FUTURE SATELLITE COMMUNICATIONS: SATELLITE CONSTELLATIONS AND CONNECTIVITY FROM SPACE

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Abstract – *Satellite communications is currently undergoing a massive growth, with a rapid expansion in Low Earth Orbit (LEO) networks, and a range of new satellite technologies. Until very recently, satellite communication systems and terrestrial 5/6G wireless networks have been complementary distinct entities. There is now the opportunity to bring these networks together and deliver an integrated global coverage multi-service network. Achieving this will require solving some key research challenges, and leveraging new technologies including high frequency phased-array antennas, onboard processing, dynamic beam hopping, physical layer signal processing algorithms, transmission waveforms, and adaptive inter-satellite links and routing. By integrating seamlessly with terrestrial 5/6G networks and low altitude flying access points, future satellite networks promise to deliver universal connectivity on a global scale, overcoming geographical limitations. In this special issue, we focus on the future of satellite communications, exploring topics ranging from beam hopping and design to space routing and THz satellite communications. Our aim is to shed light on the potential of these emerging technologies and their role in reshaping the landscape of global connectivity.*

Keywords – 5G+, 6G, beam hopping, channel models, inter-satellite routing, mega constellations, phased arrays, satellite communications, THz communications

1. INTRODUCTION

Satellite communications technology is currently on the cusp of a massive paradigm shift, transitioning from traditional geostationary service to multi-layered space networks [1, 2]. These networks will integrate Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationaory Earth Orbit (GEO) satellites with terrestrial networks and low altitude airborne access points (e.g., drones). They will provide global coverage with high throughput and low latency, initiating a new era of space-based cellular connectivity [3, 4].

This future is illustrated in Fig. 1, which shows an interplay between space, terrestrial and low-altitude airborne networks, all interconnected to form a vertically integrated multi-layer network. This network spans from the ground to space, and offers a diverse array of global connectivity services.

The satellite-based connectivity, potentially direct from space to mobile terminals and Internet-of-Things (IoT) devices on the ground, will be a key component of fifth generation plus (5G+) and sixth generation (6G) networks [5, 6, 7, 8]. A wave of recent announcements from industry leaders underscores this trend. Examples include partnerships like Apple and Globalstar for satellite messaging services, Starlink and T-mobile for global voice and data coverage, Huawei and China Telecom for satellite video and voice calling, and AST SpaceMobile conducting test trials for 5G voice and data connectivity [9, 10, 11, 12]. In addition to high rate data services, IoT is set for significant growth under this joint satellite-terrestrial network framework, especially in rural and remote areas, with a compound annual growth rate of 25% [13]. New game-changing IoT services will be possible in near future, leading to new research challenges in direct device-to-satellite data collection, computation, and device battery life [14, 15, 16].

The revolution in satellite communications activity is driven by several key recent technological advancements. Chief among these is the progress in LEO communications satellites. LEO satellites orbit the earth at an altitude ranging from 500 to 1500 km (just below the inner Van Allen belt) with velocities in the range $7.11 - 7.61$ km/s. They can be deployed in large quantities to form mega-satellite constellations in orbit. When deployed in a constellation, they provide global coverage with low propagation latency for the nadir ingress (ground-to-satellite) and egress (satellite-to-ground) links in the range $1.7 - 5$ ms.[1] Companies such as Starlink, OneWeb and Iridium Next are at the forefront of LEO advancements, rolling out large constellations of up to thousands of satellites. Crucial design considerations for these emerging LEO satellite constellations include orbital altitude, inclination and

[1]The propagation delay varies based on the elevation angle between the LEO satellite and the ground terminal. For instance, at an altitude of 1500 km with 30 degrees link elevation angle, the delay is approximately 8 ms.

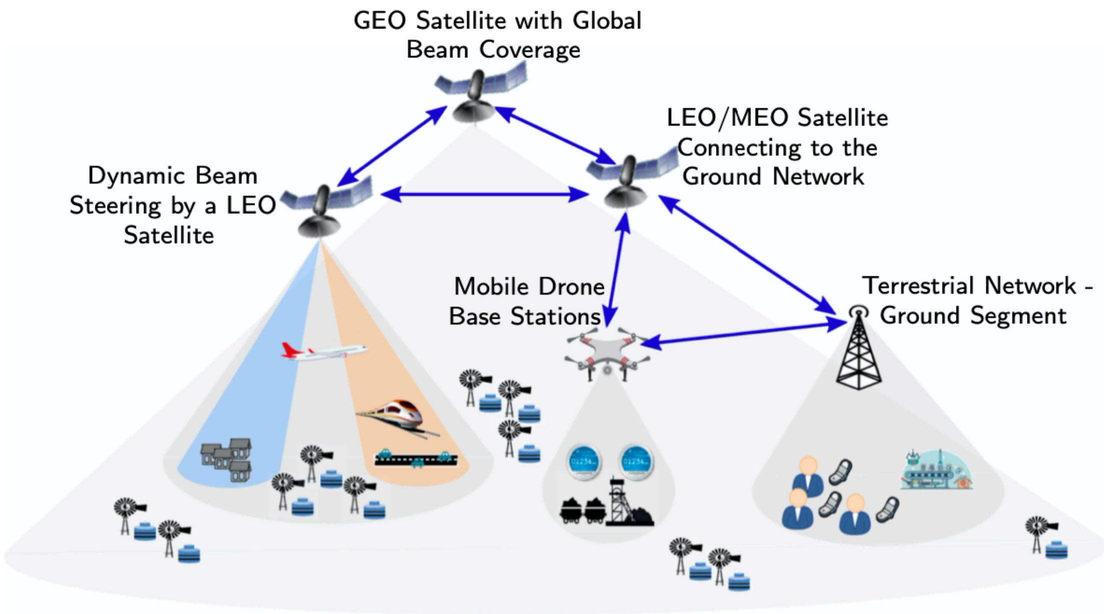

Fig. 1 – A multi-layer space network integrated with terrestrial and low-altitude drone base stations.

eccentricity, number of orbital planes, number of satellites in each plane, frequency assignment and minimum elevation angle for connectivity.

Other important technological advancements driving the surge in satellite communications activity are the evolution of phased-array antennas and enhanced onboard signal processing capabilities. Phased-array antennas are growing in size, exemplified by AST SpaceMobile's second-generation satellites with antenna sizes of 128m^2, with future plans aiming for antennas up to 400m^2. Larger antennas directly translate to improved signal reception quality on the ground and increase the channel capacity, a crucial factor for reliable broadband connectivity. In addition, the phased-array antennas enable generation of adaptive spot beams in increasing quantities, with real-time updates to beam steering directions to meet dynamic traffic demands. The onboard satellite signal processing capability allows for real-time data regeneration in space, enabling dynamic and optimized inter-satellite packet routing. Last but not least, the reduction in satellite launch and manufacturing costs has also further sparked industry interest in the development of multi-layered space networks [17].

With all these expectations from the new multi-layer satellite modalities and recent enabling technological advancements, there remain many important research challenges to be overcome, in order to deliver a fully integrated satellite-terrestrial network. These challenges include:

- How to jointly optimize the design of LEO/MEO/GEO satellite constellations to ensure uninterrupted coverage, deliver Gbps mobile satellite services and minimize deployment costs?
- What waveforms, physical layer techniques and antenna designs offer the best performance for multi-layer space networks, achieving block error rates as low as 10^{-6}?
- What strategies are most effective for coordinating spectrum access among LEO, MEO, and GEO satellites to mitigate interference?
- How can we design new multiple-access protocols that minimize satellite access latency (additional to free space path delays)?
- Which are the best rules for satellite association and harnessing satellite diversity?
- What role will massive MIMO (multi-input multi-output) play in enabling broadband connectivity in future satellite networks?
- Which spectrum bands are the best for inter-satellite communication links? How can we enhance the efficiency and reliability of these links to avoid congestion in space?
- How does satellite mobility impact legacy network layer and transport layer protocols? What are the new routing and congestion control algorithms tailored for future satellite networks?

- How can we leverage artificial intelligence and machine learning to optimize constellation design, resource allocation, traffic engineering and load balancing in future satellite networks?
- What novel access techniques are necessary to facilitate distributed massive machine-type communications over multi-layer space networks?
- What novel analytical and simulation models, such as stochastic geometry for constellation design and game theory for load balancing, are essential for tractable performance analysis?
- What are the emerging security and privacy challenges facing future satellite networks?

This special issue is dedicated to addressing some of these research questions and exploring potential solutions. In particular, the special issue covers several critical areas, including adaptive beam hopping and resource allocation, THz communications for inter-satellite links, satellite channel modeling, inter-satellite routing, new antenna designs and experimental testbeds. In the following sections, we will introduce each research challenge briefly and provide an overview of the contributions featured in the special issue.

2. ADAPTIVE BEAM HOPPING AND RESOURCE ALLOCATION

With an increasing number of spot beams and satellites in orbit, effective management of radio resources and interference coordination become paramount for the future of satellite networks. This calls for the development of new algorithms capable of adapting to mobility and shifting traffic demands across both space and ground segments. These algorithms are essential for mitigating harmful interference among beams and satellites operating in different orbits. Techniques such as multi-antenna strategies (e.g., hybrid beamforming), spatial and frequency multiplexing, optimized beam pointing, and adaptive beam hopping are among the potential solutions proposed in current literature to address interference challenges in next-generation satellite networks [18, 19].

Paper [20] in this special issue focuses on the problem of developing optimized adaptive beam hopping schedules for high throughput GEO satellite networks. This is especially important in scenarios where the user locations exhibit heterogeneous distribution across the terrain and the satellite's RF chain availability is limited. The problem is formulated as one in discrete optimization, aiming to maximize the minimum separation between simultaneously served user cluster centers. It is shown that finding the optimum user cluster grouping maximizing the minimum inter-cluster separation has exponential complexity. The paper develops a near-optimum polynomial time algorithm with small optimality gap. When compared with other benchmark algorithms such as greedy grouping, iterative K-means clustering and fixed cell beam hopping design, the developed algorithm manages inter-beam interference much more effectively, increasing the worst case signal-to-interference-plus-noise-ratio (SINR) up to 13 dB and providing a twofold increase in zero-outage target rates.

3. SPECTRUM ACCESS AND CHANNEL MODELING

Another key challenge facing future satellite systems is the issue of spectrum scarcity. Addressing this challenge demands either an expansion of the available RF spectrum to higher frequency bands or a substantial enhancement in the efficiency and effectiveness of spectrum utilization. This becomes increasingly important as the number of satellite systems operating in both GEO and non-GEO orbits continue to rise, especially given their reliance on frequencies below 30 GHz.

One potential solution to address this challenge is by using higher frequency bands for satellite communications [5, 21]. The possibility of using the frequency band $231.5 - 252$ GHz for earth exploration satellite services with passive sensors has also been explored by ITU under the agenda item 1.14 for the WRC 2023 [22].

Paper [23] in this special issue provides a detailed study of atmospheric effects such as rain, fog and ionospheric fading on THz LEO satellite communications. The paper's findings indicate that frequency bands between $102-109.5$ GHz are optimum for communication between earth stations and satellites, with a potential to achieve data rates in the range $2.6 - 12$ Gbps in the uplink and 25 Gbps in the downlink. For inter-satellite links, the frequency bands $111.8 - 114.25$ GHz, $116 - 123$ GHz, $174.5 - 182$ GHz and $185 - 190$ GHz are identified as promising options, achieving data rates of up to 2.5 Gbps when using uniform rectangular arrays with 625 radiating elements.

Paper [24] in this special issue presents an alternative solution to address the spectrum scarcity issue in future satellite systems by employing cognitive radio techniques. It explores a shared downlink scenario between GEO and LEO satellites and provides a mechanism for assigning frequency slots.

A related research problem is the development of channel models which will capture the multi-path effects on the signal-to-noise-ratio (SNR) in satellite-to-ground links. In addition to the atmospheric influences which impact RF wave propagation; signal scattering, reflections and Doppler shifts are also important factors that determine the received signal quality for such links. Paper [25] in this special issue introduces a two-ray model that incorporates Doppler shifts over the paths due to satellite motion. This model expands upon the classical two-ray model [26, 27] by taking the frequency change between the rays into account. In conventional two-ray models, only the phase and amplitude differences across the rays cause fluctuations in the received signal level. However, the fixed frequency assumption does not necessarily hold for LEO satellite-to-ground channels due to the highly mobile nature of these satellites. This issue is addressed in [25] for a wide range of antenna radiation patterns, including omni-directional, dipole and patch antennas.

4. INTER-SATELLITE ROUTING

Future satellite networks will have the onboard signal processing and data regeneration capabilities, transforming them from simple bent-pipe relay networks into multi-hop mobile networks in space. This important feature enables the regeneration and routing of data packets between satellites in space [28, 29, 30]. Unlike the zig-zag paths that rely on gateway-satellite connectivity, multi-hop routing in space has the potential to significantly reduce the physical distance a packet must traverse from source to destination ground terminals, providing low-latency end-to-end connectivity. Additionally, inter-satellite routing eliminates the need for numerous ground-based gateways and associated infrastructure to connect the ground terminals, which typically entail significant installation costs.

An important challenge for inter-satellite packet routing is to develop robust packet forwarding algorithms that can adapt to topological changes in the satellite network while minimizing the routing overhead. Paper [31] in this special issue tackles this challenge by developing a new information-centric routing protocol, named Galor, for LEO satellite networks. When compared to IP-based routing, Galor enables in-network content caching and aggregation. The proposed algorithm accommodates intermittent inter-satellite connectivity by maintaining localized and fine-grained inter-satellite link states within some certain range from each satellite. The link failures resulting from antenna tracking errors and other random phenomena are taken into account while maintaining local link states. The routing decisions are made based on the proactively maintained local link states and coarse-grained global deterministic neighbor relations in a given LEO satellite constellation. The simulation results indicate that Galor provides up to twofold increase in packet delivery rates when compared to the standard open-shortest-path-first (OSPF) routing protocol. The control overhead is reduced by over 30%, accompanied by a nearly four-fold decrease in the algorithm convergence time compared to the OSPF algorithm.

5. ANTENNA DESIGN

Antenna design stands as a critical factor in unlocking the full capabilities of next-generation satellite networks. Various types of antennas find applications on satellites today, including wire antennas like monopoles and dipoles, feed-horn antennas, reflector antennas, lens-based antennas, and phased-array antennas [32, 33, 34, 35].

Among these, phased-array antennas emerge as one of the most popular choices for future satellite systems. Their antenna apertures are made up of multiple small antenna elements such as monopoles, dipoles, or patch antennas arranged in linear or planar configurations. By controlling these elements with phase shifters, phased-array antennas can generate multiple spot beams whose orientations can adapt dynamically to traffic demands and satellite elevation angles. Additionally, they can be used to establish inter-satellite links in mmWave and THz frequency bands [23]. These important features open avenues for optimizing satellite networks across physical and network layers, including analog, digital, and hybrid beamforming, beam hopping, beam direction optimization, and inter-satellite routing [19, 20, 31].

Paper [36] in this special issue proposes a new dual parabolic cylindrical reflector antenna design for LEO satellite networks. Similar to phased-arrays, these antennas have the capability to generate multiple beams for covering extensive geographical areas when multiple feeds excite the antenna. In this design, the beams can be dynamically tilted both vertically and horizontally by adjusting the location of any feed relative to the sub-reflector focus. Notably, a single dual parabolic cylindrical reflector antenna can operate across the frequency range of 17.8 GHz to 30 GHz, a key frequency band in LEO satellite communications. It is shown that a compact antenna design with size $14.8 \times 10.4 \times 3.7$ cm^3 and weight of 0.37 kg can provide a directivity gain between 20 dB and 24 dB.

6. WAVEFORM DESIGN

Waveform design is another key research challenge for future satellite networks to enable robust high data rate connectivity with wide coverage. The design constrains the traffic-carrying user capacity of satellite networks. Classical techniques include the waveform designs based on various access methodologies, including time division multiple access (TDMA, as seen in Iridium Next), frequency division multiple access (FDMA, as seen in Orbcomm OG2), code division multiple access (CDMA, as seen in Globalstar second generation) and variations thereof based on traffic demands such as demand assigned multiple access (DAMA) [32]. Furthermore, Starlink signals have recently been reverse-engineered. It has been shown that LEO satellites in Starlink use orthogonal division multiple access (OFDM) like waveforms for downlink communications [37, 38].

Future challenges come with the demand to communicate with fast moving vehicles. High Doppler shifts and Doppler spreads pose problems for current modulation formats, and this has led to the proposal of a new approach in the delay-Doppler domain, called orthogonal time frequency space (OTFS) modulation [39, 40, 41]. This has great potential for application, particularly for highly mobile LEO satellites.

7. EXPERIMENTAL TESTBEDS

Experimentation and testbed design are critical for advancing the state-of-the-art in satellite communications, allowing researchers to validate theoretical concepts and demonstrate performance of proposed algorithms in real-world scenarios. This becomes increasingly crucial for future satellite-terrestrial integrated networks, where the proliferation of spacecraft in orbit, convergence of frequency allocations between 5G new radio and satellite systems, and the management of interference between terrestrial and non-terrestrial networks pose significant coordination challenges. Notable testbed designs, spanning physical, multiple access, and network layers, have been proposed in the literature [42, 43, 44, 45], with software-defined radio emerging as a key enabling technology in the proposed designs.

Paper [46] in this special issue introduces a new testbed design, named SeRANIS, aiming to integrate 5G non-public networks with satellite communications. Developed at the University of the Bundeswehr Munich, SeRANIS utilizes the ATHENE-1 satellite as its space segment. ATHENE-1, a LEO satellite, has a mass of 200 kg, with an experimental payload weighing 75 kg. Its communication capabilities span various frequency bands including UHF, L, S, X, and Ka bands, supplemented by laser links for inter-satellite connectivity. The ground segment of SeRANIS consists of an optical ground station for free-space communications, several full motion radio frequency antennas, multiple gNodeBs and multiple 5G core solutions. Furthermore, the testbed includes a laboratory with software defined radios, channel emulators and a 5G on-the-move solution implemented in a van.

This is the first testbed to combine 5G non-public deployment with a LEO satellite and a comprehensive ground segment, which includes an optical ground station. The important use cases of the testbed encompass experimenting with direct satellite-to-device connectivity and LEO satellite backhauling. Initial experiments presented in the paper involve reference signal received power values to estimate coverage and handover locations, round-trip time measurements using ping attempts for latency estimation, and TCP throughput measurements with and without LEO satellite backhauling. For the LEO satellite connectivity, Starlink system was used due to ATHENE-1 not being operational at the time of writing.

8. CONCLUSIONS

A significant paradigm shift is needed in the development of 6G technology in order to achieve ubiquitous connectivity through seamless integration of terrestrial infrastructure with future satellite networks. These future satellite networks will comprise multiple network layers characterized by varying degrees of heterogeneity, ranging from highly-mobile LEO communications satellites to those stationed in the geostationary orbit. The dynamic nature of the space segment in these space-terrestrial integrated networks introduces rapidly evolving network topologies, necessitating the development of new adaptive and resilient communication strategies across all layers, from physical to application layers. This is required to fully exploit the potential benefits offered by emerging satellite constellations.

This special issue is dedicated to exploring future satellite communications and novel space-based connectivity paradigms. Key areas addressed within this issue include adaptive beam hopping and resource allocation, spectrum utilization and THz communications, satellite channel modeling, inter-satellite routing, and new antenna and experimental testbed designs.

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