Secrecy Enhancement and Distributed Architectures in LEO Satellite Networks: A Survey on AN-Assisted Scheduling and SUSDA Design

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***Abstract*—The rapid deployment of low Earth orbit (LEO) satellite constellations has created new opportunities for high-capacity, low-latency global communication services. However, the broadcast nature of wireless links and the constraints of satellite hardware present unique challenges for ensuring physical-layer security (PLS). At the same time, emerging distributed satellite architectures promise unprecedented flexibility and scalability in cooperative transmission. This survey highlights two complementary research directions that exemplify these trends. First, we review a secrecy outage analysis that introduces an artificial-noise (AN) assisted scheduling strategy in multi-satellite networks. Second, we examine the Spatial Ultra-Sparse Distributed Antenna (SUSDA) architecture in distributed satellite clusters, which leverages laser inter-satellite links, coherent arraying, and adaptive beam synthesis to deliver large-aperture gains, interference suppression, and reconfigurable transmission.**

***Index Terms*—low Earth orbit (LEO), physical-layer security (PLS), artificial noise (AN), user scheduling, distributed antenna**

I. Introduction

(To Md Sakil Hasan: Please add some relevant references to some of the sentences below.) my anme mndksfksd. The emergence of large-scale low Earth orbit (LEO) satellite constellations has reshaped the landscape of global communications. Compared with traditional geostationary systems, LEO satellites offer lower latency, higher spatial reuse, and seamless integration with terrestrial networks. These advantages make LEO constellations an attractive platform for supporting broadband Internet access, Internet-of-Things (IoT) connectivity, and mission-critical applications. However, the open nature of wireless propagation combined with the limited hardware resources of small satellites introduces significant challenges in ensuring secure and reliable communications.

Physical-layer security (PLS) has attracted increasing attention as a complementary approach to cryptographic methods. By exploiting channel characteristics such as fading, interference, and noise, PLS enables information-theoretic secrecy without relying solely on computational complexity. Among existing techniques, artificial noise (AN) injection and cooperative transmission have shown promise in improving secrecy performance under adversarial conditions. Nevertheless, the effectiveness of these methods in LEO satellite networks is shaped by unique factors, including dynamic topology, time-varying channels, and resource constraints.

Parallel to security considerations, distributed satellite architectures have emerged as a transformative design paradigm. In particular, spatial ultra-sparse distributed antenna (SUSDA) systems harness multiple satellites flying in close formation to emulate a large-aperture antenna array. Through coherent combining and advanced beam synthesis, SUSDA architectures enhance link quality, suppress interference, and enable flexible reconfiguration. These capabilities naturally complement PLS strategies by providing new degrees of freedom for secure transmission.

This survey examines two representative research directions that address these issues from complementary perspectives: (i) AN-assisted satellite scheduling for secrecy outage minimization [1], and (ii) SUSDA architectures for distributed cooperative transmission [2]. The scope of the survey is twofold: first, to review the models, assumptions, and findings of each approach; and second, to explore potential synergies and open problems at the intersection of physical-layer security and distributed satellite architectures. By consolidating insights from both works, this survey aims to outline a research agenda for secrecy-aware cooperative transmission in next-generation LEO satellite networks.

II. Background

A. Physical-Layer Security in LEO Satellite Networks

(At least 3 paragraphs, To be written by Md Sakil Hasan)

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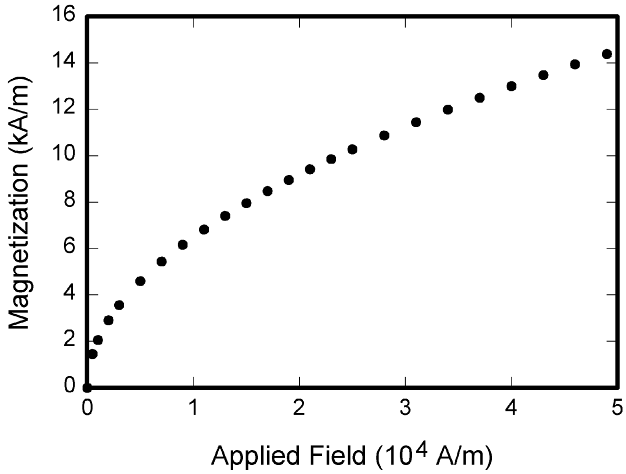
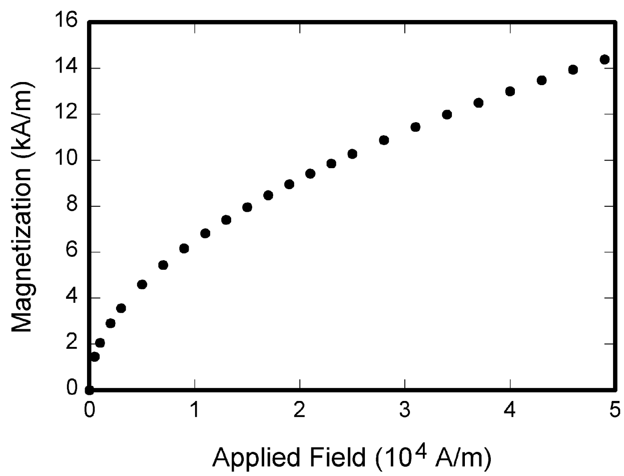
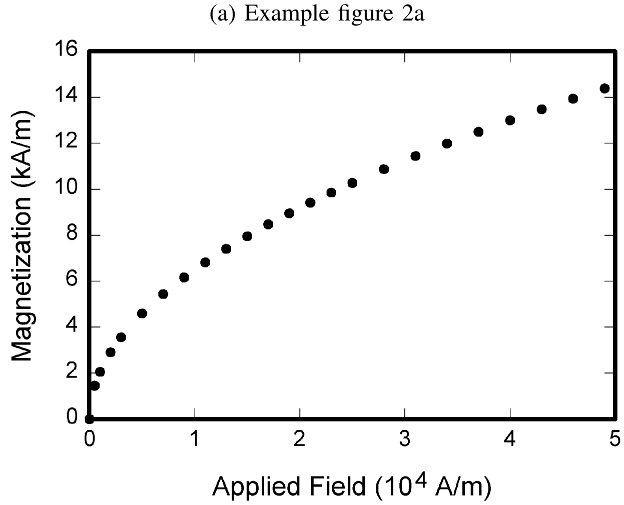


Fig. 1: Example figure



(a) Example figure 2a



(b) Example figure 2b

Fig. 2: Example figure 2

B. Distributed Satellite Architectures and SUSDA

Distributed Satellite Clusters (DSCs) are emerging as a vital architecture for next-generation non-terrestrial networks (NTNs), addressing the bottlenecks of single-satellite platforms in antenna performance and in-orbit reconfiguration. Building on this concept, the Spatial Ultra-Sparse Distributed Antenna (SUSDA) enables multiple small satellites to form a virtually large, distributed array. This architecture enhances capacity, provides strong anti-interference capabilities, and supports integrated sensing and communication (ISAC). Key enabling technologies include inter-satellite links, synchronization mechanisms, and interference management, while future research directions focus on improving the performance and scalability of DSC- and SUSDA-based systems.

Multi-antenna techniques are fundamental in modern wireless communications. They play a central role in LTE, 5G NR, and emerging 6G networks by boosting data rates, increasing capacity, and reducing latency [3]. In the evolution of Wi-Fi, from IEEE 802.11n to the latest 802.11ax (Wi-Fi 6), multi-antenna systems enable multi-user MIMO (MU-MIMO) for higher capacity and more efficient connectivity [4], [5]. This capability allows routers to serve multiple devices simultaneously on the same radio resource, thereby enhancing throughput and reducing latency.

Beyond terrestrial networks, multi-antenna techniques are equally critical in satellite communications, where advanced beamforming strengthens link robustness and capacity by directing signals precisely toward targeted Earth regions [6]–[8]. Furthermore, these antenna technologies are indispensable in specialized applications such as radar and navigation for aerospace and maritime sectors, as well as in enhancing safety for autonomous vehicles and aircraft systems [9], [10].

III. Secrecy in LEO via AN-Assisted Scheduling

Artificial noise (AN) has been widely studied as an effective tool for physical-layer security, particularly in multi-antenna terrestrial networks. Extending this concept to satellite networks, recent work has investigated the use of coordinated satellites to transmit data and AN simultaneously. The key idea is to leverage the constellation-wise inherent spatial diversity by assigning one satellite to deliver confidential data while another transmits artificial noise to confuse potential eavesdroppers.

(To be edited by Md Sakil Hasan)

A. System Model

(At least 1 pargraph, To be written by Md Sakil Hasan)

B. AN-Assisted Satellite Scheduling

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C. Secrecy Outage Analysis

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D. Key Findings and Limitations

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IV. SUSDA: Capabilities and Challenges

Distributed satellite architectures have emerged as a promising solution to overcome the size, weight, and cost limitations of single large-aperture antennas. Among them, the Spatial Ultra-Sparse Distributed Antenna (SUSDA) concept represents a paradigm shift in constellation design, enabling multiple satellites to operate cooperatively as a large, reconfigurable antenna array.

A. Architectural Overview

The SUSDA architecture integrates distributed antennas and inter-satellite synchronization to enable coherent multi-satellite beamforming. Small-aperture antennas on DSC satellites form a virtual array, delivering high SNR outputs and supporting flexible topologies such as linear, ring, star, or hybrid formations.

In the uplink, ground RF signals are delay-compensated, converted, and shared via inter-satellite links, with cross-correlation ensuring precise synchronization. In the downlink, satellites pre-compensate geometric delays so ground terminals can recover synchronized signals through phase adjustment and demodulation. This cooperative design enables reliable, high-throughput space-ground connectivity.

B. Key Enabling Technologies

1) **Inter-Satellite Links (ISLs)**
ISLs are essential for real-time coordination among DSC satellites. Optical (laser) ISLs are preferred over microwave due to higher capacity, lower power use, and reduced interference, though challenges such as visibility, connectivity, and antenna size remain. Robust ISLs provide the backbone for delay compensation, synchronization, and distributed processing in SUSDA.
2) **DSC-MIMO Transmission**
DSC-MIMO exploits spatial diversity and multiplexing by using multiple antennas across satellites and ground stations. On the uplink, ground transmitters apply MIMO encoding, satellites forward signals, and ground receivers decode them. This distributed design improves spectral efficiency and resilience against fading and interference.
3) **Synchronization and Delay Compensation**
Precise synchronization is critical due to kilometer-level satellite spacing. Each DSC node computes and compensates geometric delays, sharing results via ISLs. Cross-correlation refines timing to support coherent beamforming. In the downlink, phase-aligned transmissions ensure reliable signal recovery, maintaining array coherence in dynamic orbits.

C. Challenges and Design Issues

1) **Grating Lobes and Sidelobes**
As an ultra-sparse array, SUSDA produces strong grating lobes that reduce gain and impair localization. Mitigation requires non-periodic array layouts and intelligent optimization. Sparse array synthesis helps suppress lobes while preserving safe inter-satellite spacing.
2) **Channel Modeling**
SUSDA channels suffer from mobility-induced fading, multipath, and Doppler shifts. High correlation among satellites limits capacity and reliability. Correlated shadow Rice fading models and techniques such as signal diversity, multiplexing, and advanced estimation can mitigate these effects.
3) **Adaptive Anti-Interference**
Dynamic interference demands adaptive control. SUSDA employs real-time sensing, beam adjustment, and DRL-based strategies to optimize anti-interference while maintaining service quality, ensuring robust performance under hostile conditions.
4) **Mobility and Integration**
Mobility across orbits complicates synchronization and channel stability. Extending SUSDA to LEO requires precise navigation and alignment, while integration with GEO provides redundancy. Coupling with MEC platforms supports distributed computation, reducing latency and enhancing reliability.

D. Research Opportunities

1) **Advanced Channel Modeling and Estimation**
Current models cannot fully capture Doppler, multipath, and delay effects in ultra-sparse constellations. Future research should focus on ML-driven channel prediction and hybrid deterministic–stochastic models for GEO, MEO, and LEO.
2) **Intelligent Grating Lobe and Sidelobe Suppression**
Ultra-sparse arrays produce strong lobes that degrade performance. AI-assisted array design and real-time reconfigurable synthesis could dynamically suppress lobes and improve beamforming.
3) **Adaptive Anti-Interference Through AI and DRL**
DRL enables adaptive anti-jamming but faces scalability issues. Future directions include multi-agent RL, federated learning, and cross-layer AI models for robust interference mitigation.
4) **Synchronization and Delay Compensation at Scale**
Maintaining coherence across widely spaced satellites is difficult. Research can explore quantum clock distribution, GNSS-free timing, and joint communication-sensing synchronization to improve robustness.
5) **Integration with MEC and Edge Intelligence**
Lightweight MEC nodes on satellites have limited computing power. Future work should design task scheduling and energy-aware MEC strategies to balance loads across satellites, GEO relays, and ground stations.
6) **Mobility Management in LEO and Multi-Orbit Systems**
LEO expansion requires stable swarm formation and cross-orbit integration. Research opportunities lie in swarm intelligence algorithms and standardized multi-orbit protocols for resilient NTN.

7) **OTFS and Novel Modulation Schemes**
OTFS offers Doppler resilience but needs integration with MIMO and multiple access schemes. Future work could combine OTFS with NOMA/SCMA for high-mobility 6G NTN.

V. Joint Design Opportunities

The two research directions reviewed in this survey—AN-assisted scheduling for secrecy enhancement and SUSDA-based distributed architectures—approach the problem of secure LEO communication from complementary perspectives. While the former develops analytical tools and scheduling strategies to minimize secrecy outage, the latter provides a cooperative physical infrastructure capable of amplifying such techniques. Their integration offers several promising opportunities.

A. Distributed Artificial-Noise Beamforming

AN-assisted scheduling has demonstrated that even a single AN-transmitting satellite can significantly improve secrecy. Within a SUSDA architecture, multiple satellites could jointly transmit AN in a phase-coherent manner, effectively shaping interference patterns. This would allow the constellation to direct AN energy toward potential eavesdroppers while nulling it at legitimate receivers, thereby extending single-satellite AN strategies into constellation-scale beamforming.

B. Secrecy Outage with Correlated Channels

The secrecy outage analysis in current AN-assisted schemes assumes independent fading channels. In contrast, SUSDA emphasizes channel correlation across closely spaced satellites. Incorporating correlated fading into secrecy outage probability analysis would yield more realistic performance bounds and could inform optimal satellite spacing and formation design for secrecy enhancement.

C. Robust Scheduling under Synchronization and Delay Constraints

The AN-assisted scheduling framework assumes perfect CSI at the GBS and negligible coordination delay. SUSDA architectures, however, must contend with synchronization errors, ISL latency, and Doppler dynamics. Extending secrecy-aware scheduling to account for delayed or imperfect CSI would make the framework more robust and practical in distributed satellite clusters.

D. Joint Array Pattern and Security Optimization

SUSDA research has highlighted the need to suppress grating lobes and optimize sparse array layouts. By integrating secrecy objectives, array synthesis could be extended to jointly minimize sidelobe leakage and maximize secrecy capacity. This would enable simultaneous optimization of communication performance and physical-layer security, aligning with the broader trend of multi-objective constellation design.

E. Learning-Based Security Adaptation

Both AN-assisted secrecy schemes and SUSDA anti-interference strategies can benefit from machine learning. Reinforcement learning could be applied to dynamically allocate satellites for data versus AN roles, adapt beam patterns under adversarial conditions, and balance tradeoffs between throughput, interference suppression, and secrecy performance.

VI. Conclusion

This survey has reviewed two complementary research directions addressing these challenges. The first was artificial-noise assisted scheduling, which leverages cooperative satellites to minimize secrecy outage probability and demonstrates the potential of constellation-scale diversity for physical-layer security. The second was the Spatial Ultra-Sparse Distributed Antenna (SUSDA) architecture, which exploits tightly coordinated satellite clusters to emulate large-aperture arrays, enabling coherent combining, interference suppression, and flexible reconfiguration. Together, these approaches highlighted the dual importance of secrecy strategies and distributed architectures in shaping the future of secure LEO networks. Their integration offered promising opportunities such as distributed AN beamforming, secrecy-aware array synthesis, and learning-enabled adaptive security. At the same time, several open problems remain, including multi-antenna secrecy analysis under correlated channels, robust scheduling under imperfect CSI, and geometry-aware secrecy optimization. Looking ahead, the convergence of physical-layer security and distributed cooperative architectures will play a pivotal role in the design of next-generation satellite communication systems. By unifying secrecy objectives with constellation-scale cooperation, future LEO networks can achieve both high capacity and strong resilience against eavesdropping, advancing toward secure and intelligent global connectivity.

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