satellites (Syncom), NASA launched six Applications Technology Satellites (ATS) from 1966 to 1974 to develop crucial satellite communication techniques, most importantly for television transmission. ATS-1, ATS-5 and ATS-6, additionally tested and demonstrated the use of the **L-band (around 1.5 GHz)** for mobile satellite communications, which were specifically useful for aircraft and ships communications.[17]

Figure 18: ATS (NASA)

Following ATS, in 1976, there was joint US-Canadian program Communications Technology Satellite (CTS) that tested new satellite designs and the use of small television receive-only antennas and **Ku-band frequencies (12-GHz and 14-GHz)**. This contributed to the commercialization of the Ku-bands by the 1980s and the widespread availability of Ku-, C-, and S-band satellite services in the United States.[17]

Figure 19: CTS (NASA)

From 1993 to 2004, NASA deployed the Advanced Communications Technology Satellite (ACTS), its most complex experimental communications satellite. ACTS tested the use of **Ka-band frequencies (30 and 20 GHz)** for fixed and mobile satellite communications, setting the stage for future satellites operating at these high frequencies.[17]

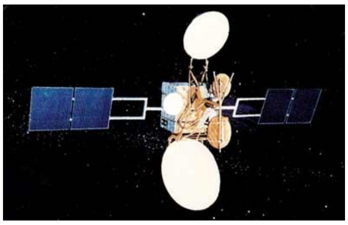


Figure 20: ACTS (Gunter's Space Page)

Chapter 4. SATELLITE TECHNOLOGY

4.1 OVERVIEW

Communication satellites are independent radio receivers and transmitters (active transmission relays), similar to relay towers used in terrestrial microwave communications. They receive signals from an *uplink* station, and retransmit the signal to either a *downlink* station or they *crosslink* the signal to another satellite with the downlink station in range.

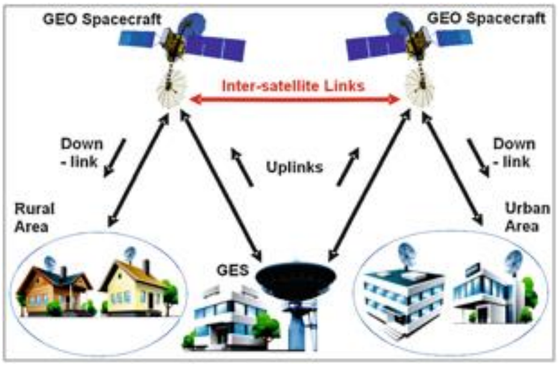


Figure 21: Satellite communications links (NASA)

As mentioned in the previous chapter, satellites began as passive technology, merely reflecting signals from the uplink station to the downlink station. Then, with the different technological advancements, satellites evolved to active satellites. The key milestone that really stimulated the development of satellite technology was the installation of solar panels, as it significantly extended satellite lifespans beyond the limitations of their batteries life. This made the development of more complex systems feasible.

Nowadays, active satellites are ubiquitous, and they typically include a series of essential components within their *Buses* (structure in which the elements are housed in). These components include radio receivers and transmitters, an electrical power system to manage energy from solar panels or batteries (used during eclipse periods), antennas, onboard navigation systems, and temperature control systems.

Satellites often require up to four different types of antennas, as they generally operate on different frequencies for uplink, downlink, crosslink, and control to avoid signal degradation. Their onboard navigation systems, usually consists of small rockets or thrusters to maintain orbit and control the satellite position.

The management and control of the different onboard satellite systems is carried out through a primary and, when needed, a back-up ground stations known as tracking, telemetry, and control (TT&C), from which operators send the orders.[18]

Satellite technology has been in continuous development since its origins. Advances have enabled new capabilities, such as onboard switching, routing, processing in the satellite, and many more which are continuous development. While useful, these capabilities add complexity and cost, which constrain the features that satellites can include. This constrains call for specialization of satellites, and dedication towards certain activities, which is precisely what generates the focus of this study, “the feasibility of LEO constellations applications for electric utility applications”.[18]

Further constrains that satellites face are physical. Satellites are small spacecrafts that need to be launched from Earth and placed into orbit. Thus, both the volume and weight has to be controlled and minimized to reduce launching and positioning costs.

4.1.1 SPACE SEGMENTS

The communications satellite infrastructure, is divided into two segments: the space segment and the ground/earth segment. The space segment elements include the satellites in orbit and the control ground stations (TT&C), while the ground segment consists of the earth surface based terminals that utilize the communications capabilities of the Space Segment and the ground stations or Gateways. The ground segment terminals consist of three basic types according to their movility: fixed (in-place) terminals, transportable terminals, and mobile terminals.[18]

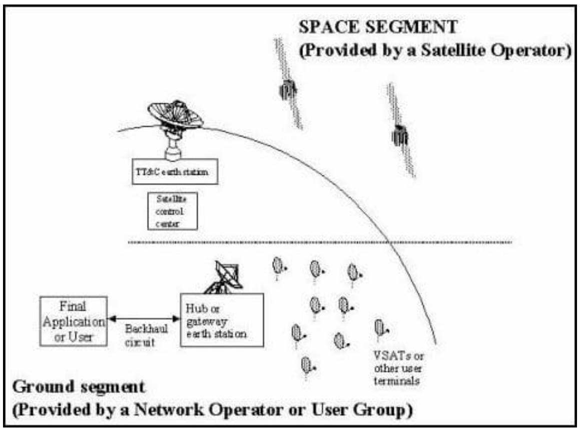


Figure 22: Space vs Ground Segments (Application Technology Strategy)

4.2 COMMUNICATION SYSTEMS

There are two types of communication systems: radio frequency (RF) and free space optical (FSO), also known as laser communications (lasercom). Most spacecraft communication systems are RF-based, operating within IEEE radio bands of 300 MHz to 40 GHz, using electromagnetic waves to send data between antennas. However, FSO communications have emerged as a compelling alternative for high-rate communication. FSO use optical frequencies, which allow wider bandwidths to support higher data rates. However, they require more precise pointing as their beamwidths are far narrower. FSO will be superficially covered in a later section as there are some emerging LEO satellite technologies that intend to use it.[17]

4.2.1 RADIO FREQUENCIES

The use of radio frequencies in satellite communications has deep historical roots that date back to the early days of radio technology and the development of wireless communication systems. From Heinrich Hertz's demonstration of electromagnetic waves and Guglielmo Marconi's practical wireless telegraph system, RF-based systems have seen uninterrupted advances. Specially since WWII, when the strategic use of different frequency bands highlighted the importance of specific frequencies for reliable communications. Post-war, these frequency bands were standardized, as all agents (industry, government, the military, and consumers) including satellite communications (like early satellites SCORE and Telstar), found that there were many radio frequencies available and some were more valuable than others for transmissions. The frequency bands were, and still are, categorized within the electromagnetic spectrum, defined by the wavelength and frequency of the electromagnetic waves. These two characteristics are inversely related: longer wavelengths correspond to lower frequencies, and shorter wavelengths correspond to higher frequencies. It is common practice to identify the radio portion of the electromagnetic spectrum by its frequency, measured in cycles per second or hertz (Hz).[18]

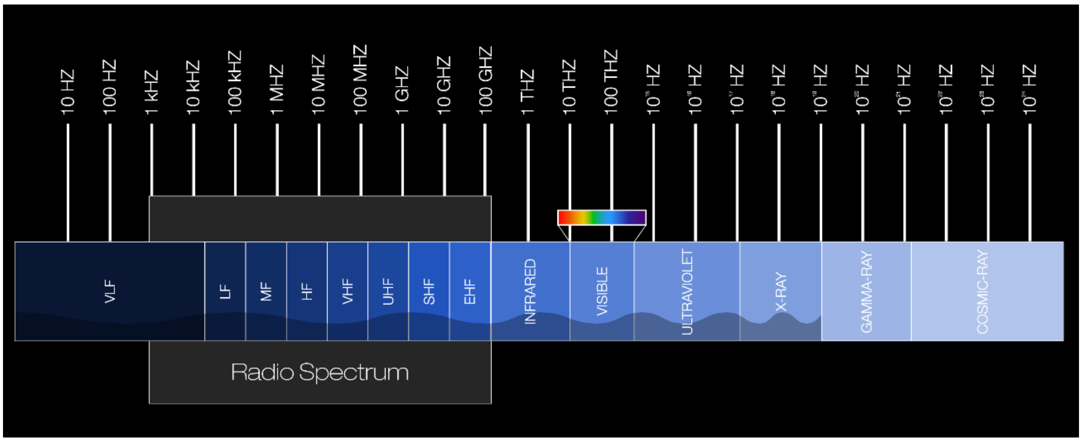


Figure 23: Electromagnetic Spectrum (NASA)

Later, as wireless communications became more widespread, it became clear that if two transmitters operated on the same frequency simultaneously within a receiver's range, their signals would interfere with each other, compromising the transmission. The solution was to assign specific frequencies exclusively to individual transmitters or groups of transmitters within a defined area, a process generally managed by governments through licensing. However, complications arise when radio transmissions cross borders, as is often the case with satellites and high-frequency radio. This was approached with the establishment of the International Telecommunication Union (ITU), a United Nations agency in the 1960s, whose role was and still is to coordinate frequency allocations globally to avoid interference and ensure harmonious use. Then, each country's government aligns its frequency use with ITU guidelines, maintaining global coherence in radio frequency management. [17]

Equally important was the realization that radio transmissions at different frequencies behave differently when traveling through solid objects and the Earth's atmosphere, particularly the ionosphere. This led to the critical study of radio wave propagation, focusing on how different frequencies travel through the atmosphere. Various phenomena affecting transmission were identified, including reflection, refraction, diffraction, absorption, polarization, and scattering.[14]

4.2.1.1 Frequency bands and characteristics

Satellites use radio frequencies for communication due to the unique properties of electromagnetic waves, which allow them to transmit information over long distances through the vacuum of space. These frequencies can penetrate the Earth's atmosphere, support high data rates, and maintain reliable connections. However, the choice of frequency bands is crucial as it affects the efficiency, reliability, and quality of satellite communications. Frequency bands are specific ranges within the electromagnetic spectrum, categorized by wavelength and frequency, each with unique characteristics.

Despite the beforementioned changes in international frequency allocations, many basic frequency allocations for satellite communications have remained constant and are likely to continue in this state. These broad international primary and secondary allocations have nicknames originating from World War II letter codes assigned by Allied engineers. Frequency allocations are typically divided between "uplink" (ground station to satellite) and "downlink" (satellite to ground station), with uplinks usually being the higher frequency, as the higher the frequency, the greater the attenuation in the signal path. Therefore it is preferable to transmit with more power from the Earth, where the energy availability is higher. For instance, the C-band is described as 6-4 GHz, where uplink transmissions are around 6 GHz, paired with downlink transmissions around 4 GHz. Figure 24 contains the different frequency bands used in satellite telecommunications.[14], [18]

Band	Frequency Range (MHz)
P	225–390
L	390–1550
S	1550–3900
C	3900–8500
X	8500–10,900
Ku	10,900–17,250
Ka	17,250–36,000
Q	36,000–46,000
V	46,000–56,000
W	56,000–100,000

Figure 24: Frequency bands (US Federal Communications Commission (FCC))

Understanding the propagation characteristics of different frequency bands is crucial for maintaining reliable connections and optimizing their properties despite environmental factors like weather and obstacles. Lower frequency bands (L and S) can penetrate clouds and rain with minimal attenuation, making them more resilient in adverse weather. In contrast, higher frequency bands (Ku and Ka) can transmit higher data rates but are significantly affected by bad weather conditions. The **key insight is that higher frequencies** offer wider bandwidths and thus **higher data rate capacities, but** they also experience **greater signal attenuation in poor weather conditions**. Conversely, lower frequencies provide greater resilience in adverse weather conditions but have smaller bandwidth and limited data rates.[14]

Frequency	Use
Parts of 137–406.1 MHz	Little LEO services
1.5–1.7 GHz (L-band)	Mobile Satellite services (MSS)
2.0–2.7 GHz (S-band)	MSS, digital audio radio, and other uses
3.4–7.1 GHz (C-band)	Fixed satellite services (FSS)
7.25–8.4 GHz (X-band)	Military/Satellite imagery
10.7–14.5 GHz (Ku-band)	FSS and broadcast satellite services (BSS)
17.7–21.2 and 27.5–31 GHz (Ka-band)	FSS, BSS, MSS, military, and inter-satellite links

Figure 25: Satellite Frequency Allocations (Cochetti, Mobile Satellite Communications Handbook)

The figure above shows the most important basic international frequency bands allocated to satellite communications by the ITU and their main use.

L-Band (1-2 GHz) is primarily used for mobile satellite services, such as maritime and aeronautical communications. It offers good penetration through the atmosphere and weather conditions, making it suitable for mobile users.

S-Band (2-4 GHz) is employed for communication, telemetry, and some satellite radio services. It balances between higher data rates and effective atmospheric penetration.

C-Band (4-8 GHz) is commonly used for fixed satellite services, including television broadcasting and data communication. It also provides a balance between data rate and resistance to rain fade.

X-Band (8-12 GHz) is mainly reserved for military communications and satellite imagery. It offers high data rates and is less susceptible to interference, making it ideal for secure military applications.

Ku-Band (12-18 GHz) is widely used for satellite television, VSAT (Very Small Aperture Terminal) networks, and data communications. It provides higher data rates but is more susceptible to rain fade compared to lower frequency bands.

Ka-Band (26.5-40 GHz) is employed for high-throughput satellite communications, providing high-bandwidth internet services. It is capable of supporting very high data rates, but requires advanced technology to mitigate rain fade effects.

4.2.2 FSO

Free-space optical (FSO) telecommunications involve the transmission of modulated light signals through the air to provide high-speed wireless communication. This technology utilizes light propagation in free space, such as air, outer space, or vacuum, to transmit data between two points. Unlike fiber-optic communications, which rely on physical cables, FSO systems offer the advantage of rapid deployment and flexibility, making them ideal for environments where laying cables is impractical or impossible. FSO systems can achieve high data rates and have low latency, making them suitable for various applications, including last-mile connectivity, backup links, and inter-satellite communications.

One of the primary advantages of FSO telecommunications is its ability to bypass the limitations of traditional radio frequency (RF) communication systems, such as spectrum congestion and regulatory constraints. FSO links can support gigabit data rates over distances of several kilometers under optimal conditions. However, the performance of FSO systems can be affected by atmospheric conditions such as fog, rain, and turbulence, which can attenuate the optical signal. To mitigate these challenges, advanced FSO systems incorporate techniques such as adaptive optics, spatial diversity, and error correction algorithms. Overall, FSO telecommunications represent a promising solution for high-capacity, secure, and cost-effective wireless communication.[14]

Despite these advantages, FSO technology is rarely seen in the satellite sector due to its high precision pointing requirements. Maintaining a stable and accurate alignment between communicating terminals is challenging, especially in the dynamic environment of space. However, there are ongoing projects and research efforts working to overcome these obstacles. These initiatives aim to harness the potential of FSO for satellite communications, which could significantly enhance data transfer rates and provide robust, interference-free links for future space missions and satellite networks.

4.3 ORBITS

The orbital locations of the spacecraft in a communications satellite system play a major role in determining the coverage and operational characteristics of the services provided by that system.[16]

The orbital locations of spacecraft in a communications satellite system are crucial in determining the coverage and operational characteristics of the provided services. The same laws of motion that govern the planets around the sun apply to artificial earth satellites. Satellite orbit determination is based on Johannes Kepler's Laws of Motion, which were later refined by Isaac Newton in his Laws of Mechanics and Gravitation. Competing forces act on the satellite: gravity pulls the satellite toward Earth, while its centrifugal (orbital) force pulls it away. This balance of simplified forces (neglecting other gravity forces from other bodies such as the sun or the moon) is illustrated in Figure 26. The forces can be represented as:

$$F_g = m\left(\frac{\mu}{r^2}\right) \quad (1)$$

$$F_c = m\left(\frac{v^2}{r}\right) \quad (2)$$

Where m = mass; v = velocity in the plane of orbit; r = orbital radius (from the center of the earth); and μ = Kepler's Constant = 3.986004×10^5 km^3/s^2.

Note that for $F_g = F_c$, the velocity required to maintain a satellite at the orbit radius r is obtained.

$$v = \sqrt{\frac{\mu}{r^2}} \qquad (3)$$

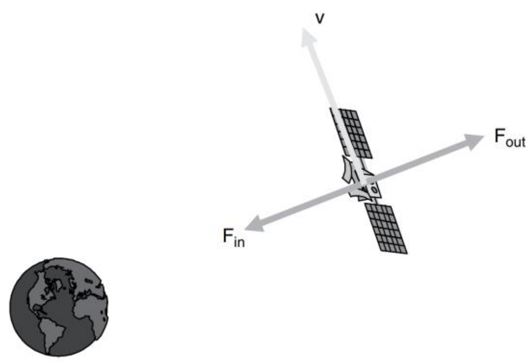


Figure 26: Forces acting on a satellite

4.3.1 KEPLER'S LAWS

Kepler's laws of planetary motion apply to any two bodies in space that interact through gravitation. The laws of motion are described through three fundamental principles.[16]

Kepler's First Law: Law of Ellipses

The Law of Ellipses applied to artificial satellites states that the orbit of a satellite around the Earth is an ellipse with the Earth at one of the two foci. This means that if no other forces are acting on the satellite, either intentionally by orbit control or unintentionally as in gravity forces from other bodies, the satellite will eventually settle in an elliptical orbit, with the earth as one of the foci of the ellipse. The 'size' of the ellipse will depend on satellite mass and its angular velocity

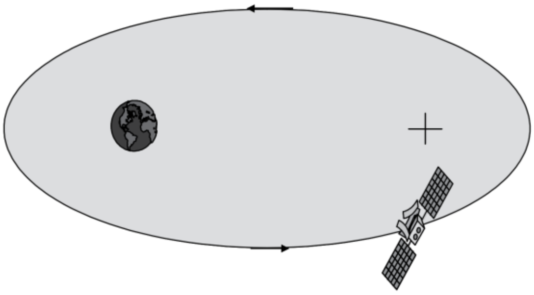


Figure 27: Kepler's First Law (Louis J. Ippolito Jr., Satellite Communications)

Kepler's Second Law: Law of Equal Areas

The Law of Equal Areas states that a line segment joining a planet and the sun sweeps out equal areas during equal intervals of time. This implies that a satellite moves faster in its orbit when it is closer to the Earth and slower when it is farther from the sun. This is because the area covered over a given time period remains constant, resulting in varying orbital speeds depending on the satellite's distance from the Earth.[16]

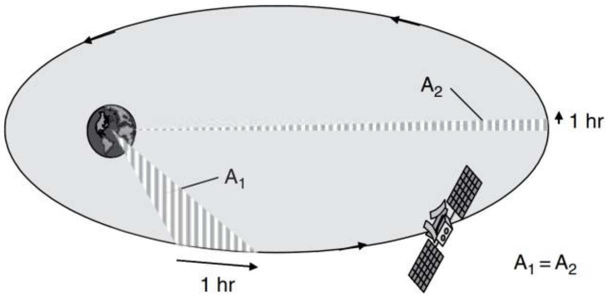


Figure 28: Kepler's Second Law (Louis J. Ippolito Jr., Satellite Communications)

Kepler's Third Law: Law of Harmonies

The Law of Harmonies states that the square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.

$$T^2 = \left[\frac{4\pi^2}{\mu}\right] a^3 \qquad (4)$$

Where T = orbital period in s; a = distance between the two bodies in km; and μ = Kepler's Constant = 3.986004×10^5 km^3 /s^2.

If the orbit is circular, then a = r, and

$$r = \left[\frac{\mu}{4\pi^2}\right] T^{\frac{2}{3}} \qquad (5)$$

Which demonstrates

$$Orbit\ Radius\ =\ [Constant]\ \times\ (Orbit\ Period)^{\frac{2}{3}}$$

Under this condition, the orbital period is determined solely by selection of the orbit radius. This enables satellite designers to choose orbit periods that best meet specific application requirements by positioning the satellite at the correct orbit altitude. The table below lists the altitudes necessary to achieve a specific number of repeatable ground traces with a circular orbit.[16], [19]

Revolutions/day	Nominal period (hours)	Nominal altitude (km)
1	24	36 000
2	12	20 200
3	8	13 900
4	6	10 400
6	4	6400
8	3	4200

Figure 29: Orbit altitudes for specified orbital periods (Louis J. Ippolito Jr., Satellite Communications)

4.3.2 ORBITAL PARAMETERS

In order to describe an orbit accurately, several parameters are used to detail its shape, orientation and position in time. These parameters are essential for predicting the motion of celestial bodies and satellites.[16] The following are the key parameters that describe an orbit:

- **Apogee:** the point farthest from earth
- **Perigee:** the point of closest approach to earth.
- **Line of Apsides:** the line joining the perigee and apogee through the center of the earth.
- **Ascending Node:** the point where the orbit crosses the equatorial plane, going from south to north.
- **Descending Node:** the point where the orbit crosses the equatorial plane, going from north to south.
- **Line of Nodes:** the line joining the ascending and descending nodes through the center of the earth.
- **Argument of Perigee:** the angle from ascending node to perigee, measured in the orbital plane.

- **Right Ascension of the Ascending Node:** the angle measured eastward, in the equatorial plane, from the line to the first point of Aries (Y) to the ascending node.
- **Eccentricity (e)**: the measure of the 'circularity' of the orbit. (r_a = the distance from the center of the earth to the apogee point; and r_p = the distance from the center of the earth to the perigee point.)[16]

$$e = \frac{r_a - r_p}{r_a + r_p} \qquad (6)$$

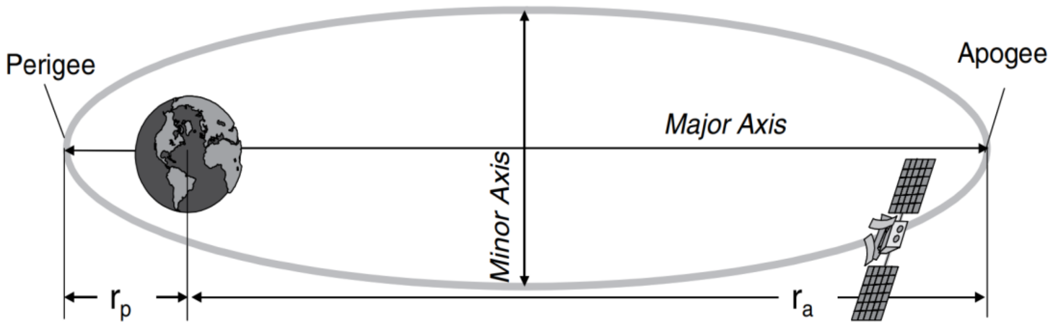


Figure 30: Orbit parameters 1 (Louis J. Ippolito Jr., Satellite Communications)

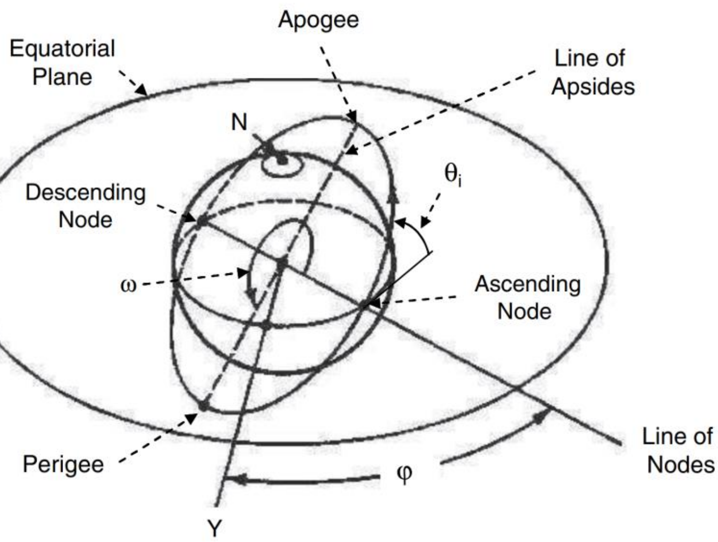


Figure 31: Orbit parameters 2 (Louis J. Ippolito Jr., Satellite Communications)

Equation (6) demonstrates that the higher the eccentricity, the 'flatter' the ellipse. A special case of ellipse is when major and minor axis are equal (e=0), which is represents a circular orbit.

- **Inclination angle** (θ_i): is the angle between the orbital plane and the Earth's equatorial plane. A satellite with a non-zero inclination angle is in an inclined orbit. When the inclination angle $\theta_i = 0$, the satellite is in an equatorial orbit. When the angle $\theta_i = 90º$, the satellite is in a polar orbit. Finally, An important characteristic of satellite orbits is their direction relative to Earth's rotation. An orbit where the satellite moves in the same direction as Earth's rotation is called a **prograde orbit** ($\theta_i \in [0º; 90º]$). Conversely, a satellite in a **retrograde orbit** moves in the opposite direction of Earth's rotation ($\theta_i \in [90º; 180º]$). Most satellites are launched into prograde orbits because Earth's rotational velocity adds to the satellite's orbital velocity, thereby reducing the energy required to achieve and maintain orbit.

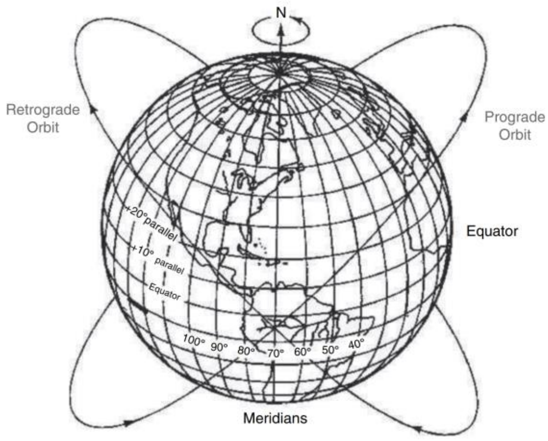


Figure 32: Inclined orbits (Louis J. Ippolito Jr., Satellite Communications)

Only six parameters (orbital parameters) are needed to uniquely specify the location of an orbiting satellite at any given time. They are essential for determining the satellite's trajectory and predicting its future locations for control. The orbital elements are:

- **Eccentricity**
- **Semi-Major Axis**
- **Time of Perigee**
- **Right Ascension of the Ascending Node**
- **Inclination Angle**
- **Argument of Perigee**

4.3.3 COMMON SATELLITE ORBITS

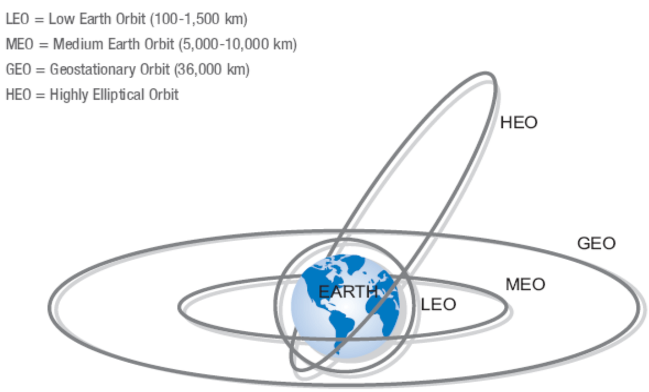


Figure 33: 2.3.3 COMMON SATELLITE ORBITS (qtorb)

4.3.3.1 GEO (36,000 km)

As demonstrated in the third Kepler's law, there is an altitude at which the satellites orbit the Earth at a pace that matches the Earth's rotation. This orbit, known as geostationary earth orbit (GEO) or geosynchronous orbit (GSO), characteristic is that it is circular ($e = 0$) is in the equatorial plane ($\theta_i = 0$), which makes the satellites appear stationary above the earth.[17]

If the period is 1 Day (86,164.09 seconds), applying (5) r = 42 164.17 km.

$$r = \left[\frac{\mu}{4\pi^2}\right] T^{\frac{2}{3}} \qquad (5 \qquad (6)$$

Then, the altitude of the orbit is the result of subtracting the equatorial earth radius; 6378 km.

$$h = r - r_e = 42{,}164\ km - 6{,}378\ km = 35{,}786\ km \qquad (7)$$

The GEO position ensures a stable path from the ground to the satellite, minimizing the need for ground-based tracking. A satellite in GEO can observe approximately one-third of the Earth's surface. Therefore, **three GEO satellites positioned 120°** apart along the equatorial plane can achieve **near-global coverage**, excluding the polar regions. This characteristic makes GEO satellites particularly valuable for a range of communication services, including television broadcasting, weather monitoring, and telecommunications.[17]

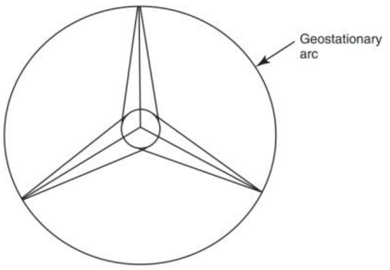


Figure 34: GEO near-global coverage (Cochetti, Mobile Satellite Communications Handbook)

Although GSO is the most commonly used for current satellite communication systems, it has some notable disadvantages. The long path length results in significant path loss and latency (time delay) for radio wave signals traveling to and from the satellite. The two-way delay, from the ground station to the satellite and back, is approximately **~600 milliseconds (ms)**. This delay can cause issues, especially for voice communications and protocols sensitive to **high latency**.[18], [20]

Furthermore, geosynchronous orbit cannot provide coverage to high-latitude locations. The highest latitude where a GSO satellite is visible, with a 10° elevation angle of the earth station, is around 70° north or south latitude. Coverage can be somewhat extended by operating at higher inclination angles, but this introduces other challenges, such as the need for enhanced ground antenna tracking, which increases costs and system complexity.

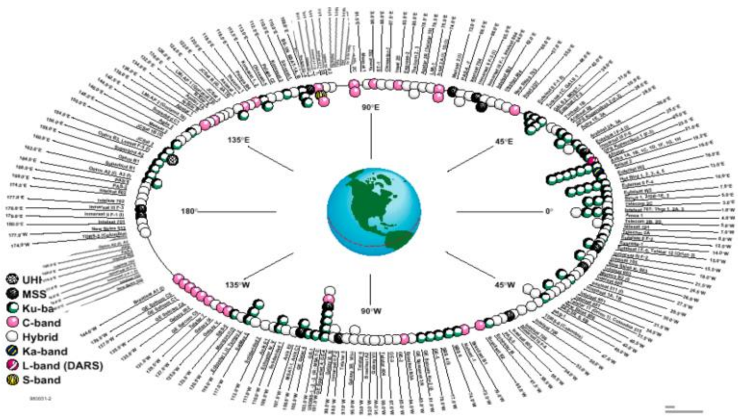


Figure 35: Geostationary Satellites (ITU)

The number of satellites that can operate in geostationary orbits is inherently limited due to the single equatorial plane and the need to space satellites to avoid interference. The allocation of geostationary orbital slots is regulated by international treaties through the International Telecommunications Union (ITU), coordinated with frequency band and service allocations as discussed in the previous section. Current allocations require satellites to be spaced 2–5° apart per frequency band and service, meaning only 72–180 slots are available globally, depending on the frequency band and service provided. [20]

4.3.3.2 MEO (10,000 km – 20,000 km)

Medium Earth Orbit (MEO) satellites, positioned between 10,000 and 20,000 km above Earth, serve as an intermediary between Low Earth Orbit (LEO) and Geosynchronous Orbit (GSO). These satellites are primarily used for navigation systems like GPS, Galileo, and GLONASS, as well as for communications, meteorology, and remote sensing. At these altitudes, MEO satellites cover larger areas than LEO satellites and have orbital periods of 2 to 12 hours, allowing longer observation times, particularly useful for applications requiring accurate and consistent data. For example, the GPS system utilizes a constellation of up to 24 satellites in 12-hour circular orbits at an altitude of 20,184 km.[16]

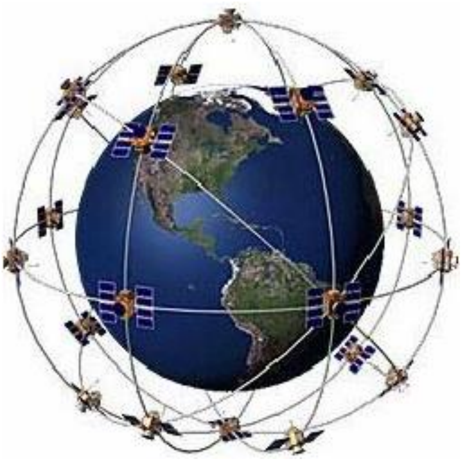


Figure 36: GPS constellation (GNSS: Status and perspective)

4.3.3.3 LEO

Earth satellites operating between 160 and 2,500 km in near-circular orbits, are referred to as Low Earth Orbit (LEO) satellites. These satellites offer several advantages for communications applications. The shorter distance to Earth results in lower path losses, allowing for lower power requirements and smaller antenna systems, as well as reduced propagation delay, which enhances real-time communication capabilities. LEO satellites can cover high-latitude and polar regions, which are inaccessible to Geosynchronous Orbit (GSO) satellites.[14], [17]

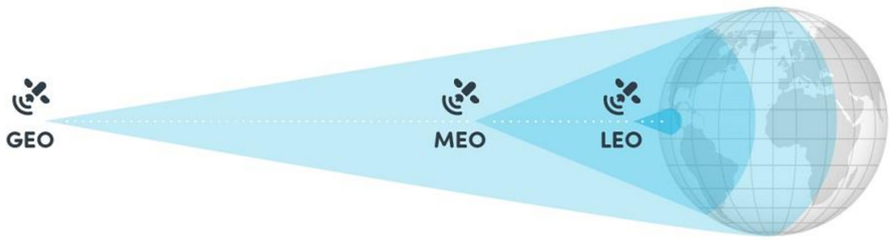


Figure 37: Orbit altitud and beam comparisson (Spirent)

However, LEO satellites also face challenges. Their rapid movement across the sky means they provide coverage for only about 8 to 10 minutes per pass from a fixed location on Earth. This necessitates the use of multiple satellites in a constellation to achieve continuous global or wide-area coverage. Current LEO satellite networks often use constellations from 66 to thousands of satellites with inter-satellite links to facilitate point-to-point communications.[21]

Another challenge is the orbital perturbations caused by the Earth's non-spherical shape. The ascending node, where the satellite crosses the equator from south to north, drifts westward by several degrees per day. Additionally, the orientation of the major axis in the orbital plane can rotate either clockwise or counterclockwise. However, setting the inclination to about 63° balances these forces, keeping the major axis direction fixed.

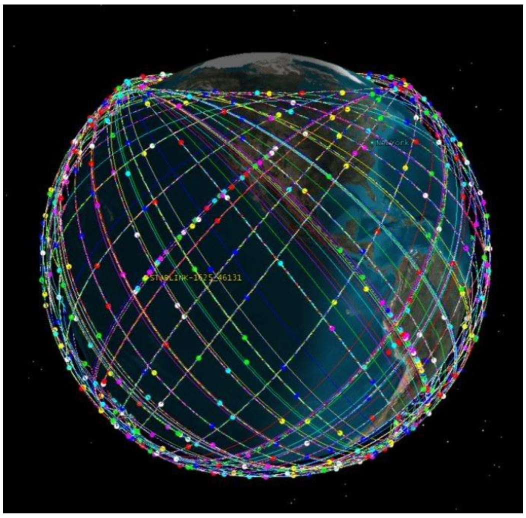


Figure 38: LEO Starlink constellation (Medium)

Despite these challenges, LEO satellites are highly suitable for mobile applications due to their low power requirements and small antenna sizes for Earth terminals. While more LEO satellites are needed to provide comparable communication services to GSO satellites, LEO satellites are much smaller and require significantly less energy to launch, potentially resulting in lower total life cycle costs.[16]

4.3.3.4 HEO

Satellites in high elliptical (high eccentricity) orbits (HEO) are designed to provide coverage to high latitude areas that GSO satellites cannot reach, and they offer longer contact periods than LEO satellites. These orbits, characterized by Kepler's second law, allow for extended dwell time near the apogee, where the satellite moves slowest and is farthest from Earth. The Molniya orbit is the most well-known HEO, named after the system used by the former Soviet Union.[17]

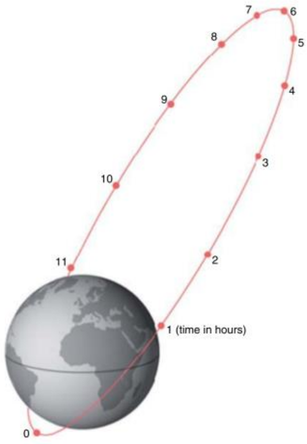


Figure 39: HEO Molniya Orbit (NASA)

A typical Molniya orbit features a perigee of about 1,000 km and an apogee of nearly 40,000 km, with an eccentricity of about 0.722 and an inclination of 63.4° to prevent major axis rotation. This 12-hour orbit repeats its ground trace twice daily, spending around ten hours over the northern hemisphere and two hours over the southern hemisphere. This setup allows for 8 to 10 hours of communication, similar to GSO operations. By using two Molniya satellites, phased correctly, nearly continuous coverage can be achieved for high latitude regions in the northern hemisphere.[20]

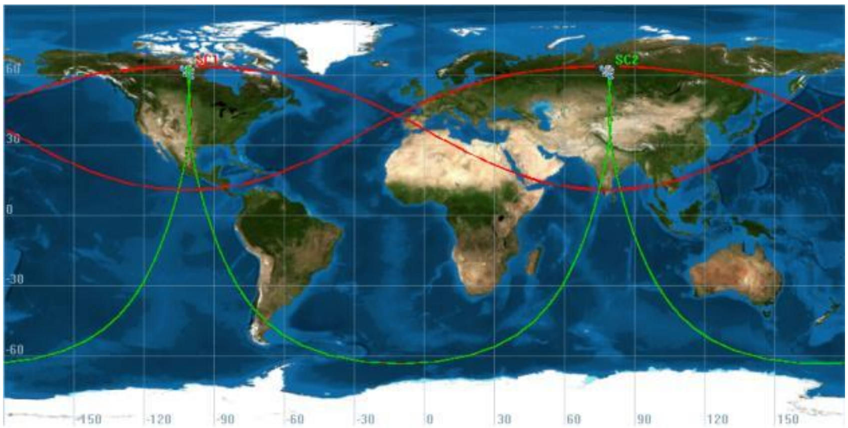


Figure 40: Ground track (green) and border of coverage region (red) for a constellation of 2 Molniya satellites. (Monitoring Earth's northern forests from spacecraft in Molniya orbits)

HEO orbits add complexity to the management of satellites. As they are not fixed at a specific altitude, it crosses several orbits of circular orbit satellites. GSO are not affected as they are fixed in the equatorial plane and do not cross. However, it is a hazard for MEO satellites. To avoid impacts between satellites and increase the number of space waste, the different operators have to be coordinated, and transmit the position and orbit of their satellites.[16]

4.3.4 NETWRK DESIGN FOR GLOBAL COVERAGE

The design of satellite constellations at various orbital altitudes is a crucial aspect of ensuring global telecommunications coverage.

As mentioned, Geostationary satellites orbit at an altitude of approximately 35,786 km in above the equator, providing continuous coverage to a large area. Only three GEO satellites are required to cover the entire globe, positioned 120º degrees apart in longitude. The formula to calculate the coverage area of a GEO satellite can be expressed as:

$$A_{GEO} = 2\pi R^2(1 - \cos(\theta))$$

Where R is the radius of the Earth and θ is the central angle from the satellite to the edge of its coverage area.

For Medium and Low earth orbit, the design is different, as in this constellations satellites have more orbits than equatorial. To provide global coverage, satellite constellations must also include polar and heliosynchronous orbits. There are numerous studies that cover the constellation design. A Walker-type constellation for instance, is represents a network design with an specific arrangement of satellites in multiple orbits, distributed in a way that maximizes coverage and minimizes gaps. The study of the Walker constellation will be sufficient to convey the idea of the number of satellites needed to provide full coverage.[21], [22]

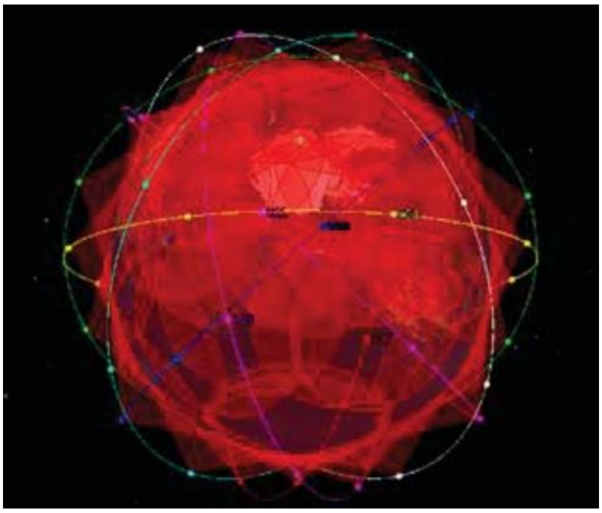


Figure 41:Walker constellation - 64/8/2 (Source: An Efficient LEO Global Navigation Constellation Design Based on Walker Constellation)

The Walker constellation follows a Delta Pattern, defined by three parameters (T/P/F); Total number of satellites in the constellation(T), number of orbital planes (P), and phasing factor that determines how the satellites are distributed among the planes (F).

The design process is the following:

1. Determine the coverage area of a satellite at a specific altitude

$$\theta \approx 2 \cdot aros\left(\frac{R}{R+h}\right)$$

   Where θ is the angle of visibility, R is the radius of the Earth (6,371 km) and h is the altitude of the satellite
2. Calculate the coverage radius (r)

$$r = (R+h) \cdot \sin\left(\frac{\theta}{2}\right)$$

3. Calculate the coverage area of a satellite (A_{SAT})

$$A_{SAT} \approx \pi r^2$$

4. Finally, with the total area of the Earth's surface being ($A_{Eatrh} \approx 510 \times 10^6\ km^2$), calculate the number of satellites needed without overlap.

$$N \approx \frac{A_{Eatrh}}{A_{SAT}}$$

For instance, the minimum number of satellites for the Iridium constellation, one of the most mature, with an altitude of 780km. Results in a minimum of 16 satellites. However, the constellation counts with 66. The reason behind constellation surpassing the minimum satellites required to give global coverage is the increase of capacity and redundancy to improve the quality of service (QoS). The best example of this is the case of starlink, with more than 4,500 satellites, and plans of increasing the constellation to tens of thousands, when in reality, their minimum number of satellites is 25 (at an orbit of 500km).[23], [24]

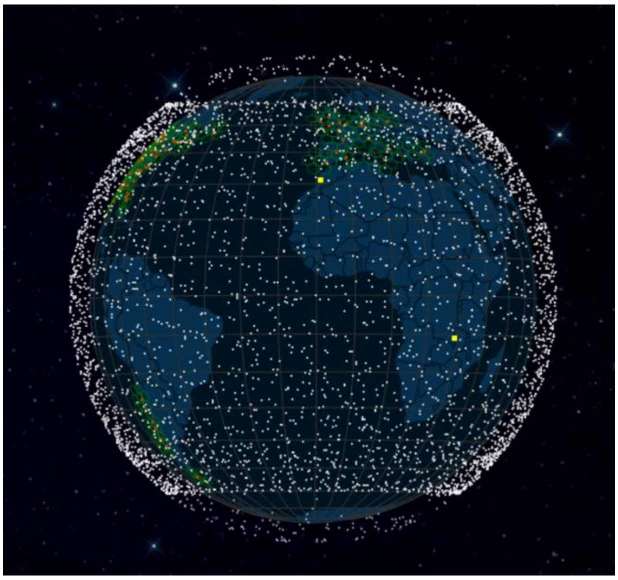


Figure 42: Starlink constellation (Source: Satellitemap.space)

4.3.5 NETWORK FUNCTIONING

As with orbit design, each technology has a different strategy for networking. On the one hand, there are networks that operate as mirrors, such as Oneweb in LEO or most GEO. The connection is made from the remote point to the available satellite and directly to the nearest gateway station. And there are other technologies that include communication between satellites, such as Starlink or Iridium, thus connecting any two points on the planet.

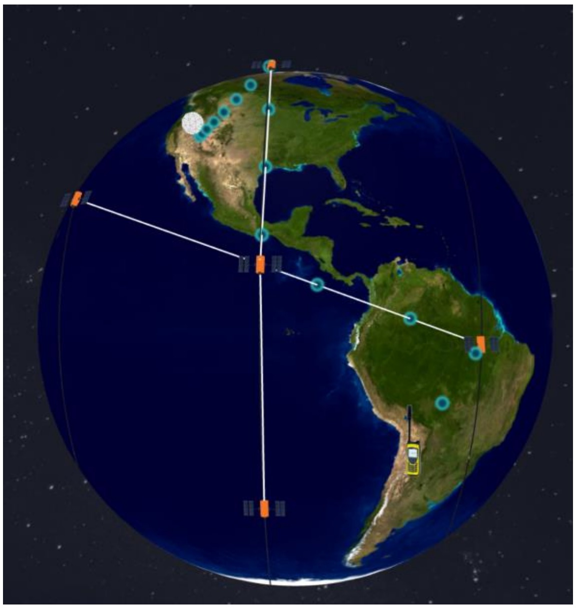


Figure 43: Satellite intercommunication (Source: Iridium)

Figure 44: Oneweb network functioning (Source: Oneweb)

4.4 SATELLITES SYSTEMS

There are numerous types of satellites, produced by various manufacturing companies, each tailored to fulfill specific functions. No two satellites are identical; they differ in size and shape. However, all satellites share a core set of essential systems. Ultimately, a satellite is a complex assembly of these systems, functioning primarily as relays, receiving and transmitting information.

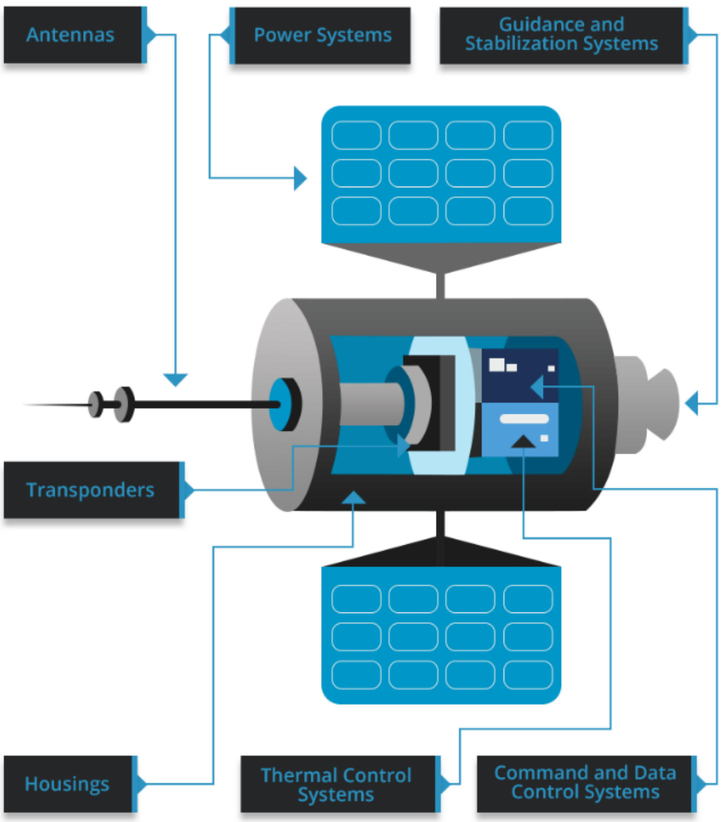


Figure 45: Satellites systems (Source: Ardel engineering)

These set of systems are the following[18]:

4.4.1 POWER SYSTEMS

Power systems are crucial for the functioning of all satellite components. The primary elements include:

- **Solar Panels:** These capture solar energy and convert it into electrical power. Solar panels are typically deployed once the satellite is in orbit and oriented to maximize exposure to the Sun.
- **Batteries:** Since satellites pass through the Earth's shadow and lose direct sunlight periodically, batteries store energy to power the satellite during these periods.
- **Power Control and Distribution Units:** These regulate the power flow to various subsystems, ensuring that each component receives the necessary voltage and current.

4.4.2 Communication Systems

Communication systems enable satellites to send and receive data to and from Earth. Key components include:

- **Antennas:** Responsible for transmitting and receiving radio frequency signals. Different types of antennas (e.g., parabolic, helical) are used based on the communication requirements.
- **Transponders:** Act as relay stations, receiving signals, amplifying them, and retransmitting them back to Earth. They are essential for maintaining strong and clear communication links.

4.4.3 Attitude and Orbit Control Systems (AOCS)

AOCS manage the satellite's orientation and position in space. This system includes:

- **Star Trackers, Gyroscopes, and Magnetometers:** These sensors determine the satellite's orientation relative to stars, the Earth's magnetic field, and inertial space.
- **Reaction Wheels and Control Moment Gyroscopes:** Provide precise control over the satellite's orientation by using the conservation of angular momentum.
- **Thrusters:** Small rocket engines used to adjust the satellite's position and trajectory, ensuring it stays in its designated orbit.

4.4.4 Payload Systems

The payload is the core of a satellite's mission. Depending on the satellite's purpose, the payload may include:

- **Observation Instruments:** Cameras, radars, and spectrometers used for Earth observation, environmental monitoring, and scientific research.
- **Communication Equipment:** Transmitters and receivers designed for telecommunication purposes, including broadcasting and internet services.
- **Scientific Sensors:** Instruments designed for space exploration and scientific experiments, such as particle detectors and magnetometers.

4.4.5 Thermal Control Systems

Thermal control systems ensure the satellite operates within safe temperature ranges. This involves:

- **Radiators:** Dissipate excess heat generated by the satellite's electronic components into space.
- **Thermal Insulation:** Protects sensitive components from extreme temperatures, using materials like multilayer insulation (MLI).
- **Heaters:** Keep components warm in the cold vacuum of space, ensuring they function correctly.

4.4.6 Structural Systems

The structural system, or the satellite's "bus," provides the framework that holds all other systems together. This structure must be lightweight yet strong enough to withstand the stresses of launch and the harsh environment of space. Components include:

- **Main Frame:** The backbone of the satellite, providing support and integration points for all subsystems.
- **Deployable Structures:** Elements like solar panel arrays and antennas that fold during launch and deploy once in space.

4.4.7 Data Handling Systems

Data handling systems manage the collection, processing, storage, and transmission of data. This includes:

- **Onboard Computers:** Control the satellite's operations and process data from various sensors.
- **Data Storage Devices:** Store collected data for later transmission to Earth.
- **Telecommand and Telemetry Units:** Handle the receipt of commands from ground stations and the transmission of status and data back to Earth.

4.5 GROUND SEGMENT INFRASTRUCTURE

The satellite ground segment is a fundamental part of the satellite system, responsible for ensuring efficient communication and proper control of the satellites in orbit. This segment includes a range of ground facilities and equipment that interact with the satellites to transmit and receive data, execute commands and monitor their status. The ground segment closes the telecommunications loop, connecting users to the satellites and vice versa, and ensuring that information is properly processed and distributed. It can be divided into two segments, the user segment and the gateways.[16], [18]

4.5.1 GATEWAYS

Gateways are the essential bridge between terrestrial infrastructures and satellites, playing a crucial role in managing and distributing communication data. They facilitate the integration of satellite information with terrestrial networks, ensuring that communication services are efficient and reliable.

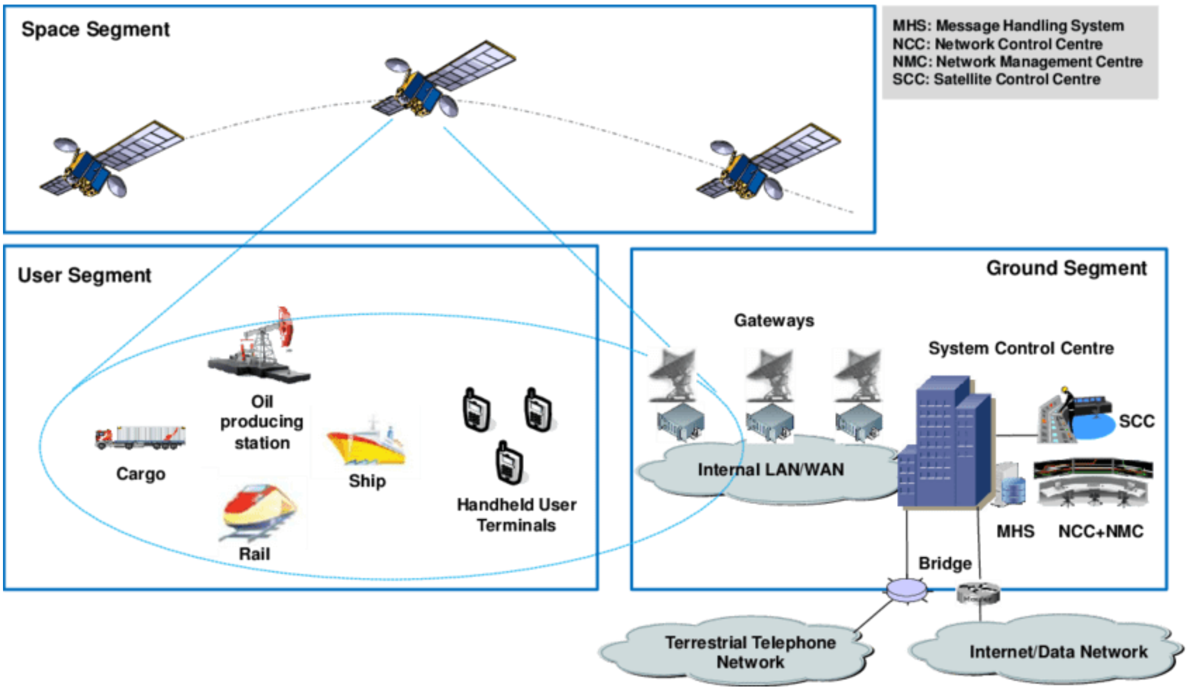


Figure 46: Gateway concept (Source: ThreatModeler)

Within the functions of Gateways there are three main activities; Data transmission, Data processing and Data distribution. First, the gateways are the systems in charge of aggregating data from numerous channels and transmitting it to the satellite (uplink), and vice versa, receiving the information sent from different user endpoints through the satellites constellation, and distribute it. This is possible thanks to the data processing systems in which decoding and error corrections is carried out. Some gateways also include the conversion and formatting of data to ensure it meets the requirements of the terrestrial infrastructures.

Figure 47: Eutelsat Gateway (Source: Eutelsat)

Gateways can be owned and operated by various entities, depending on the business model and operational structure of the satellite network. Here are two common models for operating gateways:

- **Owned and Operated by the Same Company (Integrated Ground System):** In some cases, the same company that owns and operates the satellites also owns and manages the gateways. This is the case with Starlink. By controlling both the satellites and the gateways, Starlink can optimize the integration and performance of its entire network. This model, known as an integrated ground system, allows for greater operational efficiency and better service quality, as the company can directly coordinate all aspects of the infrastructure. The advantages include greater control over the entire infrastructure, network optimization, direct integration, and potentially better service quality. However, it also presents disadvantages such as the need for significant investment in infrastructure and specialized personnel.
- **Subcontracted Gateway Services (Disintegrated Ground System):** In other cases, satellite companies may subcontract the operation of gateways to third parties specializing in these services. OneWeb, for example, uses ground stations operated by companies specialized in gateway management. This strategy, known as a disintegrated ground system, allows OneWeb to focus on launching and operating its satellites, while experts in ground stations handle the communication infrastructure on the ground. Subcontracting can offer advantages in terms of cost and flexibility,

as companies can leverage the expertise and resources of gateway service providers. The disadvantages include dependence on external providers, potential variability in service quality, and less direct control over the infrastructure.

4.5.2 ENDPOINT ANTENNAS

Satellite communication antennas are designed to operate in different frequency bands, each of which is suitable for different applications and has specific characteristics. This section provides an overview of the different types of antennas, with particular emphasis on those most commonly used in satellite communications.

To understand the reasons for the different antennas, it is necessary to keep in mind the above relationship to the frequency band used for communication. The frequency used depends on the desired communication characteristics. Frequency is directly related to transmission capacity. The higher the frequency, the more bandwidth is available, so higher data rates can be transmitted. However, there are limitations related to antenna size and weather resistance. The higher the frequency, the greater these limitations, i.e., the higher the frequency, the larger the antenna size required, and the signal has poor weather resistance.[18], [19], [21]

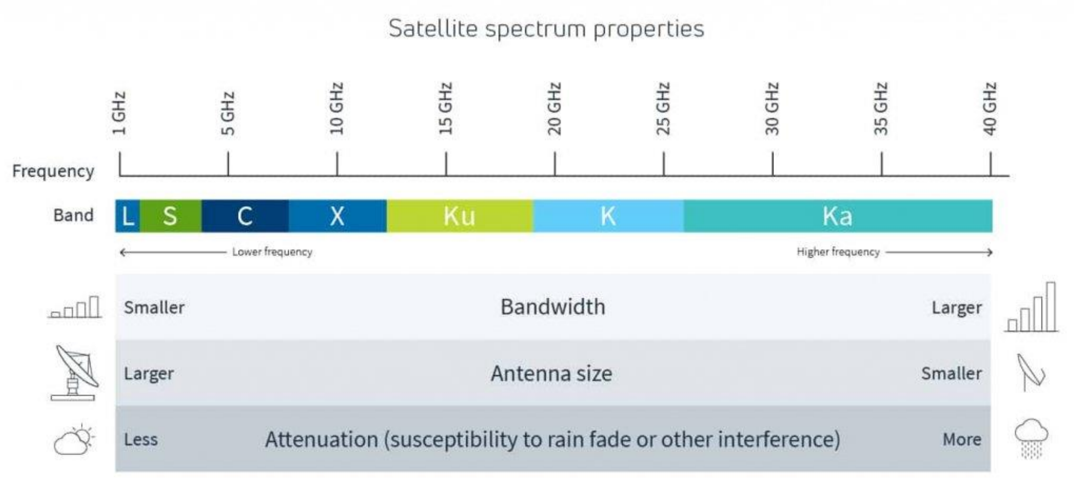


Figure 48: Frequency Bands with transmission system relationships (Source: Lotus arise)

4.5.2.1 Parabolic Dish Antennas (VSATs)

Parabolic dish antennas, also known as VSAT (Very Small Aperture Terminal) antennas, are a common type of satellite communication antenna. Originally, the term VSAT referred to a variety of small satellite antennas, but as parabolic dishes were the predominant type used in early VSAT systems, the term has become synonymous with them. These antennas gained widespread popularity with the advent of satellite television and remain the most common due to their effective design and wide range of applications. Among this applications are direct-to-home (DTH) TV services, internet services, satellite communication, and satellite-based earth observation. These antennas operate across C, Ku, and Ka bands, offering high gain and directional capabilities. They are capable of focusing signals into a narrow beam, making them essential for applications requiring high data rates and long-distance communication.

Parabolic dish antennas operate by focusing incoming signals onto a central receiver through a parabolic reflector, which is the dish itself. The key components include:

- **The Dish (Reflector):** Collects and concentrates radio waves onto the focal point.
- **Feed Horn:** Positioned at the focal point to collect concentrated signals.
- **Low Noise Block Downconverter (LNB):** Amplifies received signals and converts them to a lower frequency.
- **Mount and Positioning System:** Some systems include a mechanical pointer to track satellites, which ensures continuous and reliable communication as the satellite constellation moves across the sky.

Parabolic dish antennas are mature and are highly efficient for long-distance communication. However, they also have some disadvantages. They can be large and bulky, requiring significant space for installation. Additionally, they often need professional installation to ensure correct alignment and optimal performance, and must be precisely oriented towards the satellite, which can be challenging for end users.[14], [25]

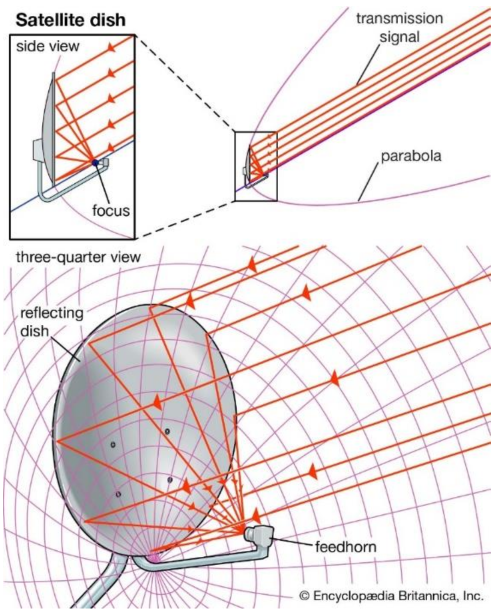


Figure 49: 2.5.2.1 Parabolic Dish Antennas – VSATs (Source: Britannica)

4.5.2.2 Helical Antennas

Helical antennas, also known as a helix antennas, are designed with a conducting wire wound in a helical shape, often supported by a ground plane. These antennas are primarily used for high-frequency operations, providing circular polarization and high gain. Helical antennas operate in two modes: normal mode, where radiation is emitted perpendicular to the helix axis, and axial mode, where radiation is emitted along the helix axis, making them highly directional technologies.

Commonly used in UHF and VHF frequencies, helical antennas are suitable for a wide range of satellite communication applications. However, as they tend to be larger than other types of antennas, requiring more installation space and generally being more expensive, they are not that common. Nevertheless, they are valued for their durability and reliability in harsh conditions.[26]

Figure 50: Helical Antenna (Source: Antenna experts)

4.5.2.3 Phased Array Antennas

Phased array antennas are employed in advanced communication systems, military applications, and broadband satellite internet services. Operating mainly in Ku and Ka bands, these antennas consist of multiple small antenna elements, each with the ability to alter the phase of the signal it emits. By adjusting the relative phase of each element, the direction of the overall signal beam can be electronically steered without physically moving the antenna. The process is known as beamforming, and allows the antenna to focus its energy in a particular direction, increasing the strength and quality of the communication signal.

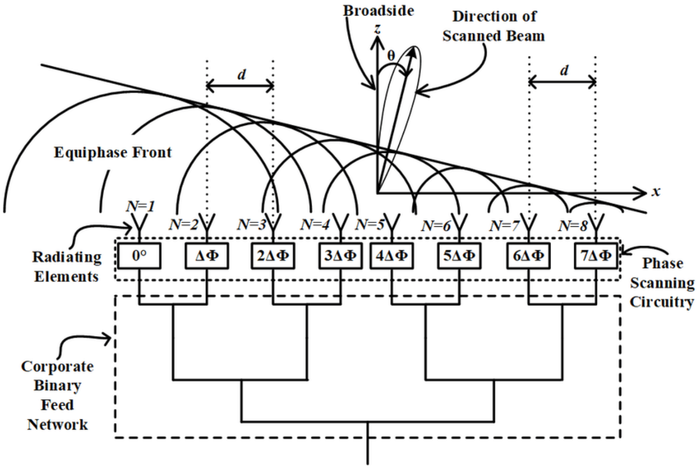


Figure 51: Phased array antenna functioning (Source: Sayan Roy)

Their ability to be electronically controlled, makes them highly suitable for Low Earth Orbit (LEO) satellite communications, where they need to track fast-moving satellites. This capability allows for rapid reconfiguration of the signal direction, providing consistent and reliable communication with satellites that move quickly across the sky.[19], [27]

Currently, phased array antennas are among the most studied technologies in satellite communications. Researchers and engineers are focused on reducing their size and cost to make them suitable and economic for residential use. This effort aims to enable the wide adoption of LEO high-speed satellite internet services.

Figure 52: Phased array antenna (Source: Viasat)

4.5.2.4 Patch Antennas (Microstrip Antennas)

Patch antennas, also known as microstrip antennas, are used in GPS, mobile satellite communications, and portable satellite devices, operating in L and S bands. These antennas are lightweight, compact, and easy to manufacture, making them suitable for applications where size and weight are critical factors.

Patch antennas, also known as microstrip antennas, are widely used in low-frequency applications due to their compact and low-profile design. These antennas are particularly favored in Internet of Things (IoT) devices for their versatility and ease of integration. A patch antenna consists of a flat, rectangular, or circular metal patch mounted on a larger ground plane with a dielectric substrate in between. This design allows the patch to act as a resonator, radiating energy when excited by an RF signal. The simplicity of their design makes them easy to print on circuit boards, reducing manufacturing complexity and cost. However, patch antennas also have some limitations, such as offering narrower bandwidth compared to other antenna types and providing lower gain than larger, more complex antenna designs.[28]

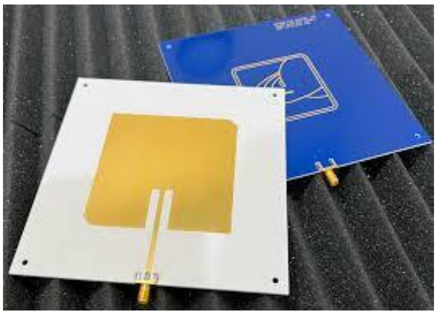


Figure 53: Patch antenna (Source: Saturn PCB)

4.5.2.5 Other Antennas

Horn antennas, known for their flared waveguide structure, are predominantly used in high-frequency applications such as microwave communications and radar systems. They excel in providing broad bandwidth and directional capabilities, making them ideal for precise beam control and high-frequency performance. Despite these advantages, horn antennas are generally not used in satellite telecommunications for end-users. This is primarily due to their large size and bulkiness, which make them impractical for residential or portable use. Additionally, the installation and alignment of horn antennas are complex, requiring precise positioning that is difficult for average users to manage. These factors limit their practicality in consumer satellite communication setups, where smaller, more user-friendly antennas are preferred.

Figure 54: Horn Antenna (Source: Millimeter Wave Products)

Yagi-Uda antennas, commonly referred to as Yagi antennas, are known for their high gain and directional properties, which make them effective for targeted communication over long distances. They are commonly used in applications such as television reception and amateur radio. However, Yagi antennas are not typically employed in satellite telecommunications for end-users. Their size and need for precise directional alignment pose significant challenges for residential installations. Furthermore, Yagi antennas usually have a narrower bandwidth compared to other antenna types, reducing their versatility in satellite communications. The complexity of installation and maintenance further diminishes their suitability for consumer satellite applications, where ease of use and compact design are critical.[21]

Figure 55: Yagi-Uda antena (Source: Duo Security)

4.6 SPACE ENVIRNOMENT

4.6.1 SATELLITES AND SPACE DEBRIS

Since 19657, the number of space launches has fluctuated significantly, with an exponential increase in recent years driven by the launch of ultra dense satellite constellations. This launches has been mainly driven by the United States and China with their own LEO satellite constellation plans. Others, such as the European Union or the United kingdom have also supported the trend, though they have done it in a smaller scale. According to NASA, there are currently about 11.000 artificial satellites orbiting the Earth, considering both active and inactive payloads. And considering that this number does not reach 50% of total orbiting, the need for efficient space traffic management is highlighted. [29]

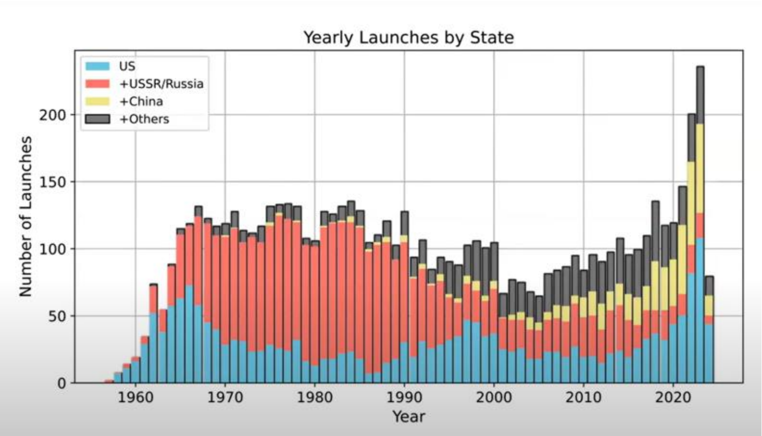


Figure 56: Humanity's launch history be April 2024 (Source: USspacecom)

The expected growth is primarily the result of the launch of the five major Low Earth Orbit (LEO) constellations from different countries. These include SpaceX and Kuiper from the United States, OneWeb from the United Kingdom, Guowang and G60 from China. Nevertheless, this predictions are made without taking into account the upcoming constellations of nanosatellites dedicated to IoT, that will really skyrocket the payload systems once their technology gains interest.

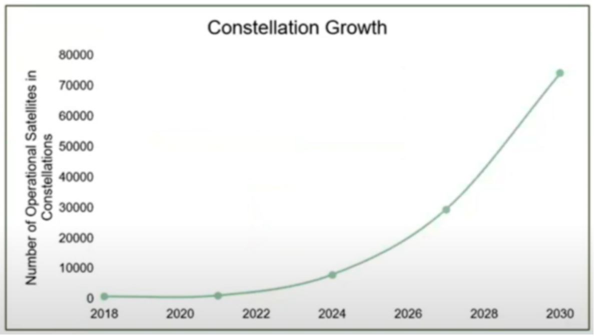


Figure 57: Expected satellite growth (Source: LeoLabs)

Not all objects in orbit are satellites; a significant portion of the objects are debris from space collisions and remnants of rockets. These fragments, known as **space debris**, originate from events such as the breakup of old satellites, anti-satellite (ASAT) tests, and rocket body explosions. Debris can remain in orbit for decades, depending on their altitude and atmospheric drag, creating an increasing threat to current and future space missions. Thus, it is essential to keep them tracked to avoid further collisions. In fact, a recent study indicates a total of 22,542 objects in Low Earth Orbit (LEO) as of April 2024, with 48% being operational payloads and 26% being rocket bodies.[29]

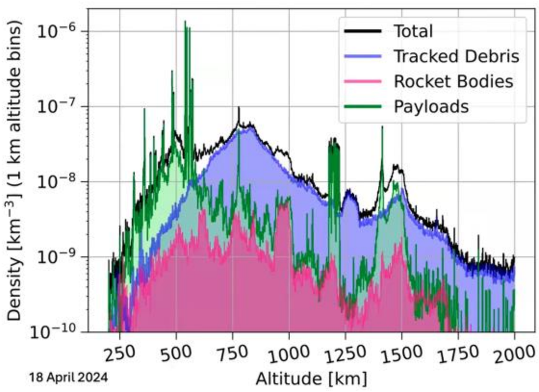


Figure 58: Altitude density of tracked objects on orbit (Source: Aaron Boley, UBC)

Multiple advances have been made in the field of object detection and collision avoidance systems. Figure 59 shows that debris levels have remained stable and have even decreased slightly due to some spatial waste recovery projects, and the share of payloads has been rising. This increase in payload systems is not necessarily positive, as it is not driven by a reduction in waste but rather by the growing number of objects being launched into orbit.

Despite public unawareness, space is a finite resource that requires careful management to prevent overcrowding and ensure sustainable use, which highlights the need of regulation and environmental measures.[29]

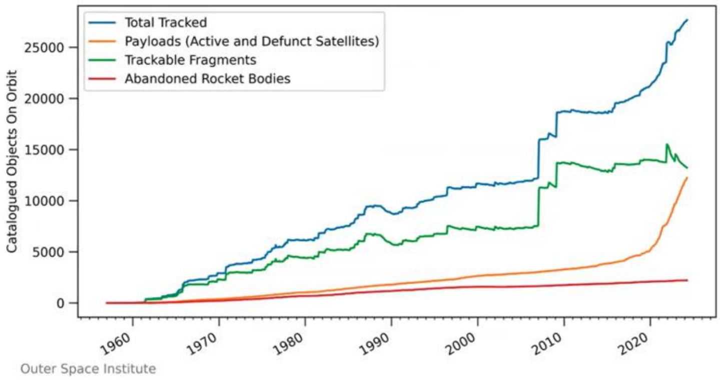


Figure 59: Evolution of tracked objects on orbit (Source: Aaron Boley, UBC)

Currently, there are over 22,000 tracked pieces of debris. Most are the result of collisions between satellites. This generate enormous amount of debris, which rapidly disperse through space and can cause the phenomenon, known as the Kessler Syndrome. This is a chain reaction where fragments from one collision cause more collisions, creating an extremely hazardous environment and complicating future operations and launches. The distribution of fragments is a significant concern.

However, specialist in satellite tracking, space management and collision avoidance LeoLabs, state that although it is true that this collisions generate numerous, these pieces are often clustered at different altitudes. For instance, the 2009 crash between an Iridium communications satellite and an inactive Russian satellite, which generated over 2,000 trackable fragments, which can be traced around the altitudes of 800 km. An altitude that is avoided by constellations. [30]

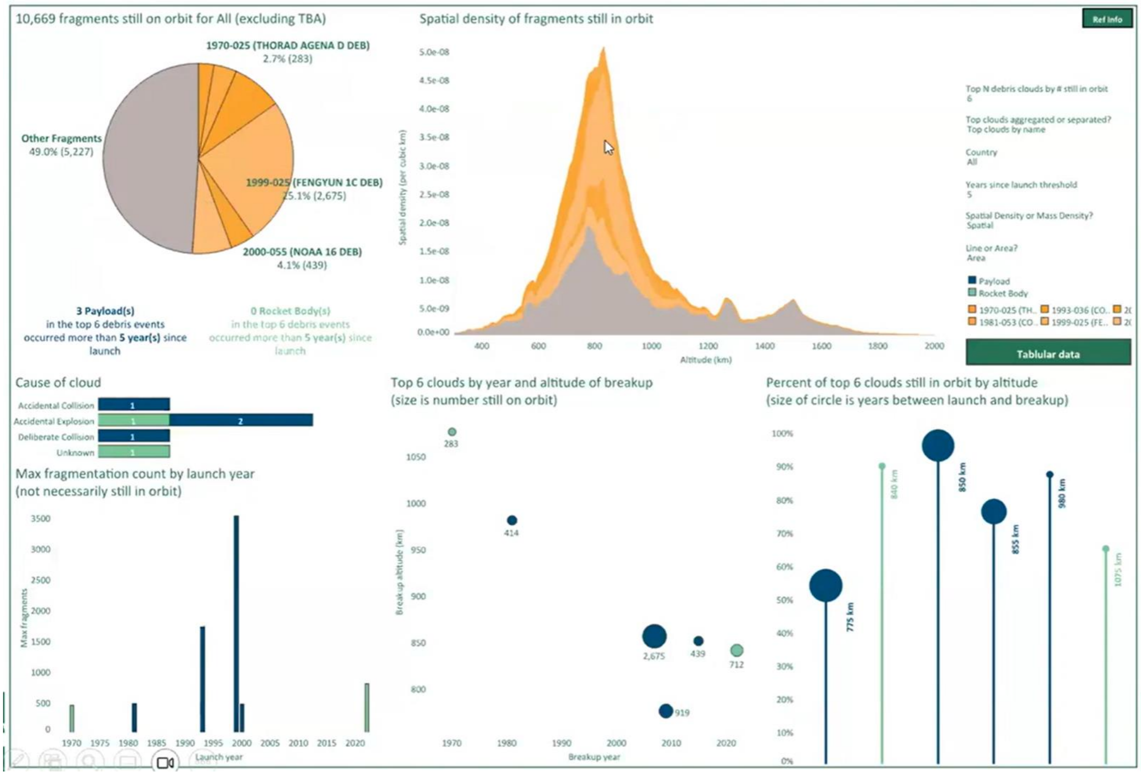


Figure 60: Fragment debris data (Source: Leolabs)

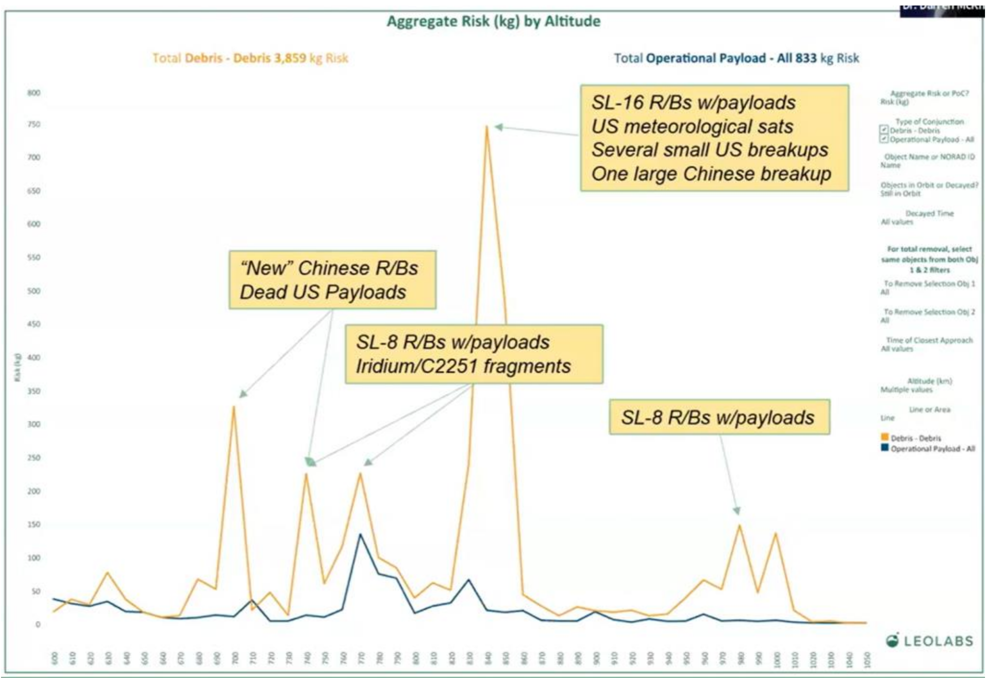


Figure 61: Presence of debris by Altitude (Source: LeoLabs)

In fact, the LEO segment can be divided into neighborhoods, as proposed by LeoLabs. It is common that a certain altitude is used only by one constellation. The reason behind this is satellite orbit management and collision avoidance. This is further justified when different constellations do not have full disclosure of their satellite positions and orbits.[30]

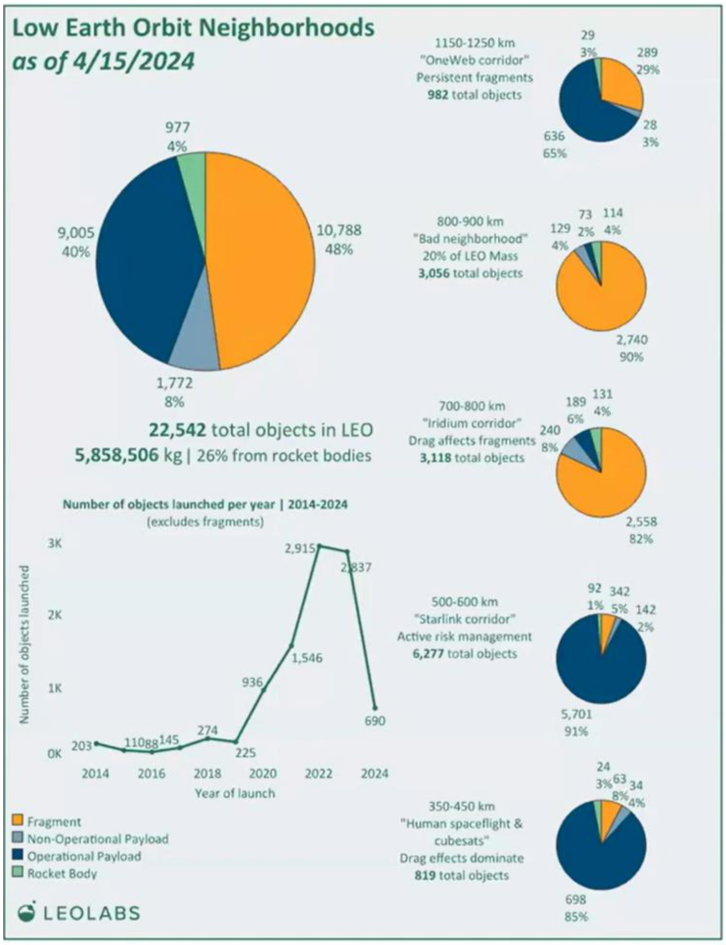


Figure 62: LEO Neighborhoods (Source: LeoLabs)

To further depict the spatial environment, Figure 63 shows the difference between spatial density and mass density of objects in orbit. The left graph shows the spatial density, indicating a large number of objects per cubic kilometer. However, the right graph, which displays mass density, reveals where the actual constellations are located based on the mass of these objects. The largest peak corresponds to Starlink, highlighting its significant presence in orbit, while the smaller peak at around 1200 km altitude corresponds to OneWeb. This comparison demonstrates that although there are many objects in space, the substantial mass is concentrated in specific constellations.

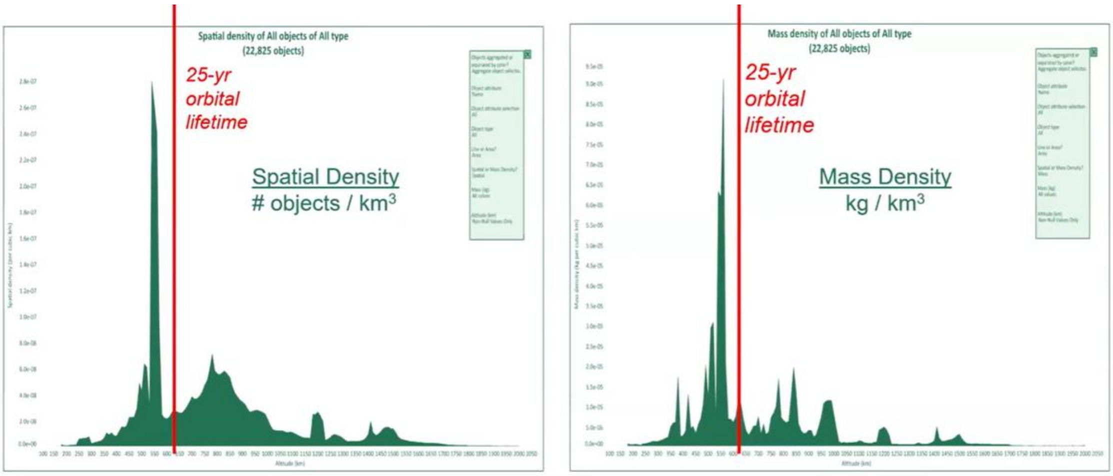


Figure 63: Objects density vs Mass (Source: LeoLabs)

Figure 64 presents a more visual depiction of the state of the environment. In the left, only considering large size objects, it can be observed that the larger presence is of active satellites (green), with some presence of rocket bodies (yellow) and some large size debris (red). While when including small sized debris, the image is tinted pink, illustrating the hazard this represents.[30]

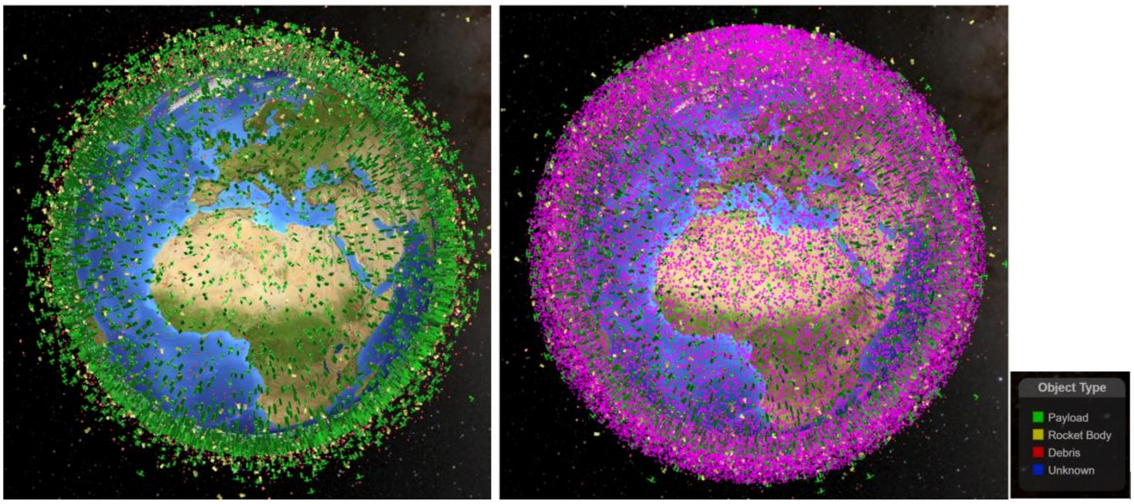


Figure 64: Left: Large size satellites; Right: Space environment including debris(Source: LeoLabs)

4.6.2 ENVIRONMENTAL EFFECTS ON SATELLITE TELECOMMUNICATIONS

Satellite telecommunications are subject to various natural phenomena that can impact signal quality and reliability. These effects include atmospheric conditions, solar activity, and other environmental factors.

4.6.2.1 Atmospheric conditions

Rain fade is a major natural factor affecting satellite communications. Under 5 GHz it can be neglected. However, for frequencies above 10 GHz, it is more than convenient to take it into account because the attenuation starts to be higher than 5 dB/km. There is a recommendation (ITU-R P.838) that allows modeling its influence through a parameter called specific attenuation (dB/km), which is obtained from the rain intensity (mm/h).[31]

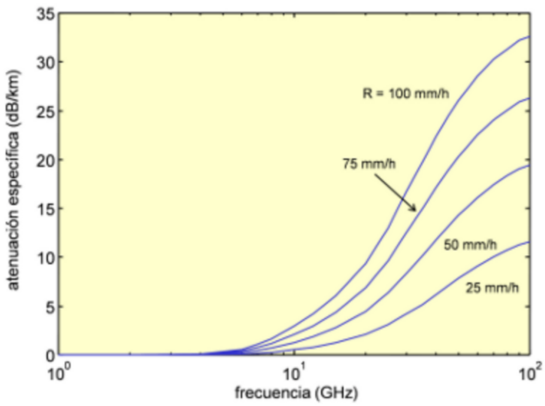


Figure 65: Signal specific attenuation (Source: ITU-R P.838)

Rain fade affects higher frequencies (Ku & Ka bands) because as the signal's frequency increase, its wavelength is shorter. When the wavelength approaches the size of a typical raindrop, rain fade occurs. Water droplets start interacting with the signal waves. Thus, the shorter the wavelength the higher the effect.[16], [31]

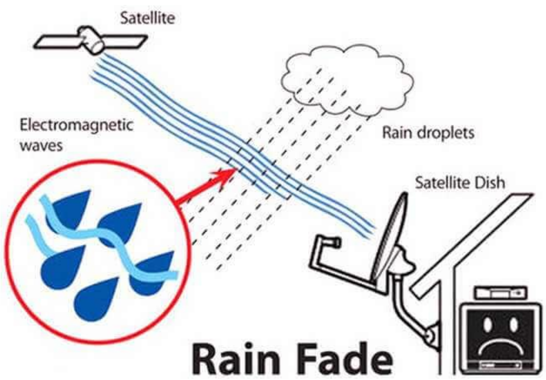


Figure 66: Rain fade (Source: BusinessCom network)

Rain fade is the combination of raindrops absorption and scattering of the microwave signals.

- **Absorption:** Water molecules in rain droplets absorb portions or all of the signal energy of the passing radio wave. The higher the frequency the higher the absorption.
- **Scattering:** It is a physical process, caused by either refraction or diffraction, in which the direction of the radio wave deviates from its original path as it passes through a medium containing raindrops. This disperses the energy of the signal from its initial travel direction. This is more severe as the signal's wavelength is shorter, more comparable to the size of the droplet.

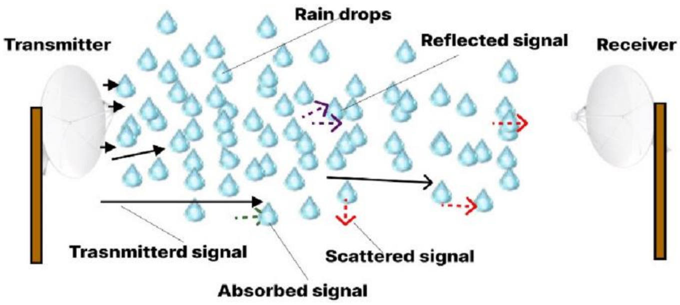


Figure 67: Absorption and Scattering (Source: ResearchGate)

The severity of rain fade increases with heavier rainfall, potentially leading to significant signal loss and interruptions in data transmission during storms.

Clouds and Fog, are masses of condensed water vapor. And while generally less harmful than rain, they can still impact these high frequency satellite signals. Commonly, they do not represent a problem, however if dense enough they can affect communications quality.[32]

To mitigate the effects of rain fade in satellite communications, several strategies are employed:

- **Diversity Techniques:**
  - **Frequency Diversity:** having backup lower frequencies ensures that if the high frequency is affected by rain fade, others may remain unaffected.
  - **Spatial Diversity:** Deploying multiple ground stations in different locations provides alternative signal paths less impacted by local weather conditions.

- **Adaptive Modulation and Coding:** Dynamically adjusting the modulation scheme and coding rate based on real-time signal quality helps maintain a reliable connection using more robust transmission techniques during heavy rain.
- **Power Control:** Increasing transmission power during heavy rain can help overcome signal loss, although this is limited by regulatory and technical constraints.
- **Site Diversity:** Using multiple ground stations in geographically diverse areas ensures redundancy, as not all stations will be affected by the same weather conditions simultaneously.
- **Link Budget Margin:** Designing satellite systems with higher link margins allows them to tolerate significant signal losses without affecting service quality, typically ensuring a margin of 4-5 dB, and increasing it to about 15 dB in moderate to heavy rain zones.

4.6.2.2 Solar Activity (Ionospheric Disturbances)

Solar activity comprehends various phenomena on the Sun, such as solar flares and coronal mass ejections (CMEs), which can significantly impact satellite communications and space weather. These activities release large amounts of electromagnetic radiation and charged particles into space, influencing the Earth's magnetosphere and ionosphere.

Solar flares are intense bursts of radiation emanating from the Sun's surface, often associated with sunspots. They emit X-rays and ultraviolet radiation, which can affect the Earth's ionospheric density within minutes of occurring. This can lead to signal refraction and fading, particularly affecting high-frequency (HF). Higher frequencies (Ku and Ka) are less affected by this ionization, but they still can suffer some noise disturbances in their signals. They are unavoidable, therefore, the only action is to monitor solar activity through space weather prediction systems to forewarning and adjusting satellite operations to minimize disruptions.[33]

Coronal Mass Ejections (CMEs) are massive bursts of solar wind and magnetic fields rising above the solar corona or being released into space. When directed towards Earth, they interact with the Earth's magnetic field, causing geomagnetic storms. This can disrupt satellite electronics, induce currents in power lines, and degrade communication signals. They can also increase drag on low Earth orbit satellites, affecting their orbits. To mitigate its effects, spacecraft shielding, robust electronic designs, and adaptive operational strategies, such as switching off non-essential systems during intense solar activity, is recommended.[34]

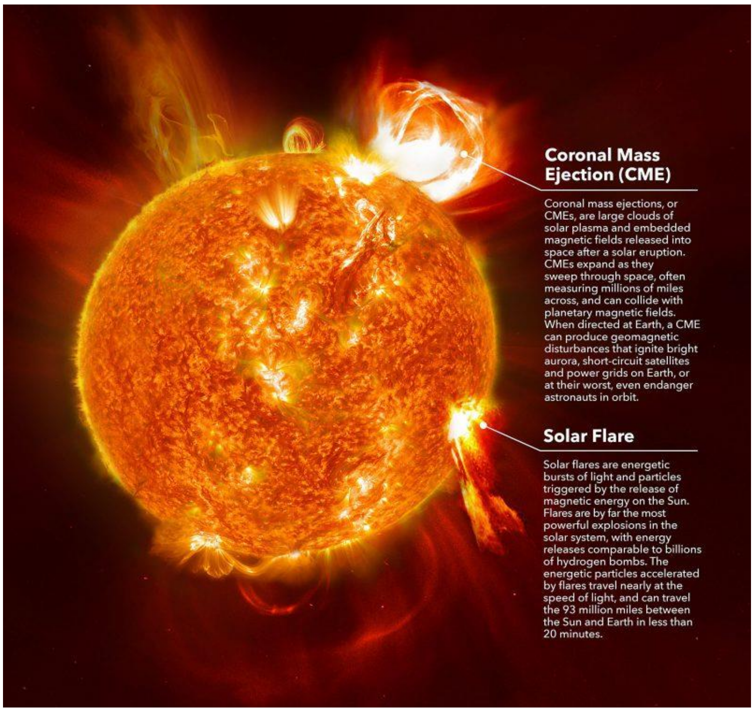


Figure 68: CME vs solar flares (Source: NASA)

4.6.2.3 Antennas maintenance

Proper maintenance of antennas is crucial for reliable satellite communication. While this weather phenomena do not directly affect satellite signals, it can affect the antenna if it is not maintained.

- **Strong winds** can misalign satellite dishes, causing signal loss. Ensuring that dishes are securely mounted and regularly checked for alignment mitigates this risk.
- **Extreme temperatures** can also impact satellite performance. High temperatures cause thermal expansion, while low temperatures lead to contraction and potential material brittleness, both of which can affect the alignment and functionality of satellite antennas and electronics. Regular inspections and adjustments help maintain optimal performance.
- **Snow and ice accumulation** on satellite dishes can block or absorb signals, leading to attenuation and degradation. Wet snow can disrupt communications similarly to rain fade. Regularly clearing snow and ice from antennas is essential to ensure uninterrupted service.

Chapter 5. SMART GRIDS

5.1 INTRODUCTION

The term "Smart Grid" represent the next step in the continuous evolution of the electric grid. Since the first electric systems in the late 19th century, the grids have been evolving and adapting to the growing needs of electrification, both in terms of reach and power consumption increase. The smart grid concept, originated in the 90's with the appearance and development of Information and Communication Technologies (ICTs). It was at this time when many business sectors started to introduced this new advances in electronics, computation, and telecommunications, leveraging the new capabilities they provided to enhance automation, control and management of their specific activities. They truly transformed the world, making tasks easier, thus their ubiquitous and continually increasing presence. [2]

The electric utilities where no exception and also integrated this technology to its assets. However, utilities technology cycles are substantially longer than most industries. The economically intensive investments required for infrastructure, as well as the necessary deep risk assessments of new technologies, has prevented the quick adoption of these upgrades. Additionally, there are other challenges that contribute to the slow adoption of ICTs, mainly technical. But there are also challenges in other areas. For instance, limitations derived from the historical development of utilities. Grids have grown and evolve to meet the needs of each area with the resources available, and therefore it can be said that no two networks are the same. This can be clearly appreciated in the fact that there are systems such as the European and the American, which work with different frequencies 50-60Hz. The lack of uniformity makes progress even more difficult, and while it is true that there are standardization organizations trying to release standards to unify progress towards a single concept, there are still different approaches and visions of what the Smart Grid is.[2]

Nevertheless, the ultimate goal of all utilities is to continue to upgrade the grid. Some of the main goals of next generation grids are the following:

- Modernization of grid infrastructure.
- Increase of the number of sensors and controls in the electricity system, managed from central systems.
- Monitoring and control of critical and noncritical components of the power system.
- Combination of bulk power generation and storage combined with distributed generation resources.

- Minimal environmental impact of electricity production and delivery.
- Automation of operational activities.
- Efficiency in the power delivery system and in the customers' consumption.
- Resilience of power supply, through the prevention of failures.
- Assurance of the power quality.

Though these are the ideal aims and most are constrained by the electric power system strong requirements and the wide spread of its components, the main idea can be summarized in *the modernization of the utility through digitalization.* Through the presence of ICT in all parts and activities of the power grid, from the generation sources to consumer loads. Always with the recognition of the complexity of the ICT concept and its limitations, from hardware (electronics) to software and telecommunications.

5.2 EVOLUTION OF THE GRID

Initially, the electric grid was an entirely analog system characterized by centralized power generation and limited monitoring capabilities. Data collection was manual, and communication infrastructure was basic, relying heavily on human operators. These early systems lacked the ability to dynamically respond to fluctuations in demand and supply, making them inefficient and prone to failures.

The transition from analog to digital began with the introduction of Supervisory Control and Data Acquisition **(SCADA)** systems in the 1970s. SCADA systems allowed for remote monitoring and control of grid operations, significantly improving reliability and efficiency. These systems used basic digital communication technologies to transmit data from various grid points to central station, now known as utility control centers **(UCC)**, enabling operators to make informed decisions based on real-time data, and later it enabled the management of operations as more network segments and components came into sight.[1]

The 1980s and 1990s saw the integration of more sophisticated ICTs into the grid. The adoption of fiber optics, cellular communications, and later, the Internet Protocol (IP) paved the way for faster and more reliable data transmission. These advancements facilitated the development of more **advanced monitoring systems** and the introduction of **automated control mechanisms**.

Firstly, the development of fiber optics provided a significant leap in data transmission capabilities due to their high bandwidth and low latency. It enabled the transmission of large volumes of data over long distances without significant loss, making it ideal for grid applications. Cellular communications meanwhile where used to complement fiber optics, providing coverage where the optic fiber network did not reach.

Then, the introduction of IP-based communication allowed for the seamless integration of various communication systems within the grid. IP facilitated the development of interoperable systems, where different devices and platforms could communicate effectively, further enhancing the grid's monitoring and control capabilities.

With this first devices, some of the concepts of the smart grid were being made available. For instance; advanced metering infrastructure **(AMI),** that enables real-time monitoring and billing of electricity usage, providing consumers with detailed insights into their consumption patterns. And the first distributed energy resources **(DER).** like solar and wind were now feasible to integrate into the grid. In addition, more and more system started to be automated. This systems, capable of making complex decisions, based on data from various parts of the network, have now become essential to utility operations. [1]

Looking ahead, the electric grids are ready to undergo further transformations driven by emerging technologies and evolving consumer needs. The World Economic Forum's 2017 report on "The Future of Electricity" highlights several key trends and technologies expected to shape the future grid.

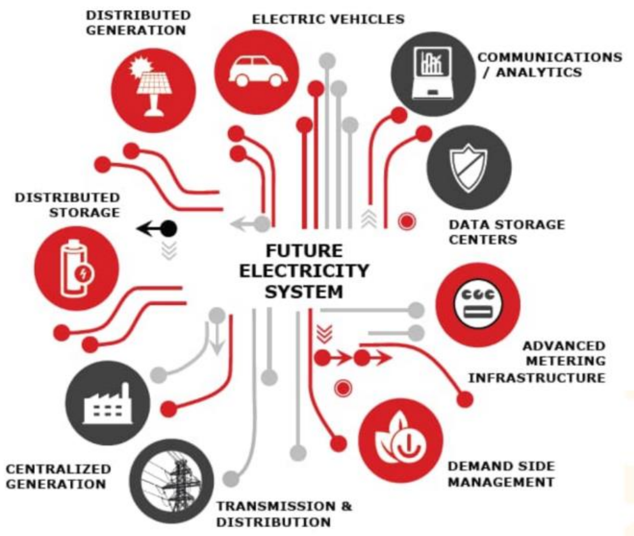


Figure 69: The Future of Electricity (Source: World Economic Forum's 2017 report)

The adoption curve for these technologies is expected to follow a pattern similar to previous technological innovations, with the current gradual increase leading to a not far in time tipping point where widespread adoption accelerates. This curve illustrates the potential rapid integration of grid edge technologies in the coming decades, driven by advancements in ICTs.

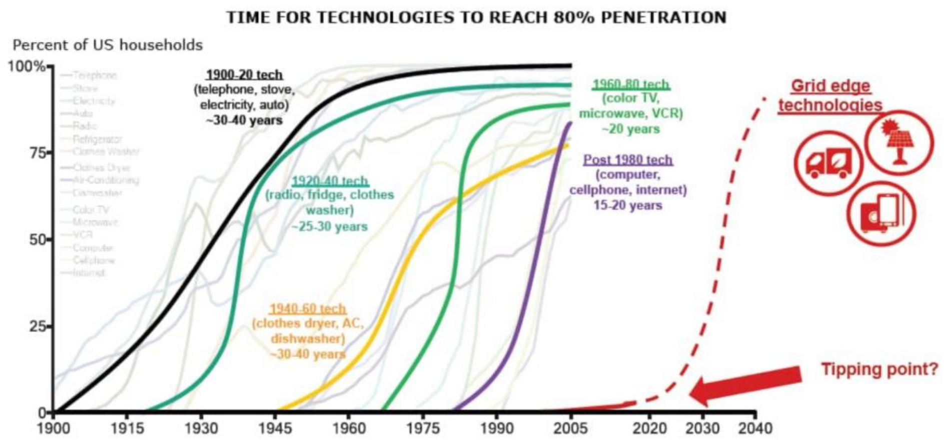


Figure 70: Grid Edge Technologies expected adoption (Source: World Economic Forum's 2017 report)

5.3 CHALLENGES OF THE SMART GRID

5.3.1 THE TRADITIONAL PARADIGM OF THE UTILITY AND ITS ICTS

The power grid can be described as a large set of interconnected elements that altogether provide a service to its end customers. The traditional system can be segmented in 4, and it is operated through a cascade model.[2]

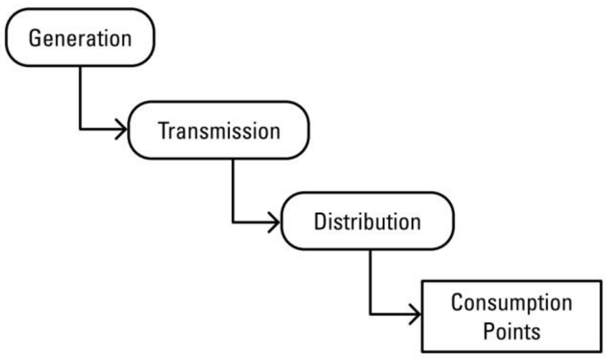


Figure 71: Electric power system segments (Source: Telecommunication Networks for the Smart Grid)

- **Generation:** This is the first stage where electrical power is produced. There are many power generation technologies. There are thermal technologies that utilize fossil fuels (coal, natural gas, oil) or nuclear power as the primary energy resource, and renewable sources technologies (hydroelectric, wind, solar, and geothermal).

- **Transmission:** Once electricity is generated, it needs to be transported over long distances to reach end users. This is done via high-voltage transmission lines, which carry electricity from power plants to substations.
- **Distribution:** After electricity reaches substations, it needs to be delivered to individual consumers. This is the role of the distribution segment. Here, the high-voltage electricity from the transmission lines is stepped down to lower voltages suitable for use in homes and businesses.
- **Demand (Consumption):** The final segment is the end use or consumption of electricity by various users. These users include residential, commercial, industrial, and public sectors.

Each segment is essential to the overall efficiency and reliability of the electrical grid, ensuring that electricity is available where and when it is needed. And in each segment ICTs are present.

5.3.2 GENERATION

The generation segment of the electrical system is undergoing significant transformations. First, it needs to meet the increasing global demand for electricity. While advancements in **energy efficiency** help mitigate the growth in consumption, the widespread adoption of **electric vehicles (EVs)** is expected to significantly boost electricity demand. Secondly, the transition towards **cleaner energy sources** is also key, driven by the need to reduce environmental impact and comply with stricter regulations. Regarding this aspect, there are two main actions; the closure of conventional highly polluting fossil-fuel power plants, such as coal, and the exponential increase of renewable power plants and distributed generation.[2]

Distributed generation (DG), is a concept that started when the generation technology of renewable sources, especially photovoltaic (PV) solar panels, was mature and prices drop. From then, the installation of rooftop PV has massively expanded and it is expected to continue in this direction, even more when it is a subsidized activity by the governments. Distributed generation is not only residential, it also includes other power generation technologies such as small wind turbines, hydrogen and biogas among others.

DG combined with **energy storage systems (ESS)** such as pump-hydro, batteries, fuel cells, super-capacitors and others, create a category called **DERs (Distributed energy resources)**. Without getting into much detail about the power electronics technologies and operating models (grid-forming, grid following) that this technologies require, it is important to state the weighted importance of ICTs presence. Most of this technologies rely on power electronics to be able to connect to the grid and operate correctly. This controls rely on network parameters, necessitating that DER devices continuously measure, process, and adjust their parameters through different ICT devices to operate efficiently.

Furthermore, because of the increasing share of DERs and renewable (solar farms and windfarms) power plants, the system is losing the inertia that the rotating machines from conventional thermal power plants provided. Inertia is crucial in the frequency stability of energy system, as it provided a natural response towards incidences. Now, the new scenario of low inertia power systems rely more on power electronics which depend on ICT elements.

An additional element that derives from DERs are microgrids. **Microgrids** are local electrical systems that can operate autonomously or connected to the main grid. They heavily depend on ICTs to manage energy generation and consumption. Nowadays, microgrids represent a security issue more than potential benefits. Traditional systems were designed around the concept of a cascade operated system. The energy was generated at the top and transmitted and distributed downstream. Therefore, protections where designed to protect from disturbances in that energy flow. However, with the incidence of DERs, **flows could now theoretically be bidirectional**. As the grid is not prepared from them, many countries have prohibited the islanded mode operation. Many more concepts are related within microgrids regarding the stability of the system. They will not be treated in this document as it is not within the focus of the study. What is important to consider is the ICT intensiveness of this segment of the grid. And the flexibility and management capabilities that they provide. [2]

5.3.3 TRANSMISSION

Comprising high-voltage transmission lines and substations, the transmission segment of the electrical system is vital for the correct functioning of the system. The responsible body of its operation are Transmission System Operator (TSO). They are the ones that manage and operate substations to control the energy flows and the saturation of the grid lines. They are able to do this thanks to the thousands of ICTs equipped in the different components of the grid assets. Furthermore, the ICTs monitoring capabilities allow the system to perform predictive and preventive maintenance to anticipate possible failures.

The operation is carried out remotely from a Utility Control Center (UCC), thus automation of the substations is essential. And regarding protections, transmission lines and substations require advanced systems, some based in the utilizing telecommunications to isolate faults and safeguard the lines. Once again, it can be appreciated how the segment is highly intensive and dependent on ICTs, to the point that they are now consider essential elements of grid operations.[2]

5.3.4 DISTRIBUTION

Distribution is the segment that provides capillarity to the system. It is the last delivery segment and connects directly to the consumer, the most widespread part of the system. With the new scenario, distribution is going to become, more than it currently is, the core of the network. It is here where most of the new technologies connect to the system. First of all, it has to develop the necessary upgrades to introduce the new system segment of DERs. Thus, it must enable bidirectional flows with everything that entails, including security, power flows and congestion management with real-time monitoring.

Further enhancements towards the efficiency, reliability, and overall performance of power grids, is the automation of the different elements, specifically **substation automation (SA) and distribution automation (DA)**, for the introduction of control systems in the operations of distribution. This upgrades were firstly present inside the substations, but the evolution of the grid now requires a progressive expansion towards the power lines and end users. Automation is key in initiatives that reduce the field interventions of the distribution system operators (DSOs), such as **self-healing grids**.[2]

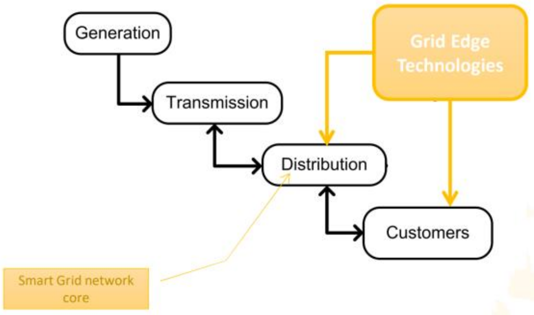


Figure 72: New electric power system segments (Source: Telecommunication for the Smart Grid)

5.3.5 DEMAND

The integration of ICTs **(Smart meters)** is transforming the demand segment. Traditionally, Distribution Network Operators (DNOs) had limited visibility into the real-time functioning of the electric grid. Their role primarily involved the operation, maintenance, and development of the distribution network to ensure a reliable electricity supply to consumers. Visibility extended only to certain key points within the grid, typically at substations, where data collection was manual and infrequent. This limited perspective hindered their ability to promptly detect and respond to issues such as outages, voltage fluctuations, or inefficiencies.[1], [2]

With the integration of smart meters, the transition from DNOs (Distribution Network Operator) to DSOs (Distribution System Operator) is possible, and represents a significant shift in the role and capabilities of these organizations. With the integration of smart meters and advanced metering infrastructure (AMI), DSOs now enjoy unprecedented visibility across the entire distribution network. Smart meters provide real-time data on electricity usage at the consumer level, allowing DSOs to monitor the grid with granularity that was previously unattainable. This enhanced visibility enables DSOs to:

- **Detect Issues Promptly**: Quickly identify and address outages, faults, and inefficiencies.
- **Optimize Grid Operations:** Balance loads more effectively and reduce peak demand.

- **Integrate Renewable Energy**: Facilitate the integration of distributed energy resources (DERs) such as solar panels and wind turbines.
- **Improve Maintenance:** Transition from reactive to predictive maintenance, reducing downtime and costs.

Smart meters also empower consumers by providing them with detailed, real-time information about their electricity consumption. This transparency transforms consumers into active participants in the energy ecosystem, encouraging more responsible and informed energy use. Benefits for consumers include:

- **Detailed Consumption Data:** Access to real-time data on electricity usage, allowing consumers to understand their consumption patterns.
- **Cost Savings**: Ability to identify and eliminate energy waste, leading to reduced electricity bills.
- **Participation in Demand Response (DR) Programs:** Consumers can actively participate in DR programs, which offer financial incentives for shifting consumption away from peak periods.

Demand response (DR) programs play a crucial role in modern grid management. Historically, the primary method for reducing peak demand was the disconnection of certain loads during peak times, often linked to special tariffs. This approach was relatively blunt and inconvenient for consumers.[2]

With smart meters, DR programs have become more sophisticated and consumer-friendly. Smart meters enable precise measurement of consumption in real-time, often down to hourly or even 15-minute intervals. This granular data supports the implementation of time-of-use (TOU) tariffs, which incentivize consumers to shift their consumption to off-peak periods. Key benefits include:

- **Load Shifting:** Consumers are encouraged to use electricity during off-peak hours, reducing strain on the grid during peak times.
- **Financial Incentives:** TOU tariffs offer lower rates during off-peak periods, resulting in cost savings for consumers who adjust their consumption patterns.
- **Grid Stability:** Reduced peak demand enhances overall grid stability and efficiency.

Finally, the rise of electric vehicles (EVs) introduces new dynamics into the energy consumption landscape. Smart meters also facilitate the integration of EVs by allowing for flexible charging schedules that align with grid needs. Benefits include:

- **Optimized Charging**: Consumers can charge their EVs during off-peak hours when electricity is cheaper and more abundant.
- **Grid Support:** EVs can serve as distributed energy resources, providing stored energy back to the grid during peak demand periods through vehicle-to-grid (V2G) technology.
- **Environmental Impact:** Encouraging the use of EVs contributes to the reduction of greenhouse gas emissions, aligning with broader sustainability goals.

5.4 TELECOMMUNICATION CHALLENGES

The integration of ICT technologies in the smart grid present several challenges. In reality, it is telecommunications that presents the greatest difficulties; information and computer technology are much less challenging. These telecommunication challenges can be broadly categorized into technological, infrastructural, and operational domains, and are further complicated by the inherent limitations of current telecommunications networks.[2]

5.4.1 TECHNOLOGICAL CHALLENGES

5.4.1.1 High Bandwidth and Low Latency Requirements

Smart grids rely heavily on real-time data collection and control, which demands high bandwidth and low latency in telecommunications networks. Applications such as Advanced Metering Infrastructure (AMI), Distributed Energy Resources (DER), and real-time grid monitoring require substantial data transmission capabilities to function effectively. Ensuring that telecommunications networks can handle these requirements without delays or data loss is a significant technological challenge.

5.4.1.2 Security and Reliability

The critical nature of electric grids necessitates highly reliable and secure communication networks. Any vulnerabilities in the telecommunications infrastructure could lead to disruptions in grid operations, making robust cybersecurity measures essential. Ensuring network reliability in diverse and often harsh environmental conditions where grid assets are located further complicates this challenge.

5.4.1.3 Interoperability

Smart grids incorporate a wide range of devices and systems from different manufacturers, each with its own communication protocols. Ensuring interoperability among these diverse systems is crucial for seamless operation and integration. Developing and adhering to common standards can help mitigate this issue, but achieving widespread compliance remains challenging.

5.4.2 Infrastructural Challenges

5.4.2.1 Coverage in Remote and Rural Areas

The distribution of smart grid assets is widespread, including urban, suburban, and rural areas. Providing telecommunications coverage in remote and rural areas, which are often underserved by commercial telecommunication service providers (TSPs), is a significant infrastructural challenge. Building and maintaining the necessary infrastructure in these areas requires substantial investment and strategic planning.

5.4.2.2 Environmental and Physical Constraints

Telecommunication devices and networks must operate reliably under the varied and often harsh environmental conditions present at many grid locations. This includes high electromagnetic interference (EMI) near high-voltage equipment and physical obstructions that can hinder radio frequency (RF) signal propagation. Designing equipment and networks that can withstand these conditions without performance degradation is critical.

5.4.3 Operational Challenges

5.4.3.1 Integration with Legacy Systems

Many existing grid systems rely on legacy telecommunications infrastructure, such as analog telephone circuits and early digital communication technologies. Integrating these legacy systems with modern smart grid technologies is complex and costly. Ensuring compatibility and smooth transition without disrupting ongoing operations poses a significant operational challenge.

5.4.3.2 Phased Implementation

The deployment of smart grid technologies cannot happen all at once but must be planned in phases. This phased approach needs to be dictated by the needs of the electric elements deployed in the power system and the progressive evolution of telecommunication solutions. Coordinating these phases effectively to ensure continuous and coherent improvements across the grid is a logistical and operational challenge.

5.4.4 Strategic Design Considerations

5.4.4.1 Balancing Top-Down and Bottom-Up Approaches

When designing smart telecommunication networks for smart grids, it's essential to balance top-down and bottom-up approaches. A top-down perspective focuses on the applications and their requirements, which might lead to unrealistic demands on telecommunications networks. Conversely, a bottom-up approach emphasizes the current capabilities and limitations of existing networks, potentially restraining innovation. An iterative approach that combines both perspectives ensures that solutions are both ambitious and feasible, promoting the evolution of telecommunication networks beyond their current capabilities.[1], [2]

5.4.4.2 Realistic Requirements and Future-Proofing

Requirements for smart grid telecommunications must be realistic and aligned with achievable expectations. Relying on simple, inexpensive, or traditional networks will result in design-limited solutions that cannot support the long-term vision of smart grids. Therefore, it's crucial to consider future-proofing when setting requirements, ensuring that the deployed solutions can adapt to future technological advancements.

5.4.4.3 Hybrid Network Solutions

No single telecommunication solution fits all the diverse needs of a smart grid. The varied requirements across different parts of the network, combined with the need for cost-effective and scalable solutions, necessitate a mix of public/private and wireline/wireless networks. This hybrid approach allows for tailored solutions that address specific challenges and leverage the strengths of different technologies.

5.5 OVERVIEW OF TELECOMMUNICATIONS APPLICATIONS OF THE SMART GRID

Finally, this section provides an overview to summarize and clarify the various applications.

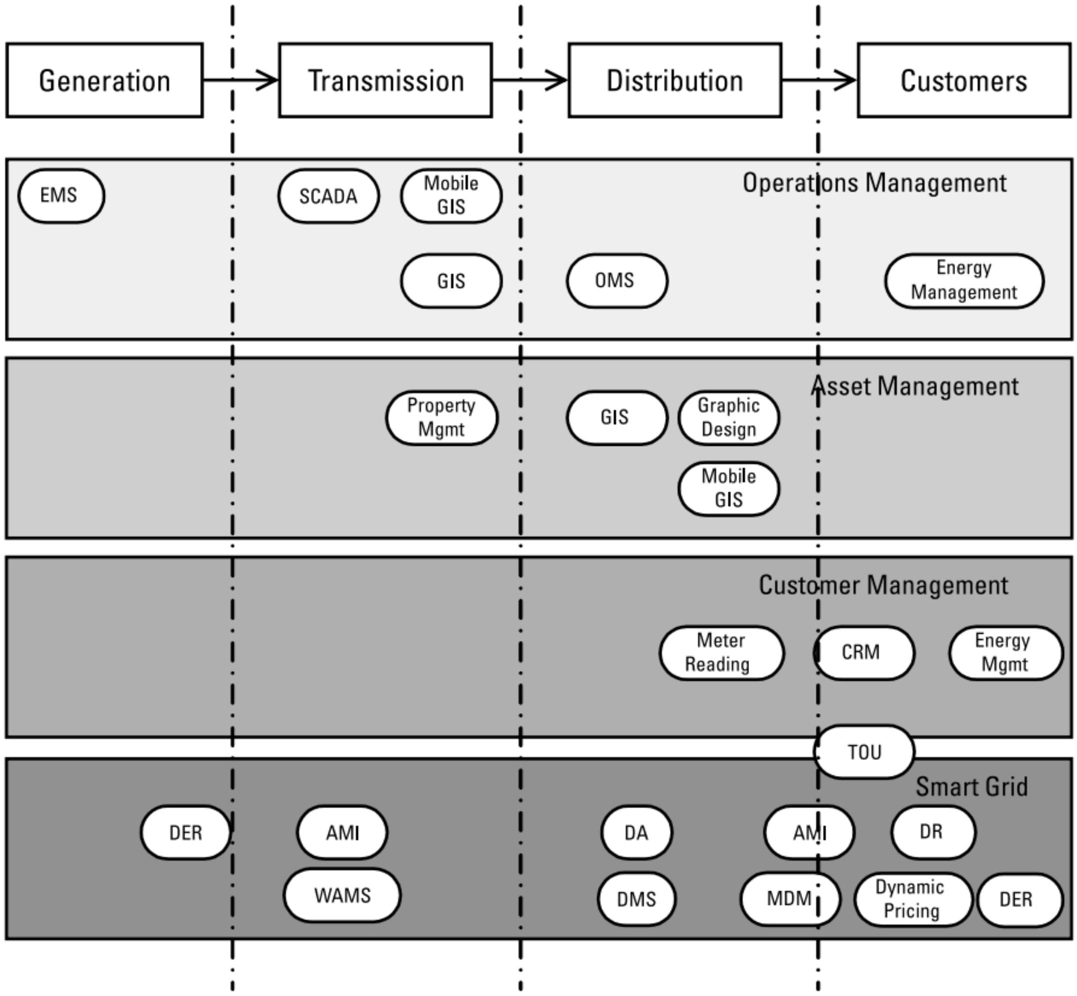


Figure 73: Utility applications summary (Source: Telecommunication networks for smart grids)

5.5.1 UTILITY INFORMATION SYSTEMS

5.5.1.1 Operations Management Systems

Energy Management Systems (EMSs): These systems are crucial for the supervision, analysis, optimization, simulation, and control of transmission and generation assets. They ensure that the power supply meets demand efficiently and reliably.

Distribution Management Systems (DMSs): DMSs monitor and control the distribution network, improving safety and asset protection. They provide operators with the tools needed to manage the distribution of electricity effectively.[1], [2]

Supervisory Control and Data Acquisition (SCADA) Systems: SCADA systems enable real-time monitoring and control of remote terminal units (RTUs) and intelligent electronic devices (IEDs). They are integral to both EMSs and DMSs, providing the necessary data to make informed decisions and execute control commands from utility control centers (UCCs). The key components of SCADA systems include:

- Remote Terminal Units (RTUs)
- Programmable Logic Controllers (PLCs)
- Intelligent Electronic Devices (IEDs)

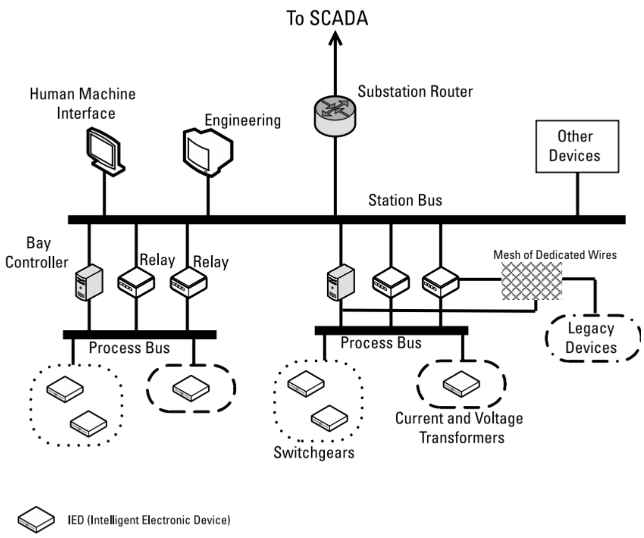


Figure 74: Example of an asset internal communications arquitecture and connection with the SCADA system (Source: Telecommunication networks for smart grids)

5.5.1.2 Outage Management Systems (OMSs)

OMSs help utilities manage power outages by analyzing their location and extent. They predict outages based on grid information and assist dispatchers and crews in restoring power, thus minimizing the economic impact of outages.

5.5.1.3 Meter Data Management Systems (MDMSs)

MDMSs manage data from smart meters, both for grid and customer management. They are essential for analyzing consumption patterns and billing.

5.5.1.4 Customer Management Systems

These systems handle the relationship between utilities and their customers, including customer relationship management (CRM) and energy management programs. They ensure effective communication and service delivery .

5.5.1.5 Asset Management Systems

These systems manage utility data and work activities, including work management, mapping, and geographic information system (GIS) applications. They help in maintaining and optimizing the physical assets of the grid .

5.5.2 SMART GRID-SPECIFIC APPLICATIONS

5.5.2.1 Advanced Metering Infrastructure (AMI)

AMI represents a significant evolution from traditional automated meter reading (AMR). It includes two-way communication capabilities and real-time data features, enabling utilities to measure various electrical parameters and manage consumption remotely. AMI supports multiple time-of-use (TOU) tariff schemes, remote connection/disconnection, and fraud detection, providing substantial benefits to both utilities and customers .[1]

5.5.2.2 Distributed Energy Resources (DER)

DER includes small-scale power generation technologies like solar panels and wind turbines that can be integrated into the grid. These resources help in decentralizing power generation, reducing transmission losses, and enhancing grid resilience.

5.5.2.3 Electric Vehicles (EVs)

The integration of EVs into the smart grid provides both challenges and opportunities. EVs can be used as mobile distributed storage systems, supplying energy back to the grid when needed. However, their widespread adoption necessitates reinforcing the distribution grid at charging points.

5.5.2.4 Microgrids

Microgrids are small, localized grids that can operate independently or in conjunction with the main grid. They consist of a group of consumers connected to a generation source, providing energy security and flexibility. They enhance the resilience of the overall grid by ensuring continuous power supply during main grid outages.

5.5.2.5 Dynamic Line Rating (DLR)

DLR technologies enable real-time monitoring and adjustment of power line ratings based on environmental conditions. This allows transmission system operators to maximize the use of existing infrastructure, avoiding unnecessary investments and enhancing grid efficiency.

5.5.2.6 Flexible AC Transmission Systems (FACTS)

FACTS controllers use power electronics to manage reactance in the grid, improving voltage stability and reducing losses. They enhance the controllability of power flow, increasing the usable capacity of power lines.

5.5.2.7 Synchrophasors

Synchrophasors, or phasor measurement units (PMUs), provide time-synchronized measurements of electrical waves, enabling real-time monitoring of grid stability. These devices are critical for preventing large-scale blackouts and ensuring the reliable operation of interconnected grids.

5.5.2.8 Demand Response (DR)

DR programs incentivize consumers to reduce or shift their electricity usage during peak demand periods. Smart meters and real-time data collection enable utilities to implement dynamic pricing models, such as time-of-use tariffs, which encourage consumers to use electricity during off-peak times. This helps to flatten the demand curve, reduce stress on the grid, and defer the need for additional generation capacity.

5.5.2.9 Distribution Automation (DA)

DA involves using digital sensors, communications, and controls to automate the operation of the distribution network. This includes fault detection, isolation, and service restoration (FDIR) capabilities, which enhance the reliability and efficiency of the grid. DA systems can quickly identify and isolate faults, reroute power, and restore service to unaffected areas, minimizing downtime and improving overall grid performance.

5.5.3 TRADITIONAL APPLICATIONS AND SERVICES IN THE SMART GRID

5.5.3.1 Teleprotection

Teleprotection systems use telecommunications to enhance the protection of power systems. They provide rapid communication between protective relays to isolate faults and prevent damage to equipment and disruption of service. This application has the strongest requirements both in latency and reliability.

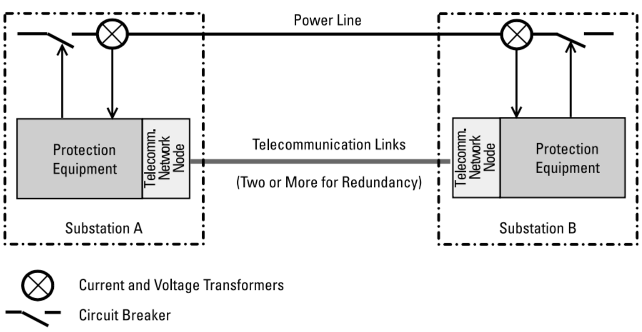


Figure 75: Teleprotections scheme (Source: Telecommunication networks for smart grids)

5.5.3.2 Video Surveillance and Other Security Needs

Telecommunications support video surveillance systems used to protect critical infrastructure such as substations and control centers from intruders. These systems enhance security by providing real-time video feeds and enabling remote monitoring.

5.5.3.3 Intra-Substation Telecommunications

Within substations, telecommunications networks connect various devices and systems to facilitate monitoring, control, and data acquisition. These networks ensure seamless communication between equipment such as transformers, circuit breakers, and switches (Figure 74).

5.5.3.4 Mobile Workforce Telecommunications

Mobile telecommunications are essential for coordinating and controlling field crews. These systems have evolved from private mobile radio (PMR) systems to public mobile (cellular) systems, providing features such as GPS positioning and data access in mobility situations. They support normal operations by enabling crews to receive orders and access corporate and operational applications while in the field .

5.5.3.5 Business (Corporate) Telecommunications

Many substations also serve as permanent utility offices, requiring telecommunications infrastructure to support both corporate and operational needs. This includes access to email, intranet, ERP software, GIS, and operational databases. Utilities have developed extensive telecommunication assets over the years to meet these needs, often leveraging optical fiber cables for internal services and third-party revenues .

Chapter 6. COMMERCIAL SATELLITES

This chapter provides a comprehensive review of some of the most important commercial satellites and some of the most attractive upcoming projects, analyzing their main characteristics. Throughout the analysis, key aspects of each satellite will be examined to better understand their capabilities and limitations. Finally, a comparison and a detailed analysis of viable technologies will be carried out, in order to identify the most suitable and effective options for different commercial applications.

In order to conduct a structured analysis, the various technologies will be firstly categorized by their orbit—Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO), or Low Earth Orbit (LEO)—and further categorized by their specific purpose. As discussed in previous sections, satellites must be specialized for particular types of services due to certain constraints.

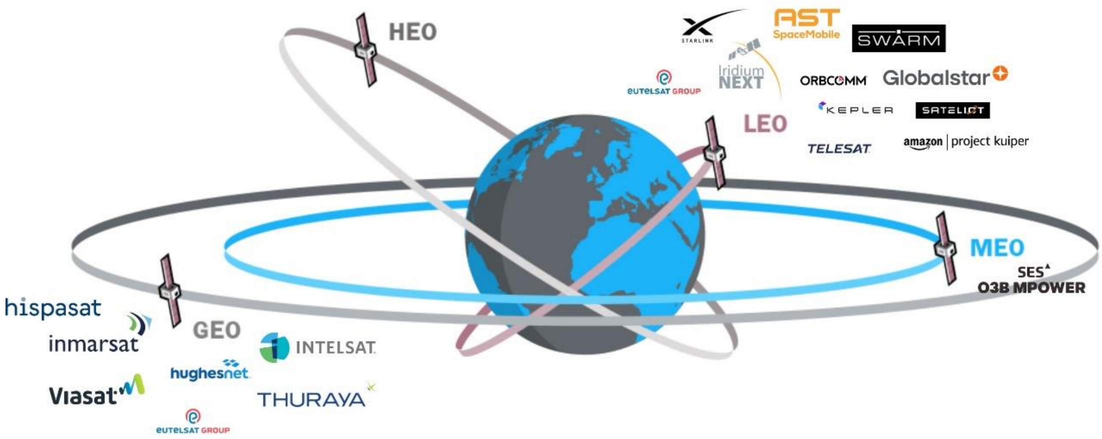


Figure 76: Commercial satellites

The technical sheets will provide comprehensive information, including a brief introduction, details on orbit, number of satellites in service and planned, frequency bands used, latency, uplink and downlink bandwidths, and whether availability exceeds 99%. It will also cover the components of the value chain (hub operator, satellite operator, satellite manufacturer and service provider), as well as the type and size of antennas and the cost of the service.

The costs have been estimated on the basis of plans from various distributors. And in order to facilitate understanding of the antennas type, size and difficulty of deployment, pictures of the antennas are included at the end of each technical sheet.

6.1 TECHNICAL SHEETS

6.1.1 GEO

6.1.1.1 Intelsat

Figure 77: Intelsat logo (Source:Intelsat)

Intelsat is a leading global provider of satellite communications services, with a long history dating back to its founding in 1964 as an intergovernmental organization. Privatized in 2001, Intelsat has evolved to offer a wide range of services, including television broadcasting, in-flight connectivity, high-speed internet in rural areas, and communication solutions for the mobile and maritime sectors. With over 50 satellites in geostationary orbit (GEO), Intelsat ensures continuous and reliable global coverage, utilizing various frequency bands, including C, Ku and Ka, to optimize its services for different applications.

One of Intelsat's most significant innovations is the **Intelsat EPICNG** series of satellites, which utilize **High Throughput Technology (HTS)** to provide enhanced capacity and flexibility. These satellites are equipped with advanced digital processing technology to handle higher data volumes, ideal for intensive applications such as video streaming and broadband connectivity. Intelsat also works with global distributors and technology partners to extend its reach and enhance the quality of its services, consistently adjusting to the evolving needs for connectivity in an increasingly interconnected world.

Characteristics

Intelsat

Orbit	GEO
Height	35,786 km
Number of satellites	52
Number of planned satellites	N/A (launches are planned)
Satellite transponder (Frequency Bands)	C, Ku, Ka
Latency	600 ms
Downlink bandwidth	160 Mbps
Uplink bandwidth	4 Mbps
Availability (>99%)	Yes
Hub operator	Intelsat
Satellites operator	Intelsat

Service provider	Distributors
Satellite manufacturer	Boeing
Antenna type	VSAT (flat-panel and parabolic antennas)
Antenna size	Parabolic (D=80cm); Flat (90cm x 90cm)
Ease of deployment	Medium-Difficult
Service cost	35€/10GB
Modem cost	22,000.00 €
Flat-rate plan	Si
Traffic price (aprox.)	0.0000033€/kB
Type of service	High speed Internet & IoT (High capacity)

Table 1: Intelsat characteristics

Antenna

Figure 78: Left: Flat pannel (Kymeta); Right: Parabolic antenna (Intellian)

6.1.1.2 Inmarsat

Figure 79: Inmarsat logo (Source: Inmarsat)

Inmarsat is a leading global provider of mobile satellite communications services, founded in 1979 with a primary focus on maritime safety. Since then, Inmarsat has significantly expanded its offering to include services for the aeronautical, land and government sectors. The company operates a robust constellation of geostationary (GEO) satellites, providing reliable voice, data and broadband services around the world, even in the most remote and challenging environments.

Inmarsat's satellite network supports a wide range of applications including emergency response, maritime safety, in-flight connectivity, remote asset management and global broadcasting. The company uses a variety of frequency bands, primarily L-band and Ka-band, to provide optimized services tailored to different requirements. With over 13 satellites in geostationary orbit, Inmarsat provides continuous and reliable global coverage.

One of Inmarsat's latest innovations is the Global Xpress (GX) network, which uses Ka-band technology to provide high-speed broadband connectivity with global reach. However, this network was built oriented towards government customers' specific needs. Inmarsat also works with global distributors and technology partners to extend the reach and improve the quality of its services, continually adapting to the evolving connectivity needs of an increasingly connected world.

Characteristics

BGAN-Inmarsat

Orbit	GEO
Height	35,786 km
Number of satellites	14
Number of planned satellites	N/A (launches are planned)
Satellite transponder (Frequency Bands)	L (Ka-government network)
Latency	600 ms
Downlink bandwidth	492.0 kbps
Uplink bandwidth	492.0 kbps
Availability (>99%)	Yes
Hub operator	Inmarsat
Satellites operator	Inmarsat
Service provider	Distributors

Satellite manufacturer	Inmarsat
Antenna type	BGAN (flat-panel and directional antennas)
Antenna size	25 cm x 12 cm
Ease of deployment	Easy
Service cost	140 €/100 MB
Modem cost	4,500 €
Flat-rate plan	No (Option to purchase more service)
Traffic price (aprox.)	0.0014 €/kB
Type of service	IoT (Low capacity)

Table 2: Inmarsat characteristics

Antenna

Figure 80: Inmarsat modems(Satellitephonestore)

6.1.1.3 Thuraya

Figure 81: Thuraya logo (Source: Thuraya)

Thuraya Telecommunications Company, a subsidiary of Al Yah Satellite Communications Company PJSC (Yahsat), is a leading provider of mobile satellite communications services. Since its inception in 1997, Thuraya has played a critical role in bringing connectivity to remote and underserved regions, providing innovative solutions to a variety of markets including energy, government, maritime, media and disaster relief. Headquartered in Abu Dhabi, Thuraya operates primarily in the Middle East, Africa, Europe, Asia and Australia, providing voice, data and IoT/M2M applications via its L-band satellite network.

Thuraya's satellites, such as Thuraya-2 and Thuraya-3, are located in geostationary orbit, 35,786 km above the equator. These satellites are designed to handle thousands of simultaneous voice calls and transmit data over large areas. Thuraya is also in the process of upgrading its fleet with the Thuraya 4-NGS satellite, scheduled for launch in 2024, to further increase capacity and coverage. In addition to satellite phones and connectivity devices.

Characteristics

	Thuraya
Orbit	GEO
Height	35,786 km
Number of satellites	2
Number of planned satellites	3
Satellite transponder (Frequency band)	L
Latency	600 ms
Downlink bandwidth	444.0 kbps
Uplink bandwidth	444.0 kbps
Availability (>99%)	Yes
Hub operator	Thuraya
Satellites operator	Thuraya
Service provider	Distributors
Satellite manufacturer	Boeing
Antenna type	VSAT (flat-panel) + other
Antenna size	Panel (200 x 200 mm); omnidireccional (small)
Ease of deployment	Easy

Service cost	3,750€/10GB
Modem cost	1,300 €
Flat-rate plan	No (Option to purchase more service)
Traffic price (aprox.)	0.00036€/kB
Type of service	IoT (Low Capacity)

Table 3: Thuraya characteristics

Antenna

Figure 82: Left:M2M modem; Center: Mobile handset ;Right; Broadband Terminals (Thuraya)

6.1.1.4 Viasat

Figure 83: Viasat logo (Source:Viasast)

Viasat is a leading satellite communications company providing a wide range of high-speed connectivity services worldwide. Viasat recently launched the ViaSat-3 satellite constellation, which is designed to provide global coverage and significantly increase network capacity. Each satellite in the ViaSat-3 constellation is designed to provide download speeds of up to 100 Mbps. These satellites operate in Ka-band, which optimizes efficiency and data transmission capacity, enabling Viasat to deliver high quality Internet services to remote and mobile areas.

In addition, though analyzed separately, Viasat recently acquired Inmarsat, expanding its satellite fleet and share of the satellite communications market. This acquisition includes both geostationary orbit (GEO) satellites and plans for a low earth orbit (LEO) constellation called Orchestra. Orchestra will combine LEO satellites, GEO and 5G terrestrial networks to deliver high-speed, low-latency internet services. Through this integration, Viasat aims to strengthen its market position and offer more robust and flexible connectivity solutions for business, government and residential customers.

Characteristics

Viasat	
Orbit	GEO
Height	35,786 km
Number of satellites	3
Number of planned satellites	19 (with Inmarsat)
Satellite transponder (Frequency Bands)	Ka
Latency	600 ms
Downlink bandwidth	100 Mbps
Uplink bandwidth	30 Mbps
Availability (>99%)	Yes
Hub operator	Viasat
Satellites operator	Viasat
Service provider	Distributors
Satellite manufacturer	Boeing
Antenna type	VSAT (Parabolic antenna)
Antenna size	Parabolic (h=72cm; Diameter= 77cm)
Ease of deployment	Difficult

Service cost	75€/25GB
Modem cost	6,000 €
Flat-rate plan	Si
Traffic price (aprox.)	0.0000029€/kB
Type of service	High speed Internet

Table 4: Viasat characteristics

Antenna

Figure 84: Viasat antenna (Viasat)

6.1.1.5 HughesNet

Figure 85: Hughesnet logo (Source: Hughesnet)

HughesNet is a leading provider of high-speed satellite Internet services (GEO) operated by Hughes Network Systems, an EchoStar Corporation company. With extensive coverage, including rural and remote areas where terrestrial high-speed connections are not available, HughesNet has established itself as a reliable solution for residential and commercial users in the United States and other American regions primarily, as well as others around the world. The service uses a network of geostationary satellites to provide a consistent Internet connection, ensuring that users have access to the digital world regardless of their geographic location.

HughesNet's technology is particularly beneficial in areas lacking traditional broadband infrastructure, offering download speeds of up to 25 Mbps and upload speeds of up to 3 Mbps. The company has continued to innovate, offering enhanced services such as HughesNet Gen5, which provides higher data allowances and better performance. HughesNet also supports a range of applications, from basic web browsing to more data-intensive activities, ensuring users enjoy a seamless online experience.

Characteristics

HughesNet	
Orbit	GEO
Height	35,786 km
Number of satellites	21
Number of planned satellites	21
Satellite transponder (Frequency Bands)	Ka
Latency	600 ms
Downlink bandwidth	25 Mbps
Uplink bandwidth	3 Mbps
Availability (>99%)	No
Hub operator	HughesNet
Satellites operator	HughesNet
Service provider	HughesNet
Satellite manufacturer	Hughes
Antenna type	VSAT (Parabolic antenna)
Antenna size	Parabolic (Diameter= 74-120cm)

Ease of deployment	Difficult
Service cost	55€/15GB
Modem cost	500 €
Flat-rate plan	Si
Traffic price (aprox.)	0.0000035€/kB
Type of service	High speed Internet

Table 5: HughesNet characteristics

Antenna

Figure 86: HughesNet antenna (HughesNet)

6.1.1.6 Eutelsat (Konnect)

Figure 87: Konnect eutelsat logo (Source: Eutelsat)

Konnect is Eutelsat's GEO initiative to deliver high-speed broadband services via very high throughput satellites (VHTS). Launching in January 2020, the Eutelsat Konnect satellite offers a total capacity of 75 Gbps, covering Europe and Africa with a network of 65 spot beams. Konnect aims to, improving high-speed internet access for rural and remote homes and small businesses.

In 2023, Eutelsat launched Konnect VHTS, its most advanced satellite with a capacity of 500 Gbps. This satellite uses 230 Ka-band beams and is equipped with the most powerful digital processor ever put into orbit, allowing flexible capacity allocation. Konnect VHTS provides fixed, mobile and government connectivity services in Europe, North Africa and the Middle East, helping to bridge the digital divide and supporting critical government and emergency applications.

Characteristics

Konnect VHTS

Orbit	GEO
Height	35,786 km
Number of satellites	2
Number of planned satellites	N/A
Satellite transponder (Frequency Bands)	Ka
Latency	600 ms
Downlink bandwidth	100 Mbps
Uplink bandwidth	5 Mbps
Availability (>99%)	Yes
Hub operator	Eutelsat
Satellites operator	Eutelsat
Service provider	Distributors
Satellite manufacturer	Thales Alenia Space
Antenna type	VSAT (Parabolic) and Flat (phased array)
Antenna size	Parabolic (Diameter= >90cm); Flat (90x90cm)
Ease of deployment	Medium-Difficult
Service cost	38€/50GB

Modem cost	300 €; 22,000€
Flat-rate plan	No (Capacidad de aumentar servicio)
Traffic price (aprox.)	0.00000073€/kB
Type of service	High speed Internet & IoT (High capacity)

Table 6: Eutelsat Konnect characteristics

Antenna

Figure 88: Left: Parabolic antenna (Intellian) ; Right: Eutelsat hybrid antenna (Kymeta)

6.1.1.7 Hispasat

Figure 89: Hispasat logo (Source: Hispasat)

Founded in 1989 and based in Spain, **Hispasat** is a leading satellite telecommunications operator providing data, television, Internet and mobility solutions in Europe, the Americas and North Africa. Its fleet of state-of-the-art satellites, including the Hispasat 30W-6 and the advanced Amazonas Nexus, provides high-speed connectivity to remote and mobile areas. Hispasat is renowned for its ability to transmit more than 1,250 television channels and DTH services, as well as for its broadband and backhaul solutions for mobile operators. The company is also committed to sustainability, implementing initiatives to reduce its carbon footprint. With plans for expansion and continuous improvement, Hispasat continues to be a leader in the satellite communications market, offering advanced and efficient services to its customers around the world.

Characteristics

Hispasat	
Orbit	GEO
Height	35,786 km
Number of satellites	10
Number of planned satellites	N/A
Satellite transponder (Frequency Bands)	C, Ku & Ka
Latency	600 ms
Downlink bandwidth	200 Mbps
Uplink bandwidth	10 Mbps
Availability (>99%)	Yes
Hub operator	Hispasat
Satellites operator	Hispasat
Service provider	Distributors
Satellite manufacturer	Thales Alenia Space
Antenna type	VSAT (Parabolic)
Antenna size	Parabolic (Diameter= 60cm)
Ease of deployment	Medium
Service cost	35€/150GB
Modem cost	1,000 €
Flat-rate plan	Si
Traffic price (aprox.)	0.00000022€/kB
Type of service	High speed Internet & IoT (High capacity)

Table 7: Hispasat characteristics

Antenna

Figure 90: Parabolic antenna (Hispasat)

6.1.2 MEO

6.1.2.1 O3b mPOWER

Figure 91: SES logo (Source: SES)

O3b mPOWER is the next-generation medium-earth orbit (MEO) satellite constellation operated by SES, one of the world's leading satellite communications companies. The constellation is designed to provide high-capacity, low-latency connectivity globally, with a particular focus on regions and applications requiring exceptional performance and high availability.

SES uses a multi-orbit system, combining satellites in different orbits to provide optimal coverage and performance. This approach includes satellites in Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO) and, soon, Low Earth Orbit (LEO).

SES has proposed a constellation of 36 LEO satellites to provide high-speed communications for Internet of Things (IoT) devices and to act as a relay network for other digital traffic.

Characteristics

Intelsat

Orbit	MEO; GEO
Height	8,062 km; 35,786 km
Number of satellites	6
Number of planned satellites	13
Satellite transponder (Frequency bands)	Ka
Latency	150 ms
Downlink bandwidth	Up to 1.6 Gbps
Uplink bandwidth	Up to 1.2 Gbps
Availability (>99%)	Yes
Hub operator	SES Networks
Satellites operator	SES
Service provider	Distribuidores
Satellite manufacturer	Boeing
Antenna type	VSAT (Parabolic antenna)
Antenna size	Parabolic (Diameter = 85 cm - 250 cm)
Ease of deployment	Difficult

Service cost	N/A
Modem cost	N/A
Flat-rate plan	N/A
Traffic price (aprox.)	N/A
Type of service	IoT (High capacity)

Table 8: SES-O3b mPOWER characteristics

Antenna

Figure 92: Parabolic antenna (SES)

6.1.3 LEO

6.1.3.1 Starlink

Figure 93: Starlink logo (Source: Starlink)

Starlink is a satellite internet constellation project initiated by **SpaceX** with the goal of providing high-speed internet services globally. Utilizing a vast network of low Earth orbit (LEO) satellites, Starlink aims to deliver reliable and fast internet access to remote and rural areas where connectivity has traditionally been unreliable, expensive, or completely unavailable.

The Starlink constellation, which is the largest of its kind in the world, leverages LEO to offer broadband internet capable of supporting streaming, online gaming, video calls, and much more. The service is designed to provide low-latency, high-speed internet, utilizing advanced satellites and user hardware combined with SpaceX's extensive expertise in spacecraft operations.

In addition, Starlink has ambitious plans to expand its capabilities, including working on direct-to-cell IoT services projected for 2025, which will enhance its service offerings and connectivity solutions even further.

Characteristics

Starlink

Orbit	LEO
Height	550 km
Number of satellites	4,408
Number of planned satellites	12,000
Satellite transponder (Frequency bands)	Ku and Ka
Latency	30 ms
Downlink bandwidth	190 Mbps
Uplink bandwidth	29 Mbps
Availability (>99%)	Yes
Hub operator	Space X / Google
Satellites operator	SpaceX
Service provider	Starlink
Satellite manufacturer	SpaceX
Antenna type	Panel (phased array)

Antenna size	57,5cm x 51,1 cm x 4,1 cm
Ease of deployment	Medium
Service cost	61€/40GB
Modem cost	2,389.00 €
Flat-rate plan	Si
Traffic price (aprox.)	0.0000014€/kB
Type of service	High speed Internet

Table 9: Starlink characteristics

Antenna

Figure 94: Starlink antenna (Starlink)

6.1.3.2 OneWeb (Eutelsat)

Figure 95: OneWeb Eutelsat (Source: Eutelsat)

OneWeb is a global satellite telecommunications company dedicated to providing high-speed, low-latency internet services through a constellation of low Earth orbit (LEO) satellites. In 2023, **OneWeb merged with Eutelsat**, a leading satellite operator, creating a powerful synergy between OneWeb's LEO network and Eutelsat's geostationary (GEO) satellite fleet.

This strategic acquisition allows the combined entity to leverage the strengths of both LEO and GEO technologies, offering a hybrid solution that ensures comprehensive global coverage and advanced connectivity services. The LEO constellation is particularly effective in delivering low-latency, high-speed internet to remote and underserved areas, while the GEO satellites provide extensive coverage and reliability.

The Eutelsat-OneWeb alliance enhances the ability to meet diverse customer requirements and deliver hybrid connectivity services with industry-leading resilience. This merger not only increases the operational scale and financial strength of the company but also positions it to capitalize on significant opportunities in the satellite communications market.

Characteristics

Oneweb (Eutelsat)

Orbit	LEO
Height	1200 km
Number of satellites	648
Number of planned satellites	900
Satellite transponder (Frequency bands)	VHF, Ku and Ka
Latency	50 ms
Downlink bandwidth	195 Mbps
Uplink bandwidth	32 Mbps
Availability (>99%)	Yes
Hub operator	Multiple suppliers
Satellites operator	OneWeb (Eutelsat)
Service provider	Distributors
Satellite manufacturer	Airbus Defence and Space
Antenna type	Panel (phased array) & VSAT (Parabolic antenna)

Antenna size	Panel (50x43cm) & Parabolic (Diameter = 85 cm)
Ease of deployment	Medium
Service cost	495€/100GB
Modem cost	€ 19,198.43
Flat-rate plan	Si
Traffic price (aprox.)	0.0000043€/kB
Type of service	High speed Internet

Table 10: Oneweb (Eutelsat) characteristics

Antenna

Figure 96: Oneweb antennas (Intellian)

6.1.3.3 Kepler

Figure 97: Kepler logo (Source: Kepler)

Kepler Communications is a Canadian satellite operator focused on building a robust Low Earth Orbit (LEO) network. The company aims to build the 'Internet of Space' by deploying a constellation of small satellites to provide global connectivity for a variety of applications, including data relay and the Internet of Things (IoT).

The Kepler optical data relay constellation provides space assets with an on-demand, two-way gigabit communications link. Connect to our network using a range of SDA-compliant optical terminals for direct, low-latency internet access for your spacecraft.

Characteristics

	Kepler
Orbit	LEO
Height	600 km
Number of satellites	21
Number of planned satellites	140
Satellite transponder (Frequency bands)	Optic & (Ku and Ka)
Latency	5 ms
Downlink bandwidth	2,5 Gbps
Uplink bandwidth	2,5 Gbps
Availability (>99%)	No
Hub operator	Kepler Communications
Satellites operator	Kepler Communications
Service provider	Kepler Communications
Satellite manufacturer	Kepler Communications
Antenna type	FSO (N/A)
Antenna size	20,5 × 8,5 cm
Ease of deployment	Easy
Service cost	N/A
Modem cost	N/A
Flat-rate plan	N/A
Traffic price (aprox.)	N/A
Type of service	High speed Internet

Table 11: Kepler constellation characteristics

Antennas not available

6.1.3.4 Amazon Project Kuiper

Figure 98: Amazon Kuiper logo (Source: Amazon)

Project Kuiper is Amazon's ambitious initiative to deploy a constellation of 3,236 satellites in low earth orbit (LEO) to provide high-speed, low-latency internet services globally. This network is designed to bridge the digital divide, especially in remote and underserved areas, by offering affordable and reliable connectivity. The first prototype satellites were launched in October 2023, and Amazon plans to have half of the constellation deployed by mid-2026 and complete deployment by 2029.

Project Kuiper's technology includes optical links between satellites for efficient data transfer and promises speeds of up to 400 Mbps for consumers, with potential of up to 1,000 Mbps for specific organizations. In addition, Amazon will integrate these services with Amazon Web Services (AWS), providing private and secure connectivity worldwide. With an investment of more than $10 billion, Amazon has secured multiple launches with providers such as Blue Origin, United Launch Alliance (ULA) and Arianespace to make this project a reality.

Characteristics

	Kuiper
Orbit	LEO
Height	630 km
Number of satellites	0
Number of planned satellites	3,326
Satellite transponder (Frequency bands)	Ku and Ka
Latency	40 ms
Downlink bandwidth	400 Mbps
Uplink bandwidth	120 Mbps
Availability (>99%)	No
Hub operator	Amazon
Satellites operator	Amazon
Service provider	Amazon
Satellite manufacturer	Amazon
Antenna type	Panel (phased array)
Antenna size	3 options (7x7cm, 71 cm^2 , 48x76cm)
Ease of deployment	Easy-Medium
Service cost	N/A

Modem cost	N/A
Flat-rate plan	N/A
Traffic price (aprox.)	N/A
Type of service	High speed Internet

Table 12: Kuiper characteristics

Antenna

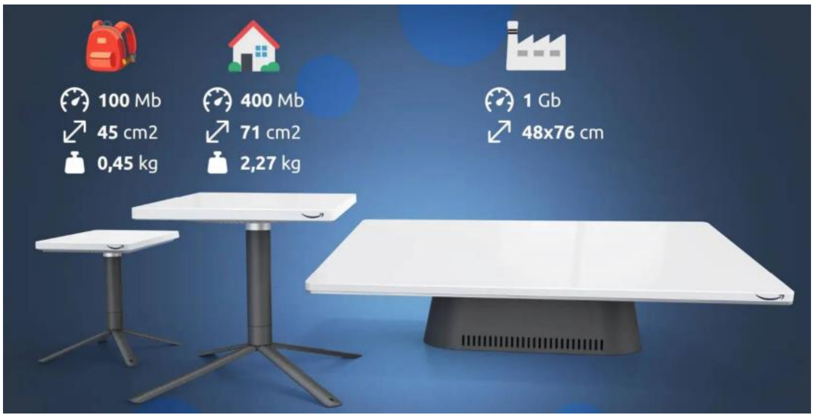


Figure 99: Kuiper antennas (Amazon)

6.1.3.5 Telesat Lightspeed

Figure 100: Telesat logo (Source: Telesat)

Telesat LEO, also known as **Telesat Lightspeed**, is an ambitious initiative by Telesat to create a global network of low-earth orbit (LEO) satellites. The constellation is designed to provide high-speed, low-latency broadband connectivity services to business and government customers around the world. The Lightspeed network will comprise 198 satellites built by MDA, each equipped with digital beam-forming antennas and inter-satellite optical links. These satellites, scheduled to be launched from 2026, will provide a total capacity of approximately 10 Tbps, offering performance similar to fibre networks in terms of speed and latency.

Telesat Lightspeed's innovative design, which includes in-space digital processing and phased array antennas, provides full global coverage, including the polar regions. This network will be capable of delivering multi-gigabit per second connections to remote users and ensuring high quality business connectivity anywhere in the world. In addition, Telesat has signed launch agreements with SpaceX to rapidly deploy its constellation and meet its goal of offering global services in 2027. The Lightspeed network promises to be a cost-effective and flexible solution for customers' critical connectivity needs.

Characteristics

Telesat Lightspeed	
Orbit	LEO
Height	1,000 km
Number of satellites	0
Number of planned satellites	198
Satellite transponder (Frequency bands)	Ka
Latency	50 ms
Downlink bandwidth	7.5 Gbps
Uplink bandwidth	7.5 Gbps
Availability (>99%)	No
Hub operator	Telesat
Satellites operator	Telesat
Service provider	Distributors
Satellite manufacturer	Thales Alenia Space
Antenna type	VSAT (Dual-parabolic antennas)
Antenna size	2 x (h=77cm; Diameter= 84,5cm)
Ease of deployment	Difficult

Service cost	N/A
Modem cost	N/A
Flat-rate plan	N/A
Traffic price (aprox.)	N/A
Type of service	High speed Internet

Table 13: Telesat Lightspeed characteristics

Antenna

Figure 101: Telesat antenna (Intellian)

6.1.3.6 Orbcomm OG2

Figure 102: Orbcomm logo (Source: Orbcomm)

ORBCOMM is a leader in industrial Internet of Things (IoT) and machine-to-machine (M2M) communications solutions. Founded in 1993, the company offers a range of services and products designed to track, monitor and control assets in a variety of industries, including transportation, maritime, oil and gas, utilities and heavy equipment. ORBCOMM provides global connectivity solutions via satellite, cellular and dual-mode (satellite-cellular) networks, ensuring reliable data transmission and communications for assets in remote and hard-to-reach locations.

In addition, ORBCOMM offers a range of IoT devices and programmable terminals for various applications, including smart and dual-mode terminals for satellite and cellular connectivity. They also provide development kits to efficiently integrate these technologies. ORBCOMM's fleet management platform provides real-time visibility and control to help reduce costs, improve safety and increase operational efficiency. Intelligent telematics solutions provide detailed information on fleet operations to optimise fleet management. ORBCOMM continues to innovate in the Industrial IoT space, improving operational efficiency across a wide range of industries.

However, ORBCOMM has announced that it will no longer commercialise low earth orbit (LEO) and will focus on acquiring part of Inmarsat's spectrum (ORBcomm IDP). Justifying the lower latency by avoiding saturation of its LEO satellites, which do not provide real-time communications, ORBCOMM has announced the acquisition of part of Inmarsat's spectrum.

Characteristics

	Orbcomm
Orbit	LEO
Height	740 km
Number of satellites	31
Number of planned satellites	31
Satellite transponder (Frequency bands)	VHF
Latency	50 ms
Downlink bandwidth	4.8 kbps
Uplink bandwidth	2.4 kbps
Availability (>99%)	Yes
Hub operator	Orbcomm
Satellites operator	Orbcomm

Service provider	Distributors
Satellite manufacturer	Sierra Nevada Corporation (Now Inmarsat)
Antenna type	Disp IoT(Patch/helicoidal)
Antenna size	12.6 cm x 12.6 cm
Ease of deployment	Easy
Service cost	45,000€/100MB
Modem cost	600.00 €
Flat-rate plan	Yes
Traffic price (aprox.)	0.53€/kB
Type of service	IoT (messages)

Table 14: Orbcomm characteristics

Antenna

Figure 103: Orbcomm antennas (Orbcommm)

6.1.3.7 Iridium Next

Figure 104: Iridium logo (Source: Iridium)

Iridium Next is the next generation of the Iridium satellite constellation, designed to replace and enhance the global communications infrastructure provided by the original Iridium constellation. Launching between 2017 and 2019, Iridium Next consists of 66 active Low Earth Orbit (LEO) satellites and spares distributed across 6 orbital planes to provide continuous global coverage. These satellites are equipped with state-of-the-art technology to deliver voice and data communications, including broadband services, worldwide, including in remote and polar regions. In addition to improving the quality and speed of communications, Iridium Next will enable new services such as aircraft tracking and the transmission of sensor data for the Internet of Things (IoT). The upgrade to Iridium Next has ensured the continuity and significant enhancement of the global communications services provided by the Iridium constellation, maintaining it as a critical tool for industries such as maritime, aviation, military and emergency response.

Characteristics

	Iridium
Orbit	LEO
Height	781 km
Number of satellites	66
Number of planned satellites	N/A
Satellite transponder (Frequency bands)	L
Latency	50 ms
Downlink bandwidth	1.5 Mbps
Uplink bandwidth	512 kbps
Availability (>99%)	Yes
Hub operator	Thales Alenia Space
Satellites operator	Iridium Communications
Service provider	Distribuidores
Satellite manufacturer	Thales Alenia Space
Antenna type	Disp IoT(Patch/helicoidal)
Antenna size	Compact, portable
Ease of deployment	Easy

Service cost	240€/100MB
Modem cost	450.00 €
Flat-rate plan	Yes
Traffic price (aprox.)	0.0023€/kB
Type of service	IoT (Low capacity)

Table 15: Iridium characteristics

Antenna

Figure 105: Iridium antennas (Iridium)

6.1.3.8 Globalstar

Figure 106: Globalstar logo (Source: Globalstar)

Globalstar is a constellation of low-Earth orbit (LEO) satellites designed to provide global communications services. Launched in the 1990s, the Globalstar constellation consists of 24 active satellites in eight orbital planes, providing worldwide coverage with a focus on voice and data communications. Globalstar is widely used in sectors such as maritime, agriculture, mining and outdoor activities, providing a reliable solution for communications in remote areas without terrestrial infrastructure. Globalstar also offers tracking and monitoring services, enabling businesses and individuals to control and manage their assets in real time. With continued investment in technology enhancements and network expansion, Globalstar remains a key choice for global satellite communications, adapting to changing market needs and providing essential services in emergency situations and locations where other means of communication are not viable.

Characteristics

	SPOT Globalstar
Orbit	LEO
Height	1410 km
Number of satellites	24
Number of planned satellites	24
Satellite transponder (Frequency bands)	L & S
Latency	70 ms
Downlink bandwidth	9.6 kbps
Uplink bandwidth	9.6 kbps
Availability (>99%)	Yes
Hub operator	Globalstar
Satellites operator	Globalstar
Service provider	Distributors
Satellite manufacturer	Thales Alenia Space
Antenna type	IoT Devices (Patch/helicoidal)
Antenna size	8.26cm x 17.78cm
Ease of deployment	Easy
Service cost	35 €/mes
Modem cost	400 €
Flat-rate plan	Yes (unlimited messages)
Traffic price (aprox.)	N/A

Type of service	IoT (messages)

Table 16:Globalstar characteristics

Antenna

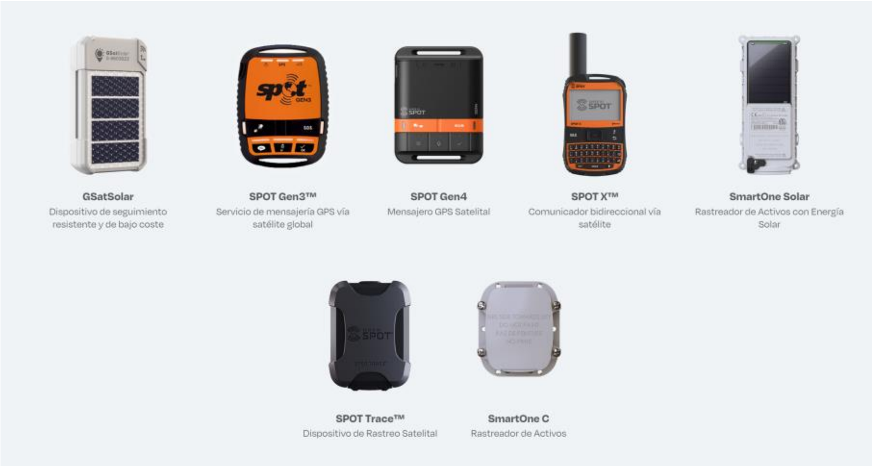


Figure 107: Spot Globalstar antennas (Globalstar)

6.1.3.9 Swarm

Figure 108: Swarm logo (Source: Swarm)

Swarm technology, inspired by the coordination of swarms in nature, uses a constellation of nanosatellites (CubeSats) in low Earth orbit (LEO) to provide global telecommunications and data collection services. These small, low-cost satellites work together to provide continuous and robust coverage. Swarm's constellation enables applications in the Internet of Things (IoT), environmental monitoring, precision agriculture, remote telecommunications and disaster management. Swarm Technologies, a pioneer in this technology and now part of SpaceX following its acquisition in 2021, exemplifies the movement towards affordable and efficient global connectivity.

Swarm was a privately held start-up before being acquired by SpaceX. The company is building a constellation of LEO satellites to communicate with IoT devices using a "store and forward" design, a technique in which information is sent to an intermediate station where it is stored and forwarded at a later time. To date, Swarm has launched about 175 small "SpaceBEE" satellites, each about the size of a slice of bread and about 2.8 cm thick, looking more like a piece of Texas toast. According to CelesTrak, these satellites are in near-polar orbits, probably sun-synchronous, providing coverage at all latitudes, and are in different orbital planes at different LEO heights. In addition, Swarm offers a pass-check tool that takes into account which satellites are actually operational, making it easier to manage and optimize the use of the constellation.

Characteristics

	SWARM
Orbit	LEO
Height	500 km
Number of satellites	160
Number of planned satellites	160
Satellite transponder (Frequency bands)	VHF
Latency	30 ms
Downlink bandwidth	1 kbps
Uplink bandwidth	1 kbps
Availability (>99%)	No
Hub operator	Swarm Technologies
Satellites operator	Swarm Technologies
Service provider	Swarm Technologies

Satellite manufacturer	Swarm Technologies
Antenna type	IoT Devices (Patch/helicoidal)
Antenna size	20 cm x 20 cm
Ease of deployment	Easy
Service cost	5 (€/device)
Modem cost	119.00 €
Flat-rate plan	N/A
Traffic price (aprox.)	N/A
Type of service	IoT (messages)

Table 17: Swarm characteristics

Antenna

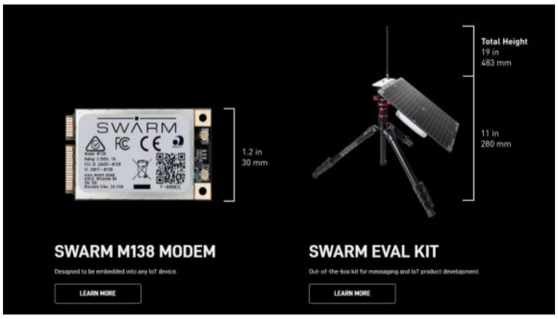


Figure 109: Swarm antennas (Swarm)

6.1.3.10 Sateliot

Figure 110: SatelIoT logo (Source: Sateliot)

Sateliot is an innovative company operating a constellation of nanosatellites in low earth orbit (LEO) to provide IoT connectivity based on the 5G NB-IoT standard. The first phase of deployment includes the launch of its satellite "The Groundbreaker" aboard a SpaceX rocket, marking the beginning of a constellation that will eventually include 250 satellites. This network will enable the expansion of 5G terrestrial network coverage, allowing IoT devices to connect without the need for additional hardware.

Sateliot's technology enables a seamless transition between terrestrial and satellite networks, using standard roaming agreements and its innovative 'Store & Forward' authentication method. Sateliot is positioned to revolutionize the IoT market by providing affordable mass connectivity, with a focus on reducing costs and minimizing environmental impact through lightweight and efficient infrastructure.

Characteristics

	Sateliot
Orbit	LEO
Height	500 km
Number of satellites	1
Number of planned satellites	250
Satellite transponder (Frequency bands)	NB-IoT band under the 5G standard
Latency	30 ms
Downlink bandwidth	N/A
Uplink bandwidth	N/A
Availability (>99%)	No
Hub operator	Sateliot
Satellites operator	Sateliot
Service provider	Sateliot
Satellite manufacturer	Sateliot
Antenna type	No need for additional hardware
Antenna size	-
Ease of deployment	Extremely easy
Service cost	N/A
Modem cost	N/A
Flat-rate plan	N/A

Traffic price (aprox.)	N/A
Type of service	5G

Table 18: Sateliot characteristics

Antennas not available

6.1.3.11 AST

Figure 111: AST logo (Source: AST)

AST SpaceMobile is building the first cellular broadband network in space that will work directly with standard, unmodified mobile devices. Known as SpaceMobile, this innovative network aims to close the current connectivity gap and bring high-speed Internet access to people in rural and remote areas. The Midland, Texas-based company is developing the BlueBird satellite constellation and plans to launch the first five commercial satellites in the first quarter of 2024. These satellites, called Block 1, are designed to provide direct connectivity to smartphones outside of existing cellular coverage in partnership with mobile network operators (MNOs) such as AT&T and Vodafone.

AST SpaceMobile's technology includes inter-satellite optical links and digital beam-forming antennas, enabling efficient global coverage and high data throughput. The SpaceMobile network promises to deliver 4G and 5G speeds, enabling seamless connectivity for consumers and businesses anywhere in the world. In addition, AST SpaceMobile has secured significant investments and strategic partnerships with companies such as AT&T, Vodafone and Rakuten, supporting its vision to transform the telecommunications landscape and bring broadband to billions of people who currently have no access to the Internet.

Characteristics

	AST
Orbit	LEO
Height	700 km
Number of satellites	1
Number of planned satellites	168
Satellite transponder (Frequency bands)	NB-IoT band under the 5G standard
Latency	50 ms
Downlink bandwidth	N/A
Uplink bandwidth	N/A
Availability (>99%)	No
Hub operator	AST SpaceMobile
Satellites operator	AST SpaceMobile
Service provider	Distributors

Satellite manufacturer	AST SpaceMobile
Antenna type	No need for additional hardware
Antenna size	-
Ease of deployment	Extremely easy
Service cost	N/A
Modem cost	N/A
Flat-rate plan	N/A
Traffic price (aprox.)	N/A
Type of service	5G

Table 19: AST characteristics

Antennas not available

6.2 TECHNOLOGY CATEGORIZATION

In order to summarize the technologies, a cauterization will be made based on their main characteristics: orbit, service, cost, and antenna type. The orbit is important for the telecommunications latency. The service encompasses the satellite's purpose, which will determine if the technology is suitable. The cost will then determine the economic feasibility of deployment. And finally, a result of the service and orbit, the type of antenna is crucial for the physical feasibility of deployment, for spatial reasons. This classification will allow for a better understanding and organization of the different types of satellites in use.

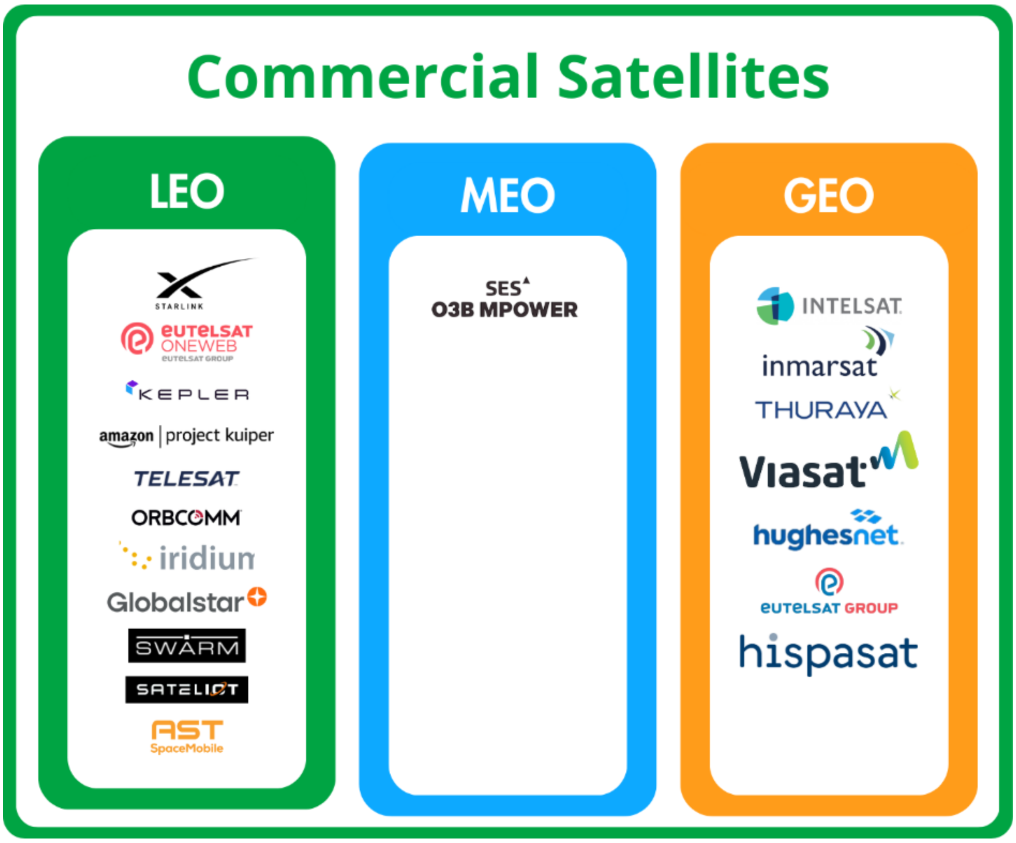


Figure 112: Orbit categorization

Regardless of the orbit, three types of service have been identified**: IoT messages, low-capacity IoT, and high-speed internet**. There are other services such as 5G, which are not yet available.

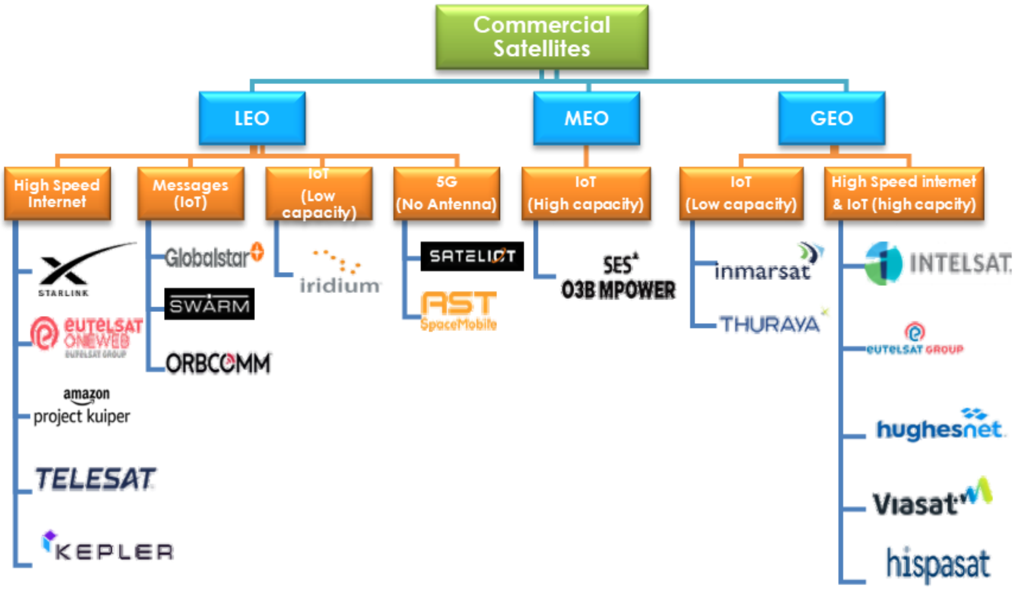


Figure 113: Service categorization

Depending on the service, higher or lower frequency bands are used. High frequencies provide greater bandwidth and, therefore, more transmission capacity, but they are more susceptible to environmental factors, such as heavy rain, which causes the phenomenon known as "rain fade", and can cause a total loss of communication. Therefore, **a higher frequency implies greater capacity but with more vulnerable communications, and vice versa.**

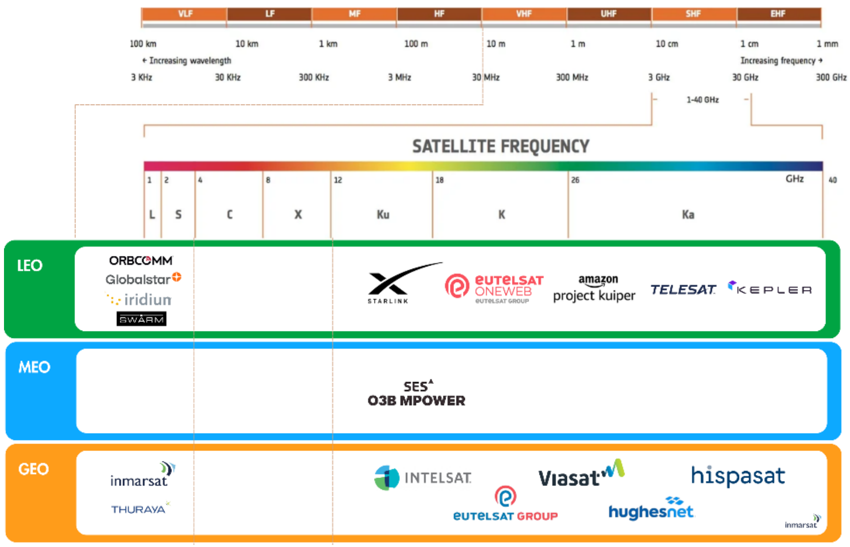


Figure 114: Frequency categorization

The frequency used also affects the type of antenna required. Robust low-frequency, low-capacity telecommunications services require small antennas (patch), while high-frequency telecommunications services require larger antennas capable of transmitting stronger signals and receiving weak signals, such as VSATs (Very Small Aperture

Terminals) or phase antennas. However, the market for the latter is focused on the development of more powerful and smaller antennas.

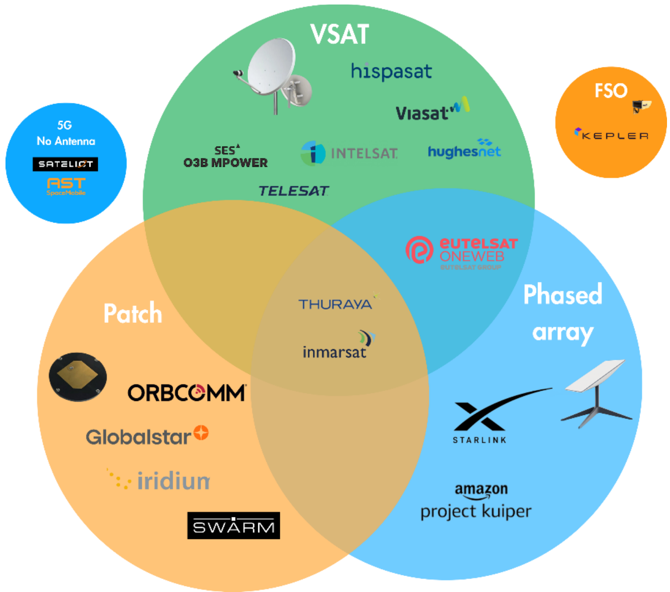


Figure 115: Antenna's sie categoriation

Costs have been estimated based on the plans offered by the main distributors. Given the difficulty in making direct cost comparisons, an approximation has been made using the cost per MB. This calculation is challenging because low-capacity technologies provide a base price for an initial range of data traffic and then charge extra for additional usage at higher rates. In contrast, high-capacity technologies often have a minimum offering that far exceeds the traffic requirements of the telecommunications system. Therefore, the following classification should be considered as a mere guidelines.

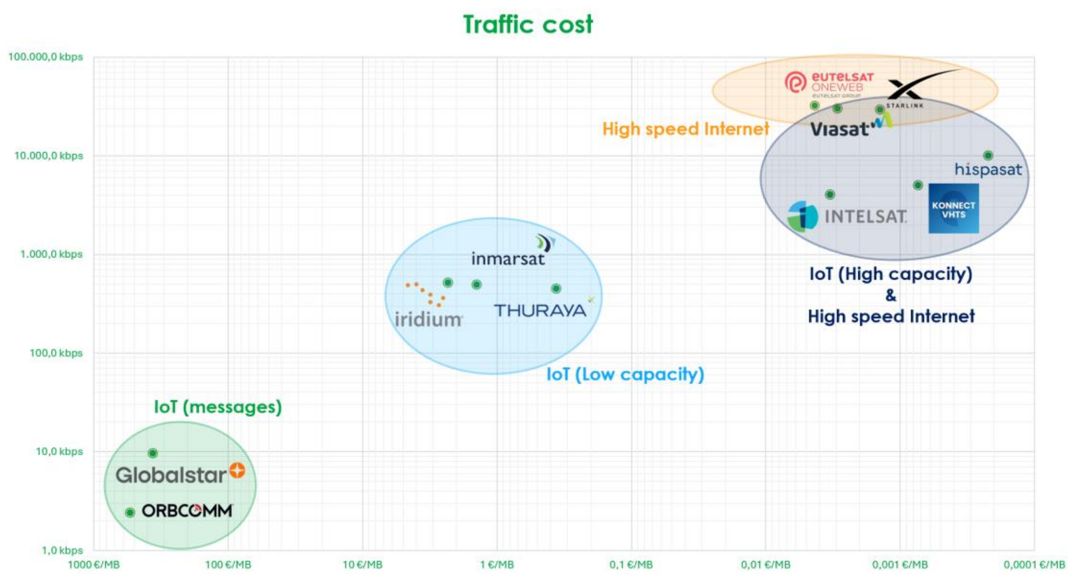


Figure 116: Cost categorization

Chapter 7. USE CASES

As mentioned in previous chapters, satellite technologies are the last technology to be considered when designing any telecommunication system. They are preceded firstly by optic fiber networks and then by wireless networks. These networks are preferred due to their technical characteristics; higher speed, higher transmission capacity, lower latency, and lower transmission costs. Thus, satellite communications are present in few circumstances, only employed where terrestrial networks are either not feasible or inaccessible, which is the case of rural and remote areas, at sea or during natural disasters, when the communications infrastructure is damaged.

This analysis delves into the identification of scenarios where satellite technologies could be considered within Iberdrola's owned assets and the analysis of the feasibility of securely communicating them, covering their crucial necessities, specific for each use case. Three use cases have been identified as potential options and will be analyzed in this chapter; large-scale electrical power plants and substations, remote secondary substations and remote reclosers and corporate offices communications.

7.1 LARGE-SCALE ELECTRICAL POWER PLANTS & SUBSTATIONS

It is not uncommon for this type infrastructures to be located in remote areas. Firstly, generation plants are designed to make the best use of resources which normally are distant from populated areas. And secondly, substations are located pursuing optimal grid development, rather than proximity to urbanized areas to be as cost effective as possible. However, there are instances where this locations are constructed elsewhere, not in the optimal site. This is because there are further considerations to include in the process of site selection. There are regulations that specify a certain distance that the infrastructure must be kept from populations in order to avoid disturbance. In addition, the design of these sites must take account of ecological constraints. No structure can be built in a protected area.

In the case of this large-scale electrical infrastructures, the disadvantages of not being close to civilization and its infrastructures, are compensated by some advantages, such as the lack of spatial constraints. Remote locations are characterized by the availability of large areas of land at low cost. Therefore, extra space can be made available for the installation of large telecommunications antennas at the design stage or at different stages of use, as expansion plans.

In terms of telecommunications, **substations** have the following telecommunication systems:

- **SCADA (Supervisory Control And Data Acquisition) systems:** for real-time monitoring and control, fault detection and management, data logging and devices and processes analysis. This are standardized and typically require a data delivery time of under 1 second.

- **AMI (Advanced Metering Infrastructure):** for metering and monitoring the energy flows, data collection and analysis to enable load balancing and demand response strategies. This systems share the delivery time with SCADAs.
- **Protection systems communications:** Some protection systems communications are; distance line protection, directional comparison protection or current differential line protection. Their criticality imposes a data information transfer delay under 10 ms. Thus, due to its characteristics, optic fiber (OF) is the only technology that can provide the service. Therefore, they are not considered in the satellite communications use case. They are treated separately, and are already included in most infrastructures.
- **Security systems:** Infrastructures need security measures to be secure from intruders. One of this systems is video surveillance. Occasionally, there is not enough capacity or this is too expensive, and a different approach must be taken. An intelligent solution is updated frames with video surveillance only connected when an alarm is triggered.
- **Mobile workforce communications:** for real-time crew communication and coordination. There are different strategies, such as push and talk, or Dedicated Communication Channel (DCC) with at least 100 kbps.

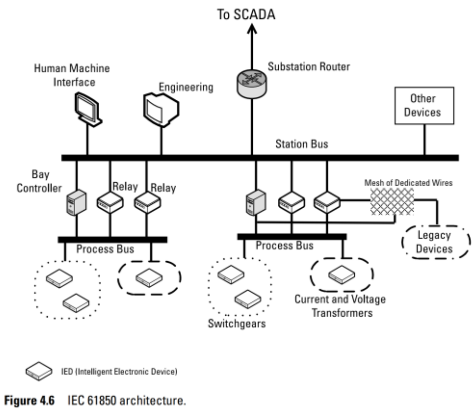


Figure 117: SCADA internal communications (Telecommunication Networks for the Smart Grid)

In **large-scale power plants**, most needs are shared with substations, though they further include.

- **Distributed Generation (DG) :** Which must be remotely monitored in terms of voltage level and power quality to control frequency, flicker, power factor, and harmonics between others

The different needs and constraints, common to this type of installation, are added up and summarized in the following table.

Large-scale electrical power plants & substations

Traffic	8 GB/month
Capacity	25 kbps
Latency	< 1s
Packet loss	Critical
Availability	> 99%
Reference feasibility cost	100 €/month/station
Antenna size	Not critical

Table 20: Large-scale electrical power plants & substations use case parameters

Once the requirements have been identified, the analysis of the commercial technologies covered in previous chapters can be carried out.

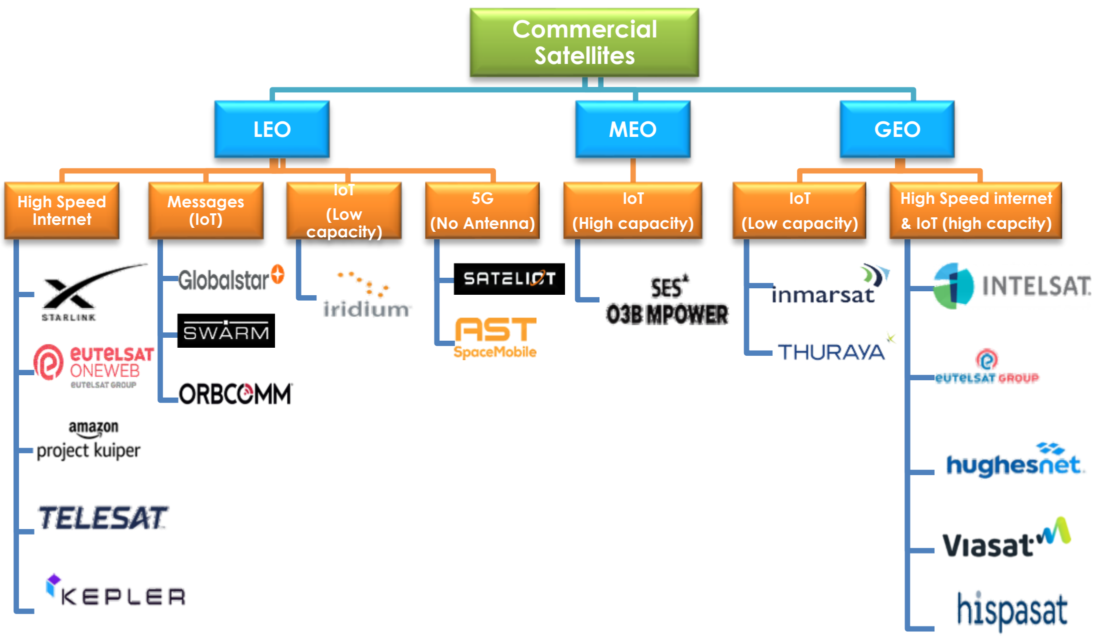


Figure 118: Studied satellite technologies

The analysis will be made within **the current available technologies**. In the near future, when promising upcoming technologies become available, a further study is recommended to be carried out. However, in this study they will not be considered.

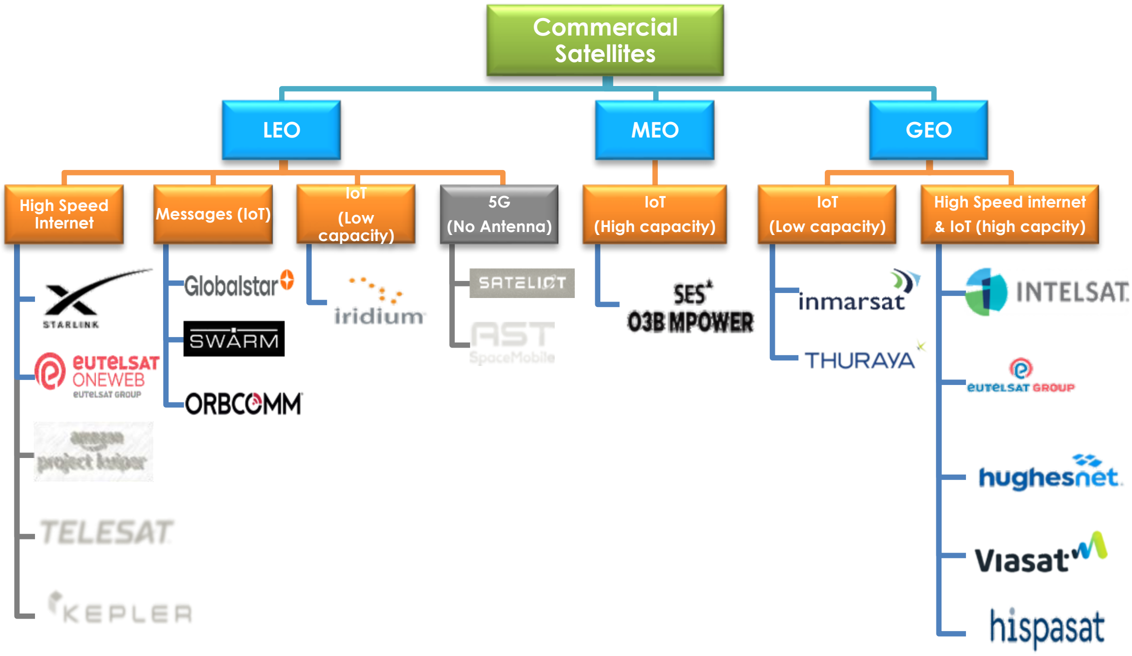


Figure 119: Shadowed not available satellite technologies. (Upcoming projects)

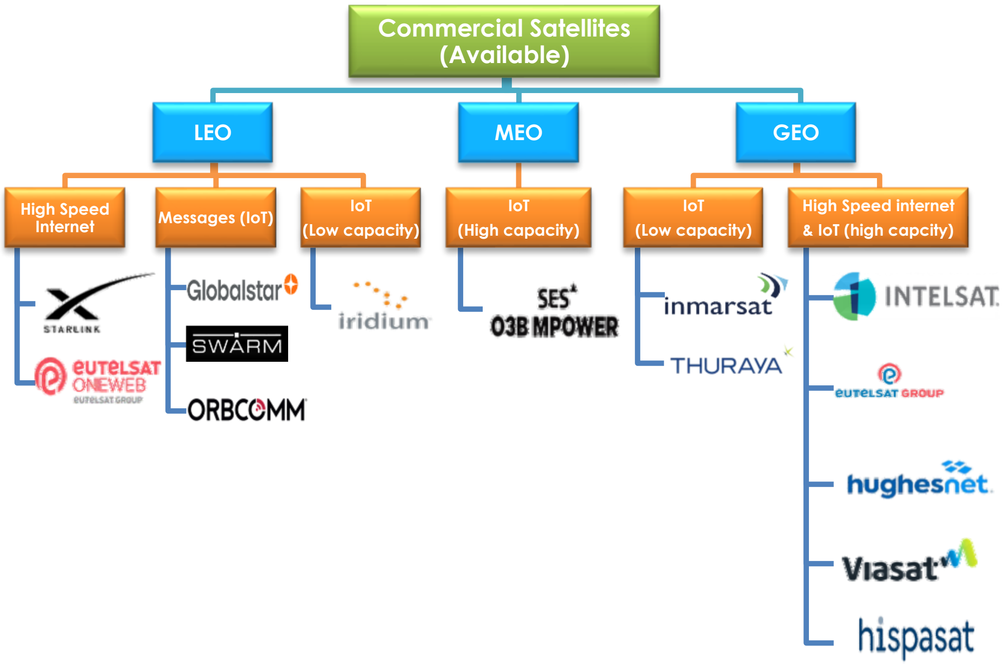


Figure 120: Available satellite technologies

A crucial necessity, not mentioned before, is the **need of Iberdrola of nearly 100% availability.** Thus, technologies under 99% coverage (Spain) will not be considered.

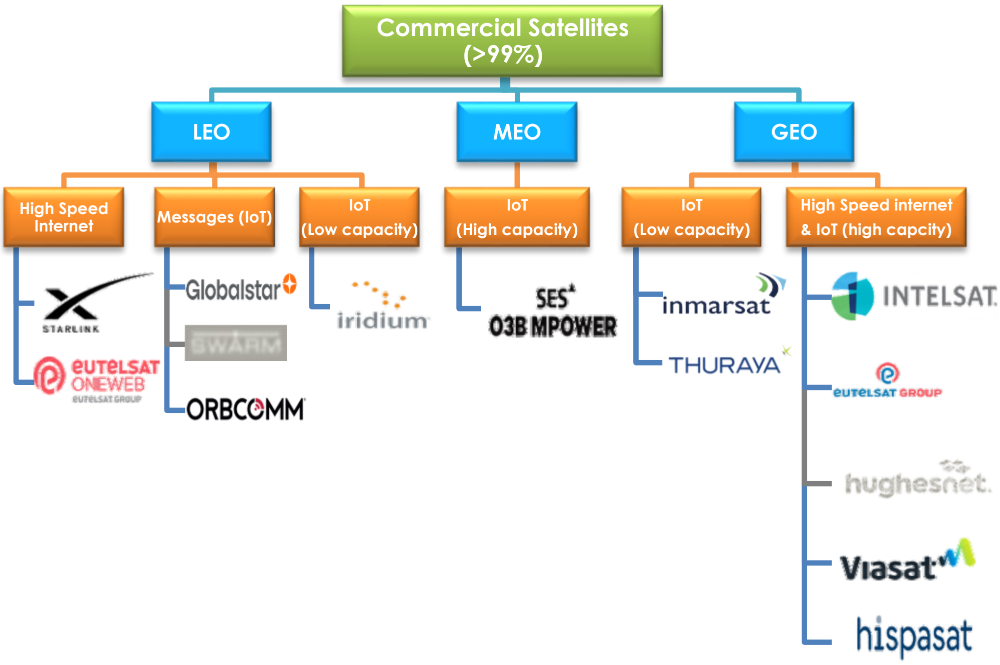


Figure 121: Shadowed not >99% available satellite technologies

Finally, IoT messaging technologies also need to be discarded because they are not really true data communication. The transmission of messages does not fit with any of the scenarios or the telecommunications architecture of Iberdrola.

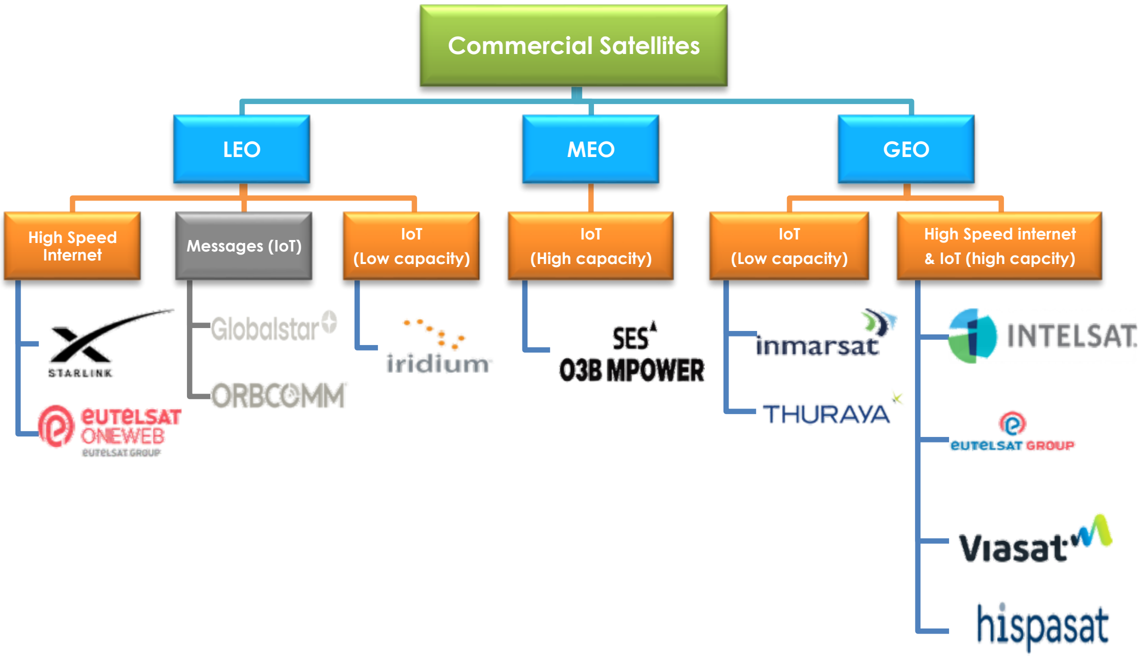


Figure 122: Shadowed non-data satellite technologies

All three use cases will base their analysis only on the technologies present in Figure 123.

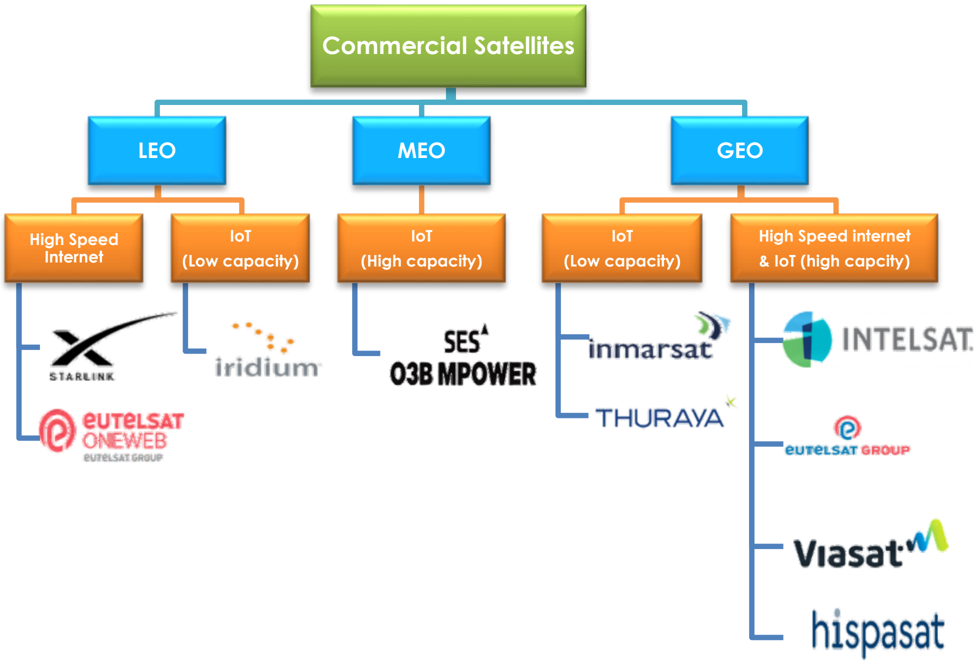


Figure 123: Suitable technologies

Without the size of the antennas constraint, the only restrictions are transmission capacities and costs. As mentioned, the capacity requirement is around 25 kbps symmetrical, which can be supplied by all of the suitable technologies. At this final stage, the analysis needs to filter through their cost feasibility. The threshold is 100€ for 8GB per month (0.0125€/MB).

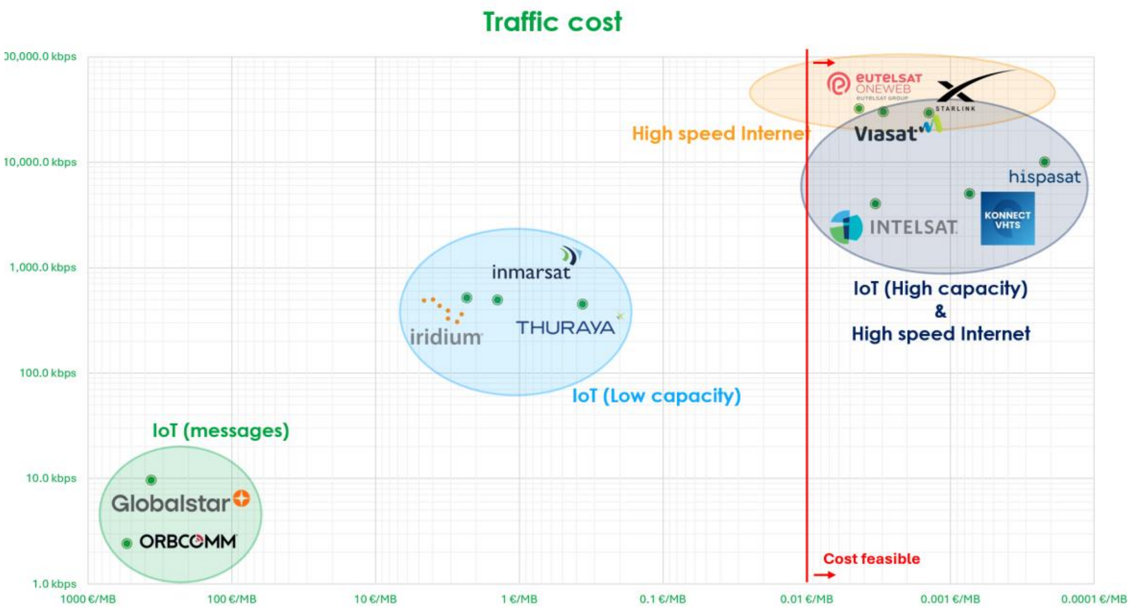


Figure 124: Commercial technologies cost feasibility (Large-scale electrical plant use case)

In terms of cost feasibility, Low Capacity IoT technologies are clearly not feasible, their cost is 2 orders of magnitude higher than the threshold. This only leaves High Speed Internet solutions, both GEO and LEO.

Currently, Iberdrola has the GEO VSAT High Speed Internet technologies in use. They have sufficient capabilities to cover all telecom requitements, including the need of dedicated private channels to ensure the telecommunications, highly important in real-time systems such as monitoring, that requires determinism.

LEO high speed internet technologies offering meet all the capabilities requirements. Nonetheless, this have to be tested to ensure the network characteristics. This tests have been carried out and are described in the following chapter, **Chapter 8**. Then, based on the results, the viability and possibilities for integration will be evaluated. This evaluation will be carried out in the **Conclusion** of the study.

7.2 REMOTE RECLOSERS AND SECONDARY SUBSTATIONS

This use case share multiple similarities with the large-scale energy sites use case. In the end, it is simply a downscale. Large-scale energy sites have a large number of assets to control, while this use case represents only a small part of those assets separately. The downscale of traffic requirements is not paired with the number of elements. If it were, the requirements would be much lower. This transmission speed capacity is also influenced by the telecommunications protocol. Thus, the downscale is not proportional to the reduction of communicating devices.

Remote reclosers and remote secondary substations have a critical downside, reduced available space. They are small assets, typically located on posts or in small buildings. Thus, technologies that utilize big antennas are not feasible.

Figure 125: Right: Recloser; Left: Secondary substation (Iberdrola)

In all the other aspects, they mirror big energy sites but in a smaller scale referring to data traffic and capacity rates. As they only require to transmit the data from SCADAs and AMIs, as well as being capable of receiving control orders. An estimate of Iberdrola's needs for this kind of assets is the following.

Remote Reclosers and Secondary Substations

Traffic	300 MB/month
Capacity	1 kbps
Latency	< 1 s
Packet loss	Critical
Availability	> 99%
Reference feasibility cost	10 €/month
Antenna size	Critical

Table 21: Remote reclosers and Transformers substations use case parameters

Filtering the technologies that require large antennas is complex. Numerous satellite operators leave the task of developing antennas to third actors that have different incentives. Nevertheless, as it is the market the one that fixes those incentives, they can be somehow classified and superficially characterized. The first classification is made in the type of antennas the technologies typically use.

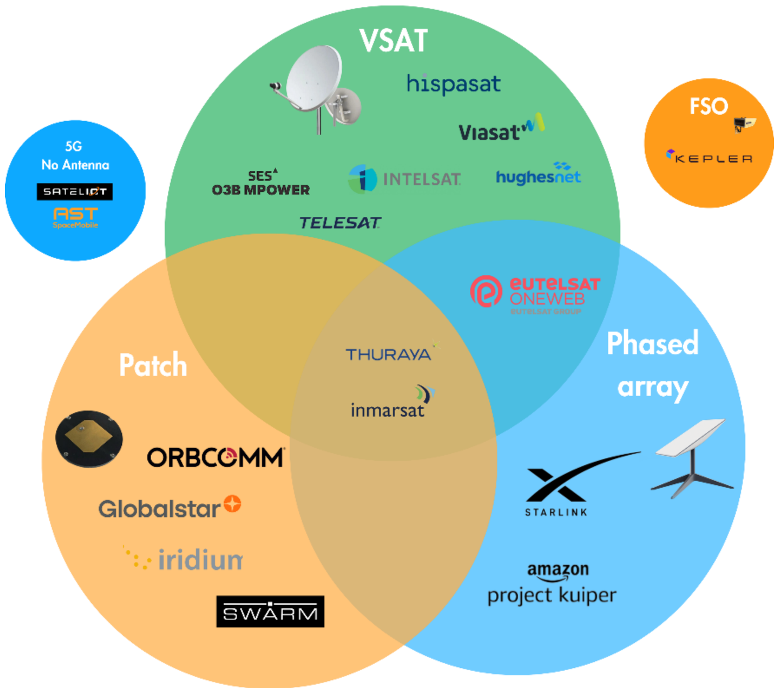


Figure 126: Antennas classification

Patch antennas are small and oriented towards small transmission capacities. As a proof of it, it can be observed that technologies that use this type of antenna are classified in Message IoT and Low Capacity IoT. On the other hand, VSAT(Very Small Amplitude Terminal) are typically large size antennas dedicated to GEO and high capacity technologies. This technology is mature as it is the technology that was firstly used in satellite communications. Apart from its size, the technology has the downside of having to be orientated. And finally, there are the phased array antennas. They are the state of the art technologies and could be considered as the evolution of VSAT. They don't require orientation, thus facilitating its installation and eliminating the installation costs. At first, their size was comparable to VSAT, however their size reduction is now in the focus of manufacturers and some small size antennas can already be found in manufacturers catalogs.

Some future projects aim to develop direct to device satellite communications (5G) with no need of antenna and others are trying to revolutionize the capabilities of transmission capacities by using the optic spectrum, as optic fiber technologies. However, this are in progress projects, and also come with some downside. More information about antennas can be found in the dedicated chapter.

Continuing with the case study analysis, considering the available technologies (Figure 123), all VSAT technologies are discarded because its size. In addition, Message IoT technologies are also discarded as they are not able to comply with the telecommunications requirements. Messages are not compatible with Iberdrola's data architecture.

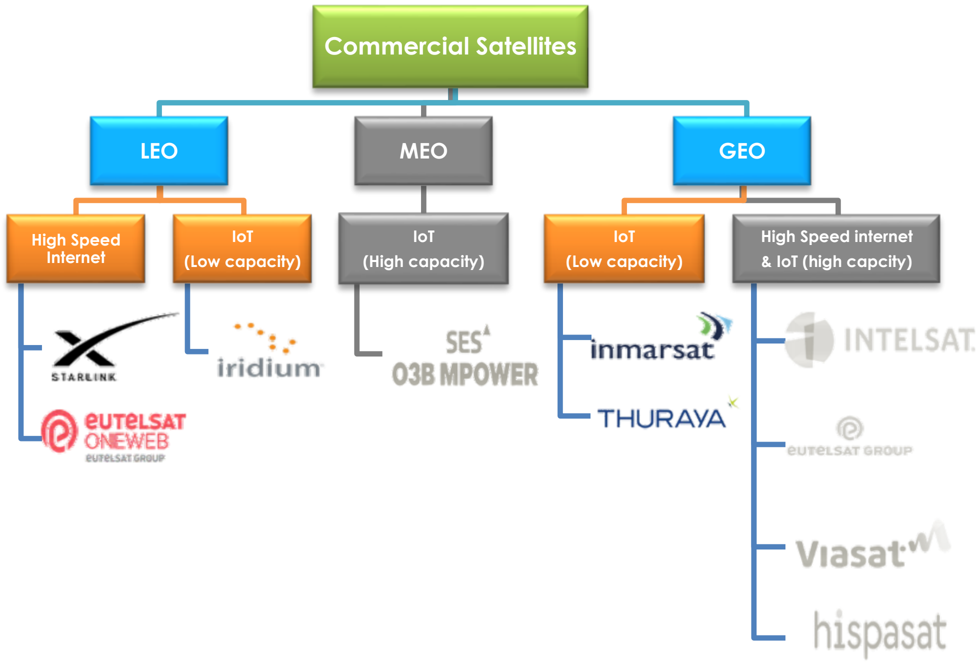


Figure 127: Suitable technologies

Only Low Capacity IoT and LEO High Speed Internet are suitable for this assets at this stage of the analysis.

Costs is the final restraining aspect. Because of the fact that this assets are small and numerous, and costs has to be more competitive than the actual system (an operator that reads the meters). Costs filter Low Capacity IoT devices, their price surpass the threshold of 0,033€/MB (300 MB/month; 10€/month). The Intelsat marketers offer 45€ for 50MB/month, Iridium 240€ for 100MB/month and Thuraya 350€ for 1GB/month. Extrapolating the prices to the needs of each device while keeping the cost €/MB, they are all much higher than the €10 budget.

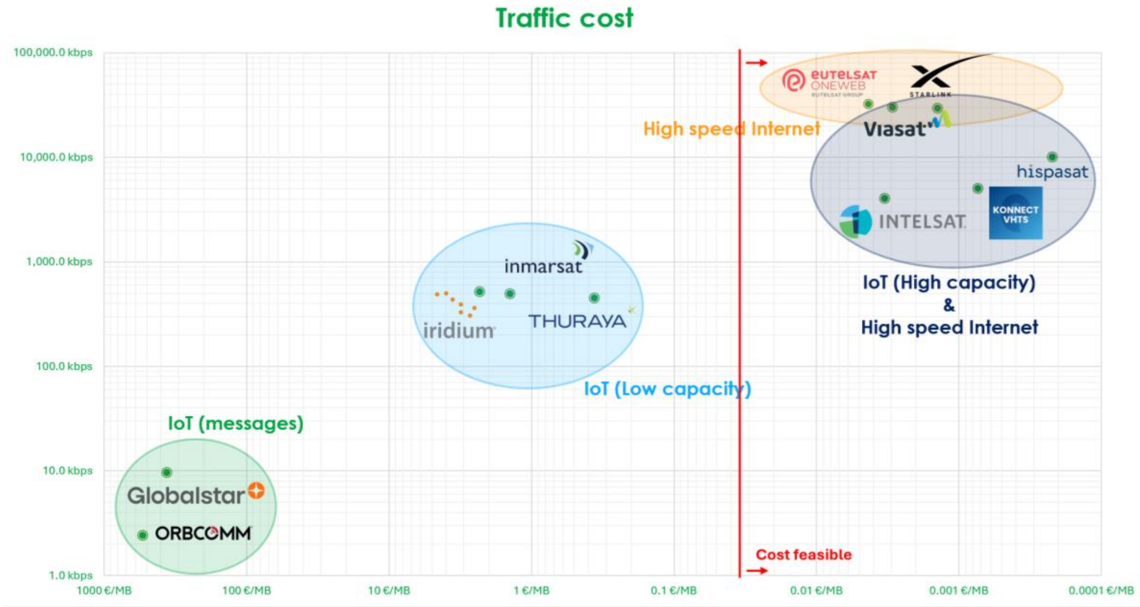


Figure 128: Commercial solutions traffic cost (Reclosers and SS use case)

Then, the remaining technology under study is the new LEO High Speed Internet. This however, could also be discarded for several reasons. First, the current antennas are a bit larger than desired. It is known that manufacturers are working on smaller antennas, but these are not expected for a few years, at least 2026, with the arrival of Kuiper. Kuiper announces that it will bring a 7cm x 7cm antenna to market, and the competition (Starlink and OneWeb) will probably be force to come up with similar options.

On the other hand, due to the residential focus, the minimum offer is 40GB. Excessive for the needs of this use case. Even if the cost (€/MB) is much lower than required, the cost exceeds the budget due to the distant minimum service contract. Finally, the cost of antennas cannot be afforded for this type of device. Currently, due to the new technology of phased array antennas, the prices are extremely high, reaching more than 15.000 €/antenna. For the other cases, the amortization can be studied, but for this case it is intuitive that it is extreme and does not even require a study. Therefore, **there is no current feasible commercial satellite technology option.**

7.3 OFFICE

There are cases where substations and generation plants have integrated offices rather than dedicated buildings in nearby towns, especially in remote locations. These need to meet the requirements of office telecommunications services for a small number of employees, while not being covered by the common technologies (fiber optic, backed up via cellular networks).

Figure 129: Remote office (Source: Iberdrola)

Corporate telecommunications can be reduced to video calls, internet access and a few activities more. Offices have high traffic sites, and require small latency for telecommunications as services are real-time and QoS might be affected.

Employee internet consumption breakdown

Email Communication	100 MB/day
Internet Browsing	400 MB/day
Video Conferencing	2500 MB/day
File Downloads/Uploads	500 MB/day
Cloud Services	500 MB/day
Total	**4 GB/day**

Table 22: Data traffic consumption breakdown

Typically, the quality of these services are not affected until the latency surpasses the threshold of 150 ms. At this point, videoconferences and calls may start to lag and the communication will be affected. Other requirements that corporate communications have are included in the following table.

Office

Traffic	1 TB/month
Capacity	10 Mbps
Latency	150 ms
Packet loss	Non critical
Availability	> 99%
Reference feasibility cost	1000 €/month
Antenna size	Non critical

Table 23: Office use case parameters

For the monthly traffic requirement, an average of 10-11 employees has been assumed. With each consuming 4GB/day, and considering that a month has 22 working days, it results in a consumption need of about 1 TB/month.

The first filter to consider is the latency, technologies that have delays over 150 ms cannot be considered. This excludes all GEO solutions which have latencies of around 600 ms, due to their distant altitude.

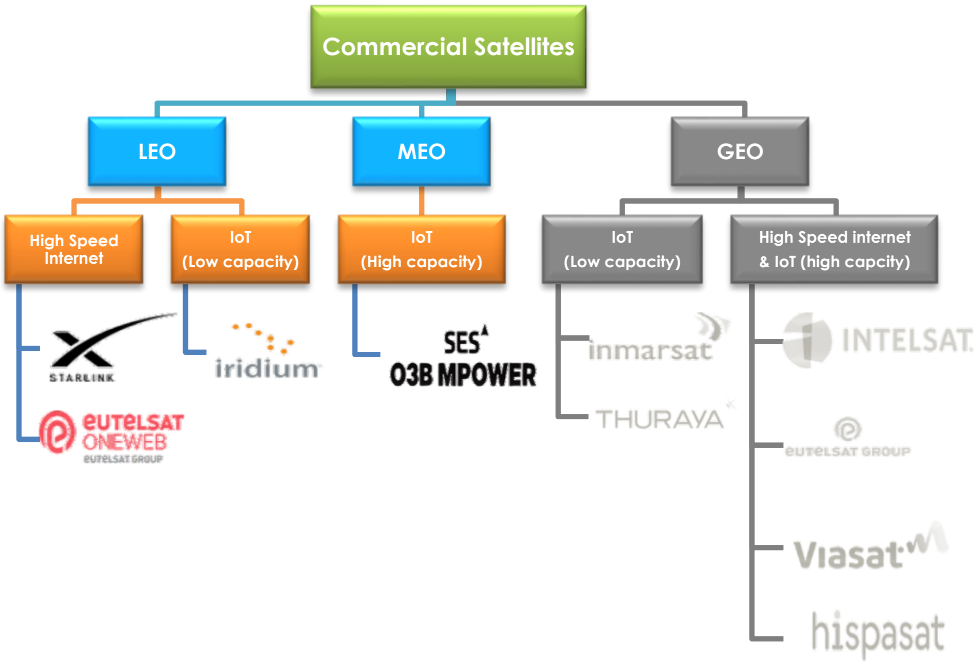


Figure 130: Shadowed GEO non-suitable technologies

Furthermore, due to the high traffic speeds IoT(low capacity) technologies are also discarded. In addition, due to their lack of price disclosure, SES technology has also been discarded.

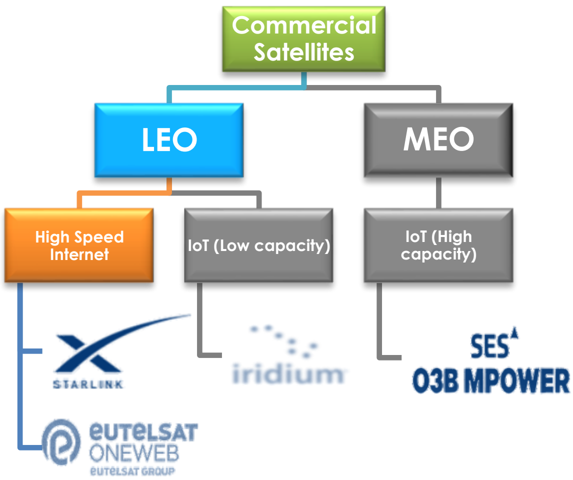


Figure 131: Shadowed GEO non-suitable technologies

Only the new LEO high speed internet technologies meet the specified requirements. Finally, for economic feasibility, the cost of service should not exceed the threshold of 1000€/month. Their prices will be covered in depth in the following chapter. However, to show the feasibility, it can be anticipated that, for instance, Starlink has a 1TB/month plan for 180€/month. Almost an order of magnitude under the threshold.

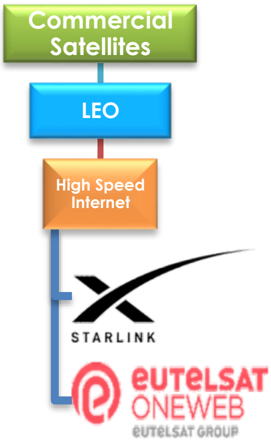


Figure 132: Corporate office suitable technologies

Once again, this technologies are suitable in theory, based on the offering. However, for an unbiased assessment, they will be tested and evaluated based on the results obtained.

Chapter 8. LEO HIGH SPEED INTERNET CONSTELLATIONS

This chapter takes an in-depth look at the new LEO technologies that promise to bring high-speed Internet to the most remote corners of the globe. We will analyze their technology, operating model, and costs, and perform a series of tests to verify their specifications.

8.1 STARLINK

Starlink, a division of SpaceX, is the first and largest low-Earth orbit (LEO) constellation with more than 5.500 satellites and plans of expansion to create a constellation of more than 30.000 satellites. Founded by Elon Musk, Starlink aims to bridge the digital divide by bringing high-speed broadband Internet connectivity to the most remote and underserved areas of the planet where traditional broadband solutions are unavailable. [35]

The **competitive advantage** that the LEO constellations have is the **lower latency** that enables to deliver **faster Internet speeds**. Which is critical for applications that require high responsiveness, such as video calling. The second concept on which Starlink business model is based on is the **ease of installation**. The Starlink kit includes a satellite dish and Wi-Fi router and can be set up **in minutes by users without technical assistance**. The antenna self-calibrates and automatically orients itself to optimize the signal.

Finally, its goal is to position itself as the best worldwide internet service provider. And it aims to achieves this by providing enormous capacity to its system through its massive constellation.

Figure 133: Starlink Logo (Source: Starlink)

8.1.1 CONSTELLATION

Starlink currently has more than 5,500 satellites in low earth orbit (LEO). These satellites are divided into two major versions: Starlink v1.0-1.5 with 4,332 satellites and Starlink v2 (mini) with 1,269 satellites. These satellites are distributed in different orbits between 450 km and 550 km altitude. Most of the orbits are prograde inclined, optimized to provide service in the central region of the Earth, where most of the landmass, and therefore the main market, is located. However, Starlink also has some polar orbits to provide global coverage. The Starlink orbits have an orbital period of about 90 minutes, allowing each satellite to pass over a particular region several times a day.

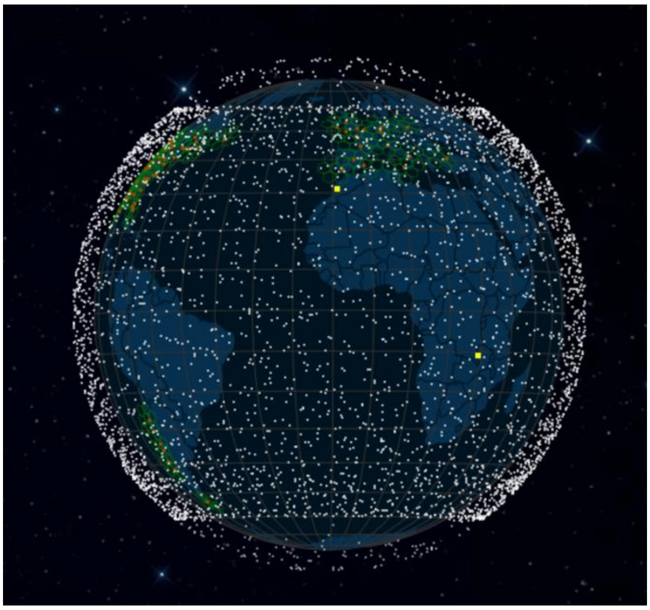


Figure 134: Starlink constellation (Source: Satellitemap.space)

SpaceX is launching the Starlink satellites in clusters using its Falcon 9 rockets, with each launch capable of carrying up to 60 satellites, allowing for rapid expansion of the constellation. The satellites are equipped with phased array antennas to communicate with ground stations and each other, forming a mesh network that optimizes data paths to improve efficiency and reduce latency. In addition, the satellites use krypton ion thrusters to maintain their orbits and perform space debris avoidance maneuvers, helping to extend their lifetime and minimize the risk of collisions in space.

Figure 135: Starlink satellites (Source: Business Insider)

8.1.2 OPERATION MODEL

Starlink operates an **integrated system** that includes ground stations (gateways) as well as in-house antenna and satellite manufacturing. This vertically integrated approach allows full control over all aspects of infrastructure and service. The network of ground stations in Spain, of particular interest in this study, includes sites in Lepe, Ibi and Loeches, as shown in Figure 136.

Figure 136: Starlink gateways stations in spain (Source: BandaAncha.eu)

8.1.2.1 Data Transmission

Starlink uses a **meshed network for data transmission**, which means that the data link between the user and the gateway travels through multiple satellites until it is **offloaded to the closest and least congested ground station.** This does not guarantee that the station used will always be the closest in terms of physical distance, but rather the most optimal in terms of traffic and capacity. In the case of Spain, any of the three stations (Lepe, Ibi, Loeches) could handle a user's traffic, depending on congestion at the time, but it could also go to a nearby station outside the national territory.

Figure 137: Starlink intersatellite communications (CNBC)

Starlink uses **CGNAT** (Carrier-Grade Network Address Translation) for its **telecommunications infrastructure**, which means that it **does not assign dedicated**

public IPs to users. This may limit certain applications that require static IPs. Although service plans offer the option of prioritized traffic, dedicated segments and public IPs are not guaranteed. Information is then transmitted over the Internet, which reduces the security of communications. Determinism in communications is an essential element for real-time monitoring and action services such as those required by Iberdrola.

8.1.2.2 Satellite Network Operations

The Starlink's satellite network is carefully managed to maintain continuous, high-quality coverage. The satellites have a relatively short lifetime of approximately 2 years. This is due to the need to keep technology up to date and operational in the challenging environment of space. The satellites are launched in groups on Falcon 9 rockets and can often be seen online from Earth during deployment, appearing as a bright comet in the night sky.

Figure 138:Starlink satellites deployment (Source: RTVE)

For end-of-life management of the satellites, Starlink carefully plans their re-entry into the Earth's atmosphere to ensure they burn up and leave no space debris. The constellation also includes about 500 backup satellites that can quickly replace any satellite that fails. The size and redundancy of the network means that even if a satellite fails, end users will rarely experience a disruption in service.

8.1.3 SATELLITE SYSTEMS

Each satellite features a compact, low-profile design that minimizes volume and allows for a dense launch stack to take full advantage of the launch capabilities of SpaceX's Falcon 9 rocket.

Figure 139: Left: Deployed Satellite; Right: Satellite stack for launch (Source: Starlink)

8.1.3.1 Star Tracker

Starlink's proprietary navigation sensors scan the stars to determine the position, elevation and orientation of each satellite, enabling precise tracking of broadband throughput.

Figure 140: Star Tracker (Source: Starlink)

8.1.3.2 Optical space lasers

Each Starlink satellite contains three space lasers (intersatellite optical links, or ISLs) capable of up to 200 Gbps, which together across the constellation form a global Internet mesh that can connect customers anywhere in the world.

Figure 141: Optical space lasers (Source: Starlink)

8.1.3.3 Antennas

Each Starlink satellite uses 5 advanced Ku-band phased array antennas and 3 dual-band antennas (Ka-band and E-band) to deliver high-bandwidth connectivity to Starlink customers.

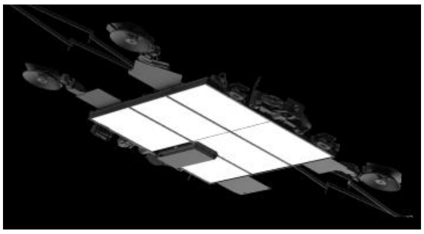


Figure 142: Antennas (Source: Starlink)

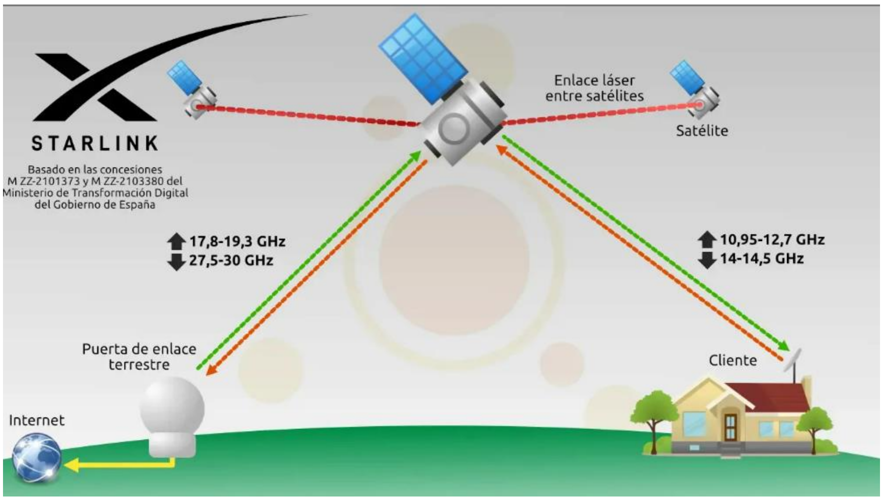


Figure 143: Starlink's telecommunications networking (Source: BandaAncha.eu)

8.1.3.4 Ionic propulsion systems

Efficient argon thrusters allow Starlink satellites to increase their orbital altitude, change their trajectory in space, and exit orbit at the end of their service life. Starlink is the first argon-powered spacecraft to fly in space.

Figure 144: Ionic propulsion systems (Source: Starlink)

8.1.3.5 Power systems

The Starlink satellites feature a dual solar array and a high-capacity battery to power the payloads. The dual solar arrays are also aerodynamic, allowing for faster maneuvering in orbit.

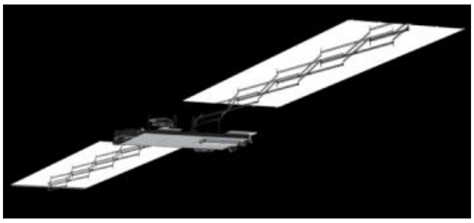


Figure 145: Power systems (Source: Starlink)

8.1.3.6 Reaction wheels

Four reaction wheels provide agile vehicle control. The hot-swappable configuration ensures highly reliable operation, and the aluminum flywheel is completely removable at the end of its service life.

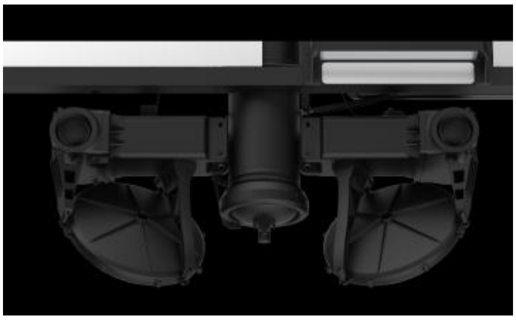


Figure 146: Reaction wheels (Source: Starlink)

8.1.3.7 Collision avoidance systems

SpaceX uses precise location and prediction data for collision avoidance, sharing it with the U.S. Space Force, LeoLabs, and other operators. Starlink satellites, equipped with autonomous systems, maneuver to avoid collisions if the probability exceeds 1/100,000. They can also "duck" to minimize collision risk. The system, reviewed by NASA, ensures safety by avoiding space stations like the ISS and Tiangong. SpaceX coordinates with other operators and advocates for transparent, sustainable space operations. This approach enhances space safety and sustainability for future exploration.

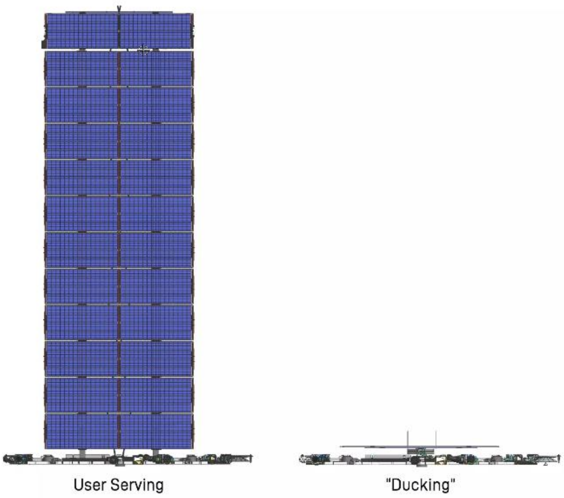


Figure 147: SpaceX's "duck" maneuver (right) minimizing area in potential collision direction (out of page) compared with worst-case orientation (left) (Source; SpaceX)

8.1.4 SEGMENTS

At a high level, Starlink divides its services into residential and business. On the residential side, they divide their services into Residential (Connection at home), Itinerant (connection in motion) and Boats (connection in the water).

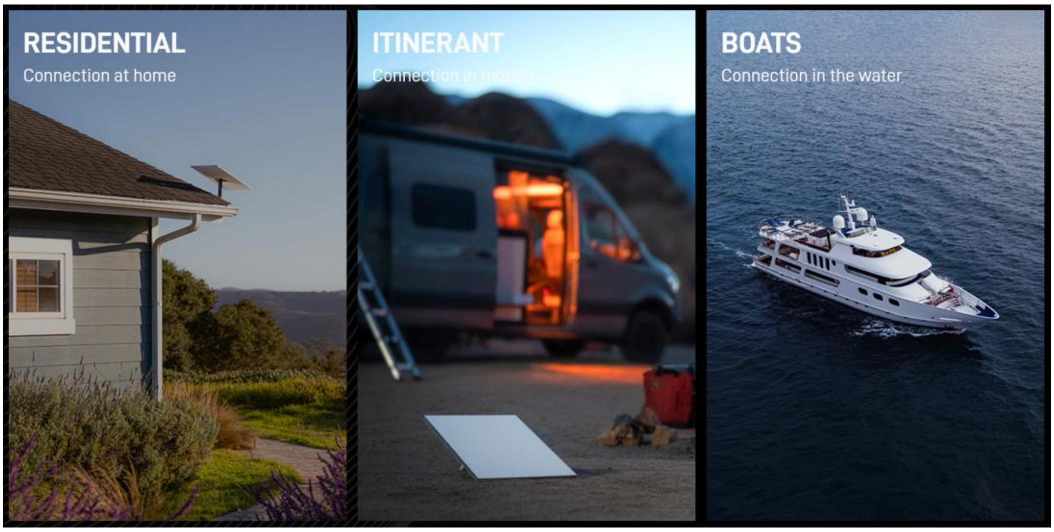


Figure 148: Starlink residential segments (Source: Starlink)

In the business sector, it extends its segments to 4, the three previous ones (Fixed, Land Mobile and Maritime) and includes Aviation.

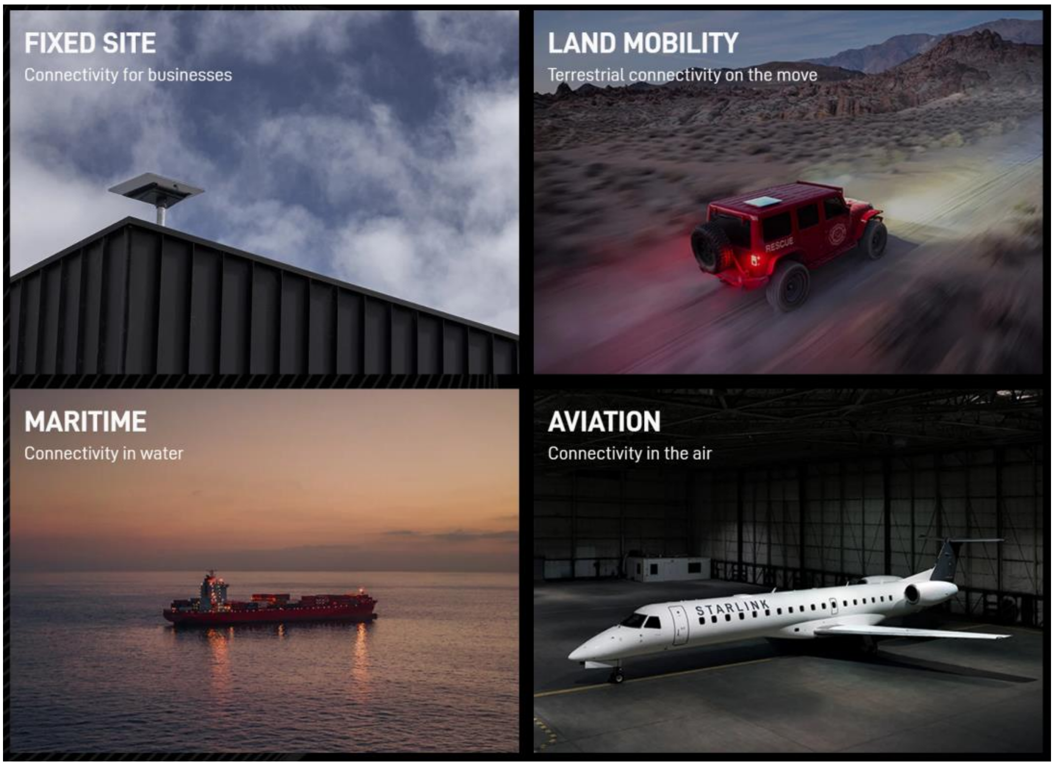


Figure 149: Starlink business segments (Source: Starlink)

8.1.5 SERVICE PLANS

Starlink differentiates its plans through its segments, and includes an upgraded plan of priority. This priority, by the moment, does not guarantee the service. It just prioritize the traffic over the standard plan. In terms of SLA, they do not guarantee their availability. However, they do state that their goal/pledge is to provide over 99.5% worldwide availability.

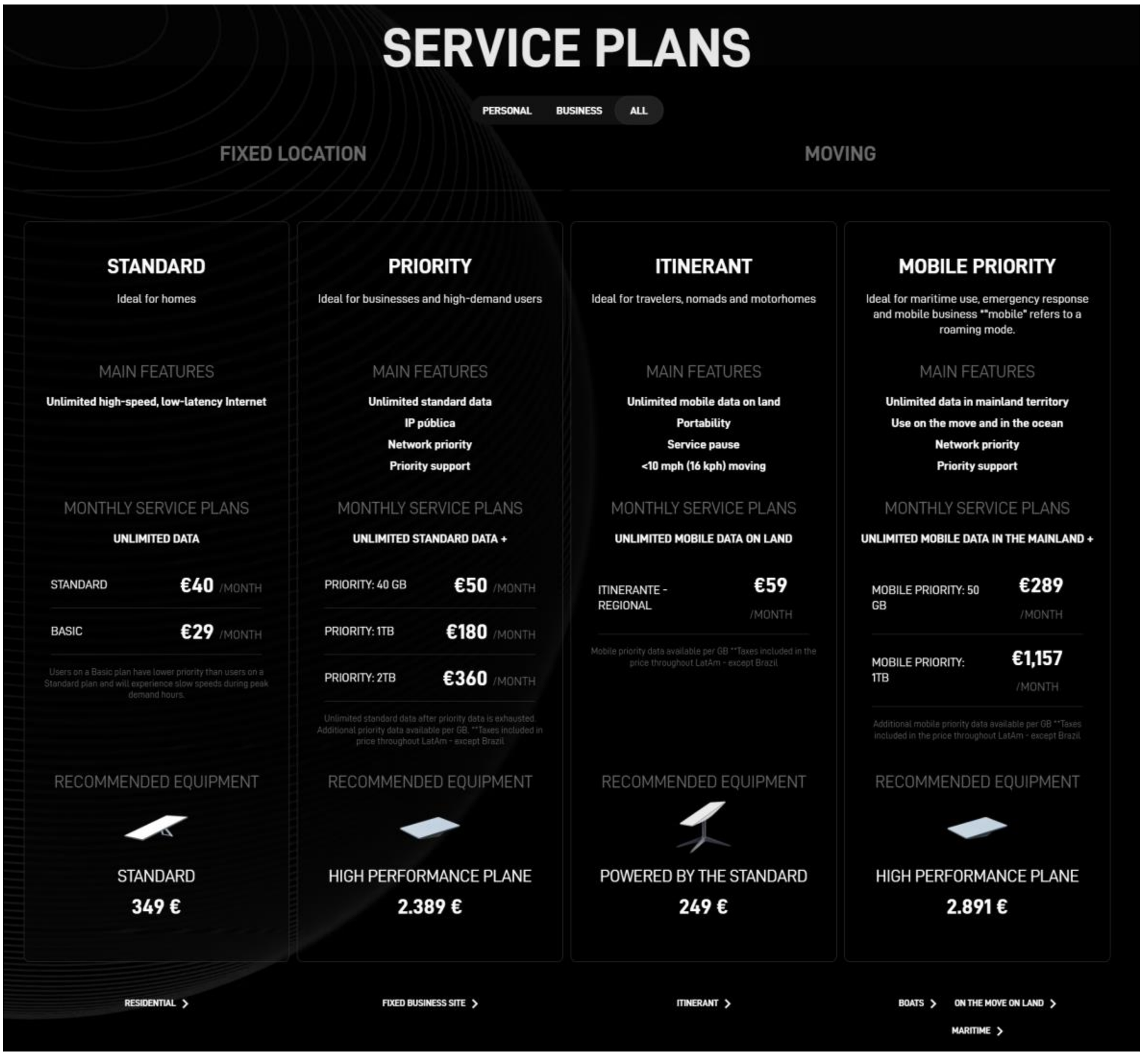


Figure 150: Starlink service plans (Source: Starlink)

8.1.6 END-USER TECHNOLOGY

Starlink offers five different kits tailored to various user needs. Mini, Standard, Standard Actuated, High Performance and High Performance Plane.

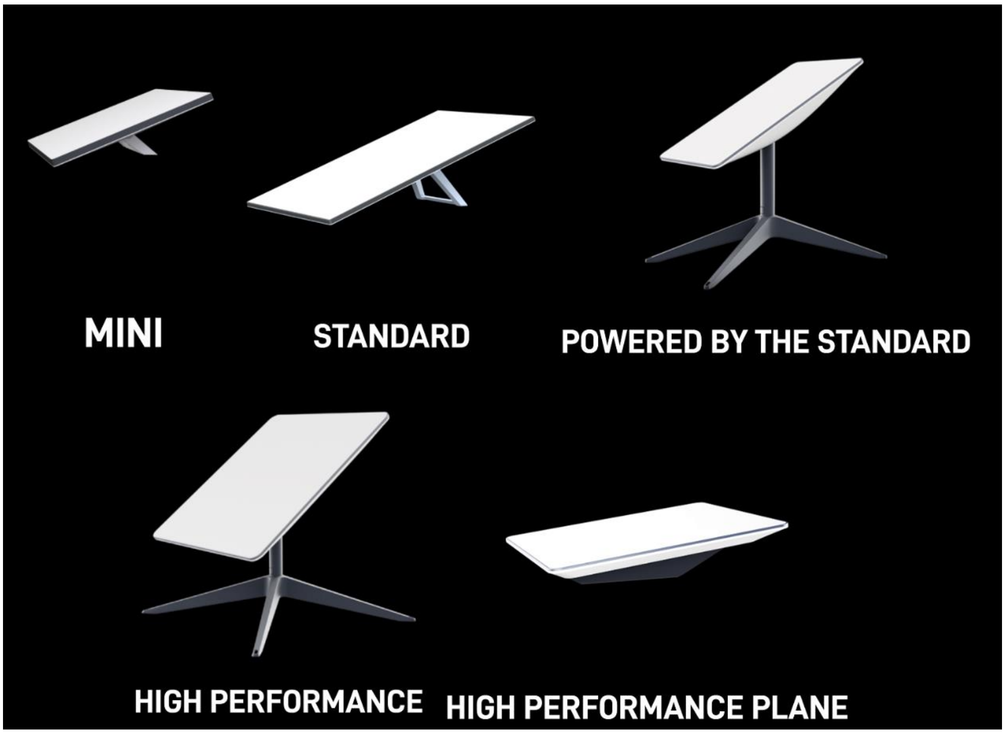


Figure 151: Starlink Antennas (Source: Starlink)

Technology Kit	**Size**
Mini	430 x 334 x 79 mm
Standard	594 x 383 x 39 mm
Standard Actuated	513 x 303 39 mm
High Performance	575 x 511 x 39 mm
High Performance Plane	575 x 511 x 41 mm

Figure 152: Starlink Kits size

They all share some fundamental components:

- **Antenna:** Each kit includes an electronic phased array antenna, designed to withstand harsh environmental conditions and can operate within a wide temperature range.
- **Wi-Fi Router:** The kits come with a Wi-Fi 5 (IEEE 802.11a/b/g/n/ac) router, providing dual-band connectivity and supporting up to 185 square meters of coverage. The routers are equipped with WPA2 security and are compatible with up to three Starlink Mesh nodes for extended coverage.

- **Cabling and Power Supply:** Each kit includes a Starlink cable (15.2 meters) and an AC cable (1.8 meters), ensuring that users have everything they need to set up their internet connection.

*Further information about the kits can be found in Starlink's website.

8.1.7 Commitment to Space Sustainability

SpaceX, and therefore Starlink, is dedicated **to maintaining space safety, sustainability, and accessibility,** ensuring the protection of astronauts, satellites, and the public. Starlink satellites operate below 600 km, naturally deorbiting within 5 years if they fail. SpaceX proactively deorbits high-risk satellites, minimizing non-maneuverable objects. They have controlled deorbits for 406 of nearly 6000 launched satellites, planning further controlled descents for early Starlink versions. SpaceX also encourages transparency in satellite positioning and proactively publishes future positions to enhance space sustainability.

SpaceX is also committed to balancing global broadband connectivity with **preserving the night sky**. Collaborating with the astronomical community, SpaceX has implemented innovative techniques to mitigate satellite brightness, ensuring minimal impact on astronomical observations. Efforts include altering flight orientations and adding deployable visors to block sunlight. Starlink satellites operate in low Earth orbit, reducing light reflection and interference. These initiatives reflect SpaceX's dedication to a sustainable and usable space environment for scientific research.

8.1.8 Starlink future plans

8.1.8.1 Direct to Cell

SpaceX is expanding its Starlink services to include Direct to Cell capabilities, which will provide seamless access to text, voice, and data services for LTE phones globally. This initiative is designed to connect areas that have traditionally been underserved by terrestrial networks. Direct to Cell will not require any changes to existing LTE hardware, firmware, or special applications, making it highly accessible. The service is set to start providing text capabilities in 2024, with voice and data services following in 2025.

8.1.8.2 Internet of Things (IoT)

In addition to expanding mobile coverage, Starlink's Direct to Cell service will also enable widespread IoT connectivity. This will allow millions of IoT devices across various industries to stay connected outside of traditional terrestrial coverage areas, using common LTE standards. The IoT service is scheduled to commence in 2025, providing robust connectivity for critical applications in industries such as agriculture, logistics, and environmental monitoring.

8.1.9 TESTS

Tests have been conducted on Starlink technology thanks to a Spanish service provider, Satlink, who has made a high-performance portable antenna available to Iberdrola. The tests aim to measure the most important telecommunications parameters: traffic speed, latency, packet loss, and availability, in addition to evaluating stability. These requirements are crucial when assessing technology for the various applications an electric company may have.

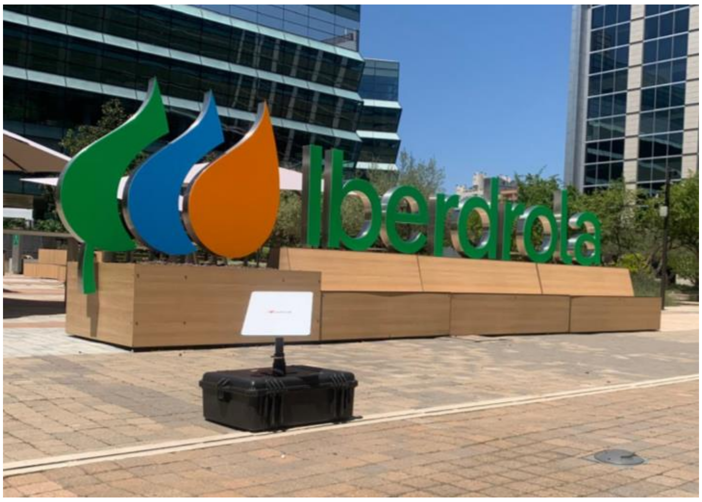


Figure 153: Satlink's Starlink antenna

Different software tools have been used to achieve the test results. Firstly, to measure traffic speed, the Cloudflare speed measurement tool was used. This tool not only provides a detailed summary of a specific test but also allows data logging. The instant speed test is useful and provides the user with interesting graphs. However, this study requires a long-term view to truly evaluate Starlink's capabilities. It is necessary to determine whether the results of instant speed tests are stable or sporadic. Therefore, this software was chosen, as the Cloudflare Speedtest allows the generation of a ping log in CSV format. For the test, measurements of 20 pings were taken every minute for half an hour in three sessions at different times of the day over several days.

CLOUDFLARE

Figure 154: Cloudfare logo (Source: Couldfare)

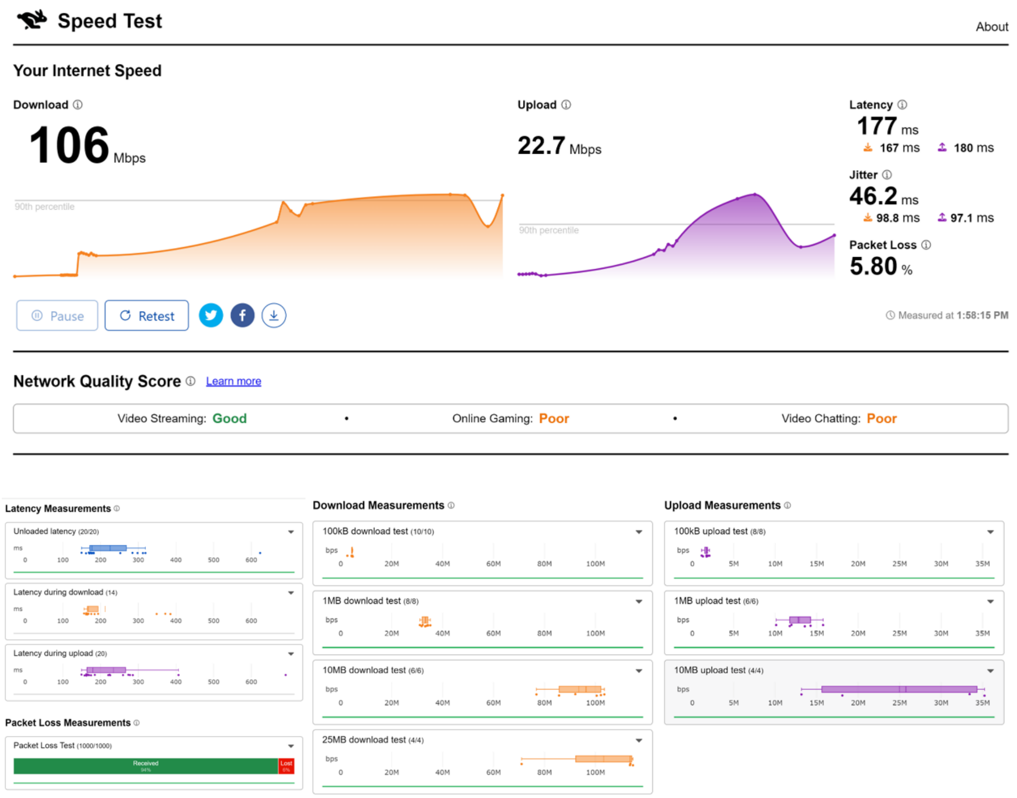


Figure 155: Cloudfare Speed instant test (Source: Cloudfare)

The recorded data has been processed with Python to create an organized database and then further analyzed with MATLAB to generate the graphs. To determine the download speed, both 10 MB and 25 MB messages have been evaluated, while for the upload speed, the data from 10 MB messages have been assessed.

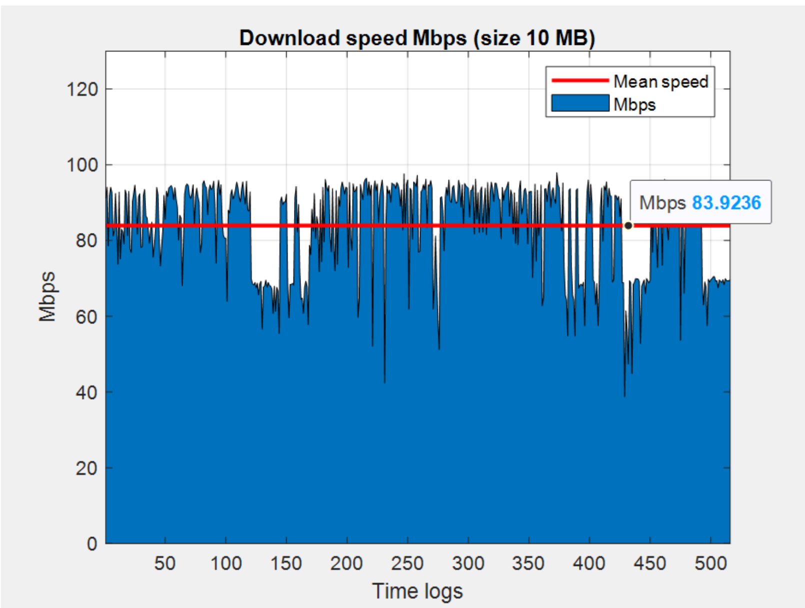


Figure 156: Download speed 10MB

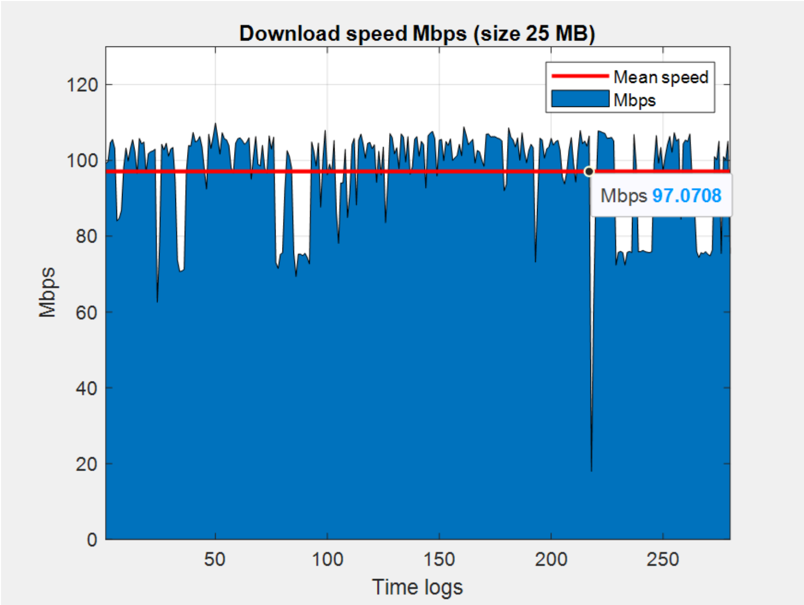


Figure 157: Download speed 25MB

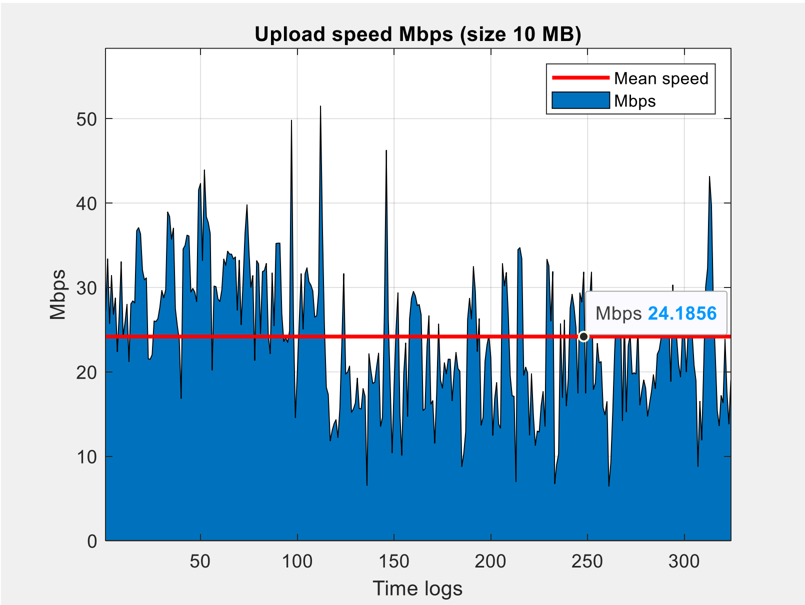


Figure 158: Upload speed 10MB

	Download		**Upload**
Message size	**10 MB**	**25 MB**	**10 MB**
Average	83.92 Mbps	97.07 Mbps	24.19 Mbps
Standard Deviation	12.01 Mbps	12.36 Mbps	7.96 Mbps
Minimum	38.75 Mbps	17.96 Mbps	6.47 Mbps
Maximum	97.91 Mbps	109.84 Mbps	51.50 Mbps
Median	90.12 Mbps	102.52 Mbps	24.49 Mbps

Table 24: Speed test results

In terms of download speed, the 25 MB messages have a higher average speed (97.07 Mbps) compared to the 10 MB messages (83.92 Mbps), suggesting that the network can efficiently handle larger downloads. The standard deviation is similar for both message sizes, around 12 Mbps, indicating **consistent variability** in download speeds. However, the minimum and maximum speeds vary significantly, with a lower minimum and a higher maximum for the 25 MB messages. This could be due to variations in network load or other external factors during the tests. When compared to the speeds advertised on Starlink's availability map on their website, which state that Spain should experience download speeds between 137 Mbps and 207 Mbps, the **recorded average speeds are noticeably lower**. The discrepancy between the advertised speeds and the measured speeds cannot be contested since Starlink does not offer a service level agreement (SLA) guaranteeing performance. This lack of guaranteed service levels is a critical consideration for utilities like Iberdrola.

Regarding upload speed, the 10 MB messages show an average of 24.19 Mbps, which falls within the range stated by Starlink for Spain (19 Mbps to 35 Mbps). The standard deviation of 7.96 Mbps, if normalized, would indicate even **greater variability than the download speeds.** Despite this, the minimum upload speed is still a relatively decent 6.47 Mbps.

To measure parameters such as latency and packet loss or availability, a more precise tool called PingPlotter has been used. This tool allows pings to be sent at a maximum frequency of 2.5 seconds per ping to various IPs. For testing, a series of 11 IPs from different websites with databases in various countries were used. These included the DNS of Google (8.8.8.8) and Cloudflare (1.1.1.1), as well as the websites of Google, Iberdrola, Comillas, IEEE, Starlink, OneWeb, X (formerly Twitter), Amazon, and PingPlotter.

PingPlotter

Figure 159: Pingplotter logo (Source: Pingplotter)

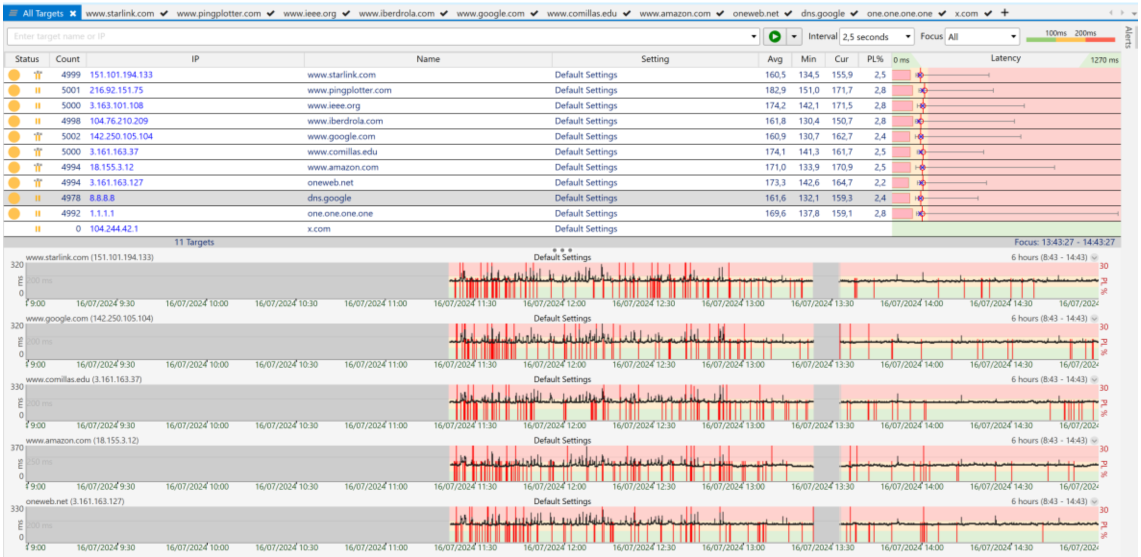


Figure 160: Pingplotter console

PingPlotter is a powerful tool used to measure parameters such as latency, packet loss, and availability. The tests conducted involved recording pings to the beforementioned 11 representative IPs every 2.5 seconds for approximately 4 hours, resulting in a total of around 5000 pings per IP. This large number of pings allows for more accurate data on the performance of the Starlink network.

The software provides a comprehensive view of the data. In the upper part of the interface, it displays box plots for latency, showing the average, maximum, minimum, and current latency, as well as the percentage of packet loss. This section also includes the IP address alongside the URL, the number of pings recorded, and the status of each target. In the lower part, dynamic graphs are generated as data is recorded, with three color bands representing latency. The actual latency is plotted in black, and red bars indicate instances of packet loss. Additionally, PingPlotter records jitter, providing a thorough analysis of network performance.

The results of the tests indicate that the overall average latency across all tested IPs is **approximately 153.63 ms**, which is significantly higher than the 30-36 ms announced on their website. This discrepancy is likely due to the fact that the website's figures do not account for delays outside physical data transmission from the antenna to the gateway, such as server and other network-related delays. Starlink satellites have inter-satellite communication (ISL), meaning that the user communicates with one satellite, which can transmit the signal to the nearest gateway, or if that gateway is very congested, it can communicate with other satellites to route the signal to a different gateway less congested. This means that the destination **gateway for the transmitted message is not guaranteed**. It can be either inside or outside the national territory where the signal was emitted. These gateways, owned by Starlink, are where the signal exits to the internet.

The overall average packet loss percentage is approximately 2.69%, reflecting the reliability and stability of the network. Within the different IPs, packet loss ranges from 2.4% to 2.8%, indicating a relatively stable network with occasional packet loss.

The gray band visible in the graphs corresponds to the suspension of equipment during the lunch break. This pause however, did not affect the accuracy of the test results. Moreover, due to the similarity of all the graphs, it can be deduced that the performance does not vary significantly based on the website, the database it uses, or its location. Therefore, for a more in-depth analysis, it was decided that focusing on one website, Google DNS (8.8.8.8), would be sufficient.

The exported data recorded was treated with MATLAB for representation and better understanding. The following graphs are displayed. The first is a representation similar to the graph presented by PingPlotter, showing latency records over time with packet loss incidents marked. The second and third graphs delve deeper into **packet loss**. In these, the **samples are grouped into 5-minute intervals, meaning 120 samples per group (1sample/2,5s)** to provide the most accurate representation of the data. Finally, to better visualize the latency, a box plot and its frequency distribution are included to observe its variability.

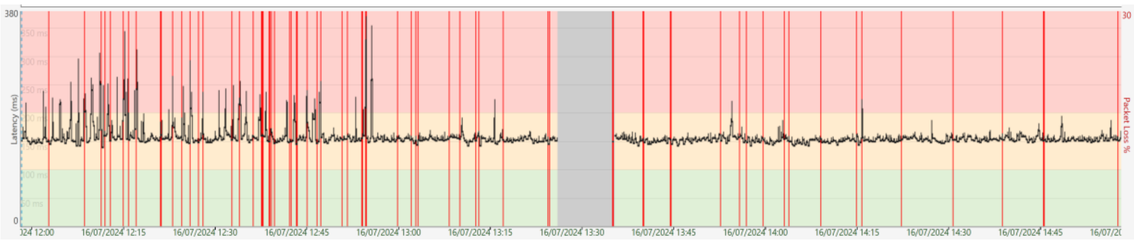
Latency statistics:

Average	Median	Variance	Standard_Deviation	Minimum	Maximum
161.64	154.61	884.42	29.739	132.12	483.68

Packet loss (PL) percentage: 2.4106%

Table 25: Google DNS (8.8.8.8) communication statistics

The results are quite promising. The average latency is 161.64 ms, with a median of 154.61 ms, which indicates that most latency values are clustered around the median. The variance of 884.42 and the standard deviation of 29.739 ms show some variability in the latency, with a minimum latency of 132.12 ms and a maximum of 483.68 ms. The packet loss percentage is 2.4%, which is relatively low, indicating a reliable connection with minimal data loss.



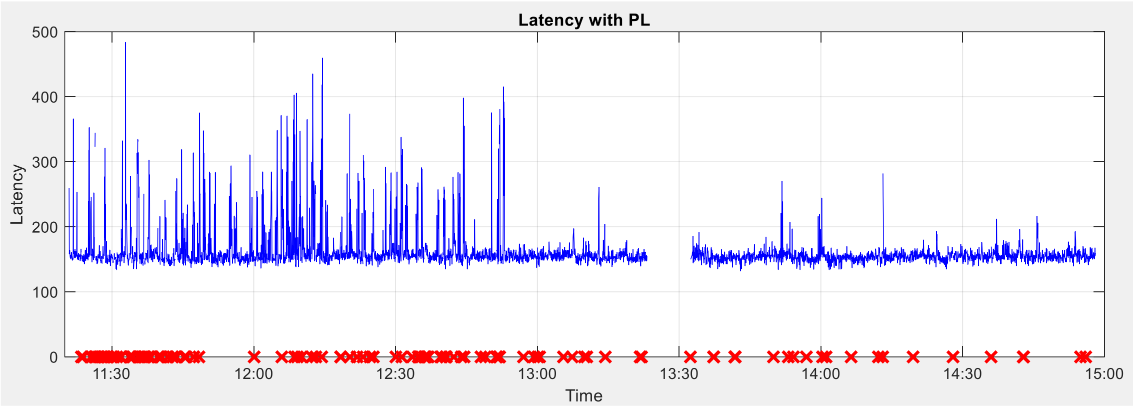


Figure 161: Latency over time, Google DNS (8.8.8.8) (Top: PingPlotter; Bottom: Matlab)

The graph shows that latency hovers around 160 ms for most of the time, with some notable spikes. These spikes are primarily observed in the first part of the test. Since the conditions remained constant throughout the testing period, these deviations can be attributed to the network itself, highlighting a lack of stability.

Regarding availability and packet loss, it is in the **initial phase of the test where most failures are observed**. Although the network **shows potential in its characteristics, especially towards the end**, it loses credibility due to its **variability**. Instances of packet loss reaching up to 10% completely rule out the network for certain utility applications, where consistent and stable performance is crucial.

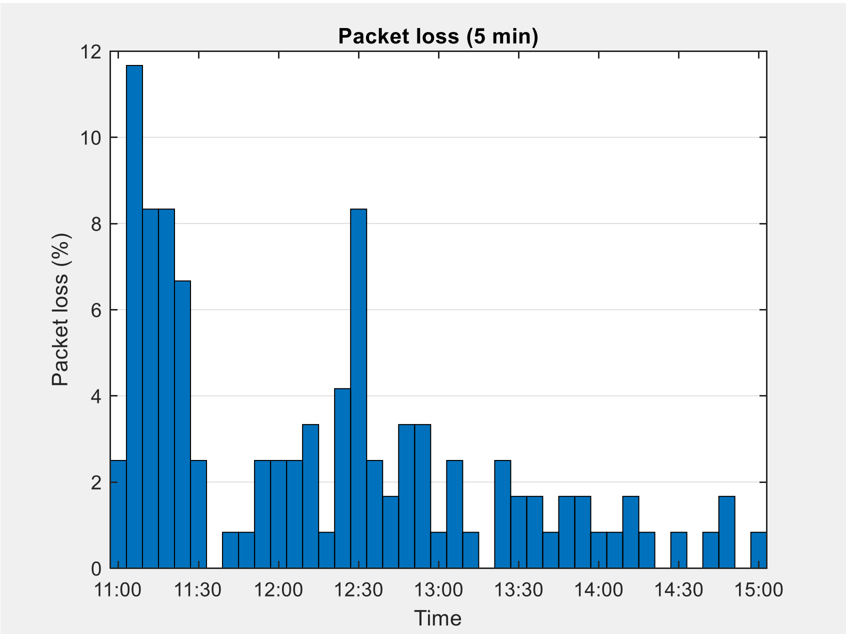


Figure 162: PL (%) over time, Google DNS (8.8.8.8)

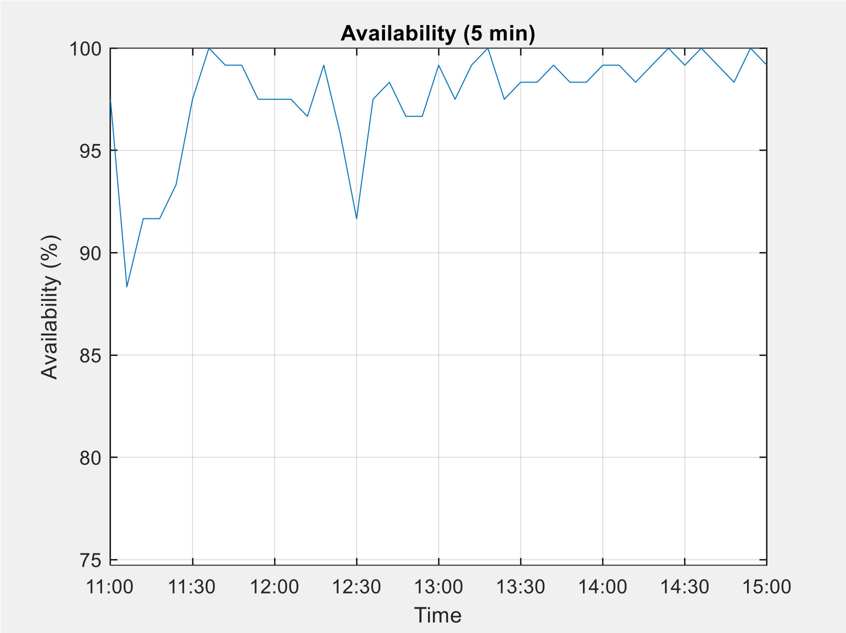


Figure 163: Availability (%) over time, Google DNS (8.8.8.8)

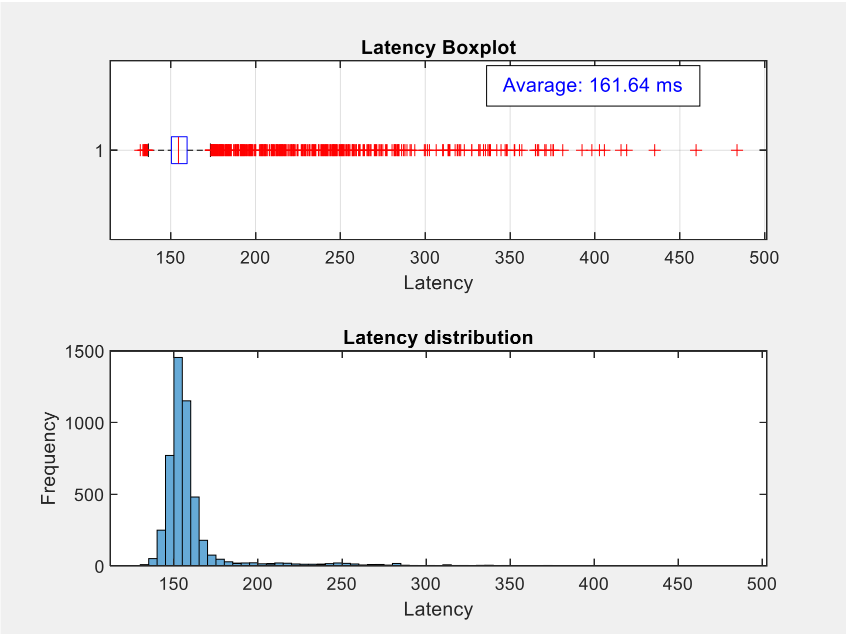


Figure 164: Google DNS (8.8.8.8), Top: latency boxplot; Bottom: latency frequency distribution

Overall, these results are comparable to mobile networks, with an even better average latency. However, the stability, as indicated by the variance and standard deviation, is not as strong, suggesting that there are occasional spikes in latency. Despite this, the performance of Starlink is quite competitive and demonstrates significant potential for specific applications.

8.2 ONEWEB

OneWeb is a telecommunications company founded in 2012 by Greg Wyler with the goal of providing high-speed, low-latency internet globally through a constellation of satellites in low Earth orbit (LEO). The initial vision of OneWeb was to connect billions of people worldwide, especially in rural and remote areas where traditional connectivity was insufficient or nonexistent. OneWeb satellites are manufactured through a joint venture with Airbus, called OneWeb Satellites, at a production facility in Florida capable of producing up to two satellites per day, representing a significant advancement in cost reduction and assembly time compared to traditional satellites.[36]

In March 2020, OneWeb filed for bankruptcy due to financial difficulties exacerbated by the COVID-19 pandemic, suspending its operations and launches. However, in November 2020, OneWeb emerged from bankruptcy thanks to a $1 billion investment from the **UK government** and Bharti Global, an Indian multinational, allowing OneWeb to resume its launches and continue developing its satellite constellation. In 2022, OneWeb merged **with Eutelsat, a European geostationary satellite (GEO)** owner and operator, creating the **first integrated LEO/GEO platform called Eutelsat OneWeb**. This combination aims to offer broader coverage and improved connectivity services worldwide.

As of 2024, OneWeb has successfully launched **648 satellites** and the joint venture with Eutelsat is developing a second generation of satellites focused on increased capacity and coverage, expected to begin launching in 2025, to better serve enterprise and government customers. OneWeb has made significant progress in its mission to provide global connectivity, positively impacting areas such as education, healthcare, and business, and continues to explore collaboration opportunities to expand its reach and improve its service offerings.

Finally, while Starlink focuses on mass residential internet coverage with its ultra-dense network, OneWeb has targeted its **business model towards B2B services** across various commercial and military sectors. Although OneWeb also offers residential coverage, its primary emphasis lies in serving enterprises and government entities, providing connectivity solutions for sectors such as maritime, aviation, enterprise networks, rural broadband, emergency response, and defense.

Figure 165: Starlink Logo (Source: Starlink)

8.2.1 CONSTELLATION

OneWeb currently has 648 satellites in low Earth orbit (LEO), distributed in orbits at an altitude of approximately 1,200 km. Unlike Starlink, which primarily uses prograde inclined orbits optimized for central regions of the Earth, OneWeb's satellites operate in **polar orbits** to ensure comprehensive global coverage, including remote and underserved areas.

Figure 166: Oneweb constellation (Source: Satellitemap.space)

The OneWeb satellites have an orbital period of about 109 minutes, allowing each satellite to pass over a particular region several times a day. This configuration ensures consistent and reliable connectivity, particularly in high-latitude regions.

8.2.2 OPERATION MODEL

OneWeb operates a **disintegrated system**, meaning that it is only responsible for the satellite operation. The satellite manufacturing is handled by a joint venture with Airbus. The launches are conducted by third-party rocket service companies such as Arianespace, SpaceX, and NewSpace India Limited. The service is offered through associated distributors, and the market for antennas is liberalized, allowing full competition in antenna development. Additionally, OneWeb does not own the gateways but rather makes agreements with various gateway operators to contract their services.

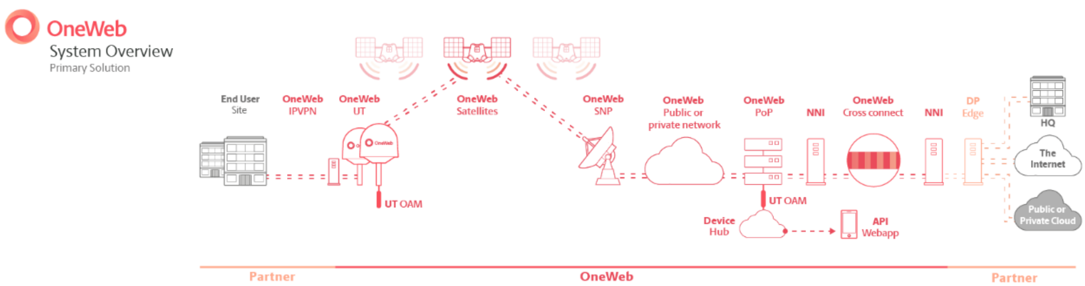


Figure 167: Oneweb's telecommunications operation (Source: Oneweb)

8.2.2.1 Data Transmission

OneWeb **satellites do not communicate data with each other**. Instead, a satellite receives and retransmits the data signal between users and the nearest gateway. From the gateway, then OneWeb then transmits the data through their secure private ground network to wherever the client desires. This unique characteristic means that while technical coverage might be globally comprehensive, the availability of **service** in different countries and regions is highly **dependent on** OneWeb's ability to **secure agreements with gateway operators**. This disintegrated model aligns well with the needs of companies, such as Iberdrola, as it promotes market competition, leading to more competitive technology and costs. Moreover, contracting companies are this way far less vulnerable to the power of subcontractors, as they can choose between different providers. Another significant advantage of OneWeb's data operation model is that since the satellite acts as a relay, **it is possible to reserve channel segments and guarantee service through fixed public Ips. This is guaranteed with SLA (Service Level Agreements) and 100% CIR (Committed Information Rate) and MIR (Maximum Information Rate)**.

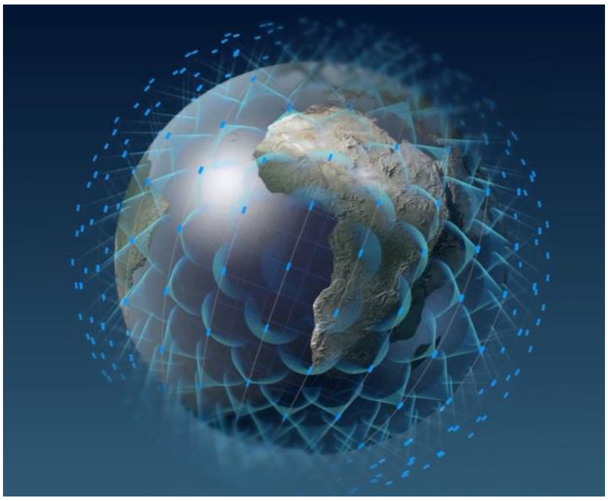


Figure 168: Oneweb constellation coverage (Source: Oneweb)

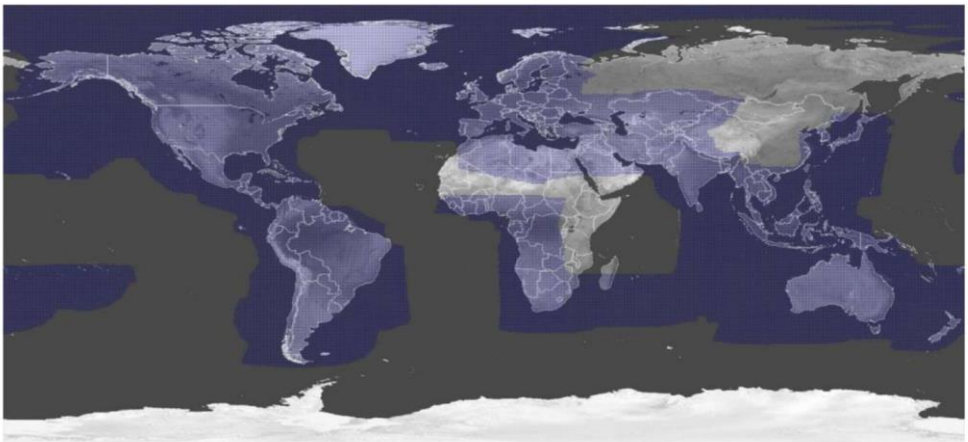


Figure 169: OneWeb's current real coverage (Source: Satlink)

8.2.2.2 Satellite Network Operations

OneWeb is responsible for the operation of its satellite network, including controlling satellite positions and performing collision avoidance tasks from its Telemetry, Tracking, and Command (TT&C) centers. This aspect of the operation ensures that the satellites maintain their correct orbits and can avoid potential collisions with other space debris, thereby maintaining the integrity and reliability of the network. This control task is centralized.

8.2.3 SATELLITE SYSTEMS

OneWeb has not published detailed information about the various systems on its satellites, but they include all the components mentioned in the previous chapter. These systems encompass phased array antennas for efficient data transmission, electric propulsion for maintaining orbits and collision avoidance, and robust communication links with ground stations to ensure reliable service.

Figure 170: Oneweb satellite (Source: Oneweb)

8.2.4 SEGMENTS

Their website state; “Whatever your industry, we connect you to the future. Whether carrier, enterprise, government, land mobility, maritime, or aviation, we have a solution for you. Fixed, mobile, or both. Primary, back-up, or hybrid. Eutelsat OneWeb’s unique system will ensure low latency and high-speed connectivity. Everywhere.”

This highlights the wide variety of industries it serves. This is much larger than Starlink because onewb is focused on the B2B model while Starlink is focused on the mass consumer market.

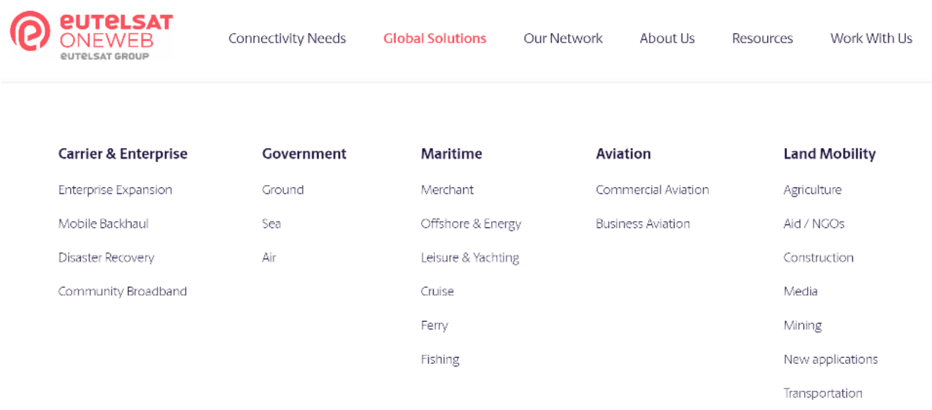


Figure 171: OneWeb global solutions (Source: Oneweb)

8.2.5 SERVICE PLANS

OneWeb delegates the responsibility of setting service tariffs to associated distributors who create various plans and pricing structures. These distributors offer different service plans, which sometimes include the rental of antennas due to their high cost. By working with these partners, OneWeb ensures that customers have access to tailored solutions that meet their specific needs, whether for primary, backup, or hybrid connectivity. This approach allows OneWeb to focus on its core satellite operations while leveraging the expertise of its distributors to manage customer relationships and service offerings.

PLAN	MONTHLY ALLOWANCE	SPEED (MBPS)	MONTHLY SUBSCRIPTION OW50L & KYMETA	MONTHLY SUBSCRIPTION OW70L & OW 130L
BROADBAND 100	100 GB	100 / 20	US$495.00	US$395.00
BROADBAND 250	250 GB	100 / 20	US$859.00	US$695.00
BROADBAND 500	500 GB	100 / 20	US$1495.00	US$1195.00
BROADBAND 1000	1000 GB	100 / 20	US$2350.00	US$1895.00
ENTERPRISE UNLIMITED 0.5	UNLIMITED	10 / 2	US$1650.00	US$1325.00
ENTERPRISE UNLIMITED 1	UNLIMITED	50 / 10	US$3295.00	US$2625.00
ENTERPRISE UNLIMITED 2	UNLIMITED	50 / 10	US$6550.00	US$5250.00
ENTERPRISE UNLIMITED 3	UNLIMITED	100 / 20	US$9995.00	US$7995.00
ENTERPRISE UNLIMITED 4	UNLIMITED	100 / 20	US$12995.00	US$10500.00

Figure 172: Associate distributor plans (Source: Europasatellite)

8.2.6 END-USER TECHNOLOGY

OneWeb utilizes a variety of antennas available in the market to ensure reliable satellite connectivity. Initially, the company primarily relied on VSAT (Very Small Aperture Terminal) antennas. These antennas use physical mechanisms to track satellites, and due to their directional nature, often require the installation of two units to avoid obstacles, as depicted in Figure 174.

Figure 173: Parabolic antennas VSAT (Source: Intellian)

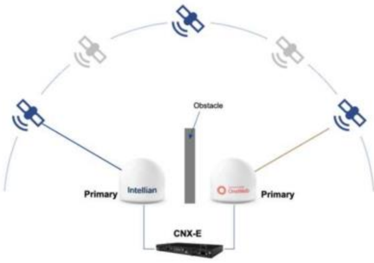


Figure 174: Double antenna obstacle avoidance strategy (Source: Satlink)

With technological advancements, there's been a shift towards flat phased array antennas, shown in Figure 175. Unlike VSAT antennas, phased array antennas do not need physical mechanisms for orientation, making them simpler. However, this technology comes at a higher cost, with current prices around 20,000 euros per antenna.

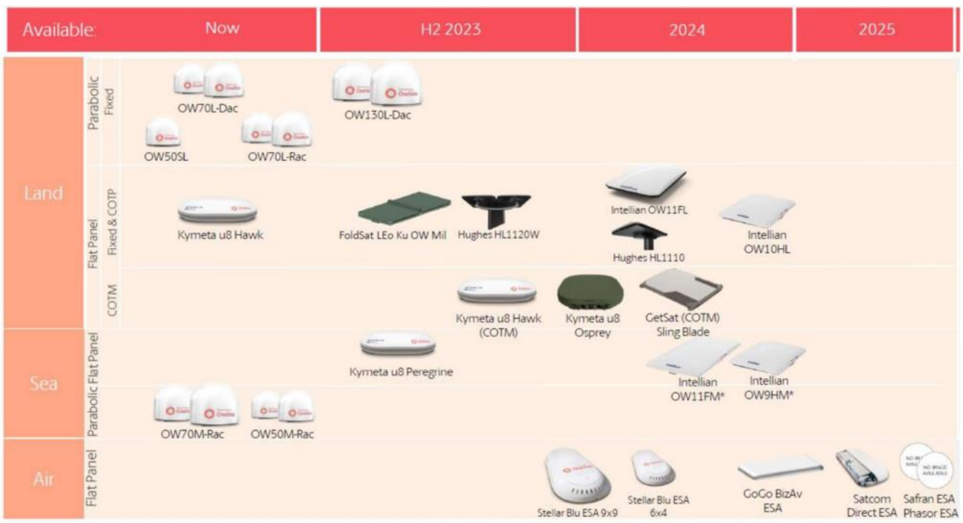


Figure 175: End-user antennas evoulition (Source: Satlink)

Each antenna type has its advantages and disadvantages, as illustrated in Figure 176. Flat phased array antennas are easier to install and maintain due to their lack of moving parts. They provide reliable performance with a lower profile, making them ideal for mobile applications. On the other hand, parabolic antennas, while more complex to install due to their mechanical components, offer superior telecommunications performance, including better signal gain and reliability over long distances.

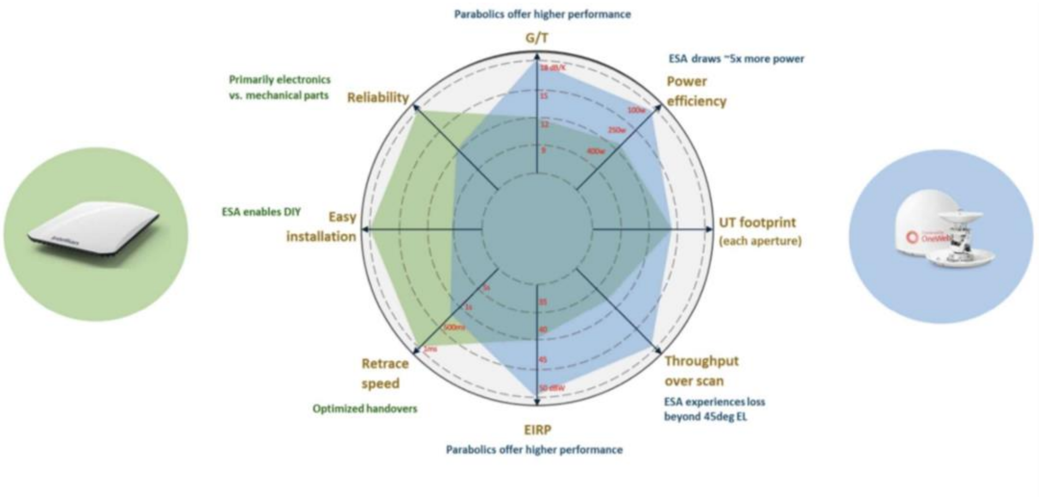


Figure 176: Antenna comparisson (Source: Satlink)

The latest flat-panel antenna technology from Intellian, a leading manufacturer alongside Hughes, competes directly with Starlink's antennas. These Intellian antennas are available in multiple sizes, including enterprise and compact versions. The larger the antenna, the better telecommunications capabilities it offers. However, their data transmission capacities is limited. Enterprise flat panel series enables 195 Mbps Rx, and 32 Mbps Tx. While the compact version only offers, 60 Mbps Rx, and 10 Mbps Tx.

Figure 177: Intellian flat antennas (Source: Satlink)

Technology Kit	***Size***
Compact	560 x 450 x 120 mm
Enterprise	960 x 500 x 120 mm

Figure 178: Intellian kits size

Chapter 9. PROJECT ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS (SDGS)

On September 25, 2015, world leaders adopted a set of global goals to end poverty, protect the planet and ensure prosperity for all as part of a new sustainable development agenda. Each goal has specific targets to be met by 2030. The goals are as follows:

Figure 179: Sustainable Development Goals (SDGs) (Source: UN)

The project presents goals that are aligned with the Sustainable Development Goals (SDGs) proposed by the United Nations in 2015.[37]

SDG 7: AFFORDABLE AND CLEAN ENERGY: "ENSURE UNIVERSAL ACCESS TO AFFORDABLE, RELIABLE, AND MODERN ENERGY SERVICES".

LEO high-speed Internet constellations dramatically improve access to affordable, clean energy by optimizing power grid management. Real-time monitoring capabilities enable rapid problem detection and resolution, reducing operating costs and improving energy efficiency. This facilitates the integration of renewable energy sources such as solar and wind into the grid, ensuring a cleaner and more sustainable energy supply. In addition, advanced connectivity supports the deployment of microgrids and distributed energy systems, providing access to reliable power in remote and hard-to-reach areas.

SDG 9: INDUSTRY, INNOVATION, AND INFRASTRUCTURE: "DEVELOP QUALITY, RELIABLE, SUSTAINABLE, AND RESILIENT INFRASTRUCTURE".

The implementation of LEO constellations for the power grid drives innovation and strengthens infrastructures, contributing to the development of more resilient and modern power systems. These technologies enable continuous and detailed monitoring of grid performance, facilitating predictive maintenance and rapid response to anomalies. By improving the ability of electrical infrastructures to adapt and evolve with technological demands, it fosters an environment of continuous innovation where advanced solutions can be seamlessly integrated, driving industrial and technological progress in a sustainable manner.

SDG 13: CLIMATE ACTION: "STRENGTHEN RESILIENCE AND ADAPTIVE CAPACITY TO CLIMATE-RELATED HAZARDS"

LEO constellations play a critical role in mitigating climate change by providing advanced tools for more efficient energy management and reducing greenhouse gas emissions. By optimizing energy use and facilitating the integration of renewable energy sources, these technologies help reduce dependence on fossil fuels. In addition, real-time monitoring enables better management of energy demand and supply, reducing waste and promoting the sustainable use of natural resources. This supports global efforts to combat climate change and promote a greener, more responsible energy future.

Chapter 10. CONCLUSIONS

After studying and testing the technology, it can be said that LEO constellations have successfully carved out a niche in the space telecommunications segment.

First and foremost, before delving into the potential of these technologies, it is important to note that this technology is now an additional option, with its own characteristics, advantages, and limitations. Each satellite telecommunication technology is dedicated to a specific type of service, and the introduction of these constellations does not render other technologies obsolete. There are military technologies, navigation technologies, weather, etc. However, if we focus on current commercial technologies, we can observe three main segments.

The first segment is messaging, characterized by using low frequencies and narrow bandwidths, but with high reliability. These are perfect for emergency communications. The second segment is low-capacity IoT, which also uses low frequencies and therefore narrow bandwidths. However, they transmit more information than the previous segment and their latency lies under 1 second, much better than the 15s that IoT messaging have. This makes them suitable and very attractive for monitoring points with very little information, such as gas pipelines within the fossil fuel sector. The third segment consists of satellites dedicated to high-capacity internet. These are characterized by using higher frequencies, resulting in greater bandwidth and higher information transmission. However, due to using these **high-frequency bands, they are vulnerable to atmospheric conditions.**

Apart from the technological segment, commercial solutions are also characterized by their orbit. There are three main zones: GEO, which orbit matches with the rotation of the Earth, thus appearing static to an observer on the ground, the farthest; MEO, the medium zone where mainly meteorological and GPS satellites are found; and LEO, the closest orbit to Earth, ranging from 400 km to 1500 km. The orbit affects **latency**, determining how fast communications can be, limited by the physical distance that telecommunications have to cover. The difference between the lowest **LEO orbit (30 ms) and GEO (600 ms) marks a significant difference.** The number of satellites needed for global coverage also varies: GEO requires only 3, while LEO needs a minimum of 25, although the actual number is much higher due to communication capacity and redundancy.

LEO satellite constellations are classified in the last of the three sectors, high-speed internet, and have significant advantages over those in GEO orbit. These satellites have emerged thanks to advancements in satellite manufacturing; they can now be smaller and faster to produce, and advancements in rocketry. With SpaceX, rockets are now reusable, significantly lowering the launch cost, and due to their size, up to 60 satellites can be launched per launch. The major advantages are thus: reduced launch and satellite costs, and shortened technological cycles. Previously, cycles were long until the satellite reached the end of its useful life, but now the cycle is around 2 years, allowing for improvements to be introduced much more frequently.

LEO constellations have arrived to stay. Now, to what extent can their capabilities reach, and where might they revolutionize the industry?

This brief contextualization within the conclusions aims to express that the first step is to understand the technologies, which was the initial phase of this project. Focusing on high-capacity LEO internet technologies, which have driven this study and, as seen in the project, possess new and greater potential for various uses, there are two main players: OneWeb Eutelsat and Starlink. Contrary to public perception and initial assumptions, they are not considered direct competitors. Both are LEO constellations dedicated to high-speed internet, but their business models are entirely different. While they might overlap in certain aspects, primarily, and to simplify: Starlink is oriented towards consumers (B2C), targeting the residential sector, whereas OneWeb is oriented towards businesses (B2B).

Moreover, their operational models are also different. Starlink operates an integrated model, managing everything from design and manufacturing to service provision and operation. In contrast, OneWeb operates a disintegrated model, where they only manage the satellite segment. For other operations, such as antennas, gateways, and service providers, they rely on business partners. A comparison can be made with tech companies Apple and Microsoft, where Starlink is Apple and OneWeb is Microsoft.

With this understanding, it is necessary to study both models as companies can benefit from either. Many businesses work with Apple and not with Microsoft regardless of their business orientation. It is essential to evaluate how well these new technologies align with the company's needs, in this case, a company in the electrical sector, Iberdrola.

They also differ in satellite technology, orbits, and telecommunications management. Firstly, there is Starlink, with over 5,000 satellites in orbit. Most of these are inclined orbits covering the central zone of the globe, where the population and thus the business is concentrated. They also have polar orbits to provide global coverage, but these are significantly fewer. Starlink satellites have inter-satellite communication (ISL), meaning that the user communicates with one satellite, which can transmit the signal to the nearest gateway, or if that gateway is very congested, it can communicate with other satellites to route the signal to a different gateway less congested. This means that the destination gateway for the transmitted message is not guaranteed. These gateways, owned by Starlink, are where the signal exits to the internet.

On the other hand, OneWeb does not have ISL; the signal sent to a satellite is routed to the nearest associated gateway, acting as a mirror. This allows for guaranteed routing, and through their terrestrial network, the message can be communicated either to the client's private network or the internet. This is a significant consideration when evaluating these technologies. **Private networks is a priority** for utilities. Iberdrola, for instance, prioritizes private network over communications capabilities. They prefer using proprietary radio communication over third-party fiber optics whenever it is possible. The reason for this is service control and the determinism they require. This is an area where OneWeb excels over Starlink, given its B2B orientation.

An additional advantage is the advancements in user antenna technology. With the development of flat panel phased array antennas, installation is minimal. These antennas simply require a clear overhead view and can orient themselves digitally. This marks a significant improvement over VSAT, high-speed GEO internet technologies. The installation cost is nearly zero, and maintenance is similarly low, as they have technologies to melt snow and ice that may cover them. However, maintenance is still required for other environmental factors that may obstruct the view. These antennas, besides being easy to install, are small and expected to reduce in size even further in the future. This is of primal importance in **cases where these technology has to be discarded due to space constraints**, as it is the case of **reclosers and secondary substations**.

Nonetheless, **their downside is the price**. Being cutting-edge technology, the price reflects that. The market antennas used by OneWeb can cost around €20,000, which is immediately prohibitive. This price is exorbitant compared to Iberdrola's budget of €800 to €1,000 per installation. In contrast, Starlink, due to its integrated antenna model, can offer significantly more competitive prices, up to 10 times cheaper.

	Starlink	**OneWeb**	**VSAT**
Orbit	LEO	LEO	GEO
Altitude	500 km	1200 km	36570 km
Latency	30 ms	70 ms	600 ms
Uplink Speed	~ 22 Mbps	~ 32 Mbps	~ 10 Mbps
Downlink Speed	~ 190 Mbps	~ 190 Mbps	~ 200 Mbps
Phased array antennas	Yes	Yes	No (some options)
Size	57cm x 51cm	56cm x 45cm	100cm x 100 cm
Price	2.000 €	20.000 €	2.000 € + 1.000€ (installation)
Installation	Easy	Easy	Difficult
SLA (Guaranteed channel)	No	Yes	Yes
Availability	95%	99%	99%

Table 26: Technology comparison

When comparing technologies, the significant advantages over traditional VSAT systems are the antenna and latency. Most of the corporate office services require low latencies. From videoconferences to maintenance operation processes of wind farms, office services are design to work with low latencies. LEO platforms are able to comply with these requirements, whereas VSAT cannot.

With the gathered information, it is theoretically proved that LEO satellites can match VSAT in installations where space constraints are not an issue, such as renewable energy parks and remote substations. In these locations, LEO satellites could handle monitoring and telecontrol services currently covered by VSAT, and additionally provide corporate office services that are often poorly supported at this sites.

Before analyzing and designing the integration of these services into the network, it is necessary to conduct a series of tests to verify that the offered specifications are met. Given that OneWeb technology is currently excluded due to equipment costs, the remaining technology to be analyzed is Starlink.

A series of speed, latency, and packet loss tests have been conducted using test equipment provided by Satlink, and the results are as follows:

	Uplink Speed	**Downlink Speed**	**Latency**	**Availability**	**Packet loss**
Avarage	24,19 Mbps	97 Mbps	153,63 ms	97,31%	2,69%
Variability (Std.)	7,96 Mbps	12,3 Mbps	29,94 ms	2,64%	

Table 27: Starlink test results

The average of the different parameters is generally good. The upload speed falls within the offered range. However, the download speed is slightly lower, but still more than sufficient for the studied needs.

Latency, the supposed strong point of LEO technologies, is significantly higher than advertised. However, it is important to consider this data in context. The 30 ms latency refers to the minimum round-trip communication time with satellites at an altitude of 500 km. This is a physical limitation, representing the minimum possible latency. External latencies, such as communication from the gateway to the database over the internet or latency due to ISLs, are not included. The relevant measure however, is the end-to-end connection latency, which is what has been tested and is still satisfactory. In fact, it is comparable to cellular technologies like 4G, which currently offers 250 ms. At first glance it may seem better, 150 ms is better than 250 ms. However, caution should be exercised with these results as the latency data for 4G includes continuous monitoring over a long period, whereas the measurements obtained in this study were taken over a single day. A more extended analysis period would be necessary to make a well-founded comparison.

The availability, or its complement, packet loss, also shows good results. An average of 97% availability is a solid figure, comparable to mobile networks that guarantee 98%. However, this is not sufficient for applications such as telecontrol, which require a minimum of 99.9%.

The primary drawback of the Starlink network is its variability. While the average performance of the network is generally good, significant variations in all metrics reduce its overall appeal. Variability in upload and download speeds is less concerning since the service has a margin that meets most needs. However, this is not the case for latency and availability. During measurements, there were instances where latency spiked dramatically, with the 99th percentile reaching 298.65 ms and a maximum of 688.05 ms, which is four times the average. These extreme values could even be considered as additional packet losses. More critically, the instability in availability makes the network unsuitable for high-demand applications, with packet loss moments exceeding 10%. This makes it unviable for applications such as telecontrol.

So, can this technology, without SLAs for traffic guarantees and with high variability, be considered? The answer is yes. Even with its shortcomings, this technology remains a viable option. Iberdrola has a ranking of communication technologies that favors private networks over those that include an operator, due to control and determinism factors. A level below, the technologies are ranked according to their specifications. In this ranking, Starlink would be at the bottom.

The possible uses for Starlink are mainly as **a backup technology, or dedicated specifically to corporate office services**. Iberdrola uses SDN (Software Defined Networking) devices to seamlessly integrate two or more telecommunication infrastructures into one installation. This devices allow full control of telecommunications, making feasible the dedication of a specific service to a certain technology.

First potential use case is renewable sites, currently served exclusively by VSAT with two antennas. Starlink could be integrated replacing one of the technologies to create a GEO-LEO service. This would not only maintain redundancy with another technology, but also will allow to enhance corporate services running them over the LEO segment.

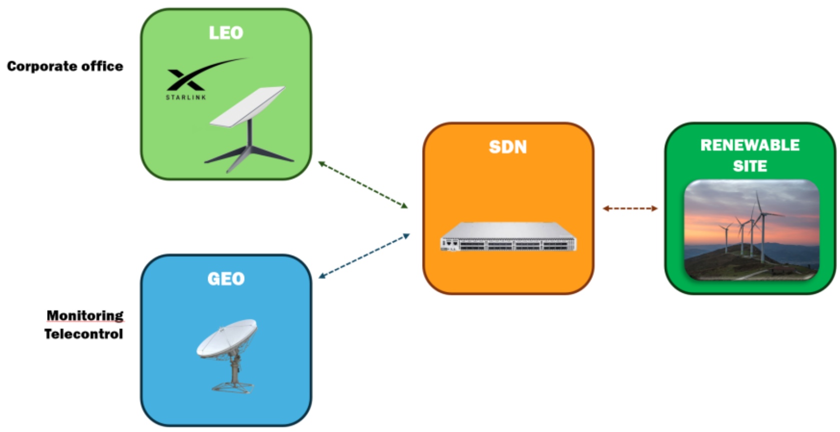


Figure 180: Architecture with Starlink integration (Renewable site)

Another scenario where Starlink has potential usefulness is as a backup technology for infrastructures currently connected via optic fiber (O.F.) or radio (P2P or P2M). Currently, Iberdrola uses the networks of operators as a backup to its own network (fiber optic, point-to-point radio (PP), point-to-multipoint radio (PMP)) in substations. While 4G can be used as a backup where coverage is available, in areas lacking coverage, GEO or LEO VSAT could be employed. The main advantage of Starlink as a backup would be its self-sufficiency with respect to power supply, as Starlink satellites are not dependent on terrestrial power supplies, unlike traditional mobile and radio networks. This autonomy is particularly advantageous compared to 4G operator networks, as private networks are already designed with power supply independence.

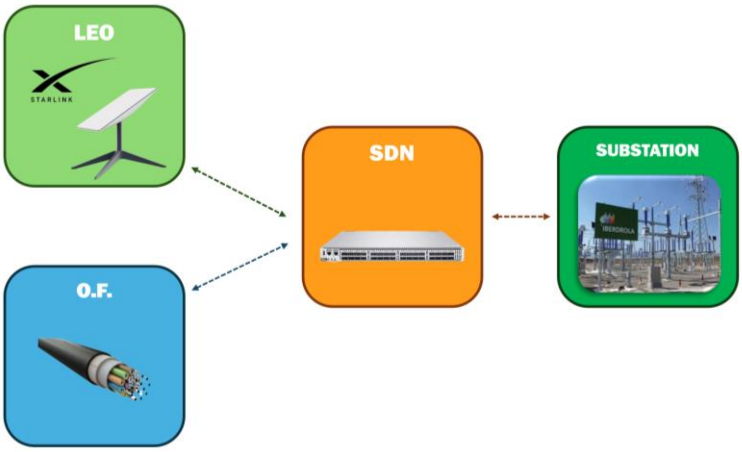


Figure 181: Architecture with Starlink integration (Substation, OF)

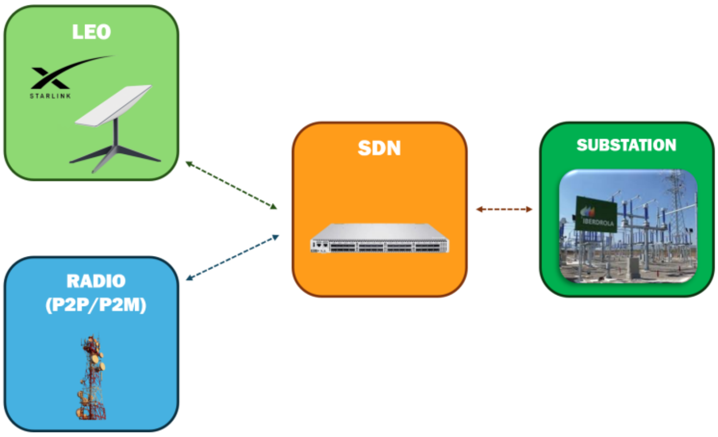


Figure 182: Architecture with Starlink integration (Substation, Radio)

To sum up, Starlink already has certain applications where it can be implemented effectively. Furthermore, as technologies evolve, the range of uses for Starlink will expand. In two years, the arrival of Amazon Kuiper promises to greatly surpass Starlink's services with more powerful and smaller antennas bringing the real competition to the market. Additionally, as the cost of antennas decreases, OneWeb will become a very attractive technology. And finally, it is known that Starlink's business customers are continuously requesting dedicated IP services. Who knows if they will respond to this demand and become a much more reliable service?

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