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From Monolithic Satellites to the Internet of Satellites Paradigm: When Space, Air, and Ground Networks Become Interconnected

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Abstract

From the first satellite launched in 1957, these systems always have drawn the attention of telecommunications operators. Thanks to their natural orbit, satellites can provide coverage to the entire globe or serve a vast region. Is this feature that makes them potential systems to extend current ground networks over the space. The first satellites were conceived as a single backhaul system to broadcast television or phone calls. Over the years, this concept evolved to a group of satellites that compose a constellation to interconnect any user around the globe. Nowadays, these constellations are still evolving to massive architectures with thousands of satellites that are interconnected between them composing satellite networks. Additionally, with the emergence of 5G, the community has started to discuss how to integrate satellites in this infrastructure. A review of the evolution of the satellites for broadband communications is presented in this chapter, discussing the novel and future proposed architectures. The presented work concludes with the potential of these satellite systems to compose a hybrid and heterogeneous architecture in which space, air, and ground networks become interconnected.

Keywords: Satellite networks, Non-Terrestrial Networks, Satellite communications, Internet of Satellites, Mega-constellations

1. Introduction

Since 1957 with the launch of the first artificial satellite *Sputnik 1*, space has been populated by a wide variety of satellite systems. The development of new technologies proliferated the emergence of different satellite platforms for multiple purposes. The global miniaturization of the technology influenced the satellite design by enabling small satellites with reduced mass. This trend not only drove the satellite shape, but also noteworthy impacted on the perception of a satellite, and its development.

This has been reflected also in satellites developed to provide broadband telecommunications services. The global coverage and large spot areas are features that naturally characterize satellites, and which telecommunications operators may leverage to deploy services. Therefore, the first satellite to provide television broadcast was launched in 1964 [1]. New missions and systems followed this launch, achieving better communications performance from space, and certifying that satellites may

become a crucial system in these services [2, 3]. The achieved results encouraged to go a step forward on the design of satellite constellations. These constellations are composed of a group of satellites that work for the same goals. In this case, these constellations were conceived to provide phone services in low-orbit regions. Iridium or Globalstar are examples of the viability of the system [4, 5].

These constellations enabled to think about systems in which satellites are interconnected with Inter-Satellite Links (ISL) to exchange data [6]. These new systems represent satellite networks that dynamically change their behavior over time. With this new concept, novel architectures to optimize this dynamic behavior were presented [7–10]. From the proper definition of a single network to the integration of different constellations, each of those proposals presented unique features to enhance satellite services.

The apparition of the New Space concept and all the associated technology development also drove the novel progress in the broadband telecommunications domain [11]. In particular, the apparition of the mega-constellations became an important disruption in the concept of traditional constellations [12–14]. This architecture proposes the deployment of thousands of satellites to provide global Internet coverage. Among the different technology challenges, this approach also triggered the discussion of other difficulties related to frequency allocation or satellite manufacture procedure [15, 16]. An alternative to these massive constellations proposed the collaboration between satellites to share unused downlink opportunities. The Internet of Satellites (IoSat) paradigm [17] proposes the establishment of temporal satellite networks according to the necessity to exchange data. This dynamic environment poses new communications challenges that must be addressed in future researches.

The fifth-generation technology standard for cellular networks (5G) has been already established on the ground infrastructure as a fast, reliable, and high-connectivity communications interface for cellphones and other devices. Nevertheless, current discussions are still been performed on how to integrate satellite systems in this infrastructure [18]. Thanks to its global coverage, satellites become potential systems to expand current ground networks with a Non-Terrestrial Network (NTN) [19]. This network leverages this high altitude architecture which awards the satellites with unique qualities for the 5G. The large coverage area of spaceborne telecommunications systems enhances the service continuity in case that is not being ensured by ground infrastructure. Furthermore, satellite coverage enhances the network capacity by serving a myriad of end-users with a single spot. Finally, the orbit trajectory of a satellite allows reaching the service ubiquity on the entire globe, being able to provide services in remote and typically inaccessible areas.

This chapter surveys the evolution of satellites for broadband telecommunications services that have been experienced in the last years. Details of each developed technology are presented and discussed the implications on current and future network infrastructure. The remainder of the chapter is structured as follows. First, the apparition of broadband telecommunications satellites is presented in Section 2. Section 3 presents the satellite constellations that provided novel broadband services. The concept of satellite networks is discussed in Section 4. The impact of the New Space trend is presented in Section 5. Section 6 presents the novel concept of IoSat, while Section 7 discusses the integration of satellites in the 5G infrastructure. Finally, Section 8 concludes the chapter.

2. The apparition of communications satellites

Satellites have always been bounded to broadband telecommunications thanks to their large visibility of the Earth. This capability is inherited from their natural

movement. Satellites are celestial bodies which constantly move tracing an elliptical trajectory around another larger celestial body. The broadband telecommunications satellites orbit around the Earth. This distinctive motion is defined by means of the Keplerian orbital parameters or elements. These six parameters determine the shape and size of the ellipse, the orientation of the orbital plane with respect to the Earth, the orientation of the ellipse in this plane, and the location of the satellite along this trajectory.

Satellite orbits are gravitationally curved trajectories which can be represented in a two-dimensional trajectory located in a plane. This plane is known as orbital plane, and two Keplerian elements determine its orientation with respect to the Earth: (1) the longitude of the ascending node (Ω) corresponds to the horizontal angle between the plane and the origin of the longitudes (the Greenwich meridian or prime meridian); (2) the inclination angle (i) determines the vertical orientation of the plane with respect to the origin of the latitudes (the equator). The orbit shape traced in this plane is determined by (3) the semi-major axis (a) that corresponds to half the distance between the periapsis and apoapsis of the orbit, and (4) the eccentricity (e) which describes how much the ellipse is elongated compared to a circle. The resulting ellipse can be rotated in the same plane determined by (5) the angle known as argument of periapsis (ω). A satellite travels this elliptical curve over time, moving periodically among numerous locations. The position of a satellite in this ellipse is represented by the (6) the true anomaly (ν) which corresponds to the angle of the satellite location at a specific epoch or time with respect to the direction of the periapsis.

The ensemble of Keplerian elements allow the characterization of the satellite position, and its complete trajectory. **Figure 1** represents these parameters to clarify their meaning.

Numerous orbits exist depending on the values of the Keplerian elements, which laid the foundation of different classifications. Among them, the classification based on satellite altitude prevails, which determines implicitly the orbit semi-major axis. In this classification, satellite orbit are structured in three main blocks: (1) Low Earth Orbits (LEO) are identified by altitude values between 200 km and 2000 km; (2) Medium Earth Orbits (MEO) correspond to those orbits with an altitude encompassed between 2000 km and 35,786 km; Finally, (3) Geosynchronous Equatorial Orbits (GEO), also known as geostationary orbits, are determined by a specific altitude of 35,786 km. Is in this last type of orbit, indeed, in which

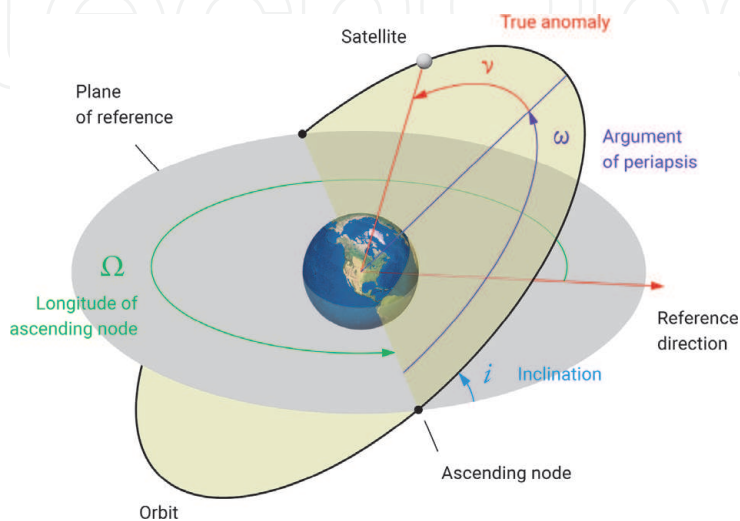


Figure 1.
Representation of the Keplerian elements that represents the orbit trajectory of a satellite (gray sphere), and its plane (yellow surface) with respect to the equatorial plane (gray surface).

telecommunications operators identified potential characteristics to deploy satellites that broadcast multiple services.

Satellites that orbit following GEO trajectories are characterized to be deployed in an orbit plane located at the equator of the Earth, and following a circular orbit (i.e. inclination 0° and eccentricity 0). This combination of inclination, eccentricity and altitude allows a satellite to constantly move at the same velocity than the Earth rotation. Therefore, a GEO satellite constantly observes the same region of the Earth, and remains them as fixed points in the sky. These characteristics are ideal to provide broadband services for specific geo-political regions, such as television delivery, military applications, or generic telecommunications.

Since the launch of the Syncom 3 satellite at 1964 [1], geostationary large-satellites became the standard configuration to provide these services. This was the first GEO satellite deployed to provide television coverage of the Summer Olympics. Its launches promoted the apparition of other GEO satellites, such as the Intelsat I (nickname Early Bird) satellite at 1965. In particular, this satellite was developed by the company Intelsat to demonstrate that communications through this kind of orbit were feasible. It was used during four years and four months to provide multiple services among different missions, standing out the first live television coverage and its participation in the Apollo 11 mission.

This satellite was the first one to provide direct communications contact between Europe and North America, handling telephone, television, and telefacsimile transmissions. This satellite paved the way to develop such kind of backhaul systems to communicate around the globe, and it was the first of a large family of Intelsat satellite that reaches current epoch with Intelsat 39 launched in 2019.

Over the different missions, the developments on these satellites have been focused on the optimization and adjustment of the Internet mechanisms, techniques, and protocols to enhance the throughput over satellites. With the advent of the different versions of the Digital Video Broadcast - Satellite (DVB-S) protocols [2], the television broadcast over satellites was also investigated as part of the digitalization of this service. The outcome of all these efforts was the development of the high throughput satellites, so-called next-generation satellites [3].

These GEO satellites has coped the broadband telecommunications activity during the last years with the mission development from companies like Hughes Space and Communications, Space Systems/Loral (SSL), Orbital Science Corporation, Lockheed Martin, Thales Alenia Space, and Airbus-Astrium. They are currently part of our space environment, and keep providing telecommunication service to interconnect fixed regions in the globe. This interconnection is also characterized by having a considerable delay transmission, around 900 ms (approximately). Although its static relative position becomes ideal for coverage region, this large delay values may not be suitable for services deployed in the Internet. Therefore, new approaches emerged to compensate this long delay with lower-altitude regions, and to integrate Internet services in these satellite systems.

3. The era of low-altitude satellite constellations

Gaffney et al. analyzed the feasibility of the new non-geosynchronous or non-geostationary satellite systems proposed on the US Federal Communications Commission (FCC) by different private companies [20]. These innovative proposals enhanced the communications end-to-end latency using MEO, and LEO satellites. Those orbit regions were not originally proposed because of the continuous relative movement—unlike the geosynchronous case—that satellite experience. Satellites in this configuration suffer from a small field of view and temporal contact with

ground devices, which leads to service disruptions. Therefore, satellite constellations have risen as a promising architecture to deal with this challenge, by performing user handovers between adjacent satellites. An in-depth study of the benefits of applying these constellations was presented in the dissertation [21]. Kashitani remarks that satellite constellations at LEO region can serve a larger number of customers with a relatively reduced deployment cost as compared to their MEO homonyms.

These performance expectations encouraged the development of numerous LEO satellite constellations by private companies. Globalstar emerged as a private company that could provide satellite phone and low-speed data communications with a dedicated satellite constellation [5]. The first satellites were launched in 1998 to start composing a constellation that would be finished in 2000. The Globalstar constellation was composed of satellites that worked as bent pipes or repeaters between two users located in the same spot. Although this design enables remote users to communicate, the system was also limited by having a common satellite to interconnect the end devices. If this common satellite was not available, the communication was not feasible.

The Orbcomm company developed a specific constellation to deal with this situation offering discontinuous coverage between end-users. Unlike the previous case, this constellation was designed to provide low-speed data communications, and it was not capable to offer telephone services. To provide this discontinuous coverage, satellites in this constellation were able to store incoming messages to download them later over another region. This store-and-forward mechanism was crucial to achieve this desired performance and became a key technology to develop the concept of Disruption Tolerant Networks (presented in the following section).

Alternatively to the previous constellations, Iridium Communications company decided to deploy its constellation to provide voice and data coverage to custom satellite phones [4]. This new constellation, known as Iridium, extended the original concept by interconnecting satellites with radio interfaces to relay data down to the ground; i.e. the development of Inter-Satellite Links (ISL). By defining a custom and specific constellation, a route between two end-users and composed of satellites could be defined. This revolutionized the concept of satellite constellation because they could transfer data among the satellites with a reduced delay. The original Iridium constellation was extended with a new generation of 66 satellites, called Iridium NEXT, in 2017. This extension aimed to enhance the satellite capacity from 2.4 kbps to 1.5 Mbps, using high-throughput techniques.

The LEO satellite constellations proposed for broadband telecommunications revolutionized the concept by evolving from a repeater-based approach for voice and data, passing through a store-and-forward solution for data, and reaching an interconnected architecture for voice and data. This last approach presented a constellation as a set of satellites that compose a network. This new satellite network concept paved the way for new interconnected architectures.

4. Interconnecting satellites to compose satellite networks

This ISL concept revolutionized the perception of satellite constellations, which started to be conceived as networks composed of satellites. Werner discusses the challenges of deploying these networks and concludes that satellite mobility is a key factor in the stability of the links that compose the network [7]. In particular, the nature of an ISL is determined by the relative motion between two satellites. Therefore, an ISL may be feasible and active during a lapse of time depending on the orbits.

These temporal links are also known as satellite contacts and drive the topology representation of a satellite network. In particular, a topology is represented by a set of nodes that are interconnected by edges. Werner proposed the representation of a satellite network topology with the concept of a snapshot. A snapshot of a network is the topology representation with the connections established between the satellites that remain stable during a lapse of time. The creation or destruction of an ISL results in the generation of another snapshot. The overall generated snapshots compose a sequence that represents the evolution of the topology over time.

Figure 2 presents an example with three snapshots, identified by s_k (s_0 , s_1 and s_2), that remain stables between the lapse of times t_i (snapshot s_0 remains stable between t_0 and t_1). This evolution is characterized by the movement of the nodes, which in this case corresponds to the orbit trajectory. Therefore, the number of snapshots and its stability time depends directly on satellite orbits and their communications means. Just as a brief reminder, this motion is determined by a set of parameters that allow estimating the complete trajectory of a satellite. Furthermore, this trajectory follows a periodic pattern, if no orbit disturbances are considered. Consequently, the sequence of snapshots is periodic and predictable.

The transition of these snapshots may represent an evolution of a satellite network in which parts of it are isolated during a lapse of time. These isolated fragments of the network may be sporadically connected with other satellites over time, depending on the nature of satellite contacts. This intermittent connectivity encourages to define an environment in which network partitions are frequent, and satellites must leverage opportunistic and sporadic satellite contacts to communicate. The understanding of this temporal nature of satellite contacts becomes crucial in the definition of end-to-end routes in this scenario.

Delay and Disruption Tolerant Networks (DTN) approaches envision the establishment of routes in this disruptive environment [9]. A proposal to solve this disruption is a store-and-forward approach, that is a way to store messages from a satellite to lately propagate them to another satellite was conceived to leverage the opportunistic and sporadic satellite contacts. Nevertheless, the definition mechanisms to identify end-to-end routes in this disruptive environment were largely discussed.

Among the different proposed techniques, a classification was conducted in [22] based on the generation of replicas of the messages. In this regard, a protocol that replicates messages is known as a replication-based protocol, which is characterized by delivering the data to the destination according to a probability, based on the number of replicas generated. Alternatively, a forwarding-based protocol estimates future satellite contacts to define routes over time, requiring a larger computational effort. Authors in [22] conclude that it must exist a balance between future knowledge of the network evolution, and the computational capacity.

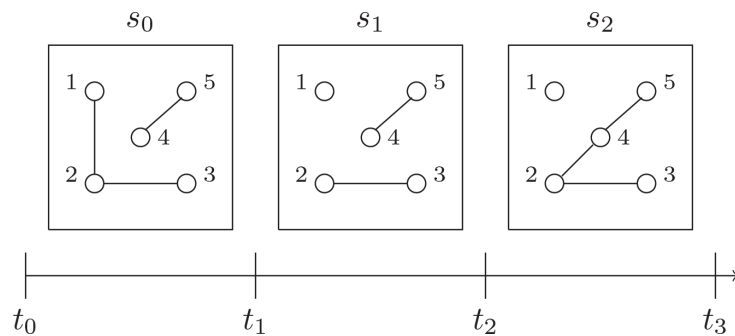


Figure 2. Representation of different snapshots (s_k) over time (t_i) associated with five satellites. Figure from [17].

The Iridium constellation aimed to compensate this topology evolution and mitigate network disruption by conceiving a custom constellation architecture that would later be known as LEO Satellite Networks. Ekici et al. started to work with a satellite constellation configuration that mitigates this mobility impact on the communications performance [6].

The constellation is designed with an orchestrated and fixed architecture in which satellites are specifically located on purpose. This constellation builds a mesh architecture in which each satellite has four satellite-to-satellite interfaces to communicate with its neighbors. The resulting topology of the network is characterized by nodes located in a grid with a set of rows and columns. Despite this design to mitigate the disruption, satellites are always in motion. However, the movement of the satellites in this constellation results in a continuous shift of the satellites in the column axis of the mesh.

This coordinated movement ensures that from the local view of a satellite the connections with its neighbors remain unaltered. This condition is satisfied in the most populated latitudes because when the satellites pass over the polar region the formation cannot be respected. Moreover, an abstract line represents a seam in this mesh that separates the direction of the satellites. On one side of this seam, the satellites move from the South to the North, while on the other side they travel in the opposite direction. Traditionally, communications through this seam were forbidden.

Figure 3 presents this satellite constellation with its corresponding mesh topology.

This constellation is founded over two classes of ISL, defined according to the vicinity of the neighbor. The intra-plane ISL allows a satellite to communicate with its two neighbors that are located in the same orbit plane. Meanwhile, the inter-plane ISL allows a satellite to communicate with its two neighbors located in adjacent planes. This differentiation was conducted because the nature of both ISL types differs: intra-plane ISL are always stable and feasible, while inter-plane ISL may be disconnected in the polar region. The goal to relay data from ground users was satisfied by defining the concept of a virtual node. This kind of node is associated with a logical location that corresponds to a square of an entire grid that covers the entire Earth surface. Each satellite is then associated with a logical location when it passes over this surface square, being responsible to serve the users allocated in this area. Due to the satellite movement, the satellite changes over time their logical

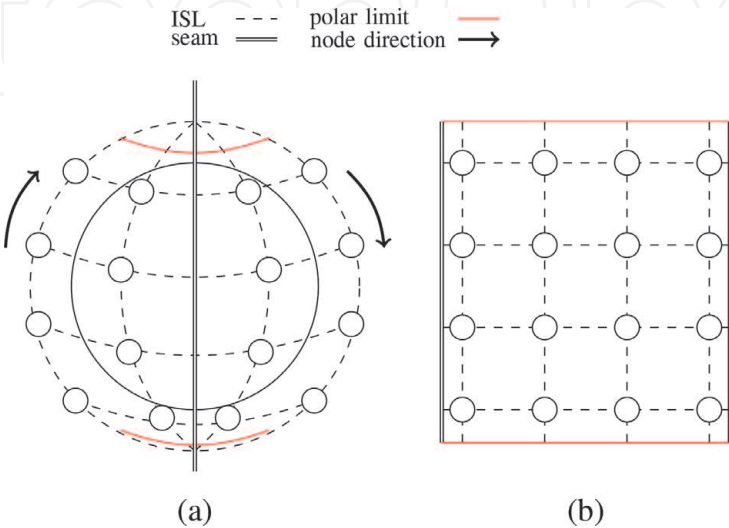


Figure 3.
Representation of (a) the constellation design that represents a LEO satellite network, and (b) its resulting map to a mesh topology. Figure from [17].

location when they bypass the corresponding square. Furthermore, the logical location is also mapped in the mesh topology by vertical and horizontal coordinates that correspond to the column and row numbers.

The LEO Satellite Network concept was extended in future researches by integrating other satellites in further orbit regions. The combination of multiple satellite systems stood out as a potential architecture to offer new capabilities or improve the capacity achieved by their own.

Multi-Layered Satellite Networks (MLSN) are a system-of-systems architecture [23] compounded of distinct satellite constellations deployed at different altitudes, which corresponds to the layers in this system. This architecture was proposed in [8] to enhance the traffic capacity and the stability of a satellite network. The proposal leverages the visibility of the satellites located at higher altitudes that can orchestrate a group of satellites deployed in lower altitudes.

A hierarchical structure in which successively upper layers always gather lower layers is designed under the previous premise. Despite the original proposal did not specifically define the type and the number of layers, the LEO, MEO, and GEO were typically the three main layers associated with this network. In this configuration, GEO satellites would manage a group of MEO satellites, which at the same time each one would gather an ensemble of LEO satellites. Satellites located in the same layer can communicate among them using Intra-Orbital Links (IOL), while they are also able to interact with satellites in adjacent layers using ISL.

Figure 4 illustrates this multi-layered architecture with the three main altitudes.

This hierarchical architecture enhances the stability of the network thanks to the large visibility of upper-layer satellites. Despite the connections between the satellites still changes over time, the topology changes correspond to fluctuations of the low-layer satellites that belong to the group of an upper-layer satellite. This feature mitigates the influence of satellite mobility on network dynamism. Nevertheless, the architecture design of the low-layer satellite system may still provoke irregular changes in the topology. [24] discussed this behavior and suggested the use of a LEO satellite network—which ensures the mesh formation—as a lowest-layer

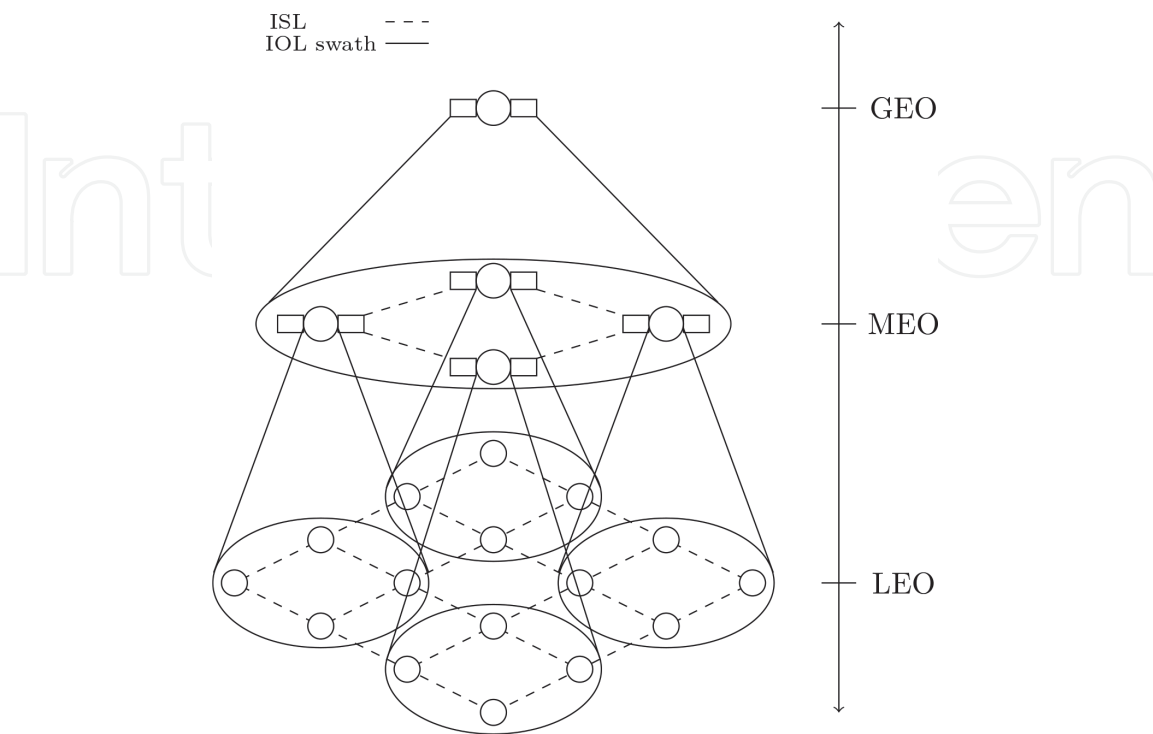


Figure 4.
Illustration of a MLSN with three layer. Figure from [17].

satellite system. This satellite constellation simplifies the computation of end-to-end routes among the layers, and in the same layer. The integration of a LEO satellite network into the MLSN demonstrates the potential of this heterogeneous architecture, that may accept including multiple distinct satellite systems.

The architectures of these satellite networks were presented considering always the traditional concept of satellite missions, in which a constellation is properly defined. Nevertheless, the apparition of new trends in the space related to the New Space movement has motivated novel concepts of satellite networks with non-conventional strategies.

5. The disruption of New Space in broadband telecommunications

Nowadays, the New Space concept is becoming an important trend that different countries leverage to encourage and promote space activities in their society. Due to the large number of new concepts associated with this movement, it is difficult to properly define the New Space trend. Authors in [11] try to clarify this concept by performing a survey of different researches. Their study concludes that this new trend is characterized by a set of key traits: (1) the apparition of new private entities that deploy novel satellite architectures in front of the traditional national space agencies; (2) novel development procedures that simplify and reduce the cost of the manufacturing of space products; and (3) the technology development is performed to always satisfy customer needs. These traits are associated with research of novel technologies related to satellite autonomy, miniaturization, satellite platforms, and crowd.

This current technological landscape would not be possible without the emergence of the CubeSat platforms [25]. This well-founded architecture was conceived in 1999 by professors Jordi Puig-Suari from California Polytechnic State University, and Bob Twiggs from Stanford University. The goal to develop a spacecraft architecture that would facilitate academic developments surprisingly triggered the creation of a new philosophy to develop satellites: the use of Commercial Off-The-Shelf (COTS) components, and the reduction of satellite dimensions. These small satellites are equipped with all the subsystems of a traditional satellite, which are composed of COTS components. This strategy speeds up spacecraft development, and drastically reduces the cost of its production. Therefore, the CubeSats are ideal platforms to investigate and develop new technologies.

The inventiveness experienced with CubeSats influenced also the traditional big-satellite activities. New private and adventurous proposals have proliferated in the last years encouraged by their commercial prospects. The most distinguished innovative application for this big platform is the deployment of satellite constellations that provide continuous Internet access. Despite the numerous improvements in the ground facilities, satellite platforms stood out as a potential system to achieve this requirement. LEO satellite constellations are naturally characterized by providing global coverage to the entire planet. Iridium constellation is an illustrative example of how this architecture can provide data access to a widespread group of ground users. Despite this infrastructure, current Iridium services are limited to a poor messages exchange (hundreds of kbps), which may not be sufficient for current and upcoming Internet services (e.g. video streaming, cloud computing, etc.) Therefore, an extension of these traditional LEO satellite constellations has been proposed to cope with this new demand.

Private companies have taken a step forward in the development of massive satellite constellations, which assemble hundreds or thousands of satellites to provide global and seamless Internet coverage with competitive interfaces; i.e. with low

latency and high throughput. These ambitious goals cannot be achieved with traditional architectures nor delay-tolerant solutions.

Among the different companies, OneWeb Ltd.—previously named WorldVu—was the first one that announced the development of this macro architecture [12]. Joining efforts with Virgin Group and Qualcomm, OneWeb expected to deploy 720 satellites at 1200 km height. This LEO satellite constellation was not designed to include satellite-to-satellite architecture, which requires the deployment of further satellites to satisfy current demand [26].

Space Exploration Technologies Corp. (SpaceX) publicly announced the development of the Starlink mega-constellation one year later [13]. Starlink comprises 4425 satellites that would be distributed across several sets of orbits. Three different layers are distinguished: the main layer at 1150 km, the secondary layer at 1110 km, and the third layer at 1130 km. This macro satellite system corresponds to an MLSN thanks to the use of satellite-to-satellite laser interfaces, although all the layers are located in the LEO region. SpaceX has already deployed 1,015 satellites of its StarLink mega-constellation, having 951 still in orbit [27].

More recently, Telesat Canada envisioned deploying a massive satellite constellation of 117 small-satellites to compete with the previous constellations [14]. These satellites would include a dedicated ISL with high transmission capacity.

Preliminary studies demonstrated that these massive satellite constellations can provide communications interfaces that can satisfy high-data volumes (up to Tbps), and low-latency communications [26]. Despite the potential performance of this architecture, its enormous size poses numerous challenges. Among the different ones that have been discussed during the last years [28], six challenges stand out: (1) The required funds to maintain the development of the entire project [29]; (2) The necessity to develop and construct a satellite manufacturing infrastructure to reduce the production cost [30]; (3) the increase of space debris due to the overpopulation of the space [15]; (4) the hoarding of frequency bands due to the necessary wide bands allocations; (5) the complex administrative registry of this large number of satellites [16]; (6) Impact on other space fields, like astronomy [31] forcing to develop custom mitigation technologies [32]. These constraints make that the deployment of this massive satellite constellation feasible to specific companies or entities. Another perspective in which does not require the launch of massive constellations from independent entities needs to be conceived to balance these problems.

6. The internet of satellites paradigm

Alternatively to these massive satellite constellations, a collaborative and distributed approach has been proposed in the last years. The concept of Federated Satellite Systems (FSS) was presented by Prof. Golkar in [10]. This new satellite system essentially consists of spacecraft networks in which satellites trade unused or inefficiently allocated resources commodities, such as data storage, data processing, downlink capacity, power supply, or instrument time. This concept is analogous to terrestrial applications, such as peer-to-peer file sharing, cloud computing, and electrical power grids. In this way, FSS tried to avoid the underutilization of expensive space assets in already existing missions. The establishment of cooperation frames beyond the common mission interactions based on ground post-processing and merging of instrument data becomes more and more a necessity. Distinct-stakeholder satellite missions would leverage the establishment of in-orbit collaborations by improving current system performance or by achieving new goals.

The terminology presented in [10] allows understanding the nature of these collaborations. A *satellite federation* is composed of a group of satellites which decide

to engage in a collaboration with each other during their mission. These federations allow the satellites to share or trade available *resources* which are the tangible and intangible assets that a spacecraft has (e.g. propellant, power, data processing, downlink capacity, etc.) Although the original definition encompasses generic assets, the later work investigated federations with data-centered resources, such as processing, downlink, and storage capacity.

The establishment of a satellite federation has a decision-making component—not necessarily autonomous—with which a satellite *opportunistically* deems if the collaboration is beneficial, where the benefit is defined as either economic profit or generic value. Despite the opportunity refers to the federation profit, a temporal aspect also is integrated with these characteristics. Due to the mission lifecycle of a satellite, resources are not constantly available, enabling temporal windows of opportunity in which they can be traded. During this transaction, the satellite that supplies the corresponding resources are defined as satellite *suppliers* or *providers*. When instead a satellite is seeking to request the resources, it plays the role of a *customer* in the federation. These roles may be switched over satellite lifetime depending on their interest, being also possible that a satellite acts as both customer and supplier at the same time. In the end, the joint set of customers and suppliers makes a satellite federation.

The FSS concept also differs from the other approaches, because they can be conceived as virtual satellite systems. These systems represent a group of satellites that are part of a distinct physical system—like a constellation—and they decide to create a new one that is fictitious. Traditional applications offered to ground users can be achieved with these systems, but new ones proliferate with this virtual group of satellites. Machine-to-machine applications may be deployed among the different satellites that conform the virtual system, like trajectory applications (e.g. flight formation, collision avoidance), applications that require data fusion (e.g. cloud detection, different instruments), among others. In terms of communications, this can be represented as an autonomous satellite application that deploys some services through and for satellites. All these characteristics require solutions that are flexible, adaptable, and scalable that must be reflected in all the development levels, included in the inter-satellite communications ones.

For this reason, our work in the last years has been focused on conceiving and developing the Internet of Satellites (IoSat) paradigm [17]. This approach proposes an interconnected space segment that follows these premises from satellite federations. A custom satellite infrastructure that corresponds to a network backbone is not proposed in this paradigm. Instead, it promotes the establishment of networks using peer-to-peer architectures, in which interested satellites are part of the network. The IoSat paradigm cannot be understood without firstly observe the nature of satellite federations.

FSS encourage the establishment of sporadic and opportunistic collaborations to share unallocated resources among heterogeneous satellites. It is important to understand concept-by-concept what this statement means.

The **sporadic** term refers to the possibility to deploy this collaboration at any moment. This feature makes satellite federations unpredictable events that may occur without notice, and they cannot—normally—be estimated in advance. Despite this randomness, the need to deploy federations is related to the satellite resources and the potential benefit that a satellite can award.

This is related to the **opportunistic** term, which suggests that federations are only established if related satellites envision to garner some benefits (e.g. enhancement of mission performance, an extension of satellite capabilities, payment for resources shared). This opportunism also refers to the mandatory non-degradation of the original mission. Satellites that establish a federation are designed to perform

a specific mission (e.g. observation of the soil moisture, relay data from ground terminals, observe the galaxy), which must remain as its main priority. Therefore, the federation cannot degrade the performance of this mission by the undesired depletion or allocation of resources.

If the satellite does not identify a potential benefit, it must be able to **decide** not establishing a federation. This decision-making capacity becomes crucial to deploy federations and entails the awarding of a certain level of autonomy to the satellites. Finally, the satellites that collaborate are equipped with different resources and capacities.

This **heterogeneous** configuration poses multiple challenges related to resource sharing, connectivity, among others.

Following these features, the paradigm suggests dynamic, sporadic, and opportunistic satellite networks that are temporally established depending on the necessity and choice to deploy federations. These temporal networks have been called Inter-Satellite Networks (ISN) following the traditional nomenclature originated in [33]. This kind of network is created by the decision to collaborate—not necessarily for free—of satellites, that become the intermediate nodes of the network. In particular, the creation of an ISN is achieved thanks to the combination of point-to-point federations among intermediate nodes that share the possibility to communicate.

Figure 5 illustrates the paradigm philosophy by showing three ISNs (ISN_1 , ISN_2 , and ISN_3) which coexist simultaneously. These ISNs are created depending on the FSS requirements and they adapt themselves to manage network dynamism. Note also that some nodes can participate in multiple ISNs at the same time.

A satellite federation is established only when the transaction is required, after that the federation is no longer needed. This temporality is also reflected in the definition ISN. This corresponds that ISNs have three phases that characterize their lifetime: (1) the establishment phase, (2) the maintenance phase, and (3) the destruction phase.

The establishment of an ISN is the negotiation process in which intermediate federations are created to configure the network. During this phase, its members can decide to not accept this interaction due to their state or strategy interests. Moreover, the establishment phase ensures that the ISN can satisfy FSS requirements by providing the required services. For instance, if a security level is required, intermediate nodes should have secure mechanisms to provide it. This implies that during the ISN establishment, nodes shall indicate which services they can provide.

Once the ISN is established, the maintenance phase ensures that the network adapts to different events. In particular, as a satellite network is a dynamic

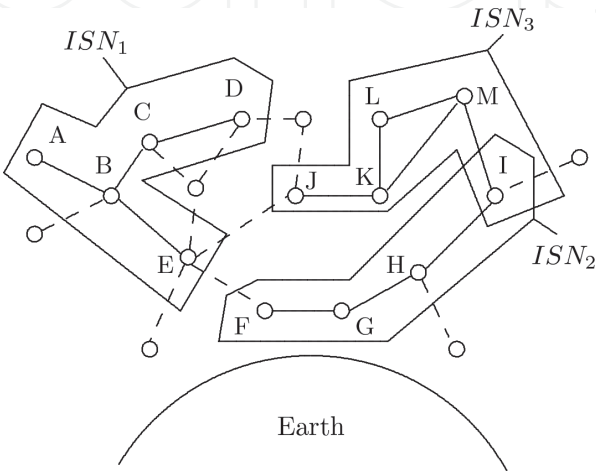


Figure 5.
IoSat space segment representation. Figure from [17].

environment in which nodes are in constant movement, this phase is responsible to update network connections when intermediate links are broken. Therefore, it should be able to replace old intermediate nodes by adding new ones. Moreover, some satellites could request to participate in an existing federation that would need to add more intermediate nodes to increase the current ISN. Thus, the ISN should be able to adhere new satellite nodes as per their request, or by the need to keep the topology stable.

Finally, in the destruction phase (once the ISN is no longer required) all the nodes that have participated in the network should perform the destruction process which cleans their internal state and recovers their usual activity. This is an important phase because the resources shall be released when they are no more needed.

There is a common need that should be respected in an ISN. Satellites are embedded systems with severe limitations in terms of energy, computation, and data storage resources, which means that additional inter-satellite communications capabilities could jeopardize the mission. This could appear because satellites are normally conceived to accomplish a specific mission, and the integration of these new capabilities could suppose an additional resource consumption that could deplete the satellite. In other words, the deployment of an ISN shall not impact the mission of intermediate satellites. Therefore, this network is deployed using a resource-aware strategy while trying to satisfy application requirements. Moreover, if a satellite decides that its participation in the network compromises the accomplishment of its mission, it can decide to leave the network. Therefore, satellites require a certain level of intelligence to autonomously take this decision. An ISN is a completely dynamic and constantly changing scenario, due to satellite mobility, node participation, and node resource state.

Our previous researches have addressed the multiple technology challenges associated with the IoSat paradigm. A predictive algorithm was developed in [34] to provide autonomous capabilities to satellites. In particular, this algorithm can estimate future satellite contacts and predict routes overtime in which federations can be established. Moreover, new protocols regarding the necessity to notify resources available (e.g. downlink opportunities) and the procedure to establish a federation were published in [35, 36]. These two protocols have been evaluated in an scenario with Earth Observation (EO) satellites that uses federations with a mega-constellation to download data. **Figure 6** presents the achieved results of these simulation, being able to duplicate the amount of bytes downloaded per day when

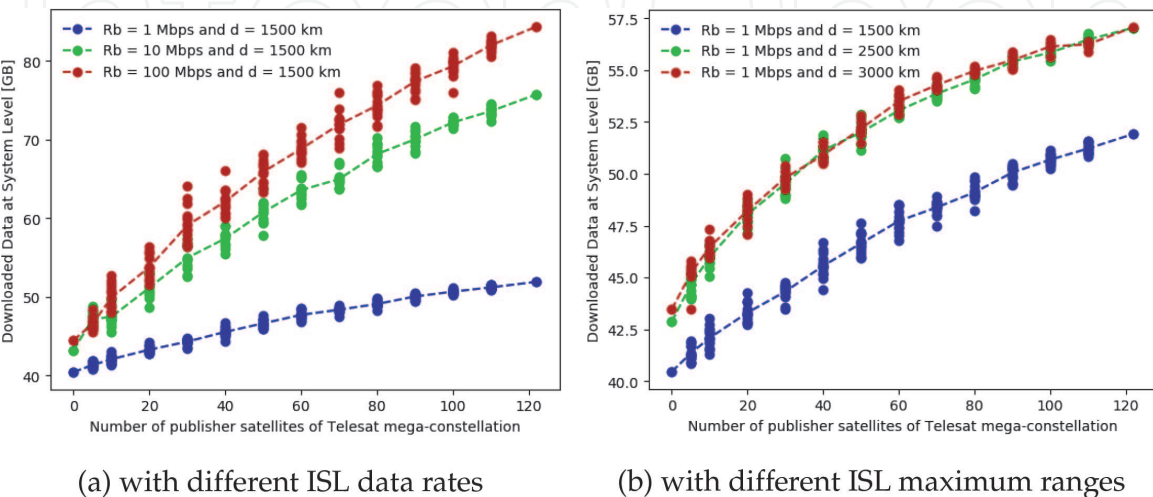


Figure 6. Downloaded data of saturated EO satellites per day according to the publisher satellites and ISL subsystems with different maximum range (left figure) and data rates d_{max} and different data rates R_b (right figure). Figure from [35].

more satellites of the mega-constellation participates as providers of the downlink service.

Apart from these innovations, the paradigm still poses considerable challenges that must be tackled in future researches.

7. The emergence of 5G in satellite systems

The fifth-generation technology standard for cellular networks (5G) has been already established on the ground infrastructure as a fast, reliable, and high-connectivity communications interface for cellphones and other devices. The 3rd Generation Partnership Project (3GPP) developed multiple specifications that conform this standard over the years [37] to satisfy the requirements of future use-cases. These requirements were presented by the International Telecommunication Union Radiocommunication (ITU-R) sector in the International Mobile Telecommunications (IMT) for 2020 and beyond [38]. The standard presents three use-cases according to the current and future telecommunications activity: the enhanced Mobile Broadband (eMBB), the massive Machine Type Communications (mMTC), and the Ultra Reliable Low Latency Communications (URLLC). The eMBB scenario is an evolution of the mobile broadband applications developed in the previous generation standard (4G) by improving the data transfer performance and increasing the seamless experience. Both URLLC and mMTC are new use-cases that were defined due to the emergence of the Internet of Things (IoT) and the apparition of Critical Communications (CC). The IoT paradigm [39] promotes the interconnection of multiple devices that can exchange data without requiring human interaction. In this way, the mMTC represents this trend which is characterized by a myriad of connected devices that typically transmit a relatively low volume of delay-tolerant data. The URLLC scenario is centered on safety and critical applications that require real-time and reliable communications, such as control of industrial manufacturing, remote medical surgery, autonomous driving, and other emergency applications.

The 5G specifications were developed to satisfy the requirements published by the ITU-R in [40]. This development has been conducted to achieve three main goals:

- Provide high data speeds — efforts were focused to conceive new transmission techniques that satisfy the necessity of high data rates of the eMBB use-case. Therefore, enhanced downlink and uplink communications would provide data rates up to 20 Gbps and 10 Gbps respectively, ensuring hundreds of Mbps on average.
- Reduce the end-to-end latency — the URLLC applications require the data delivery process to be more instantaneous because critical services cannot suffer from delay. Therefore, the enhancements would allow reaching real-time access with end-to-end latency of less than 1 ms.
- Ensure seamless and global connectivity — the emergence of autonomous and mobile devices encourages the development of an infrastructure that enhances the continuous connection with the network. Services deployed over this network would not suffer any disruption which could compromise the performance in mMTC, eMBB, and URLLC scenarios.

Is in this last goal in which satellites have stood out as a promising platform to be integrated with the 5G infrastructure. In March 2017, 3GPP started new activities to

study the role of the satellites in the 5G [19]. The outcome of these studies was the definition of the Non-Terrestrial Networks (NTN) which encompasses the multiple systems not located on the ground, such as satellites, Unmanned Aerial Vehicles (UAV), or High Altitude Platforms (HAP). This network leverages this high altitude architecture which awards the satellites with unique qualities for the 5G. In this way, the NTN are conceived following the multi-layered satellite network premise, but including in the architecture other systems than only satellites. The large coverage area of spaceborne telecommunications systems enhances the service continuity in case that is not being ensured by ground infrastructure. Furthermore, satellite coverage enhances the network capacity by serving a myriad of end-users with a single spot. Finally, the orbit trajectory of a satellite allows reaching the service ubiquity on the entire globe, being able to provide services in remote and typically inaccessible areas.

These qualities have led to the definition of multiple satellite applications in the eMBB, mMTC, and URLLC scenarios [18]. The eMBB scenario would leverage on satellite systems working as complementary traffic backhauling nodes of the network, or by reducing the handovers of those mobile nodes that perform large trajectories, such as trains or airplanes [41]. Satellites could enhance the services in the mMTC scenario depending on the area in which the devices are deployed. For wide-area services, the satellites play the important role of large visibility to become a central node that feeds device traffic. Otherwise, in local area services, the satellites become a complementary infrastructure to backhaul the traffic of a massive number of devices, like the eMBB case. Unlike the other cases, satellite altitude prevents from achieving the required end-to-end latency for URLLC cases. Nevertheless, the satellites enhance these services by providing a supporting role that broadcasts information over a wide area.

Novel private entities have observed this potential capacity of satellites to support the current 5G and IoT infrastructure, and they started the development of their satellite constellations. Lacuna Space started the development and launch of a dedicated CubeSat constellation for supporting IoT services from space [42]. Currently, they have just launched the third satellite of the constellation which uses Long Range (LoRa) communications technology. Other companies like Sateliot, Kepler Communications, or Eutelsat have also pronounced to deploy their constellations. It seems that another space race started to integrate satellites into the IoT paradigm.

8. Conclusions and way forward

During the last decades, space has been populated by a wide variety of satellite systems. From monolithic GEO satellites to current constellation approaches, space missions have experienced a considerable evolution to provide new services to the users. The traditional television broadcast and phone calls lead to more resource-demanding services based on current Internet applications. Constellations of LEO satellites have emerged as the necessary infrastructure to support these new services in space.

These constellations were originally conceived as independent satellites orbiting in an ad-hoc architecture. Nevertheless, they started to be considered as satellite networks when interactions between satellites were needed to satisfy the novel delay and throughput demands. The configuration of these interconnected satellites promoted the proliferation of different architectures to leverage on satellite altitudes or to mitigate satellite dynamics (e.g. MLSN, LEO Satellite Networks, etc.) All of them inspired satellite architectures that are currently working in space, such as

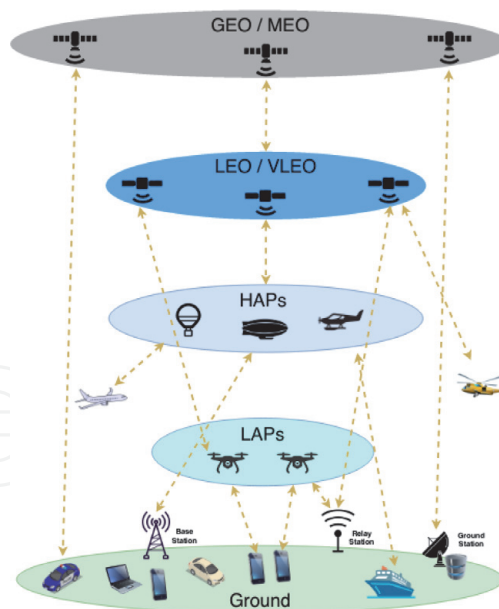


Figure 7.
NTN architecture proposed in the 3GPP. Figure from [18].

the Tracking Data Relay Satellite System (TDRSS) or the Iridium constellation [4]. In this way, the New Space trend promoted the apparition of novel flexible and distributed architectures to keep evolving the space for future user demands, like the mega-constellations or the IoSat paradigm.

The next step of this space evolution seems to be associated with the ground network revolution experienced with the 5G. The possibility to extend the current infrastructure with seamless connectivity puts satellites as potential systems for this purpose. The existence of different entities that are working on standardize the integration of satellites with ground networks, conforming the NTN concept, is an example of how satellites will become more and more a reality in our infrastructure. **Figure 7** presents a conceptual view of the NTN architecture composed of satellites, High Altitude Platforms (HAP), and Low Altitude Platforms (LAP). Different missions have started to experiment with satellite capabilities to provide IoT connection around the Earth globe. Their success demonstrates the potential of these new systems (for ground networks) and helps to believe in a promising future with heterogeneous networks composed of space, air, and ground infrastructure. Only time will tell whether this paradigm would become a reality.

Acknowledgements

This work has been (partially) funded by “CommSensLab” Excellence Research Unit Maria de Maeztu (MINECO grant MDM-2016-0600), the Spanish Ministerio MICINN and EU ERDF project “SPOT: Sensing with pioneering opportunistic techniques” (grant RTI2018-099008-B-C21/AEI/10.13039/501100011033), by the grant PID2019-106808-RA-I00/AEI/FEDER/UE from the EDRF and the Spanish Government, and by the Secretaria d’Universitats i Recerca del Departament d’Empresa i Coneixement de la Generalitat de Catalunya (2017 SGR 376, and 2017 SGR 219).

Conflict of interest

The authors declare no conflict of interest.

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