Satellite network

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A satellite network is a wireless communication system that uses one or more artificial satellites to transmit data between different points on Earth or to connect users and terrestrial networks to the Internet (Li, 2025; International Telecommunication Union [ITU], 2022).

Unlike terrestrial networks, where data mainly travels through cables, fiber optics, or radio base stations, in a satellite network part of the path is carried through space using radio signals.

Satellite networks are used for many services, including telecommunications, Internet access, television broadcasting, maritime and aeronautical communications, and connections to areas where building terrestrial infrastructure would be difficult or expensive (ITU, 2022).

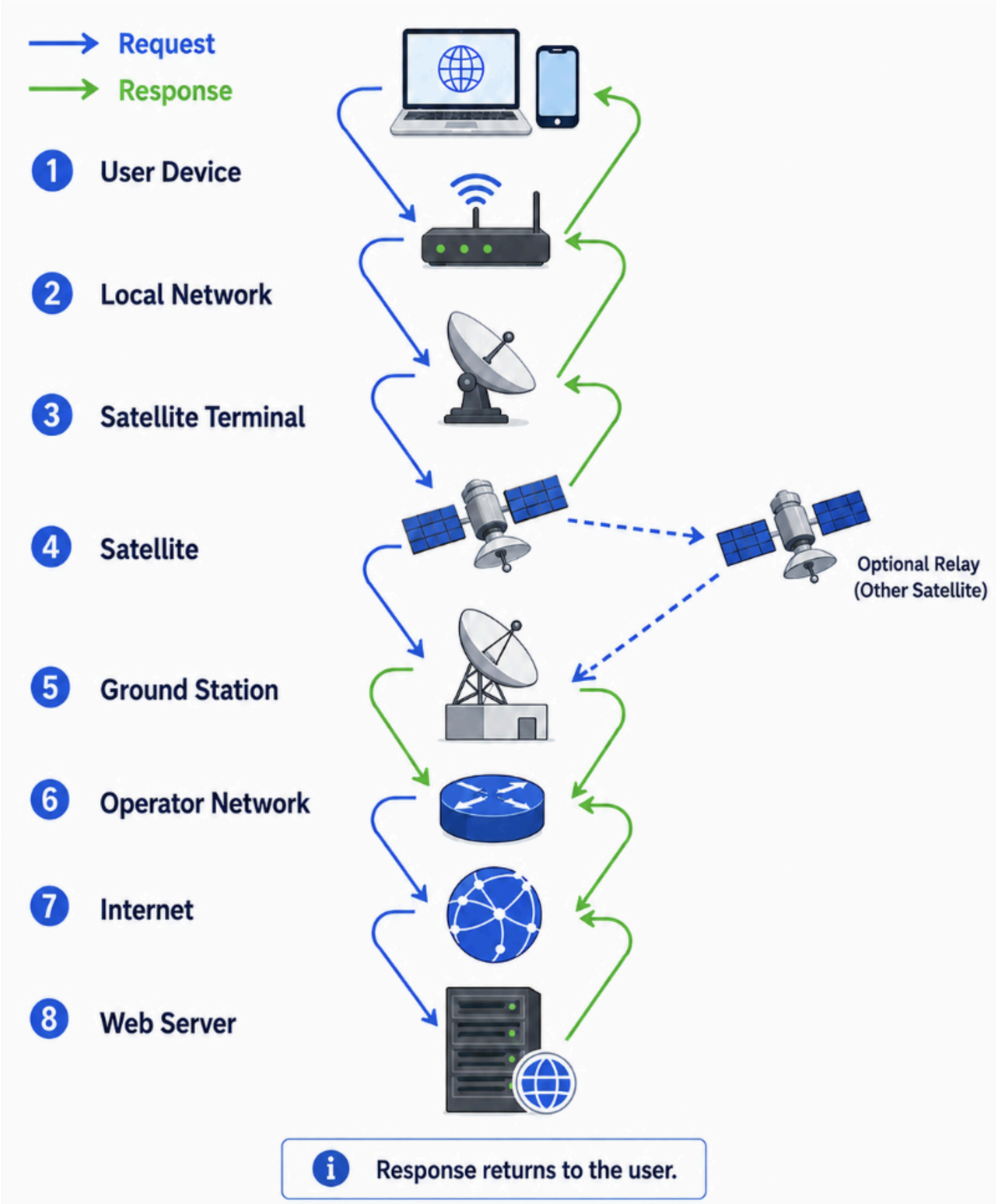
A satellite network for Internet access generally includes several elements (Li, 2025):

- The user terminal, consisting of the antenna and equipment that allow the user to communicate with the satellite.
- The satellite, which receives the signals and forwards them to another part of the network.
- Ground stations or gateways, which connect the satellite network to telecommunications infrastructure on Earth.
- The terrestrial network, through which the data can ultimately reach the Internet and its destination.

The satellite should therefore not be thought of as a server that stores the websites requested by the user (Li, 2025).
Its main function is communication and forwarding: it allows data to travel through part of the path between the user and the terrestrial network.
To understand how it works, we can consider a user who uses a satellite connection to open a web page.

The path can be described in simplified form as follows (Li, 2025):

- The computer or smartphone generates the request and sends it through the local network to the satellite terminal.
- The terminal converts the data to be transmitted into a radio signal and sends it toward a satellite visible in the sky.
- The satellite receives the signal and forwards the data.
- The data can be transmitted directly to a ground station or, in some networks, may first be forwarded to other satellites.
- The ground station then transfers the data to the operator's network and subsequently to the Internet.
- The request reaches the server hosting the website.
- The response travels through the Internet and the satellite network again until it reaches the user terminal and finally the user's device.

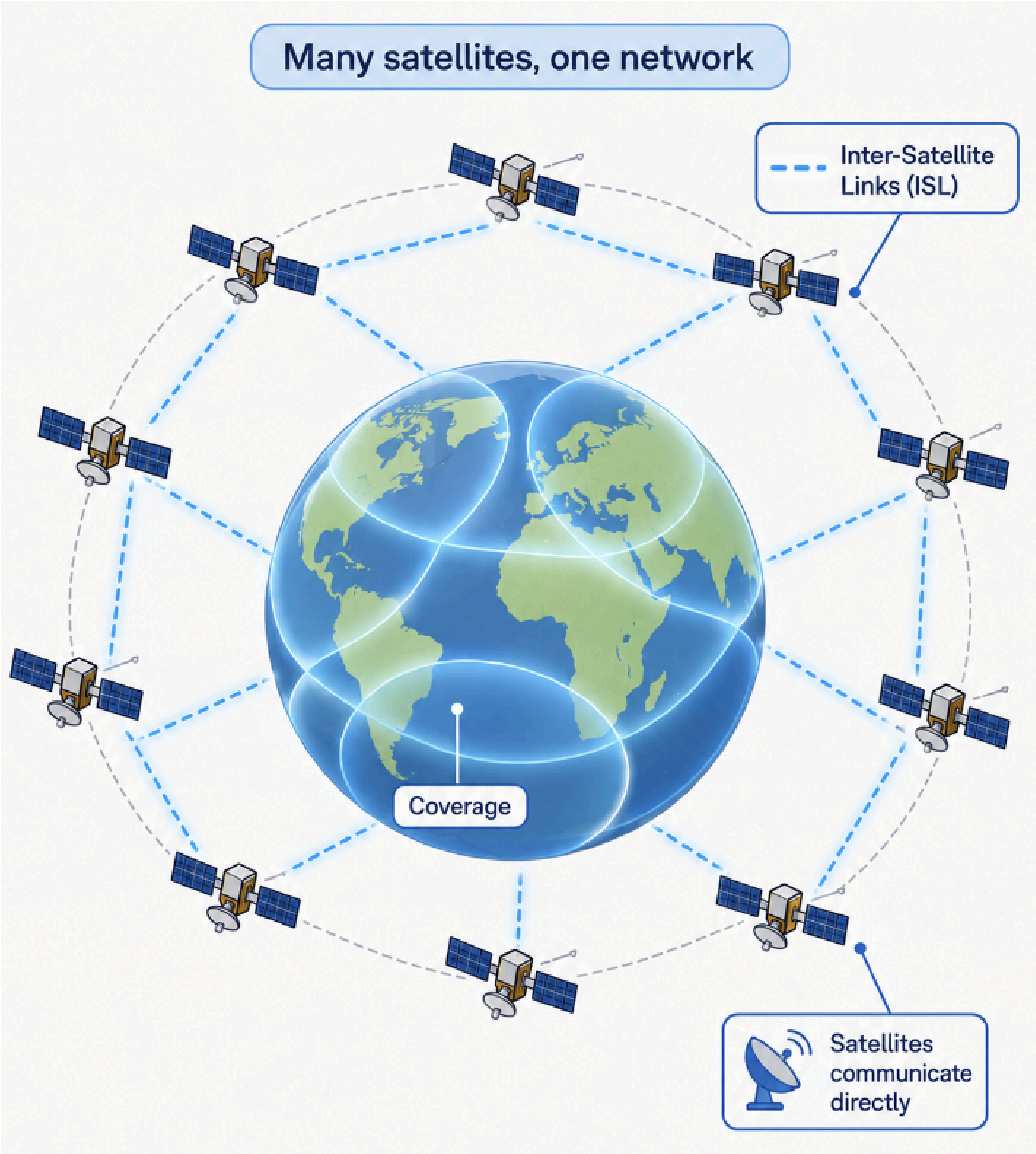


In a modern satellite network, the path does not necessarily always follow:
user → satellite → ground station (Li, 2025).

A **satellite constellation** is a group of satellites that operate in a coordinated way to provide coverage and communication services over a specific area or, in some cases, over much of the Earth (Li, 2025; ITU, 2022).

Some constellations use **Inter-Satellite Links (ISL)**, which allow one satellite to communicate directly with other satellites in the same constellation (Li, 2025).

Data can therefore travel through part of the constellation before returning to Earth.



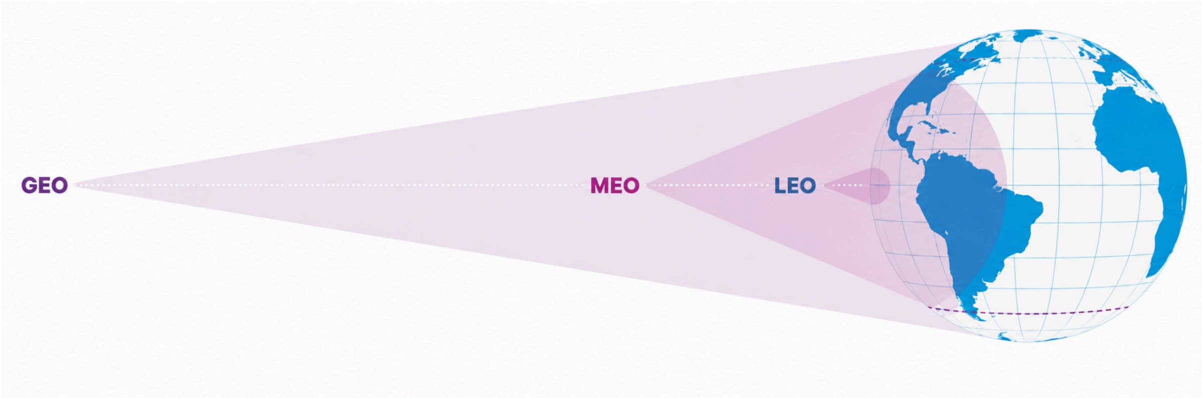
Starlink, one of the best-known satellite networks, for example, uses optical laser-based links between its satellites (Starlink, n.d.-c).

Depending on location, link availability, and destination, the network can therefore decide whether to send traffic down to a nearby ground station or forward it through other satellites in the constellation before it reaches the ground.

An important element for understanding satellite networks is orbital altitude, that is, the distance at which a satellite orbits above the Earth's surface (NASA Earthdata, n.d.).

Orbits can be divided, in simplified form, into three main categories (Allman et al., 1999; NASA Earthdata, n.d.):

- ***LEO* – Low Earth Orbit:** a low Earth orbit, generally below approximately 2,000 km in altitude.
- ***MEO* – Medium Earth Orbit:** an intermediate orbit between LEO and geostationary orbit.
- ***GEO* – Geostationary Earth Orbit:** a geostationary orbit located approximately 35,786 km above the equator (NASA Earthdata, n.d.).



GEO satellites travel in a circular orbit above the equator and take the same amount of time as the Earth to complete one revolution.
For this reason, when observed from the Earth's surface, they appear to remain stationary in the same point in the sky.

This characteristic is very useful in telecommunications (Allman et al., 1999):
- A terrestrial antenna can be pointed toward a fixed position: the dish can be installed once, aimed at that position, and does not need to track the satellite.
- A single satellite can cover a very large portion of the Earth's surface, as the image above helps illustrate.

However, the great distance from Earth has a disadvantage: the signal must travel tens of thousands of kilometers to reach the satellite and the same distance again to return to the surface (Allman et al., 1999).

Signal propagation therefore introduces a significant delay.

LEO satellites, by contrast, orbit much closer to the Earth's surface.

The shorter distance reduces the time required for the signal to travel between the Earth and the satellite, resulting in lower delay (Allman et al., 1999).

There is, however, an important consequence: a LEO satellite does not remain stationary above the same area.

From the user's point of view, the satellite moves quickly across the sky; the terminal must therefore track its movement electronically or periodically switch to another satellite in the constellation.

To provide a continuous connection, constellations are therefore required (Allman et al., 1999).

Starlink follows this principle: instead of relying on a small number of geostationary satellites located very far from Earth, it uses a large constellation of satellites in low Earth orbit, a few hundred kilometers above the surface (Starlink, n.d.-c).

This choice greatly reduces the distance traveled by the signal.

According to specifications published by Starlink, for terrestrial users the service delay is typically in the range of a few tens of milliseconds, although it can vary depending on location, network load, and the path followed by the data (Starlink, n.d.-b).

This situation has some similarities with what happens in mobile networks.

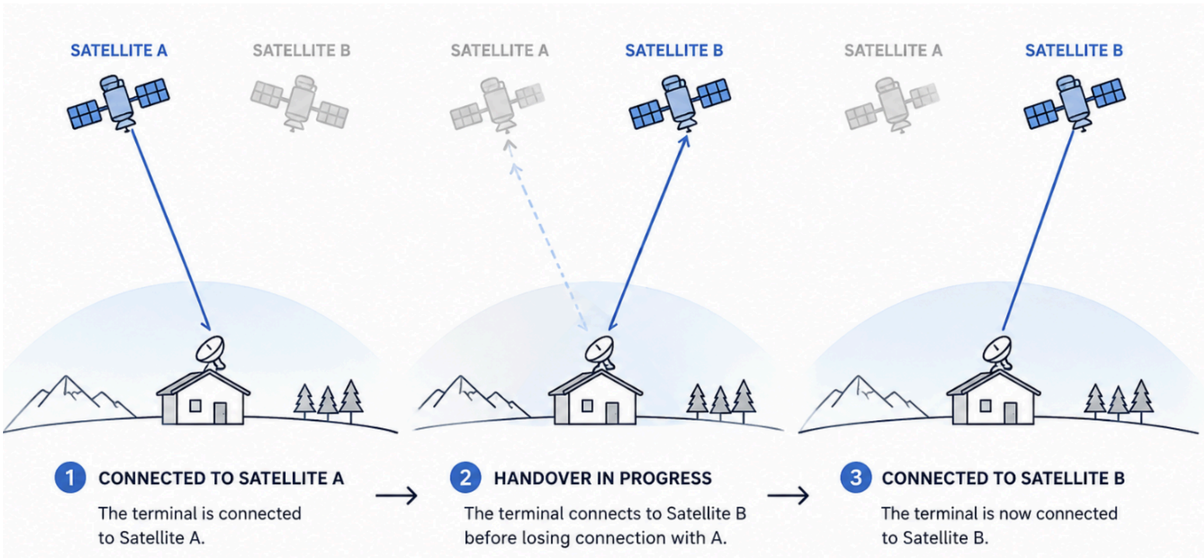
In a mobile network, a moving device can progressively switch from one cell to another.

Something conceptually similar can happen in a **LEO satellite network**, but in this case it is often the satellite that moves rapidly relative to the user, rather than the mobile phone as in a mobile network.

The terminal must therefore periodically switch communication from one available satellite to another.

This process is called **satellite handover**.

Satellite handover, or *handoff*, is the process by which a connection is transferred from one satellite, coverage beam, or link to another while attempting to maintain service continuity (Allman et al., 1999).

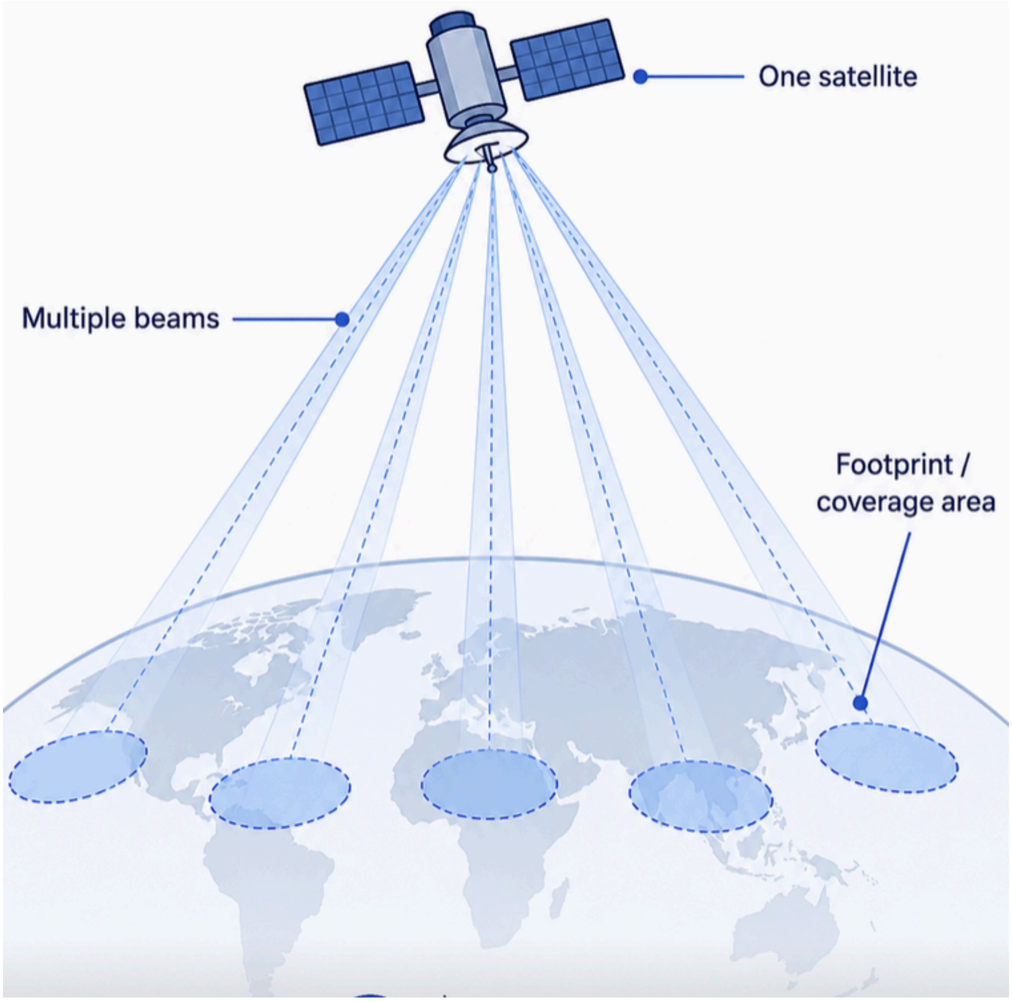


In the case of Starlink, the terminal may have several satellites available, and the system dynamically selects the most suitable one (Li, 2025; Starlink, n.d.-c).

Because LEO satellites move quickly across the sky, these changes may occur many times during the normal operation of the connection.

Satellite coverage is not normally described through a single “cell” as in terrestrial cellular networks.

A satellite uses antennas that generate one or more **radio beams.**
Each beam illuminates a specific area of the Earth’s surface, called a **footprint**.
A satellite can generate multiple beams and therefore serve several areas simultaneously.



A single satellite can produce multiple beams and reuse its radio resources in different areas (Starlink, n.d.-c).

In LEO constellations, the coverage configuration changes continuously because the satellites move relative to the Earth’s surface.

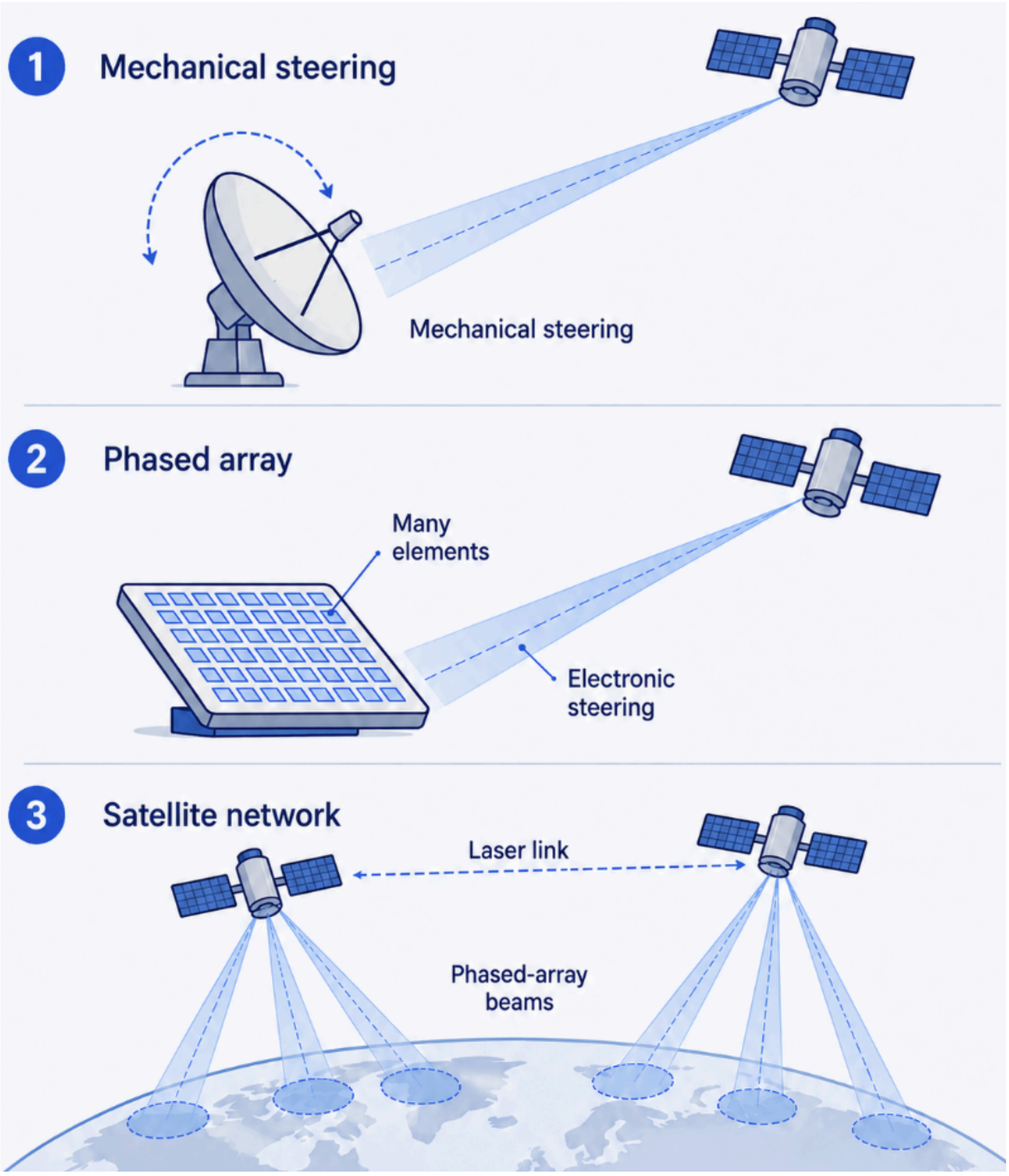
For this reason, the network must constantly know the positions of satellites, terminals, and ground stations and decide which links to use (Li, 2025).

The antennas used are also different from traditional fixed satellite dishes.

Starlink terminals, for example, use **phased-array antennas**, consisting of many electronically controlled radiating elements (Starlink, n.d.-c).

Unlike an antenna that must be mechanically pointed toward a satellite, a phased-array antenna can electronically change the direction of the radio beam without continuously rotating the entire antenna (Starlink, n.d.-c).

Starlink satellites also use phased-array antennas and different frequency bands, while links between satellites can use optical laser communications (Starlink, n.d.-c).



As with mobile networks, satellite communications use regulated portions of the **electromagnetic spectrum** (ITU, 2022).

Available frequencies must be coordinated so that different systems can operate without causing harmful interference (ITU, 2022).

However, connection quality does not depend only on the distance from the satellite.

Because the terminal must communicate with objects in the sky, it is particularly important for it to have a sufficiently clear view of the sky.

Trees, buildings, mountains, or other structures can obstruct the signal path (Allman et al., 1999).

In constellations consisting of many satellites, the system may in some cases switch to another satellite to avoid a temporarily obstructed link, but a location with a severely restricted view of the sky can still compromise the connection.

Weather conditions can also affect propagation. Heavy rain, snow, and hail can attenuate radio signals and temporarily reduce service quality (ITU, 2023).

A satellite connection also shares part of its capacity among multiple users.

The available speed therefore depends not only on terminal technology, but also on the number of users being served, the capacity of the satellites and gateways, geographical location, and network congestion (Li, 2025; Starlink, n.d.-b).

Satellite networks therefore have different advantages and limitations compared with terrestrial infrastructure.

Their main advantage is the ability to reach places where adequate terrestrial connections are not available (ITU, 2022).

- Providing a connection to an isolated house, a ship, a mountainous area, or a sparsely populated region may require building kilometers of fiber-optic infrastructure or installing new radio base stations.
- A satellite network can instead carry a significant part of the connection through space, mainly requiring a terminal and a sufficiently clear view of the sky (ITU, 2022).

This makes satellite networks particularly useful as an **access network**, that is, as the connection between the user and the operator’s infrastructure (Li, 2025).

However, this does not mean that satellites completely replace the terrestrial Internet.

When traffic returns to Earth, it can continue through points of presence, data centers, routers, fiber-optic backbones, and other traditional infrastructure (Li, 2025).

The satellite network is therefore part of a larger communication system.

Starlink is a significant example of this integration: the user terminal communicates with the satellite constellation, but the constellation is itself connected to a terrestrial network of gateways and points of presence that provide access to the Internet (Li, 2025; Starlink, n.d.-c).

Finally, mobile and satellite networks can be integrated to extend connectivity to areas that are not covered by traditional radio base stations (3rd Generation Partnership Project [3GPP], 2024).

Satellite-to-phone communication, also known as **Direct-to-Device (D2D)**, is a form of communication in which an ordinary mobile phone communicates directly with a satellite without first connecting to a terrestrial radio base station (3GPP, 2024; Starlink, n.d.-a).

The satellite therefore performs, in part, a role similar to that of a radio base station in space.

Starlink Direct to Cell is an example of this type of technology: some Starlink satellites operate as radio base stations in space and can connect directly to compatible mobile phones (Starlink, n.d.-a).

In this case, mobile and satellite networks are no longer completely separate systems, but can become integrated parts of the same communication infrastructure (3GPP, 2024).

Supplementary materials

Key points

- A satellite connection normally includes user terminals, satellites, ground stations, and terrestrial infrastructure.
- The satellite does not normally host the website requested by the user, but forwards the data to other parts of the network.
- Satellites can communicate directly with ground stations or, in some networks, use **inter-satellite links**.
- The main orbits used in telecommunications can be classified as ***LEO***, ***MEO***, and ***GEO***.
- *GEO* satellites are located about 35,786 km above the Earth and appear stationary to an observer on the surface.
- A **satellite constellation** is a group of satellites that operate in a coordinated way to provide coverage and communication services over a specific area or, in some cases, over much of the Earth.
- *LEO* satellites orbit much closer to the Earth and can reduce connection delay, but they generally require constellations made up of many satellites.
- **Starlink**, a well-known satellite network, uses a constellation of *LEO* satellites to provide Internet access.
- In *LEO* constellations, the terminal must periodically switch communication from one satellite to another.
- Satellites can use multiple radio beams to serve different areas of the Earth's surface.
- **Phased-array antennas** can electronically steer the radio beam toward the satellite.
- Obstacles such as trees and buildings, as well as severe weather conditions, can reduce connection quality.
- A satellite network can be particularly useful for providing Internet access in remote areas or places that are difficult to reach with terrestrial infrastructure.
- A satellite network does not necessarily replace terrestrial Internet, but can integrate with gateways, points of presence, and terrestrial backbones.
- **Direct-to-Device (*D2D*)** systems allow some satellites to communicate directly with compatible mobile phones through integrated mobile networks.
- **Starlink Direct to Cell** is Starlink's implementation of a *D2D* system.

Exercises

From Home to the Internet Through Starlink

Luca lives in a mountainous area where a fiber-optic connection is not available. He therefore uses Starlink to connect to the Internet.
He opens his browser and visits the school website.

Reconstruct the path followed by the data.

- Identify which device allows Luca's local network to communicate with the satellite network.

- Explain how data is transmitted from the terminal to the satellite.
- Explain what function the satellite performs along the path of the request.
- Describe the role of a ground station or gateway.
- Explain how the request can reach the Internet after returning to Earth.
- Describe the return path followed by the server's response.
- Explain how the path could change if inter-satellite links were used.
- Explain why it is incorrect to say that the website requested by Luca is located "on the satellite".

GEO or LEO?
Two operators want to provide a satellite Internet connection.
- Operator A uses a small number of geostationary satellites.
- Operator B instead uses a large constellation of satellites in low Earth orbit.

Compare the two solutions.
- Explain the fundamental difference between a GEO orbit and a LEO orbit.
- Explain why a GEO satellite can appear to remain stationary in the same point in the sky.
- Explain why a GEO satellite can cover a very large geographical area.
- Explain why the greater distance of a GEO satellite increases communication latency.
- Explain why a LEO network generally requires many more satellites.
- Explain why a terminal connected to a LEO constellation must periodically switch from one satellite to another.
- Indicate which of the two solutions may be more suitable for latency-sensitive interactive applications and justify your answer.
- Explain why it is not possible to determine which system is "better" in absolute terms without knowing the goals and requirements of the network.

Designing the Connection for a Mountain Refuge
A mountain refuge is located in a remote area far from populated centers.
It is not reached by fiber-optic infrastructure, the mobile network signal is very weak, and building a new terrestrial connection would be expensive.
The use of a LEO satellite network is therefore being considered.

Analyze the situation.
- Explain why a satellite connection could be suitable for this context.
- Identify which components would be needed at the refuge to connect users' devices to the Internet.
- Explain why the antenna should be installed in a location with a clear view of the sky.
- Identify some natural or artificial obstacles that could interfere with the connection.
- Explain why snow and severe weather conditions could affect performance.
- Explain why the available speed could decrease when many users use the same satellite infrastructure at the same time.
- Compare this solution with the installation of a fiber-optic connection, considering installation costs, performance, latency, and the difficulty of reaching the area.
- Finally, explain whether you would use the satellite network as the primary connection, as a backup connection, or in combination with another solution, and justify your choice.

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Further reading

- Marko Höyhtyä, Satellite Communications and Networks, Springer, 2025 — Provides a modern introduction to satellite communications and is particularly close to the topics covered in this chapter, including satellite orbits and constellations, system architecture, antennas and the air interface, satellite networking, and the integration of terrestrial networks with 5G/6G non-terrestrial networks.
- Gérard Maral, Michel Bousquet, and Zhili Sun, Satellite Communications Systems: Systems, Techniques and Technology, 6th ed., Wiley, 2020 — Offers a comprehensive treatment of satellite communication systems, covering satellite and ground segments, radio links, propagation, antennas, multiple access, broadband satellite networks, GEO systems, and modern LEO constellations used for Internet connectivity.
- Timothy Pratt and Jeremy E. Allnutt, Satellite Communications, 3rd ed., Wiley, 2020 — Explains the fundamental principles of satellite communication, including orbital characteristics, satellite links, propagation, antennas, earth stations, modulation, link budgets, and the design of satellite communication systems.
- Joseph N. Pelton, Satellite Communications, Springer, 2012 — Provides a more accessible overview of satellite communications, introducing orbital systems, satellite services, communication technology, ground infrastructure, applications, regulation, and the role of satellites within the wider telecommunications ecosystem.
- Muhammad Ali Jamshed and Ali Nauman, eds., Integrated Terrestrial and Non-Terrestrial Networks, Springer, 2025 — Focuses on the emerging integration between terrestrial cellular networks and satellite-based non-terrestrial networks, making it particularly useful for exploring 5G NTN, direct satellite connectivity,

mobility, coverage, latency, and the technical challenges involved in combining terrestrial and satellite infrastructures.

Editorial notes

In producing these materials, I have used generative artificial intelligence tools to support the writing process, particularly to improve the form of the text, reorganize content, refine wording, and speed up certain editorial tasks.

As I work independently on the production of these materials, I try to automate any activities that can reasonably be automated, so that I can devote more time to research, design, and content development.

However, artificial intelligence does not determine the content of this work: the choice of topics, structure, ideas, interpretations, examples, and teaching approach are developed by me. AI is therefore used primarily as a tool to support production and formal revision, while authorship and responsibility for the design and content remain mine.