

FOCUSED OVERVIEW OF HIGH-THROUGHPUT SATELLITE SYSTEMS: FROM STANDARDIZATION TO QOS MANAGEMENT

Aleksandr Yu. Troegubov,
Moscow Institute of Physics and Technology (MIPT),
Moscow, Russia, troegubov.aiu@phystech.edu

Alexander A. Maslov,
Moscow Institute of Physics and Technology (MIPT),
Moscow, Russia, maslov.aa@mipt.ru

Gennady V. Sebekin,
Moscow Institute of Physics and Technology (MIPT),
Moscow, Russia, sebekin.gv@mipt.ru

Sergey N. Stepanov,
Moscow Technical University of Communications and
Informatics, Moscow, Russia, s.n.stepanov@mtuci.r

Alexey O. Shchurkov,
Moscow Institute of Physics and Technology (MIPT),
Moscow, Russia, shchurkov.ao@mipt.ru

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Ubiquitous communication networks are crucial for many spheres of human life, yet many regions remain underserved because terrestrial infrastructure is costly or difficult to deploy. Satellite communication systems address this limitation by providing global coverage and supporting broadcast and multicast services, making them an important part of modern communication networks that complement terrestrial systems. The paper provides a focused overview of modern high-throughput satellite (HTS) systems, emphasizing architectural evolution, standardization, and quality-of-service (QoS) resource management. The development of HTS systems involves numerous technical challenges. The paper examines current standardization efforts and spectrum regulation frameworks, along with common applications and use cases. Moreover, it overviews HTS network architecture covering geostationary and non-geostationary orbits, multibeam payloads, and multi-layer deployments, and analyzes physical- and medium-access-layer design principles. The paper further discusses service differentiation and QoS support in HTS networks, outlining traffic characteristics and relevant performance metrics at different system time scales. Overall, the paper shows that queuing theory and teletraffic models can provide a suitable analytical foundation for evaluating HTS performance and guiding the design of efficient satellite networks in future communication systems.

Information about authors:

Aleksandr Yu. Troegubov, Moscow Institute of Physics and Technology (MIPT), Moscow, Russia, <https://orcid.org/0000-0001-9105-9486>

Alexander A. Maslov, Moscow Institute of Physics and Technology (MIPT), Moscow, Russia

Gennady V. Sebekin, Moscow Institute of Physics and Technology (MIPT), Moscow, Russia

Sergey N. Stepanov, Moscow Technical University of Communications and Informatics, Moscow, Russia, <https://orcid.org/0000-0002-9815-9532>

Alexey O. Shchurkov, Moscow Institute of Physics and Technology (MIPT), Moscow, Russia

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1 Introduction

Nowadays ubiquitous communication networks are essential everywhere: from economic to educational and social development [1]. At the same time, vast regions of the planet remain underserved by terrestrial infrastructure due to geography or cost reasons [2]. Satellite communications (SatCom) can fill this gap, providing complete coverage from space. In particular, satellite systems complement ground networks to provide broadcast and multicast capabilities over entire Earth's surface. Recent studies [3-6] highlight the key role of SatCom networks in forming future communication landscape and creating global digital space.

Satellites offer unique advantages over ground-based systems [7, 8]. For example, a single satellite in geostationary orbit can cover an entire continent, and large satellite constellations in low Earth orbit (LEO) can provide global broadband services. Unlike terrestrial base stations, satellites can broadcast the same content simultaneously to all users located in a wide area, making them ideal for radio and TV broadcasting, data distribution, or software updates. Moreover, satellite links are also resilient to natural disasters, while ground infrastructure can fail. All these features make SatCom an important complement to fiber and cellular networks.

Traditionally, communication satellites operated with one or a few wide beams covering large regions. Such an approach is simple, but spectrally inefficient, as a single beam cannot reuse frequency, so capacity is limited by the available spectrum. In contrast, High Throughput Satellites (HTS) employ a multi-beam architecture, in which the service area is divided into many narrow spot beams with aggressive frequency reuse as depicted in Fig. 1. Modern HTS systems employ tens and even hundreds of beams, each focused on a small region. By reusing the same frequency bands across non-adjacent beams, HTS achieve much higher spectral efficiency, which can multiply the total throughput compared to a conventional wide-beam satellite.

In addition, multi-beam HTS systems employ advanced digital payloads and onboard processing to manage complexity. Digital beamforming and signal processing enable flexible beam shapes and power allocation. In conventional geostationary Earth orbit (GEO) multi-beam HTS systems, all the satellite beams are constantly illuminated, even if there is no demand to be satisfied. Techniques like beam hopping (BH) allow the satellite to dynamically allocate capacity across beams in time, matching varying traffic demands. Furthermore, narrow spot beams have

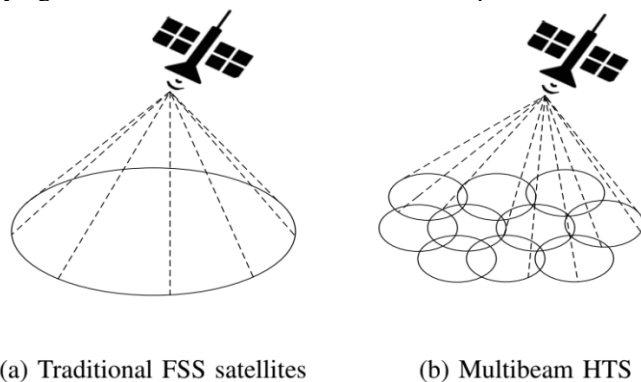


Fig. 1. Comparison of single-beam and multibeam architectures [9].

higher antenna gain, allowing smaller user terminals and higher-order modulation for further increase in data rates. Note that in LEO constellations, the dynamic demand is handled with inter-satellite links and dynamic routing [10]. As a result, HTS platforms can deliver aggregate throughputs on the order of hundreds of gigabits up to beyond one terabit per second per satellite.

Altogether, modern HTS networks offer significant capacity growth and cost reduction over legacy systems. Novel SatCom systems enable entirely new services and applications. For instance, HTS and LEO constellations are considered key components of the future 6G non-terrestrial networks framework [2, 8]. Another example is the integration of SatCom networks with the Internet of Things (IoT) [11, 12]. Moreover, the research community is working on applying AI (artificial intelligence) methods to improve the performance of SatCom networks [2, 13].

As we can see, the HTS system development involves plenty of technical challenges ranging from high-frequency radio hardware to air interfaces and communication protocols. Many of these aspects are already addressed by the research community and industry, but the specific implementation details are part of proprietary technologies and therefore are not in open access. Despite diverse challenges, the overall system performance is fundamentally constrained by resource management. Resource planning is a persistent challenge – satisfying non-uniform and time-varying traffic demands are further complicated by various system constraints.

In this sense, there is a need for analytical tools capable of describing stochastic traffic behavior and service differentiation. We believe that queuing theory and teletraffic models can be a suitable framework for analyzing HTS performance. In this paper, we offer a targeted analysis of HTS systems intended for readers working in operational research, satellite network resource management, and performance modeling of HTS networks.

The rest of the paper is organized as follows. We discuss standardization and spectrum regulation aspects of SatCom networks in Section 2. Section 3 is devoted to HTS use cases and applications. The overview of HTS networks architecture is in Section 4. Sections 5 and 6 cover PHY- and MAC-level design principles. In Section 7, we consider supported service types and QoS in HTS networks. Section 8 concludes the paper and outlines future research directions in satellite networking. The list of the accepted abbreviations is in Table 1.

2 Standardization & Spectrum

In this section, we consider two fundamental components of all wireless communication systems – standardization aspects and spectrum regulation.

2.1 Standardization bodies

Unlike well-known terrestrial systems with a single standardization body (e.g., IEEE for Wi-Fi or 3GPP for cellular), SatCom involves several overlapping organizations due to the variety of applications and stakeholders. Moreover, some operators (e.g., Inmarsat, Iridium) developed proprietary protocols. Nevertheless, we observe a clear trend toward open standards to promote multi-vendor interoperability [4, 14].

Table 1

List of abbreviations

Abbreviation	Meaning
ACM	Adaptive Coding and Modulation
ADS-B	Automatic Dependent Surveillance-Broadcast
AFR	Array-Fed Reflector
AIS	Automatic Identification System
BCH	Bose-Chaudhuri-Hocquenghem code
BH	Beam Hopping
CCSDS	Consultative Committee for Space Data Systems
CNR	Carrier-to-Noise Ratio
DRA	Direct Radiating Array
DVB	Digital Video Broadcasting
eMBB	Enhanced Mobile Broadband
FCC	Federal Communications Commission
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
GW	Gateway
HAP	High-Altitude Platform
HEO	Highly Elliptical Orbit
HTS	High-Throughput Satellite
IoT	Internet of Things
ISL	Inter-Satellite Link
LAP	Low-Altitude Platform
LDPC	Low-Density Parity-Check code
LEO	Low Earth Orbit
MAC	Medium Access Control Layer
MCS	Modulation and Coding Scheme
MEO	Medium Earth Orbit
MF-TDMA	Multi-Frequency Time-Division Multiple Access
MFPB	Multiple-Feed-Per-Beam
mMTC	Massive Machine-Type Communications
NR	New Radio
NTN	Non-Terrestrial Networks
OFDMA	Orthogonal Frequency-Division Multiple Access
PHY	Physical Layer
QoS	Quality of Service
RF	Radio Frequency
SC-FDMA	Single-Carrier Frequency-Division Multiple Access
SFPB	Single Feed Per Beam
SatCom	Satellite Communication
TDM	Time-Division Multiplexin
TT&C	Telemetry, Tracking, and Control
UT	User Terminal
URLLC	Ultra-Reliable Low-Latency Communications
VLEO	Very Low Earth Orbit
VSAT	Very Small Aperture Terminal

ETSI and DVB Project. The European Telecommunications Standards Institute (ETSI) publishes and maintains the Digital Video Broadcasting (DVB) family of open standards for satellite broadcast services (e.g., TV and radio) and broadband systems [4, 14]. ETSI specifies standards for both forward link (gateway-to-user) and the return link (user-to-gateway). The latest amendment for the forward link, DVB-S2X [15], introduces wide support for HTS systems, while the corresponding amendment for the return link is DVB-RCS2 [16].

3GPP NTN. The 3rd Generation Partnership Project (3GPP) has gradually integrated satellites into the cellular framework [17]. After initial studies in Release 14, non-terrestrial networks (NTN) became a formal part of 5G architecture from Release 15. By the

latest 3GPP Release 17 [18], NTN specifications describe transparent and regenerative payloads, inter-satellite links, and air-interface adaptations for uncommon channel conditions. Moreover, NTN includes support for satellite IoT (NB-IoT and eMTC). The primary goal of 3GPP NTN is seamless operation with terrestrial 5G/6G to extend coverage and enable disaster-resilient services [4, 8].

CCSDS. The Consultative Committee for Space Data Systems (CCSDS) is a consortium of major space agencies. It recommends standards for telemetry, tracking, command, and space data handling in space missions. However, the CCSDS standards are mainly relevant to scientific and space missions than commercial HTS broadband [14].

2.2 Spectrum regulation

Generally, spectrum is regulated globally by the International Telecommunication Union (ITU). In addition, national agencies, e.g. FCC in the U.S, can impose additional restrictions for local spectrum assignments [4, 14].

Growing demand from both terrestrial and satellite operators makes some bands crowded and leads to congestion. Thus, there is a trade-off between the robustness of lower bands and the capacity of higher bands. Specifically, modern HTS systems increasingly exploit Ku- and Ka-band with advanced frequency reuse techniques. Another challenge is the coexistence between satellite and terrestrial 5G/6G systems, especially in the C- and Ka-bands, where frequency sharing is under active study [8]. A brief description of key frequency bands (see Fig. 2) is presented below [4, 19].

- **L-band** (1-2 GHz). Offers long wavelengths that are resilient to weather conditions (clouds, rain, foliage), making it suitable for reliable services: mobile satellite services (Inmarsat, Iridium), TT&C services, and navigation systems (GPS). Although limited bandwidth constrains data rates, L-band enables compact user terminals.
- **S-band** (2-4 GHz). Offers moderate capacity with robustness against weather. It is employed for TT&C services, digital audio radio, space research and operations, and weather radars.
- **C-band** (4-8 GHz). Offers robust communication against rain fading. It is traditionally used by fixed satellite services, supporting TV broadcasting and corporate networks. However, C-band has become crowded and is a subject to coexistence conflicts with 5G cellular systems, particularly in the 3.4-3.8 GHz range.
- **X-band** (8-12 GHz). Reserved for governmental and military purposes.
- **Ku-band** (12-18 GHz). Offers higher capacity than C-band with smaller antennas. It became a preferable band for broadcast and broadband VSAT systems: direct-to-home television, enterprise VSAT networks, and aviation broadband. However, it is more sensitive to rain fade and, as C-band, suffers from spectrum scarcity.
- **Ka-band** (26-40 GHz). Offers wide bandwidth at the cost of significant attenuation in adverse weather. It forms the basis for modern HTS with spot-beam architecture. Although it supports multi-Gbps broadband

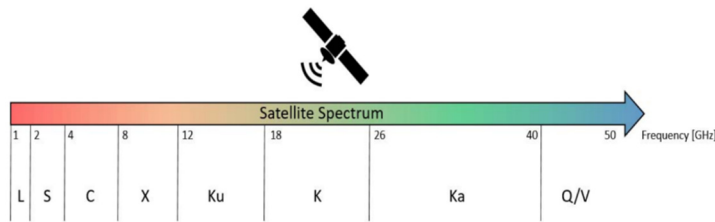


Fig. 2. SatCom frequency bands [14].

services, it requires advanced PHY-level methods.

- **Q/V-band (40-75 GHz).** Promising band for solving congestion issues in lower bands. Its feasibility for feeder links (from gateway to satellite) is still under investigation.

3 Use cases & Applications

HTS systems support a wide spectrum of applications across both commercial and governmental domains. In this section, we highlight the most relevant use cases.

3.1 5G/6G Non-Terrestrial Networks

The ITU-R IMT-2020 requirements defined three main directions for 5G: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low latency communications (URLLC) [20]. Moreover, another ITU document [21] defines novel scenarios and guidelines for 2030 networks: ubiquitous connectivity, artificial intelligence integration and sensing integration. As part of the NTN framework, HTS systems are expected to play a key role in satisfying user requirements for beyond-5G networks [4, 8, 14].

First, HTS systems can extend broadband coverage to rural and remote regions (such as oceans and forests), where common terrestrial networks are impractical or impossible. Second, SatCom systems can provide reliable service in high-mobility scenarios (in-flight and maritime cases). Third, compared to terrestrial networks, HTS systems have extremely wide service area, which can be useful in mMTC applications: HTS constellations can handle data flows from billions of IoT devices, supplementing terrestrial networks in smart agriculture or remote monitoring [22, 23]. Although SatCom systems cannot meet URLLC latency requirements due to propagation delay, they can significantly contribute by offloading terrestrial resources in hybrid terrestrial-satellite architectures.

3.2 Positioning and navigation

As discussed above, mobility support remains one of the key features of HTS networks. SatCom is suitable for safety-critical applications such as tracking and communication in aeronautical and maritime systems [8, 24].

In aviation, SatCom can become a part of Automatic Dependent Surveillance-Broadcast (ADS-B) system. Originally, the navigation is performed with terrestrial infrastructure: an Air Traffic Management (ATM) network and an Air Traffic Controller (ATC). However, ground-based facilities are insufficient in polar regions or in the middle of the oceans, and a satellite-assisted ADS-B system can be considered as an alternative [25].

In maritime, the Automatic Identification System (AIS) is used for tracking ships [26]. The system became especially widespread when it was supported by commercial SatCom systems due to extended coverage and reliability.

This demonstrates that vehicle, aircraft and ship tracking are promising applications for further development because advanced positioning and coordination are key for unmanned worldwide transportation system [8].

3.3 Space observation, exploration, and communications

Beyond communications, satellite networks play an important role in Earth observation [8, 27]. Modern constellations generate large volumes of imagery and sensor data for agriculture, logistics, and disaster management. In traditional Earth-observation systems, the downlink of payload data is typically performed only when the satellite passes over a dedicated ground station, which limits the data delivery delay to processing services on the ground. HTS systems can provide high-capacity backhaul to transfer collected data and time-sensitive messages worldwide, thereby improving data availability and operational responsiveness.

Deep-space missions depend on robust SatCom links, with unique challenges such as long delays and extreme distances. Advances at the PHY-level, such as beamforming and novel coding schemes, directly contribute to the evolution of deep-space communications. Some concepts imply hybrid infrastructures where HTS networks provide broadband-like services to support human presence on the Moon.

3.4 Multi-layer and multi-orbit architectures

A notable trend in SatCom is the development of multi-layer and multi-orbit network architectures to combine both extensive coverage and low latency [9, 28, 29]. HTS networks can be integrated with aerial networks, creating multi-layer aerial-satellite architectures [8]. Examples of such networks are outlined below.

- Very Low Earth Orbit (VLEO) satellites at 100-450 km: offer reduced latency and smaller link budgets but require frequent fleet replenishment. Several operators are exploring VLEO for high-performance mobile services.
- High Altitude Platforms (HAPs) at 15-25 km: represented by balloons or solar-powered UAVs, act as relay nodes, providing regional coverage and complementing HTS backhaul. They offer lower latency and rapid deployment but face operational and endurance constraints.
- Low Altitude Platforms (LAPs) at 0-4 km: represented by tethered balloons or drones, extend HTS services for disaster recovery and temporary events, ensuring reliable coverage in critical situations.

Another trend is to combine GEO, MEO, and LEO systems to form a multi-orbit HTS network [9]. While GEO systems offer wide coverage and long service lifetimes, LEO provides low-latency links. Hybrid architecture demonstrates that different orbital layers can complement each other to support extended number of services. At the same time, such solutions require more advanced user terminals and introduce new challenges in dynamic resource allocation and inter-orbit handover management.

4 Orbits & Network aspects

In this section, we consider the common network topology of a SatCom system. Section 4.1 provides a general description and Sections 4.2-4.4 discuss individual network segments.

4.1 Network architecture

The network architecture of a typical HTS system has several parts as shown in Fig. 3 [14, 30].

The space segment is represented by a satellite constellation. The term “satellite” typically refers to a satellite platform equipped with complex payloads, including antennas and transponders. To reduce latency, direct communication within the space segment can be performed via inter-satellite links (ISLs).

The ground segment is represented by facilities managed by network and satellite operators. Some facilities serve as interfaces between the satellite systems and terrestrial networks, while others are responsible for tracking and monitoring the satellite's health.

The user segment is represented by various user terminals (UTs) ranging from very small aperture terminals (VSATs) to compact mobile devices, which access the system via user links. User links are typically divided into the forward link (gateway-to-user) and the return link (user-to-gateway).

Altogether, these segments form the architecture of a SatCom network.

4.2 Space segment

A satellite constellation consists of satellites themselves and their orbital configurations [14]. A satellite platform is responsible for power supply and attitude (orientation) control, while its payload performs communication functions. The key aspect of constellation design is the orbit type. There are four primary orbit classes: geostationary Earth orbit (GEO), highly elliptical orbit (HEO), medium Earth orbit (MEO), and low Earth orbit (LEO) [9].

GEO systems (~36 000 km) operate at a fixed altitude where

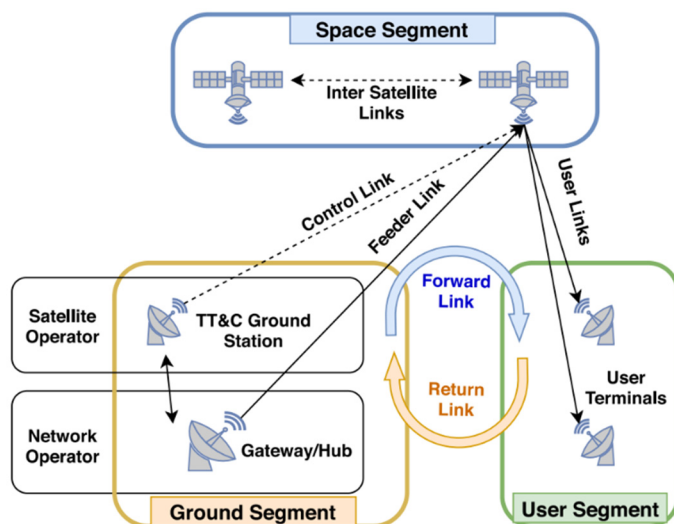


Fig. 3. Overview of a common SatCom network topology comprising space, ground, and user segments [14].

satellite position relative to the Earth's surface remains constant or near constant in the case of close-to-geostationary orbits. The orbit provides consistent, wide-area coverage, and is used for common satellite services (television and radio broadcasting, broadband Internet).

GEO systems have several advantages. First, user terminals for GEO systems do not require tracking antennas (except mobile terminals), which reduces complexity and cost. Second, they have low per-satellite deployment cost due to high coverage (one-third of the Earth's surface) and long satellite lifetime (15+ years) [9]. Third, the complex satellite payload can employ multi-beam techniques to provide high throughput. On the other hand, there are limitations: high signal attenuation, which affects capacity, and long propagation delays.

HEO systems differ from circular orbits by their high eccentricity. The key characteristic is long line-of-sight time near apogee, making them suitable for communications in high-latitude regions [14]. For example, several HEO satellite systems, e.g. Molniya and Tundra, are notably employed in Russia.

MEO systems (2 000-36 000 km) offer a compromise between GEO and LEO, with lower latency than GEO and longer visibility windows than LEO, which simplifies service continuity but requires more satellites to ensure global coverage. Currently, the orbit is used by navigation satellite systems (GLONASS, Galileo) and a few operators (e.g., SES's O3b mPOWER constellation) [9].

LEO systems (500-2 000 km) offer low-latency communication (30-50 ms), suitable for real-time and interactive applications [5, 30]. The proximity to Earth allows the use of high-frequency bands such as Ku, Ka, Q, and V, enabling high throughput and large system capacity, making such systems attractive for global broadband coverage. However, rapid satellite motion entails frequent handovers and complex constellation management to maintain continuous connections. A typical LEO constellation has hundreds to thousands of satellites, and adding new planes or satellites is straightforward, which makes the system scalable.

Inter-satellite links in LEO systems reduce dependence on ground stations, thus decreasing delays and improving connectivity.

4.3 Ground segment

The ground segment has two main responsibilities: controlling and maintaining the space segment through telemetry, tracking, and control (TT&C) operations, and enabling network access and managing traffic via gateway stations (GWs) [8, 9, 14].

GWs are responsible for user data transmission and reception, frequency conversion, baseband signal processing, and feeder link establishment with visible satellites. Specifically, a GW consists of radio frequency (RF), intermediate frequency (IF), and baseband subsystems. The RF chain integrates amplifiers, duplexers, and directive antennas. The IF stage performs frequency translation. The baseband subsystem manages modulation, multiplexing, and some advanced functions such as precoding for multi-beam operations.

TT&C stations monitor and control satellite operations. They are responsible for antenna control and tracking, updating satellite configurations, mitigating orbital drift, and monitoring overall satellite system health. Generally, TT&C stations use a special control link to communicate with satellites.

The ground segment can also incorporate elements of the terrestrial layer, e.g., cellular or Wi-Fi connectivity, that extend service to mobile and fixed users and enable network backhauling through the core network.

4.4 User segment

The user segment consists of user terminals (UTs) that provide end-users with access to HTS networks [9, 14]. UTs primarily operate in the Ka and Ku bands and can be broadly classified into fixed and mobile types.

Fixed terminals are typically implemented as very small aperture terminals (VSATs), which are two-way satellite earth stations. A VSAT has an outdoor unit (antennas, amplifiers, frequency converters) and an indoor unit (modem and customer interface). These units enable bidirectional satellite communication.

Mobile terminals encompass handheld devices, vehicle-mounted systems, and aeronautical terminals. Compared to fixed UTs, they require compact and lightweight antennas to ensure portability and optimized power management.

Future UTs are expected to evolve toward multi-radio devices integrating satellite connectivity with terrestrial technologies.

5 PHY-level design

In this section, we consider several aspects of PHY-level design in SatCom networks: channel characteristics (Section 5.1), antenna design (Section 5.2), waveform design (Section 5.3), and payload types that can be carrier by a satellite (Section 5.4).

5.1 Channel characteristics

The PHY-level design of satellite systems is notably affected by a unique propagation condition determined by orbit altitude and operating frequency [3]. Channels in GEO and LEO systems differ from those in terrestrial networks due to the long transmission paths, minimal scattering, and predominance of line-of-sight propagation [14, 19, 30]. Fixed satellite links, especially in the Ku- and Ka-bands, can often be modeled as additive white Gaussian noise channels, but they are strongly affected by atmospheric phenomena. These long- and short-term fading mechanisms degrade signal quality, especially at higher frequencies. In contrast, mobile satellite links experience additional diffuse multipath components caused by reflections from terrain and buildings. Typically, such channels are modeled using multi-state Markov channel models, which capture transitions between deep-shadowed, intermediate, and clear-sky states.

From a link-budget perspective, LEO systems generally achieve higher carrier-to-noise ratios due to a lower path loss component [30]. For handheld terminals, GEO links often achieve poor CNR, whereas LEO systems can provide performance gains of up to 15-16 dB in uplink for comparable configurations. However, the mobility of LEO satellites introduces challenges such as Doppler shifts, time-varying received power, handovers - which require advanced channel estimation and tracking techniques.

5.2 Antenna design

As satellite services move from broadcast to broadband, the antenna systems move from single-beam to multi-beam antenna architectures that generate numerous high-gain spot beams to maximize spectral efficiency [4]. Two main categories of satellite antennas are passive and active arrays [9, 31, 32].

Passive antennas rely on reflectors and feed systems to form beams through mechanical means. There are two common designs: single-feed-per-beam (SFPB) and multiple-feed-per-beam (MFPB) configurations. An SFPB system is simpler to implement but requires multiple reflectors to achieve continuous coverage, which increases payload mass. In contrast, an MFPB system generates each beam from a cluster of feeds, allowing contiguous coverage with fewer reflectors and improved efficiency, but requires a more complex beamforming network. In addition, passive antennas employ mechanical steering mechanisms, which increase payload weight and provide slower beam tracking compared to digital counterparts.

Active antennas integrate amplifiers directly with the radiating elements, providing distributed amplification. These systems can be implemented in either direct-radiating array or array-fed reflector configurations. Active arrays support electronic beam steering, enabling rapid reconfiguration and adaptive coverage without mechanical movement. Combined with digital beamforming, active arrays can dynamically adjust beam direction and side-lobe levels, thereby enhancing spectral reuse and mitigating inter-beam interference. However, active antennas consume more power and require more complex signal processing.

Recent developments in array technologies for LEO systems, such as electronically steerable antennas, enable fast handovers, simultaneous tracking of multiple satellites, and multi-orbit interoperability [30]. Furthermore, the integration of active antennas with massive MIMO and precoding techniques opens opportunities for spatial multiplexing and adaptive beam management, significantly improving system capacity.

5.3 Waveform design

Modern broadband SatCom systems mainly adopt the DVB family of standards, specifically DVB-S2 and its extension DVB-S2X standards, for both GEO and LEO systems [30]. The DVB-S2 standard supports so-called variable and adaptive coding and modulation (VCM and ACM) to cope with challenging propagation conditions. Another important feature is support for advanced channel codes such as LDPC and BCH codes. Its successor, the DVB-S2X standard, notably extends the modulation granularity and supports multi-stream transmission on a single carrier.

With the evolution toward 5G NTN, waveform design encounters new challenges such as large propagation delays, Doppler shifts, and so on. The research community is evaluating candidate waveforms capable of supporting integrated satellite-terrestrial operation, including adaptations of 5G New Radio air interfaces [3]. Related studies also explore the feasibility for NTN of other 5G NR features such as timing-advance or HARQ procedures.

5.4 Payload types

Satellite payloads can be broadly categorized into transparent and regenerative, with the former referred to as ‘bent-pipe’ transponders and the latter as on-board processing systems [4, 9].

Transparent payloads apply RF processing (filtering, frequency conversion, amplification) to received signals without regeneration. Bent-pipe transponders can be analog or digital. Using digital transponders enables advanced beamforming techniques, thus improving frequency reuse and spectral efficiency.

Regenerative payloads, in addition to RF processing, apply on-board digital processing, including demodulation and decoding, of received signals. This enables packet switching, adaptive coding and modulation, beam hopping and improved interference mitigation. Another key advantage is the support of ISLs and single-hop mesh connectivity between terminals, thereby reducing latency. On the other hand, regenerative payloads are more complex and require additional on-board computational resources.

In practice, transparent payloads remain widely deployed due to their simplicity and low cost, while regenerative payloads are increasingly integrated in next-generation HTS systems.

6 MAC-level design

The section overviews common channel access schemes on the forward (Section 6.1) and return links (Section 6.2) in SatCom systems and discusses resource management challenges (Section 6.3).

6.1 Forward link

The forward link carries data from the GW to UTs [19, 30]. In HTS systems, wideband carriers are typically assigned per spot beam. User data is multiplexed in the time domain, i.e., the satellite transmits a continuous stream of frames in a broadcast manner, and each UT decodes its own data. For example, the DVB-S2X standard employs time-division multiplexing (TDM) with ACM applied on a frame-by-frame basis.

A scheduler determines which UTs will receive data in the current frame and defines the data transmission parameters. The scheduler selects a modulation and coding scheme (MCS) based on channel state feedback from the UT. Moreover, when generating a frame, it considers many aspects: channel conditions, packet or flow priority, QoS class, and buffer status at a GW side. These factors affect both intra-beam packet multiplexing and inter-beam resource allocation across active beams. Modern systems often employ multicast scheduling within a frame, hence the selected MCS is constrained by the user with the poorest channel conditions. Additional features, such as beam hopping and carrier aggregation, are expected to further enhance throughput.

GEO HTS systems, such as Viasat, use the DVB-S2X standard described above: wideband carriers (hundreds of MHz per spot beam) with TDM multiplexing of user packets. In contrast, LEO systems, such as OneWeb and Starlink, employ proprietary protocols with waveform and channel access designs more closely aligned with cellular networks.

6.2 Return link

The return link carries data from UTs to the GW [19, 30]. The DVB-RCS2 standard specifies a Multi-Frequency Time-Division Multiple Access (MF-TDMA) scheme, in which time-frequency resources are divided into frames (time domain) and frequency channels (frequency domain). The network management system assigns specific resources to UTs based on their demand reports by broadcasting a Terminal Burst Time Plan (TBTP) on the forward link. This approach provides fine granularity and flexibility in resource allocation, supporting diverse traffic profiles. Part of each frame is reserved for user capacity requests, typically occurred via random access mechanisms.

While GEO systems follow the DVB-RCS2 standard, LEO systems adopt similar uplink principles but employ waveform and access methods closer to those used in cellular networks, such as SC-FDMA or OFDMA-based allocation across time and frequency domains.

Table 2 illustrates nominal downlink and uplink throughputs for several GEO and LEO HTS systems. The GEO satellites offer high aggregate downlink capacity ranging from hundreds of Gbps to beyond one Tbps per satellite [8, 33, 34]. The capacity is distributed across many spot beams, resulting in up to 100-150 Mbps per user in downlink. Uplink data rates on GEO consumer plans are much lower, e.g., around 5 Mbps.

LEO satellites have lower capacity per satellite, e.g., 10-100 Gbps per satellite [10, 35], but compensate it with constellation scale. Individual users can achieve nominal rates of hundreds of Mbps in downlink and tens of Mbps in uplink depending on the consumer plan. Note that nominal rate assumes ideal conditions, actual network throughput is generally lower.

6.3 Resource management

Resource management in multibeam HTS networks encompasses dynamic power and frequency resource allocation. The scheduler is responsible for optimizing resource assignment to meet QoS requirements for different traffic flows.

Physically limited transmit power should be sensibly distributed across beams to consider traffic loads and propagation conditions. Flexible per-beam power assignment enhances system performance, but finding the optimal power allocation is a challenging task due to interference and payload constraints [9, 36]. This optimization problem often requires iterative or heuristic algorithms to approximate solutions under the satellite's total power budget. Co-channel interference among adjacent beams further complicates power allocation decisions.

A notable dynamic strategy is beam hopping, where only a subset of beams is illuminated at any given time according to a predefined pattern, i.e., all available RF power is concentrated on

Table 2

Nominal throughput metrics for HTS systems

System	DL Throughput	UL throughput
ViaSat-3 (GEO)	~1 Tbps per satellite	~3-5 Mbps
Hughes JUPITER-3 (GEO)	> 500 Gbps per satellite	up to 5 Mbps
SpaceX Starlink (LEO)	20-250 Mbps per user	10-20 Mbps
OneWeb (LEO)	~150 Mbps per user	~30 Mbps

a smaller set of active beams [37, 38]. Beam hopping can track spacial and temporal demand fluctuations by periodically switching active beams, thus improving amplifier utilization and reducing simultaneous inter-beam interference. At the same time, it raises scheduling complexity. Using ML-based methods is a promising approach for solving complex resource allocation problems in BH systems [39, 40].

Effective spectrum allocation is also important. Various frequency reuse schemes can be employed. Two extreme cases are no frequency reuse (so-called orthogonal scheme) and full frequency reuse among beams [14]. In practice, many multibeam systems adopt a carefully chosen reuse factor (e.g., 3 or 4-color reuse) to balance capacity and interference, and future systems aim for higher reuse by implementing advanced interference mitigation schemes [41]. In addition to static patterns, bandwidth can be dynamically distributed among beams according to the spatial traffic demands. Digital payloads support this flexibility and can adapt the bandwidth per beam on the fly. Furthermore, the carrier aggregation feature is introduced to aggregate multiple non-contiguous carriers for a single user or beam, providing greater transmission flexibility.

With aggressive frequency reuse, managing co-channel interference is a central aspect that requires joint PHY/MAC-layer solutions [19, 42, 43]. One approach is multi-user precoding on the forward link, which involves pre-processing the signals transmitted on each beam to mitigate inter-beam interference. Precoding enables full frequency reuse by significantly reducing interference, but its performance depends on accurate channel state information and user scheduling. Therefore, precoding is typically integrated with scheduling strategies at the MAC layer: the network scheduler selects groups of users or beams to serve simultaneously in a frame that are suitable for precoding, thereby maximizing the interference cancellation benefits. In addition to precoding, advanced resource scheduling can exploit spatial separation by allowing resource reuse only among beams that are sufficiently far apart to cause negligible interference to each other [44]. Such scheduling strategies, involving spacial or time clustering of beams, effectively balance scheduling complexity to keep low co-channel interference.

7 HTS services and QoS

7.1 System timescale

SatCom networks can be viewed and analyzed at multiple time scales, which determine the detail level and relevant performance metrics in modeling [4]. In general, we can define four levels for call-driven networks: customer service time (call-level), session/application activity, flow or burst communications, and packet-level transmission. Call and session durations are measured in seconds and minutes, whereas packet-level events occur on the order of milliseconds. Different levels capture different aspects of system behavior. Queueing theory can be used to model system performance at both packet and call levels [45, 46].

Call-level models treat an entire connection as a single arrival and focus on new call admission control, mobility management, and resource planning [47, 48]. The key performance metrics include the probability of blocking a new call, the probability of dropping a handoff call, and average call service time. The aim of

call-level models is to estimate the number of channels/carriers/terminals required to maintain the desired metrics at a predefined level. Such models typically use Poisson arrival processes and exponential call durations, leading to closed-form expressions.

Packet-level models [45, 49] consider each packet within the system. They can capture link-layer protocols, adaptive coding and modulation, and cross-layer scheduling. The key performance metrics include throughput, packet loss probability, and latency. Detailed discrete-event simulators or stochastic queueing models are used to compute these metrics, often at the cost of higher computational complexity.

It is important to note that call-level and packet-level dynamics are interdependent, e.g., accepting a handoff call increases the load and may cause additional losses. Therefore, it is possible to combine both approaches, using effective bandwidth to translate variable-rate traffic into equivalent traffic demands and jointly optimize admission control and packet-level scheduling [46].

7.2 Service types in HTS networks

HTS networks can support services with different QoS requirements [4, 7, 50]. Typical HTS systems include: broadband Internet access (web browsing, file downloads), real-time communication (VoIP, video conference), media streaming (live broadcasting), corporate or cellular backhaul, and IoT sensors (bursty low-rate traffic). Table 3 illustrates the diversity of traffic types in HTS networks along with their typical traffic volume, session duration, and QoS requirements [51, 52].

Each service has a distinct traffic profile: web browsing and file downloads are tolerant to variable rate and latency (so called elastic traffic), whereas VoIP/telephony requires low latency; video conferencing and streaming require consistent bandwidth, whereas video-on-demand platforms use buffers to smooth the delay. Elastic traffic can utilize any spare capacity in a network. If some beams or time slots are underutilized by real-time services, bandwidth can be dynamically reassigned to elastic data flows, allowing temporal increase of their rate. This maximizes overall throughput without compromising the QoS of delay-sensitive traffic.

Table 3

Representative HTS service characteristics

Service type	Typical volume	Session duration	QoS needs
Broadband Internet (web, downloads)	50-100 Mb per session	10-30 min	Delay tolerant; elastic throughput
Real-time communication (VoIP, video call)	1-5 Mb per session	5-10 min	Low latency; jitter sensitive
Video streaming (HD)	0.7-1.5 Gb per session	30-60 min	Stable rate; buffering is acceptable
Backhaul (corporate / cellular)	3-20 Gb per hour	continuous link	High reliability; moderate latency tolerance
IoT sensors (telemetry)	< 0.1 Mb per session	< 1 min	Delay-tolerant; minimal bandwidth

In practice, network traffic can be modeled as a mix of real-time (delay-sensitive) and elastic (delay-tolerant) flows [47, 48, 53]. Modern HTS payloads with multi-beam architectures allow dynamic power allocation among beams, allowing reconfiguring capacity on-the-fly to meet current QoS requirements. Moreover, queuing theory methods are applicable to both LEO and GEO SatCom systems [48, 54, 55] providing analytical tools to describe both data and control channels [56, 57].

8 Conclusion

High-Throughput Satellite (HTS) systems represent a major trend in satellite communications. Their design innovations enable capacities ranging from hundreds of gigabits per second up to terabits per satellite, supporting modern broadband applications over wide geographical areas.

The development of HTS systems has many technical challenges. One of the most important issues is resource planning. The paper provides a focused overview of HTS architecture, discussing design principles at PHY and MAC layers and their impact on system performance. We believe that a suitable analytical framework can be built on queuing theory and teletraffic models. Such a framework can guide the development of resource allocation strategies and support future system design.

The complexity of HTS systems will continue to grow. Future satellite networks are likely to become multi-orbit and multi-layered to optimize coverage and latency. Moreover, dynamic and AI-driven resource management will become important for handling highly variable traffic. Advanced concepts, such as Non-Terrestrial Networks for 6G, suggest new ways to exploit HTS capacity. Addressing these challenges will require further development of both system design techniques and analytical tools.

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КЛЮЧЕВЫЕ АСПЕКТЫ СПУТНИКОВЫХ СИСТЕМ С ВЫСОКОЙ ПРОПУСКНОЙ СПОСОБНОСТЬЮ: ОТ СТАНДАРТИЗАЦИИ ДО К УПРАВЛЕНИЮ КАЧЕСТВОМ ОБСЛУЖИВАНИЯ

Троегубов Александр Юрьевич, Московский физико-технический институт (национальный исследовательский университет), Москва, Россия, troegubov.aiu@phystech.edu

Маслов Александр Александрович, Московский физико-технический институт (национальный исследовательский университет), Москва, Россия, maslov.aa@mipt.ru

Себекин Геннадий Валерьевич, Московский физико-технический институт (национальный исследовательский университет), Москва, Россия, sebekin.gv@mipt.ru

Степанов Сергей Николаевич, Московский технический университет связи и информатики, Москва, Россия, s.n.stepanov@mtuci.ru

Щурков Алексей Олегович, Московский физико-технический институт (национальный исследовательский университет), Москва, Россия, shchurkov.ao@mipt.ru

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Аннотация

Повсеместное распространение сетей связи является ключевым для многих сфер человеческой деятельности, однако значительная часть регионов имеет низкое покрытие из-за высокой стоимости или сложности развертывания наземной инфраструктуры. Спутниковые системы связи позволяют преодолеть данное ограничение за счет глобального покрытия и поддержки широкоэшелонных и многоадресных сервисов, что делает их важной составляющей современных сетей связи, дополняющей наземные системы. В работе представлен обзор современных спутниковых систем с высокой пропускной способностью (HTS) с акцентом на эволюцию архитектур, вопросы стандартизации и управление ресурсами для выполнения требований к качеству обслуживания. Развитие HTS-систем сопровождается рядом технических вызовов. Рассматриваются текущие инициативы в области стандартизации и регулирования использования радиочастотного спектра, а также типовые приложения и сценарии применения. Кроме того, анализируется архитектура HTS-сетей, охватывающая геостационарные и негеостационарные орбиты, многолучевые полезные нагрузки и многоуровневые развертывания, а также принципы проектирования на физическом уровне и уровне управления доступом к среде. В работе также обсуждаются вопросы дифференциации сервисов и поддержки требований к качеству обслуживания в HTS-сетях, приводятся характеристики трафика и соответствующих показателей производительности на различных временных масштабах функционирования системы. Показано, что методы теории массового обслуживания и телетрафика могут служить подходящей аналитической основой для оценки производительности HTS-систем и обоснования проектных решений при создании эффективных спутниковых сетей в будущих системах связи.

Ключевые слова: Спутниковые системы с высокой пропускной способностью, спутниковая связь, многолучевые системы, управление ресурсами, качество обслуживания.

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