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Satellite Networks: Past, Present, and Future Challenges—Part 1: Mobile Systems

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INTRODUCTION

The satellite telecom field, now part of the nonterrestrial networks (NTNs) family, is facing a very exciting time with the emergence of low Earth orbit (LEO) megaconstellations for ubiquitous service provision complementing terrestrial network (TN) in addition to more conventional geostationary Earth orbit (GEO)-based systems. This second-generation (2G) constellations momentum appears to be super-seeding the first-generation satellite mobile systems bankruptcies of early years of this century. Another unexpected event is the race for the provision of direct to device (D2D) [1], i.e., connecting the mass market mobile phones and Internet of Things (IoT) devices by satellite with the emergence of new-space economy actors. While the long-term economic viability of constellations has yet to be demonstrated, it is recognized that the reduced launch cost, the series production of satellites and user equipment (UE) in very large quantities, and the presence of private entities able to fund expensive developments have drastically changed the scene [2]. At the same time, the GEO-based satcom broadcasting workhorse service is declining due to the success of over-the-top streaming services in countries with good TN infrastructure. Nonetheless, GEO satellites made important evolution in support of (mobile) broadband access provision, thanks to the development of flexible high-capacity payloads. The proliferation of NTN satellite networks for interactive services is opening up a number of technical and regulatory challenges to be able to cope with the users' expectations in terms of service quality and cost.

Part 1 of this article provides a comprehensive review of the key features of major mobile satcom systems developed in recent years and their associated technologies operating in Third Generation Partnership Project (3GPP) frequency range 1 (FR1). It then outlines the key challenges facing future network classes. The rest of this article is organized as follows. Specifically, the "NGSO Mobile Satellite Networks" and "(I)GSO Mobile Satellite Networks" sections address nongeosynchronous orbit (NGSO) and geosynchronous Earth orbit (GSO) mobile networks, respectively. The "Key Challenges" section discusses the key technical challenges faced by different NTN types. Finally, the "Summary and Conclusion" section concludes this article. Part 2 of this article covers broadband satellite networks operating in frequency range 2 (FR2).

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NGSO MOBILE SATELLITE NETWORKS

High-level reviews of various D2D mobile communication solutions are available in [1] and [3]. The subsequent sections provide a more detailed analysis of the most relevant NGSO mobile satellite networks capable of supporting D2D communications.

BIG LEOS

In the 1990s, the absence of a unified global terrestrial mobile standard spurred the development of global mobile satellite networks. These networks aimed to provide worldwide roaming for users, such as business travelers, government officials, explorers, and military personnel, all using a single handset. Two prominent initiatives for global mobile personal communication system (GMPCS) emerged, both based on LEO constellations: Iridium [4], proposed by Motorola, and Globalstar [5], developed by

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Space Systems Loral, with backing from various private investors. Beyond the innovative design of these global LEO constellations, the first series production of satellites represented a significant disruptive element in the telecommunications landscape.

IRIDIUM

The Iridium LEO constellation comprises 66 operational satellites (plus spares) orbiting at an altitude of 780 km. It provides mobile telephony and low-rate data services. The satellites follow quasi-polar orbits with an inclination of 86.4°, distributed across six orbital planes, resulting in an orbit period of approximately 100 min. A key feature of the Iridium system is its payload, which includes on-board regeneration, routing, and intersatellite links (ISLs) on top of conventional terrestrial gateway (GW) feeder links. These radio frequency (RF) ISLs enable communication between satellites, significantly reducing the reliance on GWs for routing calls and data. The Iridium system was conceived in 1987 but required a decade of development and securing funding before becoming operational. Iridium's service was launched in 1998 and achieved full operational status in 2002. However, the concurrent rise of multiregional and global cellular standards, such as group special mobile (GSM), significantly diminished its market potential. This led to Iridium declaring bankruptcy in 1999, which at the time was the largest bankruptcy at $5.2 billion. Despite this setback, a group of new investors stepped in, providing the necessary funding to develop and deploy a 2G constellation of 75 satellites between 2017 and 2019. By 2023, the Iridium system had approximately 2 million subscribers. Figure 1 illustrates the Iridium network architecture. Communication between user devices and the satellites occurs in the *L*-band. The feeder links, which connect the satellites to ground GWs, operate in the *Ka*-band.

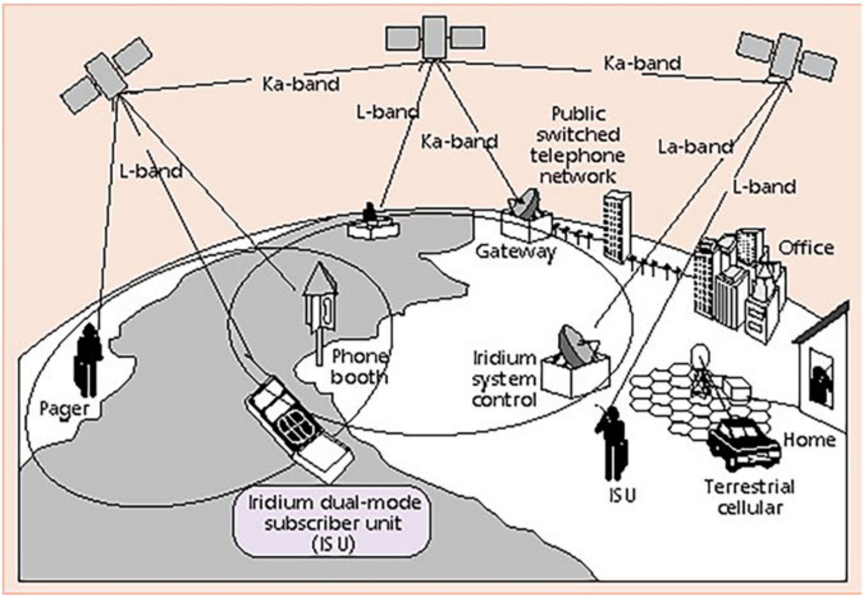

Figure 1.
Iridium network.

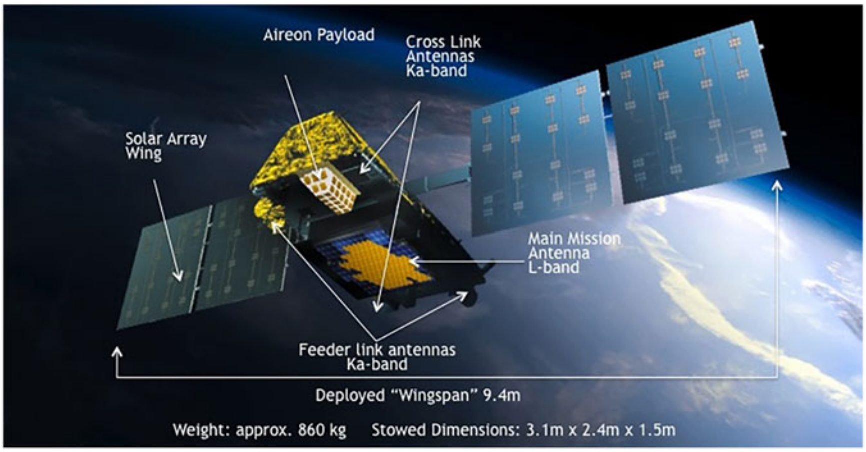

Figure 2.
Iridium NEXT satellite.

Similarly, communication between the system and its control station also utilizes *Ka*-band frequencies. ISLs, which enable direct communication between satellites in the constellation, operate in the dedicated *K*-band.

Figure 2 depicts the Iridium NEXT 2G satellite. This satellite employs a direct radiating antenna (DRA) for the user link. In contrast, it uses mechanically steerable antennas for both the ISLs and the feeder link. The payload is capable of generating 48 nonsteerable user's beams. On average, satellite handoffs occur every 7 min, while beam handoffs take place every 50 s.

Figure 3 illustrates the Iridium ground segment (GS), revealing that the hand-held (HH) UE resembles early 2G mobile terminals. The air interface utilizes a 90-ms frame with a time division multiplexing (TDM)/time division multiple access (TDMA) scheme. Coded differential quadrature phase-shift keying (D-QPSK) signals are channelized into 41.67 kHz segments [6], resulting in a total bandwidth of 10.5 MHz. To simplify the UE design, a time division duplexing scheme is employed, enabling the use of the same RF for both reception and transmission. Notably, the UE features a paging capability, which offers a degree of indoor signal penetration.

GLOBALSTAR

Launched in 1991 as a joint venture between Loral Corporation and Qualcomm, and later expanded to include several other companies, similarly to Iridium, the Globalstar project aimed to provide mobile telephony and low-rate data services via a LEO constellation orbiting at a higher altitude of 1410 km. Key companies involved in development included Space Systems Loral, Qualcomm, and Thales Alenia. The satellites are deployed in inclined orbits (52°) across eight orbital planes, resulting in an orbit period of 114 min. Unlike Iridium, Globalstar uses simple bent-pipe satellites without ISLs (see Figure 4), thus necessitating a large number of ground GWs to ensure global coverage. The first-generation constellation deployment began in 1998 and was completed in 2000, consisting of 48 operational satellites plus four spares. Like Iridium, Globalstar faced financial difficulties and declared bankruptcy in 2002. Following restructuring by a new partner in 2004, additional spare satellites were launched. A 2G constellation made of 24 satellites was launched between 2010 and 2013 to replace failed first-generation satellites. However, due to licensing and financial constraints, Globalstar does not currently provide

Figure 3.
Iridium GS: left—HH, IoT, and maritime terminals; right—GW.

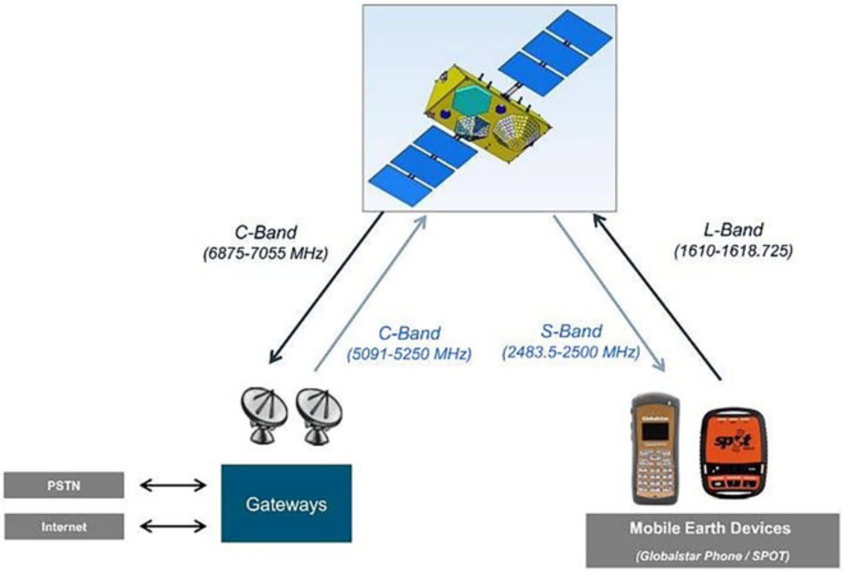

Figure 4.
Globalstar network.

truly global coverage, primarily serving the Americas, Europe, Australia, Japan, and South Korea.

Figure 5 depicts the Globalstar 2G satellite. As previously stated, it utilizes a bent-pipe payload, connecting GWs to users via separate *L*/*S*-band DRAs with an analog beamforming network. The *S*-band transmit antenna is divided into two conformal DRAs, generating 10 and 6 beams, respectively [7]. This design improves performance at varying user elevations compared to the first-generation flat array [5]. The *L*-band receive antenna, however, is implemented with a single flat DRA. Two *C*-band feeder link wide-beam horn antennas are also present, supporting the GW links.

Globalstar utilizes a 16.5-MHz spectrum across the *L* and *S*-bands, divided into 13 subbands of 1.23 MHz each. A key characteristic is the complete frequency reuse across all 16 satellite beams, achieved through a code division multiplexing/code division multiple access (CDMA) scheme closely resembling the 2G terrestrial IS-95 standard [8]. The system also supports satellite spatial diversity in both the forward and reverse links. This capability is facilitated by the full frequency reuse among beams and satellites, along with the implementation of a rake CDMA demodulator [9] at both the UE and GWs. This spatial diversity enhances system quality of service (QoS) by mitigating the effects of link shadowing and improving handover performance, while also reducing the required UE RF transmit power.

AST MOBILE LEO

AST SpaceMobile, founded in 2017, is developing a LEO constellation of 243 satellites deployed across 16 orbital planes at an altitude of approximately 740 km. This project represents a significant technological advancement [10], aiming to provide complementary global mobile satellite connectivity for 4G-like services directly to standard HH mobile phones. The core innovation lies in the use of a very large, mechanically deployable phased-array antenna on each satellite, operating around 850 MHz and reusing TNs frequencies. Figure 6 shows the first five operational Bluebird satellites, launched in September 2024. Similar to the first experimental Bluewalker 3 satellite launched in 2023, the phased array size is currently "limited" to 8 m$\times$8 m, a reduction from the initially planned 30 m$\times$ 30 m. The company reported successful demonstrations of voice and data transmission exceeding 10 Mbps using standard cellphones in 2023. Currently, the satellites operate under an experimental Federal Communication Commission (FCC) license, pending a final decision.

Commercially, AST SpaceMobile has secured funding from companies, such as Vodafone and Rakuten, and established partnerships with major players, such as Google, AT&T, and Verizon. By leveraging standard mobile handsets, the company aims to tap into a vast potential market, providing connectivity to regions currently underserved by TN. However, achieving this goal presents several regulatory and operational challenges, including demonstrating the system's ability to deliver 4G-like data services at an affordable cost.

APPLE DIRECT TO HH LEO

The adoption of the Globalstar constellation by Apple to provide emergency messaging service on new iPhones represents a significant and unexpected

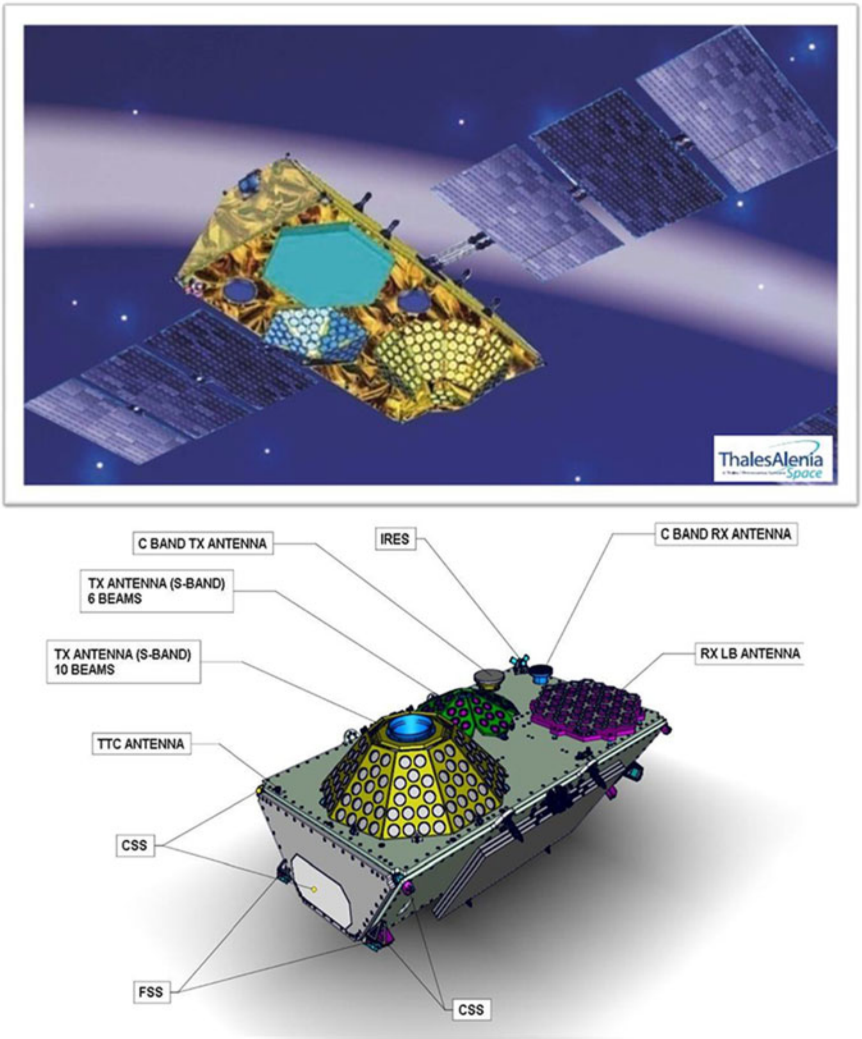

Figure 5.
Globalstar 2G satellite—courtesy: Thales Alenia Space.

development. Apple's initial investment of $450 million enabled modifications and expansions to the Globalstar GS, facilitating this new service through a proprietary protocol within the constellation's coverage area, utilizing the 3GPP NTN band n53 (*L*-band). Announced in September 2022, the service became operational two months later. In Q3 2024, Apple further committed to funding new Globalstar satellites with a substantial investment of $1.7 billion, agreeing to cover 95% of Globalstar's capital expenditures for these new satellites in exchange for 85% of their bandwidth. This partnership and significant financial backing have revitalized the Globalstar system, effectively bringing it into the mass market phone sector.

STARLINK DIRECT-TO-CELL LEO

Almost simultaneously with Apple's announcement regarding Globalstar's new emergency messaging service, SpaceX unveiled its own direct-to-cell (DtC) service in partnership with T-Mobile. This service utilizes T-Mobile's terrestrial *S*-band PCS "G-block" spectrum and is currently supported by a subset of 350 dual-band (*Ku* and *S*-band) Starlink satellites. Experimentation began in

Figure 6.
AST SpaceMobile Bluebird first five operational satellites.

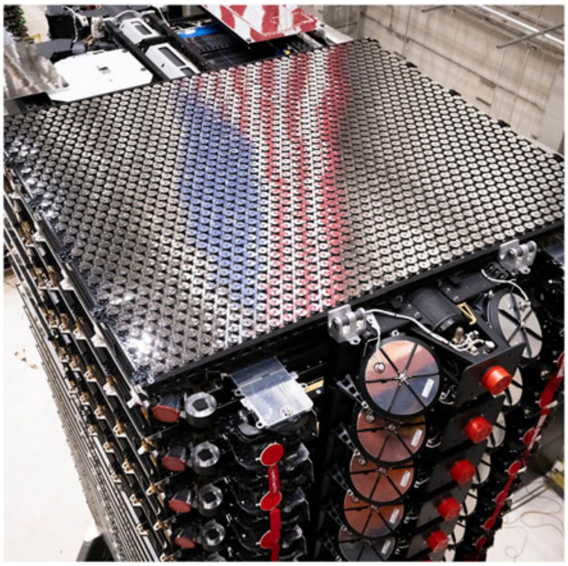

Figure 7.
Starlink dual-band *Ku*-S satellite supporting DtC.

January 2024, and SpaceX received conditional approval from the FCC in November 2024 to provide Supplemental Coverage from Space (SCS) for T-Mobile smartphone users within the United States. SpaceX has also established and continues to pursue partnerships with other operators to expand the system's coverage globally. However, securing the necessary licenses outside the US is expected to involve complex negotiations, potentially facing resistance from existing terrestrial operators.

Similar to AST SpaceMobile, SpaceX's DtC service utilizes unmodified 4G LTE mobile terminals, initially for messaging services. Voice and data services are planned for introduction in 2025, with IoT device connectivity also expected within the same year. Figure 7 shows the Starlink satellite designed for DtC, clearly displaying the approximately 1.2 m$\times$1.2 m DtC *S*-band phased array adjacent to the *Ku*-band phased arrays.

IRIDIUM PROJECT STARDUST LEO

Like Globalstar, Iridium is also undergoing a resurgence, driven by "Project Stardust," announced in January 2024. This project aims to offer global 3GPP NTN Narrowband IoT (NB-IoT) messaging and emergency message services for smartphones, tablets, cars, and other consumer applications by leveraging the existing Iridium constellation. This repurposing is facilitated by the flexibility and reprogrammability of the Iridium space segment. Similar to Apple's satellite messaging approach with Globalstar, Iridium is utilizing mobile satellite services (MSS) frequency bands, which are already allocated on a quasi-global basis. This strategy avoids the significant regulatory hurdles associated with sharing terrestrial cellular bands at regional and national levels. This advantage is, however, counterbalanced by power flux density (PFD) limitations affecting the MSS bands, which consequently restrict the maximum throughput that can be provided.

Iridium's strategic shift toward utilizing its existing constellation for NB-IoT and emergency message services, as embodied in Project Stardust, offers several potential advantages. By leveraging existing infrastructure and adhering to established 3GPP standards, Iridium could significantly reduce the cost of its products and services. This cost reduction, coupled with the use of standard, readily available chipsets, would enable a broader range of devices to connect to the Iridium network. This increased accessibility would not only expand Iridium's potential customer base but also extend the global reach and coverage of cellular network operators who partner with Iridium, providing seamless connectivity in areas where TNs are unavailable. This partnership could also create new revenue streams for Iridium through increased data usage.

BEIDOU MEDIUM EARTH ORBIT MESSAGING

The Chinese Beidou system distinguishes itself by integrating short messaging service (SMS) communication with its navigation capabilities, leveraging a mixed constellation architecture for combined communication and navigation services [11]. Beidou's s SMS is offered in two tiers: regional for users in the Asia-Pacific region and global for worldwide users. The system utilizes three GEO, three inclined geo synchronous orbit (IGSO), and 24 medium Earth orbit (MEO) satellites. The regional emergency messaging service employs the radio determination satellite service system, where users cannot independently calculate their distance. Instead, users send positioning requests and related information to GEO satellites, which then relay these data to a ground center. The ground center performs the position calculation and transmits the resulting location and relevant information back to the user via the satellite.

Beidou's messaging service offers robust anti-interference capabilities, rapid response times, and high cost-effectiveness, making it well suited for applications, such as emergency communication and search and rescue. Compared to traditional mobile communication methods, the Beidou-3 short message system boasts advantages, such as high reliability, broad coverage, and low cost. In Q3 2022, Huawei announced that its new Mate 50 mobile phone would support geo-localized emergency messaging via the Beidou Global Navigation Satellite System, utilizing its 24 Medium Earth Orbit (MEO) and three IGSO satellites and requiring 3 W of UE transmit RF power.

LYNK LEO

Lynk Global Inc., founded in 2017, focuses on connecting standard mobile phones to CubeSat-class nanosatellites in

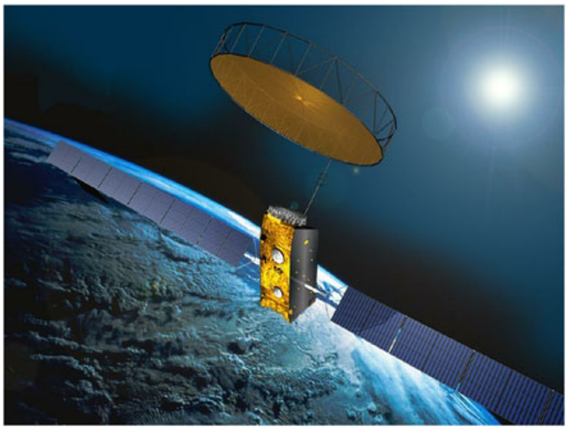

Figure 8.
Inmarsat 4 satellite.

LEO at an altitude of 500 km [3]. After launching two experimental satellites in 2020 and 2021, they have since deployed six operational satellites. Lynk has successfully demonstrated phone calls using conventional mobile handsets. The company estimates that a constellation of fewer than 200 satellites will enable messaging services, while voice services will require between 250 and 920 satellites.

(I)GSO MOBILE SATELLITE NETWORKS

INMARSAT CONSTELLATION

Inmarsat, the first GSO mobile satellite operator, was initially established in 1979 as an intergovernmental organization before being privatized 20 years later. In 2023, Viasat completed its acquisition of Inmarsat. Its initial focus was providing global maritime and aeronautical services using wide regional beams operating in the *L*-band. Later, Inmarsat developed the Broadband Global Area Network (BGAN) to deliver third generation (3G)-type services to mobile and nomadic users. BGAN utilizes multibeam, higher capacity satellites also operating in the *L*-band, within the frequency range of 1518–1675 MHz [12].

Inmarsat's *L*-band MSS system architecture is based on a GSO constellation comprising three Inmarsat-4 satellites (see Figure 8) and one Alphasat satellite [13]. The GSO orbit inclination is allowed to vary up to +/- 3° to save station-keeping fuel. These satellites support regional and spot beams, providing the following.

- Universal Mobile Telecommunication System (UMTS) 3G type of services to mobile terminals circuit-mode services up to 64 kbps (voice, video, FAX, messaging, data).
- Packet mode services (up to 492 kbps).

In 2024, Viasat conducted several demonstrations of its newly announced IoT direct service, which leverages Inmarsat's *L*-band GSO satellites. This service supports massive-scale IoT solutions by utilizing the 3GPP Release 17 NB-IoT standard.

Figure 9 illustrates the coverage and beam pattern of Inmarsat's BGAN satellites. To achieve the desired beam size and shape, each satellite is equipped with a large, 12-m deployable antenna fed reflector (AFR) with an offset-fed phased array driven by multimatrix amplifiers [14]. The payload incorporates a digital transparent processor that provides channelization and digital beamforming (DBFN) capabilities [15].

Inmarsat's BGAN GS consists of 30 GWs located in various regions, including the USA, Canada, Europe, India, Australia, China, and New Zealand, as well as four

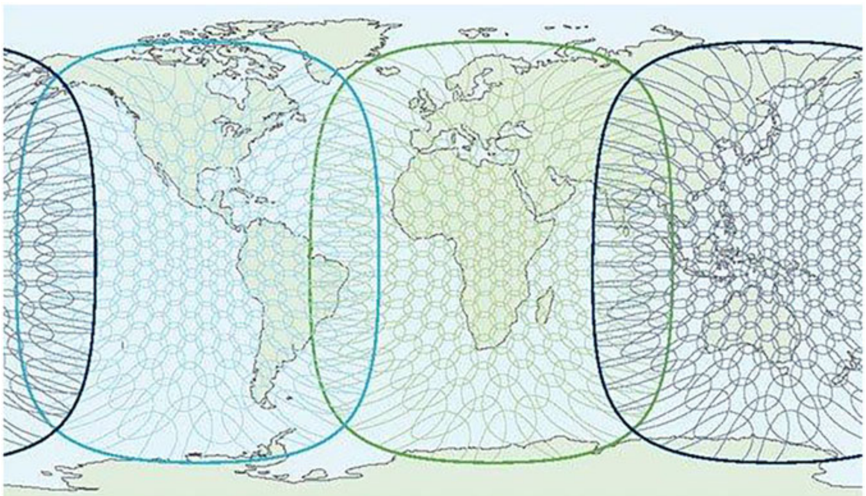

Figure 9.
Inmarsat BGAN satellite beams pattern.

Figure 10.
Inmarsat BGAN user terminals.

telemetry tracking and control (TTC) stations. Figure 10 shows examples of BGAN UE. The BGAN air interface uses a proprietary TDM/TDMA solution incorporating adaptive coding and modulation (ACM) and turbo coding [16].

To address the bandwidth limitations of its *L*-band BGAN service, Inmarsat developed the Global Xpress (GX) *Ka*-band system [17]. This system comprises a constellation of four Inmarsat-5 (I-5) GSO satellites (see Figure 11), offering broadband very small aperture satellite terminal-type services to both mobile and fixed terminals. Each I-5 satellite generates 89 spot beams (72 active), along with six steerable high-capacity beams and two steerable GW beams. The GS includes two spatially diverse GWs each in Italy, Greece, the USA, Canada, and New Zealand, as well as four TTC stations. GX utilizes the DVB-S2 standard for its air interface [18].

THURAYA REGIONAL SYSTEM

Thuraya, a United Arab Emirates-based regional MSS provider [19], operates two GSO satellites, offering telecommunications coverage in over 161 countries across Europe, the Middle East, North, Central, and East Africa, Asia, and Australia (see Figure 12). Thuraya's *L*-band network provides voice and data services with data rates comparable to 3G, similar to Inmarsat's BGAN.

Figure 11.
I-5 satellite.

Similarly to Inmarsat 4, the satellite features a 12-m large satellite deployable AFR with offset-fed phased-array of 128 elements, multimatrix amplifiers [14], digital transparent payload providing channelization and DBFN [20].

SIRIUS-XM DIGITAL BROADCASTING SYSTEM

SiriusXM stands as the most successful satellite digital radio broadcasting system, serving North America with 34 million customers. Following the FCC's allocation of *S*-band frequencies for digital audio radio systems, two licenses were granted in 1997 to XM and Sirius, with both companies launching services in 2001. Despite near-bankruptcy in 2008, the two companies merged between 2005 and 2008. Today, the system boasts a 75% penetration of the vehicular market with approximately 50 million subscribers. The service relies on six functional satellites: two GEO XM satellites at 85°W and 115°W longitude providing spatial diversity, two high elliptical orbit (HEO) Sirius satellites offering high elevation coverage over the USA, and two satellites supporting both systems (including one spare) (see Figure 13), complemented by terrestrial repeaters in urban areas. Operating in the *S*-band (2.3 GHz), the satellites employ high RF power achieved by parallelizing 16 traveling wave tube amplifiers (TWTAs) and a 5-m deployable reflector [21]. The satellites broadcast radio channels using TDM, while terrestrial repeaters utilize orthogonal frequency division multiplexing signals in separate subbands to prevent interference. To mitigate mobile channel impairments, the system employs a combination of spatial diversity, long time interleaving, and staggered time replicas of the signal.

In the 1990s, a European initiative called Archimedes supported by European Space Agency [22], aimed at

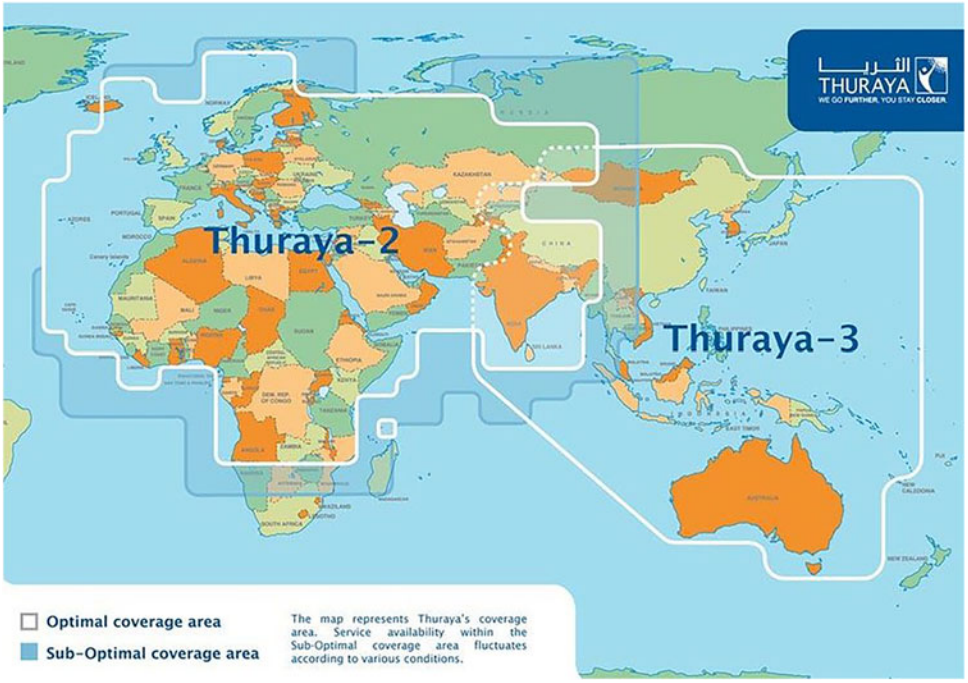

Figure 12.
Thuraya 2 and 3 coverage.

developing a similar satellite radio broadcasting system, ultimately failed due to business uncertainties. These uncertainties stemmed primarily from market fragmentation caused by the diverse range of languages spoken across Europe. Despite the project's failure, some of the technologies developed for Archimedes, such as the use of HEO satellites and a robust physical layer design, found application in US-based systems.

KEY CHALLENGES

A good overview the state of the art in satellite communications, while highlighting the most promising open research topics is reported in [23]. In particular, current satellite technology faces significant challenges in delivering satisfactory QoS and data rates to mobile users with HH devices.

- Even with advanced techniques, such as forward error correcting, time interleaving, ACM, power control, and spatial diversity, reliable communication often requires user cooperation and a clear line of sight to the satellite.
- Standard terrestrial UE suffers from link budget limitations due to the low gain of their mobile antennas, particularly in HH devices. While larger satellite antenna apertures can (partly) compensate for this, they increase the size and cost of the space segment. Solutions, such as mechanically deployable phased arrays [10], or more advanced solutions, such as formation of arrays [24], offer potential significant improvements, but their implementation relies on technical progress and higher level of PFD regulatory approval.
- The omnidirectional nature of UE antennas hinders spectrum reuse by other systems due to a lack of spatial discrimination, which limits the number of constellations capable of supporting D2D communication in FR1.
- Current MSS PFD limits significantly restrict the maximum data rates achievable by HH devices.

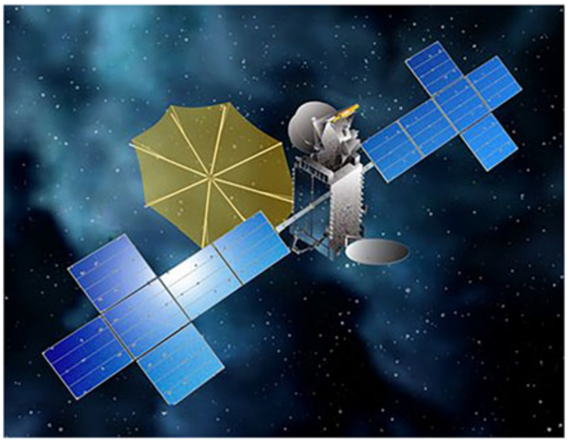

Figure 13.
Sirius XM new SXM-7 satellite.

- Reusing TN mobile bands is a potential solution but faces complex national licensing and frequency coordination procedures, which can lead to coverage limitations, particularly impacting the economic viability of LEO constellations.
- Technically, intersystem interference and spectrum sharing between both NTN and TN pose further challenges in addition to what already covered or being covered by 3GPP standardization [25]. Other causes of service disruptions and associated mitigation techniques are discussed in [26].
- The highly variable nature of traffic in both space and time necessitates the use of active phased-array satellite antennas, high-performance DBFN [15], and advanced radio resource management techniques [27].
- Another area of potential growth is the support of IoT with high performance scalable solutions based on state-of-the-art multiple access techniques [28], [29], [30].

Traditional business models are difficult to sustain for both GSO and NGSO systems, but especially for NGSO due to the typically slow service ramp-up caused by licensing and marketing complexities. However, new entrants, such as SpaceX and Amazon, with substantial capital resources and collaborations with mobile network operators, have a greater potential for success compared to previous ventures.

SUMMARY AND CONCLUSION

This article has provided a comprehensive review of the most relevant mobile NTNs developed over the past three decades, highlighting their capabilities, architectures, and key technological solutions. The review demonstrates that innovative and ingenious solutions have not always achieved commercial success due to a combination of factors, including competition from TNs, regulatory and licensing challenges, technology maturity, and marketing difficulties.

Satellite mobile networks struggle to provide adequate QoS and data rates in mobile conditions due to link budget limitations of standard UE antennas. Large deployable satellite antennas are costly and risky and may face regulatory hurdles. Omni-directional UE antennas limit spectrum reuse, and MSS PFD limits constrain achievable data rates. Reusing terrestrial mobile bands is complex due to licensing and coordination. Nonuniform traffic requires advanced antenna and resource management techniques. Business cases are challenging, especially for NGSO, although new players with substantial capital and mobile network operators (MNOs) partnerships may improve viability.

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