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Integrated Communication and Navigation Based on LEO Satellite Networks: A Survey

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***Abstract*—Advancements in communication, manufacturing, and launch technologies have significantly accelerated the development of Low-Earth orbit (LEO) satellite communication constellations. Simultaneously, the rapid expansion of LEO satellite platforms presents new opportunities for navigation enhancements and substantial benefits for internet of things (IoT) applications. This survey highlights the latest advancements in the integrated communication and navigation (ICAN) technologies, emphasizing key research issues. Specifically, we discuss the motivation and feasibility of integrating communication and navigation on LEO satellite platforms, analyzing various LEO-based navigation paradigms while assessing their respective advantages and limitations. We further explore the mutual promotion of navigation and communication under the ICAN paradigm and discuss waveform design, analyzing the characteristics of different waveform design approaches. Finally, we highlight the unique challenges and identify open research topics within the ICAN framework for future exploration.**

***Index Terms*—LEO satellite communication, integrated communication and navigation (ICAN), navigation enhancements, waveform design, Inter-satellite links (ISLs).**

I. Introduction

As key space infrastructures, global navigation satellite systems (GNSSs) offer global meter-level positioning that is essential for logistics, industry, rescue and daily life. In dense urban and indoor environments, GNSS-based positioning, navigation and timing (PNT) services suffer from multipath, Non-line-of-sight (NLOS) propagation and low carrier-to-noise ratios [1]. Emerging applications such as autonomous driving and high-speed vehicles demand higher precision. Traditional GNSS can provide meter-level accuracy and timing better than 20 ns [2], [3], but its wide-area precise point positioning (PPP) relies on Medium-Earth orbit (MEO) and Geosynchronous-Earth orbit (GEO) satellites. The geometry of these satellites changes slowly and they pass overhead in several hours. This results in a convergence time of up to 30 minutes [4], reducing the PPP's practicality in commercial use.

To overcome these limitations, upgrading GNSS services is imperative. However, no single technology upgrade can satisfy all performance demands [5]. The new generation of navigation systems is expected to integrate multiple technologies to improve overall service capabilities by increasing orbit diversity, upgrading system architecture and enhancing signal quality. In this context, Low-Earth orbit (LEO) satellites, typically deployed at altitudes ranging from 180 to 2,000 km [6], offer a viable solution. LEO constellations are approximately 20 times closer to Earth than MEO and GEO satellites. This proximity results in significantly lower path loss and enables LEO satellites to provide 24 to 34 dB higher signal strength than traditional GNSS signals [7]–[9]. Moreover, lower orbit altitudes imply faster orbital speeds, causing LEO satellites to pass overhead in just a few minutes rather than several hours, which facilitates the differentiation between direct and reflected signals and mitigates multipath effects. In addition, the faster relative movement also enhances the observation geometry for PPP, which shortens convergence time and improves positioning accuracy [8]. These characteristics render the navigation paradigm based on ultra-dense LEO constellations inherently superior in signal strength [7], geometric accuracy [10] and convergence speed [11] relative to traditional GNSS.

Owing to the superior performance of LEO signals for navigation, various organizations have proposed LEO augmentation schemes such as Iridium NEXT [12], Xona Space Systems' PULSAR project in the United States [13] and CentiSpace-1 (renamed Xiangrikui after launch) of China [14]. In addition, the German Aerospace Center (DLR) is developing the Kepler system, which plans to integrate 6 LEO and 24 MEO satellites with inter-satellite links (ISLs) to enhance orbit determination precision and improve PNT performance [15].

In the beyond 5G (B5G) era there is an expectation to provide wide-area coverage and connectivity flexibly and affordably through LEO satellites. Unlike terrestrial cellular networks, satellite communications are not restricted by complex geographical conditions [16] and can serve remote areas such as forests, deserts and oceans. LEO communication satellites, being inherently resistant to natural disasters and offering extensive coverage for robust data transmission, are ideally suited for internet of things (IoT) applications in remote and hard-to-reach areas.

Despite challenges such as the high initial investment required for global coverage, vulnerability to space debris [17]

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and shorter lifespans due to atmospheric drag [18], the benefits of LEO satellite communications significantly outweigh these drawbacks. Consequently many countries and commercial companies are actively constructing LEO broadband satellite Internet [16]. As of mid-2024, more than ten emerging broadband constellations are under construction. Companies such as OneWeb [19], SpaceX [20] and Amazon [21] have collectively deployed over 7,000 satellites with an additional 40,000 satellites planned for future deployment. This surge in broadband constellations has led to the term ultra-dense constellations [9].

Although satellite communication service providers aim to expand coverage and deliver broadband data services, LEO satellite signals have also been studied as a potential source for reliable navigation [22], [23]. The growing demand for high-precision location and timing for applications such as autonomous driving, extended reality and earthquake monitoring creates substantial value-added opportunities for LEO satellite networks. As a result the integrated communication and navigation (ICAN) framework has garnered increasing interest from both academic and commercial communities [10]. Through collaborative design and optimization of communication and navigation components, ICAN enables the sharing of network infrastructure and radio resources while fully leveraging the advantages of next-generation wireless networks. In addition, communication user equipment can utilize the location and timing information implicit in the ICAN signal to enhance network access and mobility management.

In this survey we provide a comprehensive review of the technologies involved in the ICAN paradigm based on dense LEO networks. Drawing from discussions on LEO communication and navigation from research, industry, and academia, this work presents the overall ICAN framework. It covers the mutual promotion between communication and navigation components, advanced signal design, current industry efforts, and future prospects and challenges [10]. To the best of our knowledge, no similar survey has addressed these perspectives in such depth, making this work useful to both researchers and practitioners.

Our contributions can be summarized as follows:

1) We review current LEO satellite constellations and identify their strengths and challenges for navigation and communication applications.
2) We examine various frameworks for navigation enhancement based on LEO satellites and outline their advantages and disadvantages.
3) We focus on the mutual promotion of navigation and communication components within the ICAN paradigm.
4) We review ICAN waveform designs and analyze the trade-offs between the two functions under different resource allocation modes.
5) We identify and outline the challenges that must be addressed in the coming years to fully support the ICAN vision.

Among recent contributions, the most closely related studies include [13], [23]–[28]. Liao *et al.* [24] provided a detailed account of payload co-design for a LEO-based ICAN constellation but do not consider the multiple LEO-based navigation paradigms whose differing requirements shape the joint optimization of communication and positioning. Reid *et al.* [23] and Kassas [25] presented complementary surveys on navigation using LEO satellites; however, they treated navigation and communication as independent services and did not explore the mechanisms by which each function can enhance the other. Prol *et al.* [13] reviewed LEO-PNT from space, ground, and user perspectives but omitted any discussion of hybrid navigation and communication waveform design and failed to compare integrated constellations with stand-alone deployments. Yin *et al.* [26] focused on ICAN architecture and waveform design in terrestrial networks. Their reliance on quasi-static channel models limits applicability to the high-mobility, rapidly changing links encountered in LEO. Sheng *et al.* [27] proposed an integrated communication-navigation-remote-sensing framework for vehicular applications but addressed only that use case and did not generalize to broader ICAN challenges. Ma *et al.* [28] demonstrated how LEO-derived position data can inform beamforming, yet they did not examine shared hardware and radio resource utilization or consider constellation-scale deployment and integrity issues.

Furthermore, [29]–[32] are also noteworthy as they studied the feasibility of using LEO satellites to provide navigation services. Specifically, Prol *et al.* [29] addressed the key issues of using LEO satellites for PPP, analyzing the preliminary results of attainable orbit and clock quality based on simulated observations, and the contribution of LEO constellations to precise positioning. Reid *et al.* [30] conducted a thorough investigation of user geometry, spatial ranging errors, and the use of chip-scale atomic clocks (CSAC) to achieve precise timekeeping. Additionally, Morales *et al.* [31] explored the potential of widespread LEO satellite signals for navigation, while Janssen *et al.* [32] evaluated the performance of LEO-based PNT services for IoT applications. Ge *et al.* [33] conducted a comprehensive study on LEO GNSS augmentation, highlighting its benefits and challenges in precise orbit and clock determination. All of these studies focus solely on navigation and overlook the integration of communication and navigation on a unified LEO platform. To give the readers a concise, side-by-side view of these limitations, Table I compares our survey with the above papers across the key dimensions.

By addressing these gaps, we comprehensively summarize the three paradigms of LEO-based navigation to establish the foundation for ICAN. We emphasize not only the sharing of hardware facilities and radio resources, but also the mutual enhancement of communication and navigation. Our focus is broader, encompassing both scientific literature and commercial practices.

To assist readers, Table II provides a comprehensive yet not exhaustive list of abbreviations and acronyms frequently appearing throughout this paper. Fig. 1 outlines the survey structure, which is organized into three main parts as follows:

- The first part concentrates on the foundational aspects of ICAN and the current state of LEO constellation deployment. It includes three sections. Specifically, Section I provides a basic introduction. Section II discusses the development and industry status of current LEO satellite

TABLE I: Comparison of This Work and Existing Survey Papers

Reference	Discussion of communication satellite constellation	Hybrid Nav/Comm constellation focus	Discussion of LEO satellites based navigation	Summary of LEO satellites-based navigation augmentation types	Discussion of ICAN based on LEO satellites	ICAN waveform design	Mutual promotion between navigation and communication
[13]	No	No	Yes	No	No	No	No
[23]	Yes	No	Yes	No	No	No	No
[24]	Yes	Yes	Yes	No	Yes	Yes	No
[25]	Yes	No	Yes	No	No	No	No
[26]	No	No	No	No	Focus on terrestrial scenario	Yes	No
[27]	No	No	No	No	Yes	No	No
[28]	No	No	No	No	Yes	Yes	No
[29]	No	No	Yes	No	No	No	No
[31]	No	No	Yes	No	No	No	No
[32]	No	No	Yes	No	No	No	No
[33]	No	No	Yes	No	No	No	No
This work	Yes	Yes	Yes	Yes	Yes	Yes	Yes

networks, focusing on the feasibility of ICAN based on these networks and emphasizing the limitations of using existing and planned LEO satellite networks to carry ICAN payloads. Moreover, Section III introduces several paradigms for navigation based on LEO satellite constellations, highlighting their pros and cons and applicable conditions.

- The second part demonstrates the value of ICAN, along with the design of the waveform. This part is divided into two sections. Specifically, Section IV discusses the necessity of integrating the currently independent LEO communication and navigation systems into a unified ICAN framework. It highlights the unique value ICAN brings to both navigation and communication by examining the mutual benefits between these two components, i.e., how navigation enhances communication and vice versa. Moreover, Section V explores the criteria for ICAN waveform design and reviews the latest research advancements in this area.
- The third part addresses the broader implications and future directions in the context of ICAN, which includes Sections VI and VII. In Section VI, we summarize our observations on the challenges and future directions in the context of LEO satellite networks. Finally, in the last section, we provide a conclusion of our work.

The intersection logic as follows. *Part I* (Sections I-III) establishes the *resources and boundary conditions* for ICAN-namely, the available LEO infrastructure, its commercial readiness, and candidate navigation paradigms. These premises directly inform *Part II*: Section IV analyses the *bidirectional enhancement* between navigation and communication, while Section V translates those requirements into concrete waveform designs. Finally, *Part III* projects the design insights into the future: Section VI identifies outstanding research issues, and Section VII links each challenge back to the resources and interactions highlighted earlier.

Overall, this paper follows a deliberate cascade -*resources* $\rightarrow$ *interaction* $\rightarrow$ *implementation* $\rightarrow$ *outlook* - so that every subsequent section is both informed by, and provides feedback to, the preceding ones within a unified ICAN framework.

II. Current Situation and Commercial Planning of LEO Constellations

The cost of LEO satellite deployment is decreasing thanks to improved manufacturing and launch technologies. LEO satellites, known for their full-time coverage, global connectivity, and strong signals [34], show considerable promise for both communication and navigation. The remainder of this section offers an overview of notable LEO constellations - those dedicated to navigation (Section II-A) and those primarily serving broadband communication (Section II-B).

A. LEO Navigation Constellations

LEO navigation constellations can either complement existing GNSS or provide independent navigation services. Several are already operational or in the process of deployment. For example, the Kepler system [35], [36], developed by DLR, relies on ISLs to synchronize time and determine orbits, thereby enhancing PNT. Xona's Pulsar project [37] aims to deliver high-accuracy and high-integrity positioning worldwide using dedicated low-orbit satellites. In China, initiatives such as Hongyan [38] and Hongyun [39] have launched test satellites focusing on navigation augmentation, while CentiSpace [40] is constructing a dedicated constellation.

Additionally, the Iridium satellite time and location (STL) system [41] uses the Iridium constellation to transmit specially structured signals, boosting receiver power by 25$\sim$30 dB and providing 20$\sim$50 m positioning accuracy [42]. Since Iridium also supports broadband services, further details are provided in Section II-B.

1) ***Kepler****:* Kepler, an envisioned DLR system [43], is supposed to integrate 24 MEO and 6 LEO satellites. The MEO part is similar to the Galileo system, while the 6 LEO satellites deployed at an altitude of about 1229 km carry optical

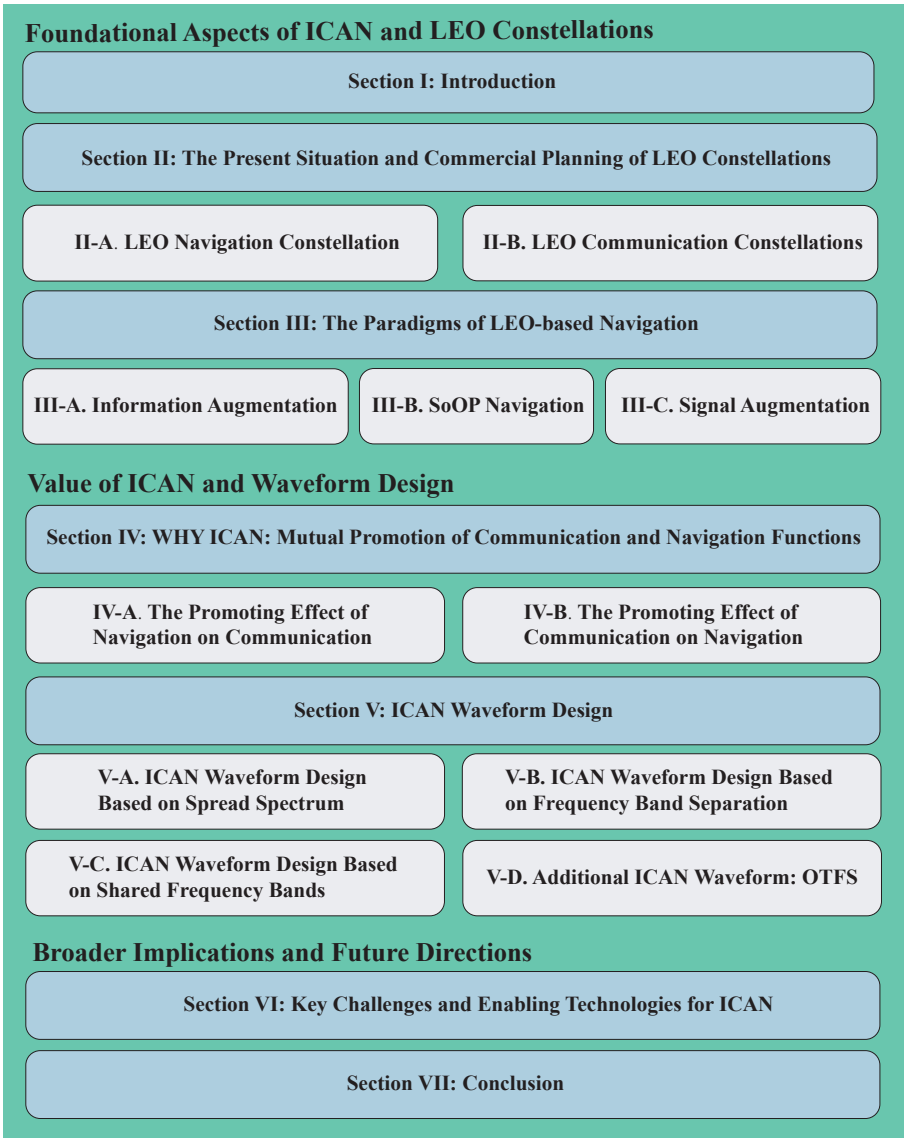


Fig. 1: Organization of the paper and the interdependencies between different sections.

terminals for high-throughput links and time synchronization without large atomic clocks [36]. Kepler targets centimeter-level orbit accuracy, global real-time PPP, and time to alert (TTA) under 3 s [44].

*2) **Pulsar**:* Xona Space Systems, a U.S. start-up, launched the first test satellite of Pulsar project at 525 km altitude [45], broadcasting navigation signals in both L-band and C-band [46]. Its rapid geometric variation accelerates the PPP convergence. The plan begins with 40 satellites to enhance coverage in mid-latitudes, expanding to around 70, and finally $250 \sim 300$ for global high-precision positioning [47].

*3) **CentiSpace-1**:* CentiSpace-1, developed by Beijing Future Navigation Technology, will eventually deploy 160 satellites at 975 km and 55° inclination orbits [14]. These satellites receive GNSS signals on L1/L5 and maintain ISLs. Observed performance includes 50 cm accuracy, integrity, and convergence below one minute [40], [48]. CentiSpace-1 also plans to verify communication functionality on the same platform.

B. LEO Communication Constellations

LEO satellites have become pivotal in providing ubiquitous high-speed connectivity. Their proximity to Earth shortens latency [49], lowers production costs [50], and allows operation in Ka/Ku bands with adequate bandwidth [51]. Despite payload and lifespan constraints [52], recent technology and reduced launch expenses have revitalized interest in LEO-based systems [53]–[55]. Among the many constellations that have been in operation or are currently in the planning stage [56], there are five representatives:

*1) **Starlink**:* SpaceX's Starlink has deployed over 6,700 LEO satellites up to now [20], [57], [58]. It uses Ku-band for users, Ka-band for gateways, and aims to provide global broadband communications with observed latencies around 33 to 65 ms in the United States [57].

*2) **Kuiper**:* Amazon's Kuiper [21] plans to deploy 3,232 LEO satellites across three orbital shells (altitudes at 590, 610, and 630 km) [59]–[61], all operating in Ka-band. According to

TABLE II: List of Common Abbreviations and Acronyms

Acronym	Description
GNSS	Global Navigation Satellite System
PNT	Positioning, Navigation, and Timing
NLOS	Non-Line-of-Sight
PPP	Precise Point Positioning
MEO	Medium-Earth Orbit
GEO	Geosynchronous-Earth Orbit
LEO	Low-Earth Orbit
DLR	German Aerospace Center
ISL	Inter-Satellite Link
B5G	Beyond 5G
ICAN	Integrated Communication and Navigation
CSAC	Chip-Scale Atomic Clocks
STL	Satellite Time and Location
TTA	Time to Alert
3GPP	The Third Generation Partnership Program
NTN	Non-Terrestrial Network
OISL	Optical Inter-Satellite Links
LOS	Line of Sight
SoOP	Signals of Opportunity
DOP	Dilution of Precision
COTS	Commercial Off-The-Shelf
INS	Inertial Navigation System
QZSS	Quasi-Zenith Satellite System
STAN	Simultaneous Tracking and Navigation
TA	Time Advance
OFDM	Orthogonal Frequency-Division Multiplexing
ICI	Inter-Carrier Interference
OFDMA	Orthogonal Frequency-Division Multiple Access
CP	Cyclic Prefix
SNR	Signal-to-Noise Ratio
TTFF	Time to First Fix
SBAS	Space-Based Augmentation Systems
WAAS	Wide Area Augmentation System
CCSK	Coded Composite Signal Keying
MC-BOC	Multi-Carrier Binary Offset Carrier
BPSK	Binary Phase Shift Keying
V-OFDM	Vector Orthogonal Frequency Division Multiplexing
TC-OFDM	Time and Code Orthogonal Frequency Division Multiplexing
MS-NOMA	Multi-Scale Non-Orthogonal Multiple Access
ZC-NOMA	Zadoff-Chu Sequence Superposed Non-Orthogonal Multiple Access
OTFS	Orthogonal Time Frequency Space
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
AltBOC	Alternate Binary Offset Carrier

its plan, initial launches should occur in 2024 and commercial services should start in 2025 [21].

*3) **Lightspeed**:* Telesat's Lightspeed includes 198 satellites at various orbits, expanding possibly to 298 satellites at final [62], [63]. Focusing on enterprise and government users, it employs advanced beam-forming technologies and ISLs, within Ka-band [64].

*4) **OneWeb**:* OneWeb plans 716 satellites at an altitude around 1,200 km [19], lacking ISLs but using Ku-band for user links and Ka-band for gateway links [65]. As of mid-2024, OneWeb had successfully launched 634 satellites, approaching its full deployment target.

*5) **Iridium NEXT**:* Iridium NEXT replaced the original Iridium system with 75 new satellites at 780 km and 86.4° inclination orbits [66]. Besides broadband services, it provides the STL service to complement GNSS, supported by ground-based atomic clocks [67].

C. Brief Summary

Table III summarizes the information of typical LEO navigation and communication constellations. While most are designed for communication, their vast scale offers navigation potential. For example, a fully deployed Starlink could provide more than 20 satellites in Line-of-Sight (LOS) in dense areas [56]. If integrated with GNSS signals, such constellations could significantly improve current PNT capabilities.

III. Paradigms of LEO Satellites based Navigation

In this section, we discuss the advantages and challenges of using LEO constellations for navigation, establishing their role as a key complement to existing GNSS. We then explore various strategies for implementing PNT services via LEO constellations, which are organized into three distinct paradigms: information augmentation, signals of opportunity (SoOP) navigation, and signal augmentation. A brief summary and a comparative table are provided at the end.

As noted in Section II-A, several companies and organizations have begun developing LEO navigation constellations, and feasibility studies have examined enhancing GNSS with LEO satellites [10], [31], [68]. Integrating LEO constellations into GNSS can enable real-time, high-precision, and robust carrier phase positioning over wide areas [69]. The unique benefits of LEO-based navigation include stronger signals, improved anti-jamming performance, greater use of commercial off-the-shelf (COTS) components, and enhanced geometric diversity from dense satellite deployment, which are detailed as follows:

1) More Powerful Signal and Strong Anti-jamming Ability: Traditional GNSS is designed for open environments, and its received signal power is significantly limited in deeply attenuated conditions, making it difficult to have effective anti-jamming capabilities [70]. Even a low-cost consumer-grade jammer can disrupt GNSS signals over tens of kilometers, while military-grade jammers can affect signals over thousands of kilometers [71]. In contrast, as LEO satellites are closer to the ground, they can provide stronger signals with much lower path loss, thereby improving anti-jamming performance. The

TABLE III: Construction Information of Typical LEO Satellite Constellations.

Type	Name	Number of sats	Altitude (km)	Orbit inclination	Operator / Country	Status / Launch	Main business	ISL	Radio frequency	Coverage region
NAV	Kepler	6** (LEO) 24** (MEO)	1 229 23 229	89.7° 56°	DLR Germany	Planned	$\mathbb{N}$	√	◊	Global
	Pulsar	1* Hundreds**	525 (the first)	97°	Xona Space Systems USA	Demo (2022)	$\mathbb{N}$	√	L-band C-band	Global
	CentiSpace-1	4* 120**	975	55°	Future Nav. Tech. CN	Demo (2018)	$\mathbb{N}$	√	L-band	Global
COM	Lightspeed	298**	1 015 1 325	98.98° 50.88°	Telesat Canada	Planned (2026)	$\mathbb{B}$	√	Ka-band	Global (incl. polar)
	Starlink	6 700* 42 000**	550 570 560 540 560 340 345 350 360 525 530 535 604 614	53° 70° 97.6° 53.2° 97.6° 53° 46° 38° 96.9° 53° 43° 33° 148° 115.7°	SpaceX USA	Op. (2019)	$\mathbb{B}$	√	Ku-band (user) Ka-band (gateway)	Global
	OneWeb	634* 716**	1 200	87.9° 55°	OneWeb UK	Op. (2019)	$\mathbb{B}$	×	Ku-band (user) Ka-band (gateway)	Global (high-lat)
	Iridium NEXT	75*	780	86.4°	Iridium USA	Op. (2017)	$\mathbb{B}$ + $\mathbb{N}$ (STL)	√	L-band (user) K/Ka-band (ISL & GW)	Global
	Kuiper	3 232**	590 610 630	33° 42° 51.9°	Amazon USA	Demo (2023)	$\mathbb{B}$	√	Ka-band	Global (±56°)

Note: "NAV" = Navigation constellation; "COM" = Communication constellation; $\mathbb{N}$ = Navigation augmentation; $\mathbb{B}$ = Broadband communication; ◊ = Unknown; ∗ = In orbit; ∗∗ = Planned; "Op." = Operational; "Demo" = Demonstration.

higher signal strength eventually leads to improved positioning accuracy [72].

2) Higher Availability of Payload Components: LEO satellites offer a unique environment that favors the use of COTS components in satellite design [73]. Located within the Earth's magnetosphere, particularly inside the Van Allen belts [74], LEO satellites experience significantly lower radiation levels than MEO and GEO satellites. This situation minimizes the need for expensive radiation-hardened components, allowing the use of cost-effective commercial parts while ensuring reliable operations [10]. Furthermore, the thermal environment in LEO is more stable than in MEO and GEO [75], where satellites endure extreme cycles of intense sunlight and darkness. The milder thermal conditions enable simpler thermal management systems, enhancing the cost-effectiveness and efficiency of deployments using COTS components.

3) More Diverse Geometry and Radio Frequency: One advantage of LEO constellations is the sheer number of satellites. The deployment of tens of thousands of LEO satellites can collectively yield a threefold improvement in dilution of precision (DOP) and allow for a relaxation of the stringent requirements on signal-in-space user range error (SIS URE) [10]. Since positioning error depends on both user ranging error and geometry, tests have shown that, thanks to the superior geometry, the positioning accuracy of LEO communication satellites can be equivalent to that of global positioning system£¨GPS£©, reaching around 3 meters [76], even without specialized navigation payloads. Additionally, the ability of LEO satellites to operate in multiple frequency bands significantly enhances navigation capabilities by mitigating selective fading, improving signal penetration in obstructed environments, and increasing resilience against interference and jamming [77], [78].

Certainly, as a novel positioning paradigm, LEO satellites based navigation offers numerous benefits, but several significant challenges, as outlined below, must be addressed.

1) Global Coverage: Because LEO satellites are much closer to the Earth, each covers a considerably smaller area than MEO or GEO satellites. For example, even if the number of Iridium satellites is twice that of GPS, the number of LEO satellites visible at the equator is ten times less than that of GPS [10]. Thus, achieving the same coverage as GNSS requires an order of magnitude more LEO satellites. Moreover, while communication users benefit from multiple satellites in view for service continuity, navigation users require an even larger number of visible satellites to ensure high geometric precision, which directly impacts positioning accuracy. The required number also depends on whether the constellation functions as a GNSS augmentation or as an independent LEO PNT system, as full autonomy demands a larger deployment.

2) Ephemeris Design and Storage: Current GNSS ephemerides are designed for MEO satellites. Although LEO and MEO orbital dynamics are fundamentally similar, the Earth's oblate shape has a stronger impact on LEO satellites due to their proximity. This results in higher-order gravity terms dominating the gravitational effects, and thus necessitating more complex and larger correction terms in their ephemerides [79]. In addition, the rapid movement of LEO satellites and more pronounced gravitational and atmospheric perturbations require more frequent ephemeris updates compared to MEO satellites [80]. These factors increase computational demands, bandwidth requirements for data transmission, and the potential for errors [81]. Moreover, transmitting and storing ephemerides for tens of thousands of satellites pose significant challenges, which may be alleviated through more efficient packaging formats and the use of satellite broadband channels (see Section IV-B).

3) Clock Synchronization: Due to system construction costs, it is infeasible to equip all LEO satellites with high-precision atomic clocks. Although the geometry of LEO constellations is superior to that of traditional navigation systems, the ranging error caused by clock deviation re-

mains unacceptable. A practical solution is to equip LEO satellites with CSAC [82] and oven controlled crystal oscillators (OCXO) [23] for short-term calibration. For long-term synchronization, time transmission via ISL or satellite-ground links can be used. For example, the Kepler system uses optical inter-satellite link (OISL) to transmit synchronization signals from the optical domain to the L-band, achieving constellation-wide clock synchronization [83]. More details on time transmission are provided in Section III-C5.

In particular, some works [30], [84]–[86] have compared the location methods based on LEO, MEO and GEO satellite systems. There may be diverse paths for LEO satellites to achieve navigation functions, such as carrying the navigation payload by broadband communication satellites or carrying out more integrated designs. Several typical LEO satellite navigation paradigms in the literature are described hereafter.

A. Information Augmentation

An information augmentation system uses ground base stations or standard communication satellites to transmit correction information, such as orbit, clock, ionospheric, and integrity corrections [8], to support precision positioning.

The satellite-based augmentation method leases the broadcast channels of communication satellites to enable wide-area broadcasts. Owing to their wider bandwidth compared to GNSS, LEO communication satellites can transmit more correction data without relying solely on ground facilities. This allows global PPP services to achieve real-time performance, robustness, and centimeter-level precision. For example, the navigation satellites of CentiSpace in Table III fall into this category.

Based on the type of enhanced information, these systems can be divided into two types:

- Integrity Augmentation: Primarily used for civil aviation, this type of augmentation not only provides higher navigation integrity but also modestly improves positioning accuracy [87].
- Precision Augmentation: This approach broadcasts real-time precision orbit and clock error products, as well as information like carrier phase fractional deviations and regional ionospheric/tropospheric enhancements, to support precise positioning services [88]–[90].

The entire enhancement process is illustrated in Fig. 2. Global monitoring stations transmit real-time GNSS observations to the data control center via the network. The control center processes these observations to generate real-time clock error and orbit corrections. When LEO satellites are used for navigation enhancement, the control center sends the enhancement data to a gateway station, which incorporates the information into its antenna. The LEO satellite then receives and broadcasts the enhancement information to improve real-time PPP. Users combine the received GNSS observations, broadcast ephemeris, and navigation enhancement data to perform PPP.

B. SoOP Navigation

As shown in Table III, most LEO satellites primarily target broadband internet coverage rather than navigation. However,

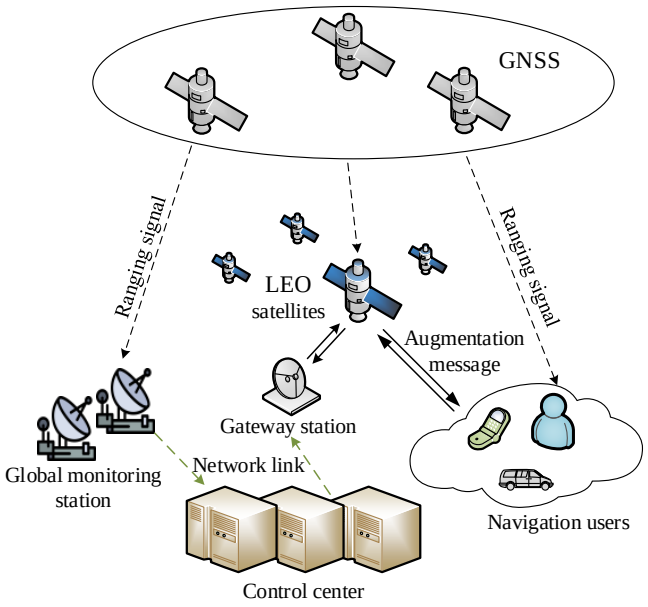


Fig. 2: System architecture for information augmentation.

these ubiquitous LEO communication satellites offer unexpected benefits. One significant advantage is that their signals can be opportunistically used in navigation systems, known as SoOP [91].

SoOP leverages characteristics of LEO communication signals, such as high receive power, global coverage, and Doppler information from their rapid movement [1], [92], extending their application to navigation, despite their original design for communication. SoOP can effectively compensate for the weak signal strength, poor anti-jamming capability, and limited visibility of GNSS satellites, while also serving as a backup for GNSS. Additionally, SoOP signals from different constellations and diverse orbits, transmitted in various frequency bands, can further enhance positioning accuracy [93]. Since there are no restrictions on receiving these signals, users can freely access SoOP with appropriate devices, making navigation services more accessible without the need for special subscriptions [94].

The following sub-subsections elaborate on several SoOP navigation aspects.

1) Doppler Positioning: The rapid movement of LEO satellites induces large Doppler shifts between the transmitted and received carrier frequencies [95], making them particularly effective for Doppler-based positioning even when no dedicated ranging signals are broadcast. A closed-form expression for the Doppler variation along a circular orbit is given in [96].

Fig. 3 illustrates the SoOP navigation process, whereby each non-PNT LEO satellite continuously downlinks a wide-band communication waveform. The receiver first strips away the payload data to extract the instantaneous carrier frequency and compute the resulting Doppler shifts, which define equal-Doppler cones. Simultaneously, a terrestrial real-time ephemeris server delivers time-stamped satellite state vectors (position and velocity) to the receiver over the network. Finally, the receiver fuses these Doppler measurements with the known auxiliary ephemerides to yield real-time estimates

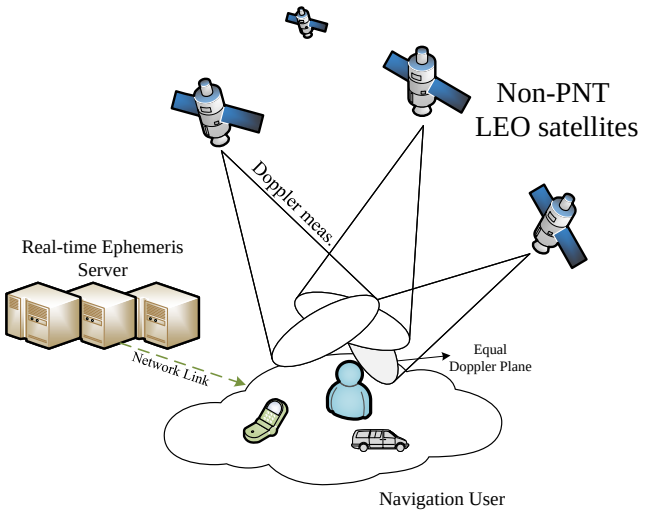


Fig. 3: System architecture for SoOP navigation.

of three-dimensional position, velocity, and receiver clock bias. According to the Doppler principle, the received carrier frequency f is given by

$$f = \left(1 + \frac{\mathbf{V}^T \mathbf{e}}{c}\right) f_0 + \dot{T}_u + \varepsilon_f, \tag{1}$$

where $\mathbf{V} = [v_x, v_y, v_z]^\mathsf{T}$ is the satellite's velocity relative to the user, $\mathbf{e} = (\mathbf{x} - \mathbf{x}_s)/\|\mathbf{x} - \mathbf{x}_s\|$ is the line-of-sight unit vector, the vectors $\mathbf{x} = [x, y, z]^\mathsf{T}$ and $\mathbf{x}_s = [x_s, y_s, z_s]^\mathsf{T}$ denote the user's and satellite's Earth-centered position vectors, respectively. c is the speed of light, $\dot{T}_u$ models the receiver clock frequency bias, and ε_f denotes random Doppler measurement noise.

The relationship between Doppler shift and receiver location can be derived based on (1), i.e.,

$$\begin{aligned} f\left(x, y, z, \dot{T}_u\right) &= \dot{T}_u + \varepsilon_f \\ &+ \left(1 + \frac{v_x\left(x - x_s\right) + v_y\left(y - y_s\right) + v_z\left(z - z_s\right)}{c\sqrt{\left(x - x_s\right)^2 + \left(y - y_s\right)^2 + \left(z - z_s\right)^2}}\right) f_0. \end{aligned} \tag{2}$$

Equation (2) is the fundamental formula for Doppler-based positioning.

As shown in Fig. 3, each Doppler measurement constrains the receiver to lie on a constant-doppler circular cone with the satellite at its apex. The intersection of this cone with the Earth defines an equal-doppler curve. With two satellites, the receiver lies along the crossing of two such curves; adding a third reduces the candidate positions to two. A fourth Doppler measurement absorbs the receiver's clock bias $\dot{T}_u$ and yields a unique intersection, which corresponds to the true position. In practice, a real-time ephemeris server supplies each satellite's position $\mathbf{x}_s$ and velocity $\mathbf{V}$ [97], so that only the receiver's coordinates (x, y, z) and clock drift $\dot{T}_u$ remain unknown in (2). The actual computation of the receiver position from these measurements involves solving a nonlinear system, which is beyond the scope of this paper; readers can refer to [98], [99] for comprehensive treatments of Doppler-based positioning algorithms.

2) Ephemeris Acquisition: A significant advantage of Doppler positioning, as seen in (2), is that it does not require high time synchronization of the system, which is a major difference from the GNSS-like positioning method based on pseudo-range measurement.

Satellite orbit errors and Doppler observation errors are considered as the main error sources for satellite SoOP positioning [97]. The positioning in this scheme relies on real-time ephemeris server data, as highlighted in Fig. 3, making accurate ephemeris data fundamental for SoOP positioning. The key is finding effective ways to acquire this ephemeris data to ensure reliable positioning. Feasible methods include obtaining it through real-time ephemeris servers [100], ground tracking networks [101], or orbit prediction based on historical data [101].

3) Applications of Doppler-Based Positioning: A notable example of Doppler positioning is the STL service provided by Iridium Next. Several studies have explored positioning based on STL. For example, Tan *et al.* [102] attempted to use instantaneous Doppler for navigation, but since the positions of non-navigation satellites are not accurately known, Benzerrouk *et al.* [103] proposed updating the TLE-SGP4 file with each Doppler measurement to predict the orbit and position. Chen *et al.* [104] analyzed the error range of time-shifted one-way Doppler positioning for static users using a LEO satellite, demonstrating that the Doppler effect can yield practical positioning accuracy, although its theoretical precision remains inferior to that of spread spectrum methods. In [105], a receiver architecture was proposed to acquire and track LEO satellite signals and extract Doppler measurements. While fusion positioning with multiple GNSS constellations is common, PNT results based solely on multiple LEO constellations remain limited. The cooperation between Iridium Next and Orbcomm for PNT was demonstrated in [106], which is the first experimental use of multiple LEO constellations for navigation.

In addition, Kassas *et al.* [22] reported Doppler tracking and positioning using Starlink signals, the first attempt to exploit opportunistic signals from Starlink. Furthermore, a LEO navigation framework called carrier phase difference (CD)-LEO was proposed in [107], where both a "mobile station" on Earth and a nearby "base station" measure the carrier phase of the same broadband LEO satellite. The resulting double-difference measurement allows for the determination of the mobile station's position and the resolution of integer ambiguity without requiring accurate satellite transmission timing.

Although Doppler positioning has not yet achieved the precision of GNSS, it offers significant potential. The enhanced service provided by SoOP demonstrates a robust, cost-effective, and seamless navigation solution that can operate independently of GNSS, making it a powerful alternative for users.

4) Single Satellite Positioning: Doppler positioning estimates both the receiver's frequency deviation and its three-dimensional coordinates, requiring at least four observations similar to GNSS. However, due to their lower orbital heights, LEO satellites cover smaller areas and a receiver may not

simultaneously observe four satellites. In such cases, multiple Doppler surfaces will be obtained through continuous observation, and once at least four observation equations are established, the receiver's position can be determined by solving these equations. For example, Ye *et al.* [108] proposed a single-satellite integrated navigation algorithm based on a broadband LEO constellation. Although single satellite positioning requires a longer observation time, it compensates for the limited simultaneous visibility. As satellites move continuously into view, Doppler observations from multiple satellites within the same epoch enable accurate single-epoch positioning.

5) Multi-Sensor Information Fusion: SoOP serves as a PNT source in GNSS-denied environments. To further improve SoOP's positioning accuracy, a promising approach is multi-sensor fusion which can integrate SoOP signals with inertial navigation systems (INSs), effectively mitigating uncertainties caused by user movement [109]. For example, Kassas *et al.* [110] proposed a simultaneous tracking and navigation (STAN) framework, where navigation vehicles use SoOP extracted from LEO satellite signals to assist INS when GNSS is unavailable, achieving meter-level positioning. Once GNSS is available, the system tightly fuses INS and SoOP measurements.

C. Signal Augmentation

While Doppler-based positioning can theoretically achieve high accuracy, its precision is significantly lower than that of pseudo-range-based methods [111]. To achieve higher precision navigation, dedicated navigation signals are required. In the signal augmentation paradigm, LEO satellites generate and broadcast special navigation signals that work in conjunction with the existing GNSS system. The addition of LEO satellites enriches the orbital diversity of GNSS and thus improves positioning accuracy [112]. When GNSS is interfered, LEO satellites can serve as an independent backup [113]. Fig. 4 depicts the signal-augmentation architecture, wherein a dedicated LEO ranging layer is superimposed on the legacy GNSS constellation. A gateway station equipped with a high-stability atomic clock uplinks clock-synchronization pulses to one of the LEO satellites, after which sub-nanosecond time is disseminated to the rest of the swarm through high rate ISLs. Assisted by this common time base, every LEO satellite broadcasts an independent wideband ranging signal that reaches the user with 20-30 dB higher power than the GNSS component. Meanwhile, a terrestrial control-center pushes updated orbit and integrity data to the gateway over a secure back-haul, enabling the constellation to refresh its navigation message in real time. The user receiver combines the high-dynamics LEO observations with the GNSS measurements to obtain faster convergence, higher accuracy, and enhanced integrity.

The navigation constellations of Xona and Kepler in Table III belong to this type as they enhance GNSS by broadcasting independent navigation signals. Being closer to Earth than traditional GNSS satellites, LEO satellites experience faster geometric changes, which contribute to the rapid convergence of PPP. In contrast, the Japanese quasi-zenith satellite

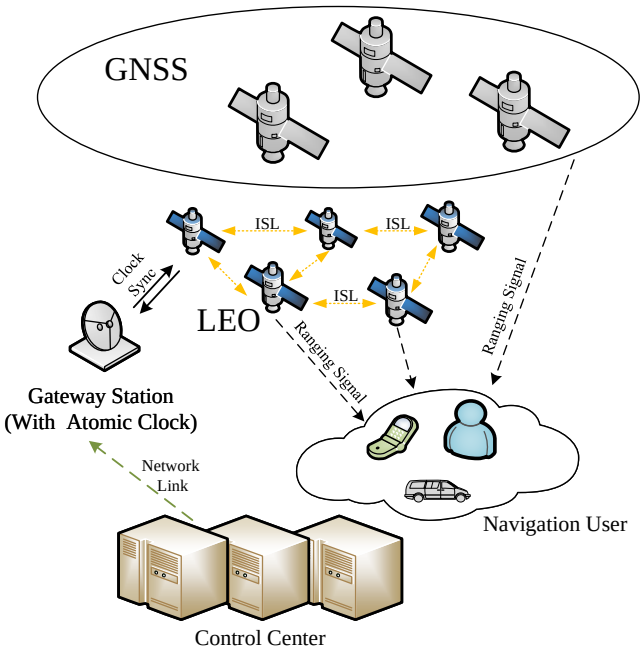


Fig. 4: System architecture of signal augmentation.

system (QZSS) connects to GPS through cascading [114]. QZSS receives signals from GPS satellites in higher orbits and retransmits additional signals back to Earth, thereby enhancing GPS performance in the Asia-Oceania region. This process occurs on several frequency bands (L1C/A, L1C, L2C, and L5) [114], ensuring compatibility with GPS. Moreover, since LEO satellites are deployed well above the troposphere, onboard measurements are less affected by tropospheric errors [115]. Whether broadcasting independent signals or forwarding GNSS signals, LEO satellites can effectively improve positioning accuracy.

The paradigm of LEO-based signal enhancement mainly addresses the following issues:

1) Constellation Design: Effective LEO navigation constellation design is critical to enhance signal availability and positioning accuracy. As the coverage area of a single LEO satellite is small, it necessitates deploying many satellites for global coverage. Strategies such as those in [116] focus on cost-effective designs, while Guan *et al.* [117] and Deng *et al.* [118] used the Walker model to explore LEO-based global navigation and augmentation constellations by considering factors like constellation height, minimum observation elevation, coverage multiplicity, number of satellites, and position dilution of precision (PDOP) values.

2) PPP: Carrier phase-based PPP is a key method for precision positioning worldwide, but the long initialization time caused by the slow geometric changes of GNSS satellites and the inadequate atmospheric delay corrections limits its practical use [115]. Moreover, re-initialization after a signal interruption is nearly as long as the first positioning [119], [120]. Researchers are working to reduce its PPP convergence time by exploiting the high dynamic spatial diversity of LEO satellites. Their faster angular velocity induces rapid geometric changes and reduces static multipath, thereby shortening

the convergence time [121]. For example, Su *et al.* [68] demonstrated that integrating the Beidou system with 150 LEO satellites can reduce the PPP convergence time by at least ten times, and Joerger *et al.* [122] showed that the fast moving Iridium satellites can help reduce the periodic ambiguity determination time.

3) Satellite Orbit Determination: Accurate orbit determination for LEO satellite navigation requires a highly nonlinear dynamics model that accounts for position, velocity, and external forces including gravity, atmospheric resistance, solar radiation pressure, third-body effects, Earth tides, and relativistic effects. These factors make orbit determination more challenging for LEO satellites than for MEO/GEO satellites. While GNSS receivers installed on LEO satellites can provide accurate orbit determination [123], using terrestrial uplinks for orbital data and clock information is another option, although it may require impractical ground resources for large constellations.

4) Broadcast Message: Broadcast ephemeris that meets high precision requirements is essential for reliable ranging and positioning. Most works in this area focuses on MEO, inclined geosynchronous orbit (IGSO), and GEO systems [124]. However, the shorter orbital periods and stronger perturbations in LEO demand more complex ephemeris models. Xie *et al.* [80] improved the GPS legacy navigation (LNAV) ephemeris by adding parameters for LEO orbits, and Meng *et al.* [125] designed an improved set of non-singular elements for LEO Broadcast ephemeris, achieving a fitting accuracy better than 10 cm over a 20-minute arc length at altitudes between 500 and 1,400 km.

5) Onboard Clock: Onboard clocks directly affect user ranging error and positioning accuracy [126]. Navigation satellites typically use high-performance atomic clocks (rubidium or cesium) [113], but these are expensive, bulky, and heavy [100] and are not practical for LEO platforms. Instead, thermostatic crystal oscillators, which are smaller and less expensive, and can provide adequate short-term stability, are preferred. Their clock drift can be simulated and corrected using an onboard GNSS receiver, achieving errors within tens of nanoseconds that meet positioning requirements [126]. Additionally, the Kepler system uses OISL to transmit synchronization signals from the optical domain to the L-band, thereby achieving clock synchronization [127]. Note that hardware deviations between the receive and transmit clocks may occur, and Wang *et al.* [113] treated this error as a fixed offset.

D. Brief Summary

Table IV summarizes the three LEO navigation paradigms, highlighting significant differences in system architecture, implementation difficulty, and performance indicators.

The simplest way to achieve LEO navigation is through SoOP navigation, which utilizes existing satellite signals (usually from communication satellites) to achieve positioning. Since these satellites do not broadcast special ranging waveforms and navigation messages, a terrestrial network connection is required for real-time ephemeris, limiting the application of SoOP in network-free environments.

The information augmentation strategy uses the broadband channels of LEO communication satellites to broadcast augmentation messages, which substantially improve the availability of PPP in network-free environments. However, it can only serve as an auxiliary to GNSS and cannot operate independently.

In contrast, the signal augmentation strategy can cooperate with GNSS and provide standalone navigation services when GNSS signals are unavailable. Due to the use of dedicated navigation signals, LEO satellites can improve the geometry of the navigation system and accelerate the convergence speed of PPP. As such, the signal augmentation paradigm might be a more promising LEO satellites based navigation approach.

IV. WHY ICAN: MUTUAL PROMOTION OF COMMUNICATION AND NAVIGATION FUNCTIONS

With the extensive deployment of LEO communication satellites, integrating navigation functions into these platforms represents a significant advancement in satellite services. Compared with operating two independent constellations, an ICAN system delivers tangible advantages in three aspects:

1) Payload efficiency: Co-hosted payloads share the same bus, power conditioning, antennas, and launch services. Trade studies indicate that a dual-use constellation can achieve a 20-30% reduction in combined capital and operating expenditures and require approximately 30% fewer satellites compared to two independent constellations [129]. This consolidation also lowers launch mass, thereby reducing the environmental impact.

2) Communication performance: Real-time access to satellite ephemeris and sub-microsecond timing from the on-board navigation payload enables precise uplink time-advance control, Doppler pre-compensation, and predictive beam steering. By exploiting the predictable orbital dynamics and spatial distribution of LEO satellites to reduce signaling exchanges between the access and core networks, handover latency can be decreased by an order of magnitude [130].

3) Navigation performance: The shorter LEO-to-ground path yields a 20-30 dB power advantage over MEO GNSS signals [131] and an order-of-magnitude faster change in satellite geometry. These factors shorten real-time PPP convergence from about 30 minutes to below 3 minutes and enable centimetre-level positioning, even in dense urban environments [132]. The broadband forward link can also broadcast zero-age ephemeris and integrity data that are impractical with a 50 bps GNSS navigation message [133].

ICAN implementations follow two modes. In the "hosted mode" [10], a largely independent navigation payload is added to a communication satellite. In the "fused mode" [86], the two functions are combined at the signal level-sharing time, frequency, and beam resources. Both approaches inherit the benefits listed above, although the extent may vary depending on implementation choices. The fused mode, however, builds on these advantages and offers additional spectrum-efficiency gains through joint waveform design.

The remainder of this section details the bidirectional benefits: how the navigation component enhances the communi-

TABLE IV: Comparison of Typical LEO Satellite Navigation Paradigms

Comparison Item \ Paradigm	Information Augmentation	SoOP Navigation	Signal Augmentation
Pros	No need to carry special navigation load	No need for special space segment construction	High positioning precision and fast convergence
Cons	High-quality GNSS signal is required	Only tens of meters of positioning precision	Special signals are required, and the construction of the system is complex
Requirement of GNSS	$\surd$	$\times$	Optional
Requirement of broadcast special navigation signals	$\times$	$\times$	$\surd$
Number of satellites required	One is enough	Four for a single epoch, and one for multi-epoch	Four of LEO and GNSS satellites
Typical constellation scale (95% global availability)	Dozens of near-polar communication satellites	Tens-hundreds inherited from chosen comms/IoT constellations	Hundreds of dedicated LEO-PNT satellites
High-latitude ($> 60°$) coverage capability	Broadcast link nearly gap-free; positioning geometry still limited by MEO GNSS	Good if the source constellation is near-polar (e.g. Iridium, OneWeb)	Native near-/polar or sun-synchronous design enables continuous coverage
Requirement of the onboard high-precision atomic clock	$\times$	$\times$	$\times$
Positioning precision	Medium	Low	High
Convergence time of PPP	Same as GNSS	Not support PPP	Ten times faster than GNSS
Terrestrial network requirements of receivers	$\times$	$\surd$	$\times$
References	[8], [87]–[90], [128]	[1], [22], [91]–[95], [97], [100]–[110]	[68], [80], [100] [111]–[126]

cation link and how the broadband payload, in turn, improves navigation performance.

A. The Promoting Effect of Navigation on Communication

The promoting effect of navigation on communication is primarily reflected in the following key aspects.

1) Estimation of Time Advance (TA): Communication users at different locations compensate for varying propagation delays using different TA values to maintain the orthogonality of orthogonal frequency division multiplexing (OFDM) uplinks [134], effectively avoiding inter-carrier interference (ICI).

Compared with terrestrial 5G networks, LEO satellites face a more complex situation of high time delay and large frequency offset. For satellites employing orthogonal frequency division multiple access (OFDMA) [135] as the uplink access scheme, the uplink time alignment of signals from different communication users in the same beam is crucial for maintaining the orthogonality of different subcarriers. Therefore, only the correct TA value can ensure that the OFDM signal is correctly demodulated by the LEO satellites.

Considering the high mobility of LEO satellites, communication users are required to continuously track and adjust the TA value, and using special signaling to complete this procedure may cause significant overhead. The vision of ICAN proposes that unified system design and resource scheduling can be adopted to realize resource sharing and service complementarity between navigation and communication functions. For TA estimation, communication users can achieve orthogonality of the uplink via real-time and accurate TA values based on the relative location obtained from the navigation component in ICAN.

2) Frequency Synchronization: In addition to TA estimation, another challenge for OFDMA in LEO satellite communications is the high Doppler frequency shift. At an orbit altitude of 600 km, the Doppler shift can reach approximately 24 ppm [136], greatly exceeding the typical oscillator inaccuracies and substantially compromising the orthogonality of the OFDMA strategy.

An effective solution is to continuously predict the Doppler shift. With ICAN, receivers equipped with navigation capabilities can obtain satellite ephemeris data while determining their own positions and speeds. These information provide insights into the relative motion between satellites and users, allowing the system to dynamically compensate for most of the Doppler shift and its rate of change during signal transmissions.

3) Time Synchronization: Time synchronization is another critical problem in OFDM systems, which is directly related to the subsequent channel estimation, equalization, and decoding.

Symbol timing synchronization refers to the process of extracting the clock synchronized with the received symbol rate from the baseband signal at the receiver, which is the basis for correct sampling decision. In OFDM systems, the algorithms to solve the problem of symbol timing synchronization can be mainly divided into the following three categories.

- Estimation according to the autocorrelation of the cyclic prefix (CP) of OFDM symbols, the implementation complexity of which is low, but the accuracy is not satisfactory.
- Estimation according to training symbols or pilots inserted in OFDM symbols, which will lead to more overhead.
- Estimation based on blind algorithms, which usually require a large number of channel and signal characteristic statistics and high signal-to-noise ratios (SNRs).

Each of the three methods mentioned above has its pros and cons. By contrast, ICAN is considered as an efficient way for timing synchronization, which can not only obtain precise location coordinates, but also provide high-precision timing service. Through real-time tracking of the navigation signals, high-precision time information can be obtained, and thus accurate symbol timing synchronization can be obtained.

4) Beam Alignment: Conventional antennas may take tens of seconds to locate and track subsequent LEO satellites [137]. Although this type of communication interruption is brief and predictable, it is still undesirable for low-latency data communications. Based on the high-precision satellite ephemeris carried in the navigation component of ICAN, the satellite motion can be tracked and predicted, and based on the known users' and satellite's positions, the beam search process can be greatly accelerated.

For downlink communication, LEO satellites are typically equipped with phased array antennas, which can dynamically steer beams to track the rapidly changing positions of users on the ground. By utilizing ICAN, user locations can be accurately determined and transmitted back to the satellite to assist in downlink channel prediction, thereby facilitating the alignment of downlink beams.

B. The Promoting Effect of Communication on Navigation

The integration of communication capabilities within the ICAN framework significantly enhances navigation functions in several key areas.

1) Ephemeris Transmission: High-precision positioning depends on rapidly delivering fresh orbit and clock information. The legacy GPS navigation message, limited to 50 bps, requires roughly 750 s for a receiver to collect a complete set of parameters [139], which lengthens the time-to-first-fix (TTFF) [140]. In an ICAN architecture the same LEO satellite that broadcasts navigation signals also owns a broadband forward link, so it can distribute ephemeris updates at kilobit-per-second rates instead of tens of bits per second.

Each second the control segment fits a short-arc quadratic to the most recent 30 s of precise orbit/clock estimates and transmits the six coefficients [125]

$$\begin{aligned} \Delta\mathbf{x}(t) &= \mathbf{A}_0 + \mathbf{A}_1\,\Delta t + \mathbf{A}_2\,\Delta t^2, \\ \delta t_s(t) &= a_0 + a_1\,\Delta t + a_2\,\Delta t^2, \\ \Delta t &= t - t_0, \end{aligned} \tag{3}$$

where $\Delta\mathbf{x}$ and δt_s correct the broadcast position $\mathbf{x}_{\mathrm{brdc}}$ and clock t_{brdc}. Quantising each coefficient to 18 bits and adding an 8-bit issue of data, clock (IODC) plus a 6-bit cyclic redundancy check (CRC) yields a compact 12-byte record for every satellite. Injected into a reserved ICAN channel, these records refresh a 200-satellite constellation in under 0.25 s, while ISL/OISL forwarding keeps end-to-end latency below 250 ms.

On reception a satellite verifies the IODC, evaluates the polynomials with Horner's rule (about 18 multiplies and 15 adds) [141], and updates $\mathbf{x}_s = \mathbf{x}_{\mathrm{brdc}} + \Delta\mathbf{x}$, $\dot{\mathbf{x}}_s = \dot{\mathbf{x}}_{\mathrm{brdc}} + \dot{\Delta\mathbf{x}}$, $t_s = t_{\mathrm{brdc}} + \delta t_s$. If the residuals satisfy $\|\Delta\mathbf{x}\| \le 0.05\,\mathrm{m}$ and $|\delta t_s| \le 5\,\mathrm{ns}$ [142]. The resulting signal-in-space (SIS) error is less than 0.12 m at the 1σ level, which supports centimetre-level PPP once the LEO data are fused with conventional GNSS. Thus, broadband delivery and lightweight processing together let ICAN satellites supply real-time ephemeris corrections without over-taxing the payload.

TABLE V: Comparison of Clock Synchronization Techniques in LEO Satellite Systems

Technique	Accuracy (ns)
Atomic Clock Synchronization [144]	< 1
GNSS Time Synchronization [144]	10-100
OISL [145]	< 1
Two-Way Time Transfer (TWTT) [145]	1-10
One-Way Time Transfer (OWTT) [146]	10-100
CSAC [147]	100-1000
OCXO [147]	100-1000

2) Clock Deviation Elimination: As discussed in Section III, clocks on LEO satellites, typically CSAC or OCXO, are designed to support traditional communication waveforms but do not adhere to the same standards as the high-precision atomic clocks used in GNSS satellites. As a result, these LEO satellite clocks often lack the stability required to maintain nanosecond-level precision for periods longer than one minute [143].

The common clock synchronization techniques are summarized in Table V. As shown in the table, each technique offers varying degrees of accuracy. Under the ICAN paradigm, high-precision atomic clocks, used as reference clocks, are typically deployed on the ground or in space, rather than on every individual satellite. Using the broadband burst communication capabilities of LEO satellites, high-throughput data links can be established between the satellites and the control centers. This allows for higher data rates and more frequent broadcast updates, ensuring that the latest orbit and clock products are continuously available. Consequently, the need for atomic clocks on each individual LEO satellite can be mitigated by using zero-age ephemeris products [10], [86]. Based on this idea, Ye *et al.* [108] made use of the bidirectional link between the observation point and the LEO satellite to eliminate the clock error and reduce the unknown variables needed by the traditional algorithm.

Furthermore, Table V underscores the crucial role that OISLs play in eliminating clock deviations. They represent a feasible solution for synchronizing satellites to the stability levels provided by onboard atomic clocks [138]. Fig. 5 illustrates the OISL configuration in the Kepler constellation, which consists of navigation satellites equipped with cavity-stabilized lasers and bidirectional optical link terminals [138]. The neighboring MEO satellites within the same orbital plane are permanently connected through laser links, providing traditional broadcast navigation signals to users via conventional radio frequency carriers. The LEO satellites are responsible for transferring information between orbital planes. Each MEO

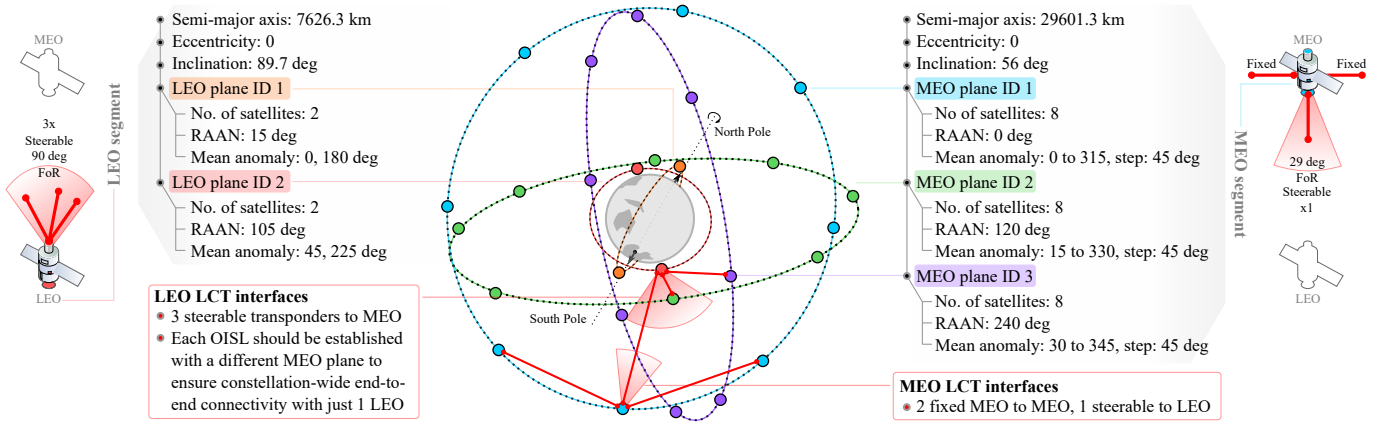


Fig. 5: Kepler GNSS constellation supported by OISLs [36]. This constellation design is consistent with the planning in [138]. Published design data in [138] give orbit eccentricities below 0.0003, so circular arcs are an adequate first-order depiction. Straight segments denote logical OISL connectivity, not satellite trajectories.

and LEO satellite is equipped with three Laser Communication Transceivers (LCTs) to establish bidirectional optical links, thus enabling high-precision clock synchronization across the whole system with minimal latency.

However, apart from the Kepler constellation, most navigation constellations either lack LCTs or only equip a few satellites with them. In contrast, OISLs are widely adopted in communication satellites [148], owing to their advantages in high-speed data routing and inter-satellite networking. With the rapid expansion of broadband satellite networks, OISLs are being extensively deployed on LEO communication satellites, not only to support communication functions but also to enhance clock synchronization accuracy and mitigate deviations in navigation components.

Nevertheless, scaling OISLs across a large LEO constellation requires optical terminals with extremely precise pointing, acquisition, and tracking capabilities, far beyond those of many current satellite platforms [149]. Continuous laser operation also drives up power consumption and heat dissipation, creating major design constraints on small spacecraft. Gaps in cross-plane visibility can interrupt optical links for extended periods, increasing reliance on less stable on-board oscillators. Moreover, the high unit cost and complexity of laser terminals, together with the need for redundancy, pose significant economic and schedule risks. Overcoming these hurdles is essential to deploy OISL-enabled ICAN systems at scale.

3) Orbit Determination: Precise orbit determination is crucial for the formation of satellite ephemeris. In large-scale LEO constellations, tracking numerous satellites simultaneously requires a high density of monitoring stations, making timely updates challenging.

As shown in Table III, some broadband LEO constellations, such as SpaceX's Starlink, plan to establish ISLs primarily for communication traffic and networking. However, these ISLs can also enhance navigation by serving as additional ranging sources, which significantly improve the accuracy of orbit determination. When combined with terrestrial networks, the accuracy of orbit determination in the radial, cross-track, and along-track directions can be tripled compared to using terrestrial networks alone [150]. For example, the inclusion of ISLs can reduce the standard deviation of radial accuracy from 35 cm to 8 cm [150]. Meanwhile, advanced OISLs enable sub-millimeter [138] ranging between platforms, and the ISL contact plan can be optimized for orbit determination purposes [36].

4) Improvement in Data Integrity: In navigation systems, integrity information plays a critical role in ensuring the accuracy and reliability of the positioning data provided to users. This information is especially vital in safety-critical applications, such as aviation and maritime navigation, where it is imperative to detect and alert users to any potential degradation in the quality of the navigation signals. The primary function of integrity information [151] is to monitor the health of the navigation signals and provide timely warnings if the data is no longer trustworthy. Traditionally, integrity information can be obtained and disseminated through space-based augmentation systems (SBASs) [152]. The SBAS relies on a network of ground-based monitoring stations to continuously assess the quality of signals from GNSS and then relays this information to geostationary satellites. These satellites, in turn, broadcast the integrity data to end-users. The wide area augmentation system (WAAS) [153] in the United States is a typical example of SBASs, which can provide highly accurate and reliable navigation services to aviation users in North America.

However, with the emergence of the ICAN framework, a more efficient approach to managing integrity information has become possible. The ICAN framework uses the bidirectional communication links of LEO satellites to receive real-time integrity data from ground-based monitoring stations which continuously evaluate the quality of navigation signals, and the LEO satellites, equipped with high-throughput communication capabilities, can then broadcast this integrity information back to users, thereby effectively eliminating the need for a dedicated SBAS to disseminate integrity data.

5) Enhanced Security Features: Current GNSS systems are increasingly vulnerable to security threats such as signal spoofing, jamming, and unauthorized access, which can com-

TABLE VI: Mutual Promotion Between Communication and Navigation in The ICAN Framework

Navigation's Promotion on Communication	
Factor	**Justification**
① Estimation of TA	Real-time, accurate positioning data from the navigation system enables precise TA estimation, keeping uplink synchronized.
② Frequency Synchronization	Continuous prediction and compensation for Doppler shift ensure the reliability of frequency synchronization.
③ Time Synchronization	Real-time tracking of navigation signals provides high-precision time synchronization, improving overall system timing.
④ Beam Alignment	Navigation data helps in predicting satellite motion, enhancing the efficiency of beam alignment processes.
Communication's Promotion on Navigation	
Factor	**Justification**
① Ephemeris Transmission	High-bandwidth communication allows for faster and more reliable ephemeris data transmission.
② Clock Deviation Elimination	Bidirectional communication links enable frequent updates and corrections, reducing the need for on-board atomic clocks.
③ Orbit Determination	ISLs enhance the accuracy of orbit determination by providing additional ranging sources.
④ Data Integrity Improvement	Communication links facilitate real-time integrity monitoring, ensuring the reliability of navigation data.
⑤ Enhanced Security Features	Strong security protocols and bidirectional links prevent unauthorized access and ensure reliability of navigation information.

promise the reliability and safety of navigation services. A key advantage of the ICAN framework for navigation is its implementation of robust authentication protocols, commonly utilized in communication networks [154], such as mutual authentication [155]. This approach allows both the satellite and ground station (or user) to independently verify each other's identity before data exchange, preventing unauthorized access and ensuring that only trusted entities can influence navigation data. In addition, the bidirectional links establish a continuous feedback loop, enabling immediate corrective actions and ensuring the accuracy and reliability of navigation data, even in the presence of potential threats.

C. Brief Summary

The ICAN framework exemplifies a powerful synergy between communication and navigation functions, where each domain enhances the performance and reliability of the other. On one hand, the integration of precise navigation data significantly improves communication systems in LEO environments by optimizing spatial, temporal, and frequency estimations. This leads to better synchronization, reduced interference, and more efficient beam alignment, enhancing the overall communication reliability and network access efficiency. On the other hand, the robust communication capabilities within the ICAN framework, including high-bandwidth bidirectional links, ISLs, and strong security authentication and access protocols, significantly bolster the navigation functions. By facilitating real-time transmission of integrity data, efficient ephemeris updates, and secure authentication processes, these features ultimately improve the accuracy, integrity, and security of navigation services.

The mutual promotion between communication and navigation, along with the underlying mechanisms driving these interactions, are detailed in Table VI. Together, these interdependent enhancements show that the ICAN framework goes beyond merely combining communication and navigation functions. It forms a unified system where their integration creates a synergy, making the whole greater than the sum of its parts.

V. ICAN Waveform Design

As more countries and commercial organizations participate in the construction of satellite communication or navigation systems, the rapid saturation of frequency resources and the increasingly complex interference between signals have become major challenges impeding the development of satellite navigation systems. In such situations, designing an integrated signal for navigation and communication, which can be used for both communication and PNT services through a single link, becomes a highly meaningful research point. The multiplexing and integration of communication and navigation systems in terms of time, frequency, beam resources, and onboard components are expected to address the issues of tight spectrum resources and constrained transmit powers of ICAN signals.

Communication signals typically use various multiplexing methods to maximize effective transmission bandwidth and optimize point-to-point delivery services, while navigation

signals need to ensure continuous coverage of users and regularly broadcast navigation messages to provide high-precision navigation and positioning services [156]. The bursty nature of communication services and the discontinuity of communication channels in the time and frequency domains differ significantly from the broadband continuous signal system of navigation, which must be considered in the waveform design process of ICAN.

Therefore, the waveform of ICAN should include the following three components:

- **Communication Signal:** A modulated bitstream that conveys communication data and essential signaling required for various communication processes.
- **Navigation Message:** A message that includes critical satellite information, such as satellite ephemeris, clock deviation, and other supplementary data necessary for navigation.
- **Ranging Information:** Assuming continuity and compatibility with current GNSSs, whose working principles are based on pseudo-range multilateration, the ICAN signal must also encapsulate a ranging signal, which is crucial for enabling accurate user positioning.

A. ICAN Waveform Design Based on Spread Spectrum

GPS, Galileo, BeiDou, and other satellite navigation systems all use pseudo random noise (PRN) codes based direct sequence spread spectrum (DSSS) technology, with PRN codes serving as ranging signals [157]. In these systems, the high-speed PRN code is multiplied with the low-speed baseband information signal, effectively broadening the bandwidth and reducing the power spectral density.

Given the strong similarity between DSSS communication and satellite navigation in signal forms, the ICAN communication channel can primarily transmit data using coded composite signal keying (CCSK) modulation. Zou *et al.* [158] optimized the cyclic shift times of the CCSK signal by aligning its larger cross-correlation with the autocorrelation peak to overcome cross-correlation interference and improve communication performance. Cui *et al.* [159] proposed an integrated I/Q branch separation scheme that assigns orthogonal signals to navigation and communication functions, respectively. Huang and Ou *et al.* [160] addressed spectrum fluctuation by employing multi-carrier binary offset carrier (MC-BOC) modulation in the integrated navigation system, which, compared to traditional BPSK used in GNSS, effectively improves data transmission under limited bandwidth conditions.

Although the code division ICAN scheme is well compatible with the GNSS system, a common issue is that, while it can perform data transmission alongside navigation, its transmission rate does not meet the requirements of broadband communications.

In particular, if R_c denotes the PRN chip rate and N is the spreading factor, the resulting user bit rate is $R_b = R_c/N$, while the one-sigma pseudorange error varies as $1/\sqrt{N}$ [161]. Thus, halving N to double R_b increases the pseudorange error by a factor of $\sqrt{2}$, sacrificing ranging precision for higher data throughput. Designers can therefore adjust N (or equivalently R_c) to achieve the desired trade-off between data rate and positioning accuracy in an ICAN system.

B. ICAN Waveform Design Based on Spectrum Separation

The concept of spectrum separation in ICAN waveform design involves allocation of distinct frequency bands to navigation and communication signals, thereby minimizing mutual interference and enabling the independent optimization of signal parameters for each function. A typical implementation of this design strategy is the filtered OFDM (F-OFDM) waveform, where the communication and navigation signals occupy separate portions of the available bandwidth, each fulfilling its respective role [162], [163]. In [164] and [165], the authors proposed a new transmission signal model comprising a pilot channel and a communication channel. The pilot channel's main function is to transmit navigation information and synchronization information, which can be directly used in traditional satellite navigation systems.

Furthermore, Feng *et al.* [166] proposed the use of vector OFDM (V-OFDM) to achieve integrated communication and navigation functionalities. The navigation function is implemented through the pilot signals within the OFDM structure, while the remaining subcarriers are reserved for communication.

While this approach offers clear advantages of intuitive design and effective control over the interference between navigation and communication signals, it introduces significant challenges. Specifically, the separation in frequency bands causes the navigation waveform to lose its desirable time-domain autocorrelation and cross-correlation properties under bandwidth constraints. This degradation complicates the temporal acquisition and tracking of the navigation signal, thus imposing significant demands on the receiver's processing capabilities. Moreover, this method diverges considerably from existing navigation signal frameworks, posing potential compatibility issues.

To formalize the band-allocation scheme, let B_{tot} denote the total RF bandwidth centered at f_0. The total bandwidth is then partitioned as

$$B_{\mathrm{tot}} = B_{\mathrm{NAV}} + B_{\mathrm{G}} + B_{\mathrm{COM}}, \tag{4}$$

where B_{NAV} and B_{COM} represent the navigation and communication sub-bands, respectively, and B_{G} denotes an optional guard band. In this configuration, the navigation sub-band occupies

$$f \in \left[f_0 - \tfrac{B_{\mathrm{NAV}}}{2},\ f_0 + \tfrac{B_{\mathrm{NAV}}}{2}\right], \tag{5}$$

whereas the communication sub-band spans

$$f \in \left[f_0 + \tfrac{B_{\mathrm{NAV}}}{2} + B_{\mathrm{G}},\ f_0 + \tfrac{B_{\mathrm{NAV}}}{2} + B_{\mathrm{G}} + B_{\mathrm{COM}}\right]. \tag{6}$$

Setting $B_{\mathrm{G}} = 0$ yields contiguous navigation and communication allocations.

C. ICAN Waveform Design Based on Spectrum Sharing

The Design of ICAN waveforms based on spectrum sharing uses the same spectral resources for both communication and navigation, thereby improving spectrum efficiency and system compatibility, especially in the scenarios with limited spectrum resources or stringent regulatory constraints. This approach conserves bandwidth and supports continuous operation of

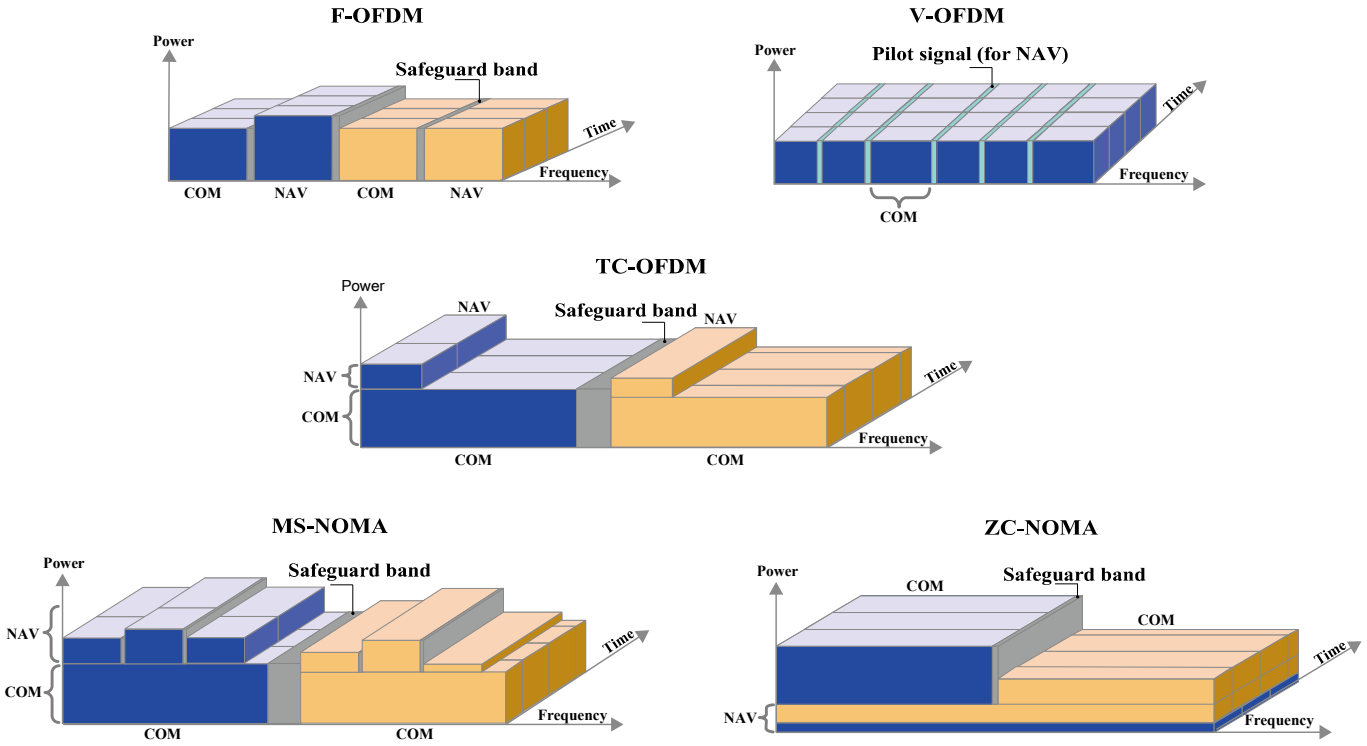


Fig. 6: ICAN waveform design schemes. "NAV" refers to navigation resource block and "COM" refers to communication resource block.

communication and navigation signals within their allocated spectra, facilitating the adoption of mature signal schemes and seamless integration with existing systems.

However, the use of shared frequency bands also introduces challenges in managing interference between navigation and communication signals. Advanced signal processing techniques, such as adaptive filtering and interference cancellation, are required to mitigate these issues, and the system must be carefully engineered to ensure that interference levels remain within acceptable limits.

Several strategies have been proposed for designing ICAN waveforms using shared frequency bands. For example, Deng and Yin [167] introduced time and code OFDM (TC-OFDM), which employs BPSK for navigation and OFDM for communication, which can effectively mitigate mutual interference through careful power allocation. Based on this, Liu *et al.* [168] proposed a carrier loop algorithm that integrates maximum likelihood estimation (MLE) and Kalman filter (KF) to enhance the tracking sensitivity of TC-OFDM receivers in complex indoor environments under weak signal conditions, and later improved TC-OFDM by replacing BPSK with a BOC signal for better navigation performance [169].

In addition, Yin *et al.* [170] introduced multi-scale NOMA (MS-NOMA) along with a joint power allocation method for the downlink, enabling configurable power levels for different positioning users to enhance ranging accuracy and coverage while meeting quality of service (QoS) requirements (e.g., bit error rate (BER)). This research was further extended to the uplink and a joint iterative power allocation algorithm was proposed to improve ranging accuracy while preserving energy efficiency [171]. Moreover, Yin *et al.* [172] investigated the feasibility of MS-NOMA for next-generation integrated systems and introduced a constrained positioning power allocation algorithm that iteratively optimizes power allocation to improve positioning accuracy compared to traditional methods. Dai *et al.* [173] addressed the interference between device-to-device (D2D) and MS-NOMA signals in indoor environments and use a particle swarm optimization (PSO) based power allocation strategy to enhance the overall system performance. Moreover, our previous work *et al.* [174] proposed Zadoff-Chu sequence superposed NOMA (ZC-NOMA), which enables the simultaneous reception of integrated communication and navigation signals from multiple satellites.

Spectrum separation places navigation and communication in distinct sub-bands, essentially eliminating cross-interference and easing ranging, but it wastes bandwidth and adds extra RF chains. Spectrum sharing overlays both services in the same band, improving spectral efficiency, yet it requires tight power control, sophisticated interference cancellation, and joint processing to meet accuracy and BER targets. For instance, adaptive filtering algorithms (e.g., least mean squares (LMS) or recursive least squares (RLS)) [176] can be deployed to track and suppress navigation pseudocode components in real time, while iterative successive interference cancellation (SIC) [177] can decouple communication carriers from navigation codes. In more demanding environments, additional measures such as frequency-domain filtering, space-time adaptive beamforming (e.g., minimum variance distortionless response (MVDR) [178]), or deep learning-based source separation [179] can be integrated to further enhance

TABLE VII: Comparison of Different Approaches for ICAN Waveform Design

Waveform Design Approach	Advantages	Challenges	References
Schemes based on spread spectrum	- Effective suppression of interference due to wideband signal, which improves the robustness of communication and navigation systems. - High compatibility with existing GNSS systems, making it easier to integrate into current infrastructures.	- Data transmission rate is relatively low, limiting its capacity for high-bandwidth communications. - May not fully meet the demands of modern broadband communication, especially in dynamic and high-speed environments.	[158]–[160]
Schemes based on spectrum separation	- Enables independent optimization of communication and navigation signal parameters, reducing cross-interference. - Facilitates flexible adjustment of signal characteristics for different applications, allowing for greater adaptability in system design.	- Separation in frequency bands reduces the time-domain autocorrelation and cross-correlation properties, complicating signal acquisition and tracking. - Imposes significant computational and processing demands on receivers, potentially reducing real-time performance.	F-OFDM: [162], [163]; V-OFDM: [166]; Others: [164], [165]
Schemes based on spectrum sharing	- Maximizes spectrum efficiency by allowing communication and navigation signals to coexist within the same frequency band. - Enhances system compatibility by integrating both functionalities in a unified framework, reducing the need for additional bandwidth resources.	- Managing interference between the communication and navigation signals is complex and requires advanced filtering and cancellation techniques. - System design must ensure interference levels stay within acceptable limits to avoid degrading overall system performance.	TC-OFDM: [167]–[169]; MS-NOMA: [170]–[173]; ZC-NOMA: [174]
Other schemes (*e.g.*, OTFS)	- Demonstrates strong resilience to Doppler effects, making it ideal for high-velocity environments such as LEO satellites. - Offers superior time-frequency resource utilization, supporting both communication and navigation functions simultaneously.	- Higher implementation complexity due to the need for new receiver designs and advanced signal processing techniques. - Adoption of new technologies may face challenges related to backward compatibility with existing infrastructure.	OTFS: [175]

interference mitigation.

D. Additional ICAN Waveform: OTFS

The satellites' high-speed movement requires that LEO ICAN systems need to overcome severe Doppler effects. New modulation schemes such as the orthogonal time frequency space (OTFS) [180] are potential candidate solutions for the future ICANs. OTFS is capable of supporting both communication and navigation within a unified signal framework by multiplexing these functions over time-frequency resource blocks, thereby ensuring synchronization and efficient spectrum utilization. This not only simplifies system design, but also significantly enhances overall system performance. In terms of navigation and ranging, OTFS combines time delay estimation with Doppler correction, offering higher accuracy than traditional methods. Even in complex mobile environments, OTFS can provide stable and precise positioning capabilities.

Considering these advantages, Li *et al.* [175] designed an OTFS-based integrated communication and navigation waveform. A hybrid modulation constellation by superimposing quadrature amplitude modulation (QAM) and dual-code alternating BOC (AltBOC) modulation was proposed, which achieves signal-level integration well-suited for ICAN systems.

E. Brief Summary

In this section, we reviewed several ICAN waveform design strategies that address challenges such as spectrum scarcity, interference management, and system compatibility. Waveform designs based on spread spectrum, frequency band separation, and frequency band sharing offer distinct advantages and challenges. For example, spread spectrum approaches are effective for interference mitigation, while frequency band separation approaches allow independent optimization of communication and navigation signals. In contrast, frequency band sharing approaches offer high spectrum efficiency but require advanced signal processing to manage mutual interference. Fig. 6 illustrates the time-frequency structures of these waveforms, with resource blocks of the same color representing allocations from the same satellite.

To clarify the interaction between communication and navigation signals in each design approach:

1) Spread-spectrum schemes: Communication data is superposed on navigation PRN codes, so both functions share the same wideband correlator. Navigation tracking loops suppress data as noise, while decision-directed demodulators remove code contributions to recover the information bits.

2) Spectrum-separation schemes: Navigation pilots and communication carriers occupy disjoint bands or subcarriers. Each branch employs independent filters and correlators, eliminating mutual interference but requiring separate RF chains or filtering stages.

3) Spectrum-sharing schemes: Navigation and communication symbols coexist on the same subcarriers (e.g., TC-OFDM or NOMA). Receivers perform joint multiuser detection or successive interference cancellation to disentangle pseudo-

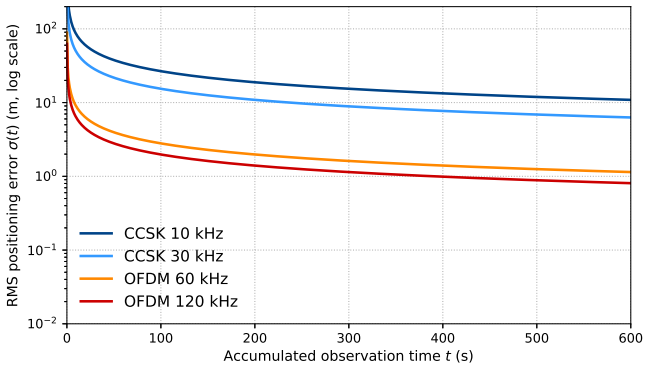


Fig. 7: PPP convergence of CCSK-BPSK and OFDM-like waveforms under different bandwidth settings.

range codes from payload data.

4) OTFS-based schemes: Both functions are multiplexed in the delay-Doppler domain. Navigation ranging exploits the delay profile, while data demodulation uses the Doppler structure, enabling unified channel estimation and robust separation in high-mobility LEO channels.

Additionally, novel waveform designs such as OTFS-based scheme show significant potential for ICAN systems in dynamic LEO environments due to their resilience to Doppler effects and time-frequency synchronization issues. Table VII summarizes the advantages and challenges of the different design strategies.

It is noteworthy that waveform design substantially influences PPP convergence speed. Fig. 7 quantitatively compares the convergence of the root-mean-square (RMS) positioning error $\sigma(t)$ for an OFDM-based ICAN waveform versus a CCSK-BPSK design at comparable transmit power. Thanks to its larger effective bandwidth (60-120 kHz) and much shorter integration interval (66 µs), the OFDM waveform drives $\sigma(t)$ to meter-level accuracy in well under 3 minutes. In contrast, the CCSK alternatives require more than 8 minutes, even at 30 kHz, to reach similar precision. These results confirm the theoretical relation

$$\sigma(t) \propto \frac{1}{\sqrt{t}}, \tag{7}$$

demonstrating that increased bandwidth and reduced integration time accelerate the white-noise averaging process and thus expedite PPP convergence.

VI. Key Challenges and Enabling Technologies for ICAN

The integration of communication and navigation at the payload, signal, and system levels has the potential to reshape current communication and navigation architectures, offering numerous advantages. However, as summarized in Table VIII, several critical challenges must still be overcome to achieve seamless global broadband communications and ensure reliable, high-precision navigation services. These identified challenges and the corresponding enabling technologies are presented as follows.

A. Integrated Frameworks

Although recent work has shown that LEO constellations can support both broadband communications and high-precision navigation, most approaches treat these functions as parallel services sharing only the same hardware. For example, Wang *et al.* [181] optimized 3GPP-NTN beam-hopping schedules to serve both high-throughput users and centimetre-level PPP simultaneously, Sheng *et al.* [27] pooled orbital, spectrum, and data resources but still managed traffic and positioning in separate planes, Li *et al.* [182] enforced positioning constraints in beam selection while retaining distinct communication and navigation workflows, and You *et al.* [183] demonstrated that a 64×64 Ka-band massive-MIMO payload can deliver 10 Gb/s links alongside meter-level delay-Doppler positioning.

A truly integrated ICAN framework must collapse these service silos and present a single orchestrated offering. At its core lies a unified service plane, implementable via network slicing or virtualized network functions, that abstracts radio, computing, and timing resources into dynamically composable "comm+nav" instantiations. These instantiations host joint waveforms, beam schedules, and integrity monitors under a common north-bound application programming interface (API) so that one session request yields both data connectivity and positioning outputs. The control plane coordinates across terrestrial 5G/6G cores and multi-shell satellite networks through software-defined interfaces, while the data plane carries internet protocol (IP) flows and navigation measurements in harmonized packets or delay/disruption-tolerant networking (DTN) bundles, preserving sub-millisecond latency and end-to-end integrity. By embedding navigation services as native network functions, complete with real-time ephemeris distribution, on-board clock steering, and distributed-ledger message validation, this architecture delivers a seamless one-stop ICAN service rather than two co-located but separate capabilities.

B. Protocol Stack Harmonization

In current practice, the communication and navigation domains rely on separate, specialized stacks that have evolved independently. Satellite broadband systems follow the 3GPP-NTN standards for the physical and medium access control layers, such as OFDM framing with link adaptation [184], and digital video broadcasting - satellite - second generation extension (DVB-S2X) for beam-hopping and multiple access [185], with IP routing and transport protocols such as quick user datagram protocol (UDP) internet connections (QUIC) [186] or transmission control protocol (TCP) carrying user traffic. In contrast, navigation systems use GNSS signal structures, for example L1 C/A and L2C, and a dedicated navigation message format for ephemeris and clock corrections [187], [188]. Differential and integrity data are delivered via radio technical commission for maritime services (RTCM) messages [189] or consultative committee for space data systems positioning, navigation, and timing ephemeris (CCSDS PNT-EPH) packets [190], and, when needed, by two-way time transfer beacons or satellite-based augmentation system overlays [191]. At the network layer, navigation augmentation often employs networked transport of RTCM via IP (NTRIP) [192] or DTN

TABLE VIII: Summary of Open Issues and Challenges in ICAN Framework

Challenges	**Descriptions and Key Issues**	**Suggested Solutions / Considerations**
Integrated frameworks	A unified service plane integrates comm + nav into network slices with shared payloads and coordinated waveform / beam schedules, enabling seamless space-ground orchestration, virtualization, and stringent end-to-end latency.	Use SDN-enabled network slicing with virtual network functions (VNFs) to jointly manage RF, timing, and compute resources via a common north-bound API, enabling a single session to deliver both connectivity and PNT.
Protocol stack harmonization	LEO uses 3GPP / DVB, GNSS custom formats; ICAN needs one stack carrying ephemeris / clock / integrity with IP traffic while preserving QoS and security.	Embed PNT into NR-NTN frames, carry RTCM / CCSDS via QUIC / DTN, unify authentication / integrity, and employ dual-mode receivers with a common physical layer (PHY)/MAC.
ISL contact plan optimization	Optimizing ISLs for orbit determination and data routing, to balance communication and navigation requirements.	Design optimized ISL contact plans to ensure real-time positional data exchange and efficient data routing, minimizing the need for ground stations.
Acquisition and tracking of enhanced signals in high dynamic navigation	Doppler shifts and shorter satellite transit times in LEO create challenges for fast acquisition and tracking of navigation signals.	Use real-time Doppler compensation with high-precision positional information. Adjust transmit power and receiver complexity for balance.
Anti-interference and anti-spoofing	Growing threats of jamming and spoofing in critical applications like aviation and intelligent transportation.	Incorporate real-time signal processing techniques for interference detection and suppression. Leverage encryption and authentication protocols to enhance signal security.
Satellite handover and session time management	Frequent satellite handover due to low orbits and shorter transit times creates challenges in maintaining continuous service for both communication and navigation users.	Design intelligent handover schemes considering user density, channel resources, and geometric accuracy, with AI for traffic prediction and session management.
Routing strategy design	LEO satellite networks must meet different QoS requirements for communication and navigation, with low delay tolerance for navigation data and varied link rates for communication.	Develop robust routing algorithms that consider both navigation data requirements and the QoS needs of communication applications.
Waveform design	Impacting both communication and navigation performance makes it a critical challenge, with its complexity arising from balancing both functions while minimizing interference.	Research new optimization frameworks that can jointly consider physical-layer waveform design and resource allocation based on advanced waveform techniques and adaptive filtering schemes.
Constellation design	Balancing communication and navigation needs for global coverage, geometric accuracy, and high throughput, especially in challenging high-latitude regions.	Optimize satellite spacing and orbits to support both high-precision positioning and reliable communication with cost-effectiveness and scalability.

bundling [193], distinct from the IP-centric routes used by broadband.

A unified ICAN stack must bridge these two worlds. It should present a single service plane in which radio, timing, and computing resources are sliced into combined "comm+nav" instances [194], [195]. Joint waveforms, such as new radio (NR)-NTN OFDM frames with embedded PRN markers, replace separate physical channels [184]. Medium access control (MAC) schedules reserve micro-slots for ephemeris and integrity alongside user payload [185]. Network routing carries IP flows and PNT measurements seamlessly, using DTN bundles when links are disrupted yet preserving native IP forwarding for data [193]. Transport protocols expose slice identifiers so that broadband and PNT flows receive appropriate scheduling and security treatment [194]. Finally, ephemeris data, clock corrections, and integrity reports are carried as prioritized streams via QUIC frames or CCSDS mission operations (MO) messages [196], allowing a single session setup to provide both high-speed connectivity and centimetre-level positioning under one coherent framework.

C. ISL Contact Plan Optimization

In the ICAN framework, optimizing orbit determination, data routing, and networking through ISLs requires a strategic balance between communication and navigation needs. Traditional GNSS relies on ground-based stations for precise orbit determination, but this approach becomes less feasible in LEO satellite systems due to the need for higher-density ground monitoring stations. Instead, using ISLs for joint orbit determination between satellites might be a practical solution.

The dynamic nature of LEO orbits presents challenges in timely orbit determination due to high computational demands and limited ground station connectivity. ISLs address these challenges by enabling direct inter-satellite communications, which can support real-time positional data exchange while improving the geometric configurations essential for accurate orbit determination. In addition, ISLs facilitate efficient data routing across the satellite constellation [197], ensuring reliable communication even with limited access to ground stations.

To fully utilize the benefits of ISLs within the ICAN framework, the ISL contact plan must be meticulously designed. By

optimizing the ISL contact plan for both orbit determination and seamless communication data routing, the system can effectively balance the dual demands of communication and navigation [36].

D. Acquisition and Tracking of Enhanced Signals in High Dynamic Navigation

LEO satellites are close to the ground, move quickly, face more severe Doppler shifts, and have shorter transit times. In reception of the integrated navigation signals, it is necessary to consider fast acquisitions of the high dynamic signals and the subsequent tracking accuracy [61]. A feasible solution is to use the high-precision position and the satellite state information provided by the navigation components to compensate for the Doppler shift in real-time, improving the tracking stability of the integrated navigation signal. However, the higher is the receiving post-filtering SNR of the navigation signals, the lower is the dependency of such compensation mechanisms to achieve a successful signal acquisition and tracking [198]. Hence, a proper balance between these competing needs should be achieved when considering the transmit power allocation for navigation signals and the receiver complexity.

E. Anti-Interference and Anti-Spoofing

Interferences can be categorized into man-made and natural interferences according to their sources. Man-made interference, particularly malicious activities such as jamming and deception, poses significant threats to wireless communication and positioning systems. As navigation systems become increasingly critical in applications like aviation, maritime, and intelligent transportation, the risks associated with intentional interference are also increasing [199]. Therefore, integrating robust interference management solutions into ICAN systems is essential to safeguard these vital services.

As mentioned in Section IV-B5, the integration systems of communication and navigation differ from traditional GNSS systems, as strong communication capabilities provide opportunities to enhance navigation signals with new elements, such as reliable identity authentication to achieve anti-spoofing. Moreover, the flexible system architecture allows service providers to offer encryption services for different users, thus enhancing the commercial value of the integrated navigation system [46].

Therefore, it is crucial to design security mechanisms tailored to the specific needs of ICAN systems. It includes developing advanced signal processing techniques that can detect and suppress jamming and spoofing attempts in real-time, as well as incorporating robust encryption and authentication protocols to ensure the integrity and authenticity of navigation signals. Additionally, using the strong communication capabilities within the ICAN framework can achieve dynamic adjustment of anti-interference measures based on the operational environment and threat levels, thereby providing a more adaptive and resilient defense against evolving threats.

F. Satellite Handover and Session Time Management

LEO satellites have lower orbits and shorter transit times. In mega-constellation scenarios, the number of visible satellites for users is much larger compared to traditional constellations, making it suboptimal to select access satellites based solely on the maximum service time [55], as this approach extends the access waiting time.

For communication users, satellite handover ensures service continuity, mitigates link interference, and balances loads, while navigation users typically connect to as many satellites as possible to achieve better geometric characteristics. In addition, communication users allow sudden session connections, whereas the location solution for navigation user equipment requires continuous satellite observation [200]. Furthermore, user switching to a new satellite requires re-implementation of the navigation signal acquisition and tracking process, making handover more expensive from the navigation perspective. Therefore, for ICANs based on LEO satellites, a reasonable handover scheme must be designed considering the number of users, channel resources, signaling overhead, navigation geometric accuracy, and navigation service continuity.

One of the key tasks for ICAN satellite handover is to perceive and predict changes in navigation and communication service requests, network traffic, geometric characteristics, and mobility within the system. Artificial intelligence (AI) has great potential in these areas due to its ability to analyze complex data patterns and adapt to dynamic environments [201].

G. Routing Strategy Design

As highlighted in Section VI-C, a hallmark of LEO mega-constellations is the dynamic mesh of ISLs enabling direct spacecraft communication [202]. While Section VI-C addresses when these links should be activated via off-line contact-plan optimization, this subsection examines how they are exploited on-line through real-time path selection, link scheduling, and resource allocation so that latency-critical ephemeris updates and heterogeneous QoS traffic coexist efficiently on the same ISL fabric.

For navigation, ISLs can be used to update the satellite broadcast ephemeris without ground station coverage, increasing the update frequency and effectively shortening the age of satellite ephemeris data. Hence, the navigation component has low tolerance for delay. For the communication function, the LEO satellite network will serve different types of applications, each with varying QoS requirements [203], such as end-to-end transmission delay and link data rate. To satisfy the needs of both navigation and communication components, robust routing strategies are necessary.

In the context of ICAN systems, we must consider the shared requirements, mutual constraints, and cost trade-offs of both components and realize routing via a unified joint-optimization framework. Such a framework jointly optimizes routing paths, link scheduling, bandwidth allocation, and power control, employing weighted priority schemes or adaptive resource allocation to dynamically balance the timeliness of ephemeris updates against the throughput and latency needs

of communication services. Future work can leverage deep reinforcement learning or distributed optimization algorithms to further enhance the adaptive capability and robustness of this integrated routing strategy in dynamic network environments.

H. Waveform Design

As discussed in Section V, waveform design is a critical challenge for ICAN systems, as it has direct influence on both communication performance and navigation precision. The complexity arises from the need to balance the requirements of both functions while maintaining system efficiency and minimizing interference.

In ICAN systems, interference management becomes particularly crucial when communication and navigation signals share the same frequency bands. Traditional interference mitigation techniques may be insufficient, and it requires more advanced methods such as adaptive filtering and efficient resource allocation schemes that can dynamically adjust resource distribution and filtering parameters based on real-time channel conditions. In addition, waveform design must consider the acquisition, tracking, and synchronization characteristics required for navigation signals, ensuring their continuous broadcast capability. Therefore, waveform design must carefully balance the communication and navigation functions, optimizing the overall performance without significantly compromising either. In particular, new optimization frameworks that can jointly consider the physical waveform design and resource allocation are needed, which is also a promising research direction.

The dynamic environments of LEO constellations present additional challenges for waveform designs. High Doppler shifts and rapidly changing channel conditions demand advanced waveform techniques capable of adapting to these variations. Novel designs such as OTFS have shown promise in addressing these dynamics, although challenges related to system complexity and backward compatibility remain to be resolved.

I. Constellation Design

The constellation design for ICAN systems must carefully balance the distinct objectives of navigation and communication while integrating them into a unified framework. For navigation, it is essential to ensure continuous, precise global coverage with high geometric accuracy, especially in high-latitude regions where traditional GNSS may underperform. This requires strategic planning of satellite orbits and spacing to minimize service gaps. On the communication side, the constellation must support high data throughput, low latency, and reliable connectivity across various locations, meeting various QoS requirements.

From the perspective of visible satellite count, communication services aim to maintain robust and stable links for data transmission, often necessitating multiple satellites in view to ensure uninterrupted connectivity and balanced network load. In contrast, navigation services prioritize high geometric accuracy for positioning, which benefits from satellites being visible from different angles to ensure precise triangulation.

Therefore, the constellation design must be optimized to balance these different needs, ensuring that both communication and navigation functions are fully supported while maintaining cost-effectiveness, service reliability, and scalability.

VII. Conclusion

LEO-based satellite navigation offers advantages such as stronger signals, improved anti-jamming capabilities, and faster geometric changes compared to traditional GNSS. However, building large LEO constellations remains costly and presents significant maintenance challenges. The ICAN paradigm integrates navigation functions into the widely deployed LEO communication satellites, enhancing navigation systems and creating new value-added opportunities for satellite communications. This survey offered a comprehensive review of the latest developments in satellite communication and navigation within the ICAN framework, with a focus on the synergies between these two domains.

We summarized the current and planned constructions of LEO communication and navigation constellations, examining the strengths and challenges associated with various LEO-based navigation frameworks. Key areas such as precise orbit determination, high dynamic signal tracking were highlighted. A thorough review of the mutual enhancement between communication and navigation components within the ICAN framework was presented, revealing the unique value provided by the ICAN framework. In particular, we made comparative analyses of different approaches for ICAN waveform design and identified the key open issues that could inspire further researches in development of the highly efficient ICAN systems.

Overall, integrating navigation and communication functions on LEO platforms is expected to significantly advance both components, leading to further innovations and practical implementations.

References

[1] R. M. Ferre and E. S. Lohan, "Comparison of MEO, LEO, and terrestrial IoT configurations in terms of GDOP and achievable positioning accuracies," *IEEE Journal of Radio Frequency Identification*, vol. 5, no. 3, pp. 287–299, 2021.

[2] S. Camacho-Lara, "Current and Future GNSS and Their Augmentation Systems," in *Handbook of Satellite Applications*. New York, NY: Springer, 2013, pp. 617–654.

[3] L. Zhu, H. Zhang, X. Li, F. Zhu, and Y. Liu, "GNSS Timing Performance Assessment and Results Analysis," *Sensors*, vol. 22, no. 7, p. 2486, Jan. 2022.

[4] L. Wang, D. Li, R. Chen, W. Fu, X. Shen, and H. Jiang, "LEO satellite navigation enhancement technology– opportunities and challenges," *Chinese engineering science*, vol. 22, no. 02, pp. 144–152, 2020.

[5] N. Boguspayev, D. Akhmedov, A. Raskaliyev, A. Kim, and A. Sukhenko, "A Comprehensive Review of GNSS/INS Integration Techniques for Land and Air Vehicle Applications," *Applied Sciences*, vol. 13, no. 8, p. 4819, Jan. 2023.

[6] Holli Riebeek and Robert Simmon, "Catalog of Earth Satellite Orbits," https://earthobservatory.nasa.gov/features/OrbitsCatalog/page1.php, Sep. 2009.

[7] A. El-Mowafy, K. Wang, and A. Allahvirdir Zadeh, "The potential of LEO mega-constellations in aiding GNSS to enable positioning in challenging environments," in *XXVII FIG Congress*, 2022, pp. 1–11.

[8] Y. Yang, Y. Mao, X. Ren, X. Jia, and B. Sun, "Demand and key technology for a LEO constellation as augmentation of satellite navigation systems," *Satellite Navigation*, vol. 5, no. 1, p. 11, Apr. 2024.

[9] D. Lawrence, H. Cobb, G. Gutt, M. OConnor, T. Reid, T. Walter, and D. Whelan, "Navigation from LEO: Current capability and future promise," *GPS World Magazine*, vol. 28, no. 7, pp. 42–48, 2017.

[10] T. G. R. Reid, A. M. Neish, T. Walter, and P. K. Enge, "Broadband LEO constellations for navigation," *NAVIGATION, Journal of the Institute of Navigation*, vol. 65, no. 2, pp. 205–220, 2018.

[11] S. Guo, C. Liu, W. Gao, and J. Lu, "Construction and development of satellite navigation augmentation systems," *GNSS World China*, vol. 44, no. 2, pp. 1–12, 2019.

[12] W. Xue, M. Hu, Y. Ruan, and X. Wang, "Analysis performance of navigation constellation satellite failure and enhancement of LEO navigation," *Journal of Physics: Conference Series*, vol. 2551, no. 1, p. 012012, Jul. 2023.

[13] F. S. Prol, R. M. Ferre, Z. Saleem, P. Välisuo, C. Pinell, E. S. Lohan, M. Elsanhoury, M. Elmusrati, S. Islam, K. Çelikbilek, K. Selvan, J. Yliaho, K. Rutledge, A. Ojala, L. Ferranti, J. Praks, M. Z. H. Bhuiyan, S. Kaasalainen, and H. Kuusniemi, "Position, navigation, and timing (PNT) through low earth orbit (LEO) satellites: A survey on current status, challenges, and opportunities," *IEEE Access*, vol. 10, pp. 83 971–84 002, 2022.

[14] Krebs and Gunter D, "CentiSpace Satellite Launch Status," https://space.skyrocket.de/index.html.

[15] S. Glaser, G. Michalak, B. Männel, R. König, K. H. Neumayer, and H. Schuh, "Reference system origin and scale realization within the future GNSS constellation "Kepler"," *Journal of Geodesy*, vol. 94, no. 12, p. 117, Nov. 2020.

[16] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis, "Satellite communications in the new space era: A survey and future challenges," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 70–109, 2021.

[17] B. Li, J. Huang, Y. Feng, F. Wang, and J. Sang, "A Machine Learning-Based Approach for Improved Orbit Predictions of LEO Space Debris With Sparse Tracking Data From a Single Station," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 56, no. 6, pp. 4253–4268, Dec. 2020.

[18] P. Yue, J. An, J. Zhang, J. Ye, G. Pan, S. Wang, P. Xiao, and L. Hanzo, "Low Earth Orbit Satellite Security and Reliability: Issues, Solutions, and the Road Ahead," *IEEE Communications Surveys & Tutorials*, vol. 25, no. 3, pp. 1604–1652, 2023.

[19] T. Sesnic, "Iridium-9 & OneWeb 19 | Falcon 9 Block 5," https://everydayastronaut.com/iridium-9-oneweb-19-falcon-9-block-5/, Jun. 2023.

[20] "Starlink satellite tracker," https://satellitemap.space.

[21] A. Staff, "What is 'Project Kuiper,' Amazon's New Satellite Internet Initiative?" https://www.aboutamazon.com/news/innovation-at-amazon/what-is-amazon-project-kuiper, Mar. 2023.

[22] Z. Z. Kassas, M. Neinavaie, and J. Khalife, "Acquisition, doppler tracking, and positioning with starlink LEO satellites: First results," *IEEE Transactions on Aerospace and Electronic Systems*, p. 1, 2021.

[23] T. G. R. Reid, T. Walter, P. K. Enge, D. Lawrence, H. S. Cobb, G. Gutt, M. O'Conner, and D. Whelan, "Navigation from low earth orbit: Part 1: Concept, current capability, and future promise," *Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications*, vol. 2, pp. 1359–1379, 2020.

[24] Y. Liao, S. Liu, X. Hong, J. Shi, and L. Cheng, "Integration of Communication and Navigation Technologies toward LEO-Enabled 6G Networks: A Survey," *Space: Science & Technology*, vol. 3, p. 0092, Oct. 2023.

[25] Z. M. Kassas, "Navigation from Low-Earth Orbit Part 2: Models, Implementation, and Performance," *Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications, Volume 2*, John Wiley & Sons, 2020.

[26] L. Yin, Y. Ma, G. Li, R. Zhao, and Z. Deng, "Research progress of communication and navigation integration technology," *Navigation, positioning and timing*, vol. 7, no. 04, pp. 64–76, 2020.

[27] M. Sheng, C. Guo, and L. Huang, "Integrated Communication, Navigation, and Remote Sensing in Leo Networks with Vehicular Applications," *IEEE Wireless Communications*, vol. 32, no. 3, pp. 140–147, Jun. 2025.

[28] J. Ma, P. Zheng, X. Liu, Y. Zhang, and T. Y. Al-Naffouri, "Integrated Positioning and Communication via LEO Satellites: Opportunities and Challenges," Nov. 2024.

[29] F. S. Prol, M. Z. H. Bhuiyan, S. Kaasalainen, E. S. Lohan, J. Praks, K. Çelikbilek, and H. Kuusniemi, "Simulations of Dedicated LEO-PNT Systems for Precise Point Positioning: Methodology, Parameter Analysis, and Accuracy Evaluation," *IEEE Transactions on Aerospace and Electronic Systems*, pp. 1–19, 2024.

[30] T. G. Reid, A. M. Neish, T. F. Walter, and P. K. Enge, "Leveraging commercial broadband leo constellations for navigating," in *29th International Technical Meeting of the Satellite Division of the Institute of Navigation (Ion Gnss+ 2016)*, vol. 12, portland, oregon, 2016, pp. 2016–16.

[31] F. R. Morales, L. E. Simona, K. Heidi, P. Jaan, K. Sanna, P. Christina, and E. Mahmoud, "Is LEO-Based positioning with mega-constellations the answer for future equal access localization?" *IEEE Communications Magazine*, vol. 60, no. 6, pp. 40–46, 2022.

[32] T. Janssen, A. Koppert, R. Berkvens, and M. Weyn, "A Survey on IoT Positioning Leveraging LPWAN, GNSS, and LEO-PNT," *IEEE Internet of Things Journal*, vol. 10, no. 13, pp. 11 135–11 159, Jul. 2023.

[33] H. Ge, B. Li, S. Jia, L. Nie, T. Wu, Z. Yang, J. Shang, Y. Zheng, and M. Ge, "LEO enhanced global navigation satellite system (LeGNSS): Progress, opportunities, and challenges," *Geo-spatial Information Science*, pp. 1–13, 2021.

[34] D. Tang, G. Zhang, T. Li, and W. Hao, "Analysis of Characteristics and Requirements of Large LEO Constellations Management," in *Signal and Information Processing, Networking and Computers*, Singapore, 2023, pp. 857–865.

[35] C. Günther, "Kepler – Satellite Navigation without Clocks and Ground Infrastructure," in *Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018)*, Sep. 2018, pp. 849–856.

[36] A. Nardin, J. A. Fraire, and F. Dovis, "Contact Plan Design for GNSS Constellations: A Case Study With Optical Intersatellite Links," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 58, no. 3, pp. 1981–1995, Jun. 2022.

[37] "GET PULSAR," https://www.xonaspace.com/ecosystem.

[38] X. Guo, "Chinese Satellite Program," in *Handbook of Space Security: Policies, Applications and Programs*. Springer International Publishing, 2020, pp. 1381–1399.

[39] M. Su, X. Su, Q. Zhao, and J. Liu, "BeiDou Augmented Navigation from Low Earth Orbit Satellites," *Sensors*, vol. 19, no. 1, p. 198, Jan. 2019.

[40] L. Chen, F. Lv, Q. Yang, T. Xiong, Y. Liu, Y. Yang, H. Pan, S. Wang, M. Liu, R. He, D. Zheng, L. Zhang, and Y. Jin, "Performance Evaluation of CentiSpace Navigation Augmentation Experiment Satellites," *Sensors*, vol. 23, no. 12, p. 5704, Jan. 2023.

[41] L. Xiao and Z. Lei, "Analysis of iridium-augmented GPS positioning performance," *The Journal of Engineering*, vol. 2019, no. 20, pp. 7139–7143, 2019.

[42] X. Li, K. Jiang, P. Li, X. Tang, and X. Guo, "Analysis of Navigation Augmentation Performance Based on LEO Satellite Communication Constellation," in *China Satellite Navigation Conference (CSNC 2024) Proceedings*. Singapore: Springer Nature, 2024, pp. 200–214.

[43] "Kepler - 3rd generation satellite navigation," https://www.dlr.de/en/kn/research-transfer/projects/kepler-3rd-generation-satellite-navigation.

[44] T. Schuldt, M. Gohlke, J. Sanjuan, K. Abich, M. Oswald, K. Döringshoff, E. Kovalchuk, A. Peters, and C. Braxmaier, "Optical clock technologies for future GNSS," in *Proceedings of the 31st International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2018)*, 2018, pp. 857–860.

[45] Tyler Gerald Rene Reid, Brian Manning, Adrien Louis Henry Perkins, and Andrew Michael Neish, "Satellite for Transmitting a Navigation Signal in a Satellite Constellation System," USA Patent US20 200 379 118A1.

[46] T. Reid, "Launching Xona's Ravens: Commercial Satnav from LEO," May 2022.

[47] S. Erwin, "Aerospacelab to build Xona Space's first navigation satellite," Mar. 2024.

[48] S. Xu, Q. Yang, X. Du, X. Xu, Q. Zhao, L. Yang, Y. Qin, and J. Guo, "Multi-GNSS Precise Point Positioning enhanced by the real navigation signals from CENTISPACETM LEO mission," *Advances in Space Research*, vol. 73, no. 8, pp. 4175–4186, Apr. 2024.

[49] C. Wu, S. Han, Q. Chen, Y. Wang, W. Meng, and A. Benslimane, "Enhancing LEO Mega-Constellations with Inter-Satellite Links: Vision and Challenges," Jun. 2024.

[50] I. Leyva-Mayorga, B. Soret, M. Röper, D. Wübben, B. Matthiesen, A. Dekorsy, and P. Popovski, "LEO Small-Satellite Constellations for 5G and Beyond-5G Communications," *IEEE Access*, vol. 8, pp. 184 955–184 964, 2020.

[51] G. Amendola, D. Cavallo, T. Chaloun, N. Defrance, G. Goussetis, M. Margalef-Rovira, E. Martini, O. Quevedo-Teruel, V. Valenta, N. J. Fonseca, and M. Ettorre, "Low-Earth Orbit User Segment in the Ku and Ka-Band: An Overview of Antennas and RF Front-End Technologies," *IEEE Microwave Magazine*, vol. 24, no. 2, pp. 32–48, Feb. 2023.

[52] S. Liu, Z. Gao, Y. Wu, N. D. W. Kwan, X. Gao, K.-K. Wong, S. Chatzinotas, and B. Ottersten, "LEO satellite constellations for 5G and beyond: How will they reshape vertical domains?" *IEEE Communications Magazine*, vol. 59, no. 7, pp. 30–36, 2021.

[53] W. A. Hanson, "In their own words: Oneweb's internet constellation as described in their fcc form 312 application," *New Space*, vol. 4, no. 3, pp. 153–167, 2016.

[54] P. B. de Selding, "SpaceX to build 4000 broadband satellites in Seattle," *Space news*, vol. 19, 2015.

[55] H. Xie, Y. Zhan, G. Zeng, and X. Pan, "LEO mega-constellations for 6G global coverage: Challenges and opportunities," *IEEE Access*, vol. 9, pp. 164 223–164 244, 2021.

[56] d. P. Inigo, G. C. Bruce, and F. C. Edward, "A technical comparison of three low earth orbit satellite constellation systems to provide global broadband," *Acta Astronautica*, vol. 159, pp. 123–135, 2019.

[57] SpaceX, "Starlink | Updates," https://www.starlink.com/updates, 2024.

[58] T. Pultarova, E. H. f. A. Mann, and D. D. last updated, "Starlink satellites: Facts, tracking and impact on astronomy," https://www.space.com/spacex-starlink-satellites.html, Apr. 2022.

[59] "FCC Authorizes Kuiper Satellite Constellation | Federal Communications Commission," https://www.fcc.gov/document/fcc-authorizes-kuiper-satellite-constellation, Jul. 2020.

[60] Amazon, "Application of kuiper systems LLC for authority to launch and operate a non-geostationary satellite orbit system in ka-band frequencies and attachments," Federal Communications Commission, Tech. Rep., 2019.

[61] A. Nardin, F. Dovis, and J. A. Fraire, "Empowering the tracking performance of LEO-Based positioning by means of meta-signals," *IEEE Journal of Radio Frequency Identification*, vol. 5, no. 3, pp. 244–253, 2021.

[62] J. Rainbow, "Telesat's initial LEO constellation fully funded after manufacturer switch," Aug. 2023.

[63] Editor, "Telesat struggles, but Lightspeed coming," May 2024.

[64] "Telesat Low Earth Orbit Non-Geostationary Satellite System," Federal Communications Commission (FCC), Tech. Rep., 2020.

[65] "OneWeb non-geostationary satellite system (LEO) phase 1: Modification to authorized system," Federal Communications Commission (FCC), Tech. Rep., 2020.

[66] Apollo, "Iridium Satellite System Operation," Jun. 2016.

[67] "What frequency does the Iridium satellite system use," https://www.everythingrf.com/community/what-frequency-does-the-iridium-satellite-system-use, Apr. 2022.

[68] X. Su, H. Chen, J. Zhang, T. Geng, Z. Liu, X. Xie, and Q. Li, "Navigation performance analysis of LEO augmented BDS-3 navigation constellation," in *China Satellite Navigation Conference (CSNC 2021) Proceedings*, C. Yang and J. Xie, Eds. Singapore: Springer Singapore, 2021, pp. 521–530.

[69] M. Joerger, J. Neale, and B. Pervan, "Iridium/GPS carrier phase positioning and fault detection over wide areas," in *Proceedings of the 22nd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2009)*, 2009, pp. 1371–1385.

[70] R. Morales-Ferre, P. Richter, E. Falletti, A. de La Fuente, and E. S. Lohan, "A survey on coping with intentional interference in satellite navigation for manned and unmanned aircraft," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 249–291, 2020.

[71] A. Brown, D. Reynolds, D. Roberts *et al.*, "Jammer and interference location," in *Proceedings of the 12th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 1999)*, 1999, pp. 137–142.

[72] J. Durán, D. Socías, E. Carbonell, A. González, D. Calle, and I. Rodríguez, "Exploring the Contribution of PNT LEO Satellites to Precise Positioning Applications," *Engineering Proceedings*, vol. 54, no. 1, p. 33, 2023.

[73] "Navigation Via Commercial LEO Satellites," https://gps.stanford.edu/research/current-and-continuing-gpspnt-research/multi-constellation-gnss/navigation-commercial-leo.

[74] W. Li and M. Hudson, "Earth's Van Allen Radiation Belts: From Discovery to the Van Allen Probes Era," *Journal of Geophysical Research: Space Physics*, vol. 124, no. 11, pp. 8319–8351, 2019.

[75] M. Eilenberger, H. Gunasekar, D. Gomez Toro, and C. Bänsch, "Analysis of the thermal design of a COTS-based modular battery system for satellites by thermal vacuum testing," *CEAS Space Journal*, vol. 16, no. 4, pp. 511–523, Jul. 2024.

[76] G. W. Hein, "Status, perspectives and trends of satellite navigation," *Satellite Navigation*, vol. 1, no. 1, p. 22, 2020.

[77] M. Troglia Gamba, B. D. Polidori, A. Minetto, F. Dovis, E. Banfi, and F. Dominici, "GNSS Radio Frequency Interference Monitoring from LEO Satellites: An In-Laboratory Prototype," *Sensors*, vol. 24, no. 2, p. 508, Jan. 2024.

[78] P. J. Teunissen and O. Montenbruck, Eds., *Springer Handbook of Global Navigation Satellite Systems*. Cham: Springer International Publishing, 2017.

[79] Y. Zhuang and L. Wang, "Analysis of the gravity models impact on LEO satellite orbit prediction," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLVI-3-W1-2022, pp. 307–313, Apr. 2022.

[80] X. Xie, T. Geng, Q. Zhao, X. Liu, Q. Zhang, and J. Liu, "Design and validation of broadcast ephemeris for low Earth orbit satellites," *GPS Solutions*, vol. 22, no. 2, p. 54, Apr. 2018.

[81] J. Li, D. Wang, L. Liu, B. Wang, and C. Sun, "Satellite Ephemeris Broadcasting Architecture for 5G Integrated LEO Satellite Internet," in *2022 IEEE 22nd International Conference on Communication Technology (ICCT)*, Nov. 2022, pp. 1437–1441.

[82] A. Batista, E. Gomez, H. Qiao, and K. E. Schubert, "Constellation design of a lunar global positioning system using Cubesats and chip-scale atomic clocks," in *Proceedings of the International Conference on Embedded Systems and Applications (ESA)*, 2012, pp. 1–4.

[83] C. Trainotti, M. Dassie, G. Giorgi, A. Khodabandeh, and C. Günther, "Autonomous Synchronization of Satellite Constellations via Optical Inter-Satellite Links," in *2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*. Toyama, Japan: IEEE, 2023, pp. 1–6.

[84] F. Vatalaro, G. E. Corazza, C. Caini, and C. Ferrarelli, "Analysis of LEO, MEO, and GEO global mobile satellite systems in the presence of interference and fading," *IEEE Journal on Selected Areas in Communications*, vol. 13, no. 2, pp. 291–300, 1995.

[85] V. Capuano, C. Botteron, and P.-A. Farine, "Gnss performances for meo, geo and heo," *Space Communications and Navigation Symposium-Space-Based Navigation Systems and Services*, 2013.

[86] P. A. Iannucci and T. E. Humphreys, "Economical fused LEO GNSS," *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, 2020, pp. 426–443.

[87] T. Yan, Y. Wang, X. Liu, L. Bian, and Y. Meng, "Method of GNSS Security Augmentation Based on LEO Satellite," in *China Satellite Navigation Conference (CSNC) 2020 Proceedings: Volume II*, J. Sun, C. Yang, and J. Xie, Eds. Singapore: Springer Nature, 2020, pp. 634–642.

[88] B. Li, H. Ge, Y. Bu, Y. Zheng, and L. Yuan, "Comprehensive assessment of real-time precise products from IGS analysis centers," *Satellite Navigation*, vol. 3, no. 1, p. 12, Jun. 2022.

[89] Y. Xue, F. Zheng, G. Zhou, W. Chao, D. Zhang, and C. Shi, "A new quality monitoring method for real-time precise orbit and clock products," *GPS Solutions*, vol. 28, no. 3, p. 125, May 2024.

[90] Meng Yansong, Bian Lang, Han Lin, Lei Wenying, Yan Tao, He Mu, and Li Xingxing, "A global navigation augmentation system based on LEO communication constellation," in *2018 European Navigation Conference (ENC)*, 2018, pp. 65–71.

[91] L. A. Merry, R. M. Faragher, and S. Scheding, "Comparison of opportunistic signals for localisation," *IFAC Proceedings Volumes*, vol. 43, no. 16, pp. 109–114, 2010.

[92] P.-R. J. A. del, R. Raulefs, J. A. López-Salcedo, and G. Seco-Granados, "Survey of cellular mobile radio localization methods: From 1G to 5G," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, pp. 1124–1148, 2018.

[93] I. GNSS, "A Look at the Stars: Navigation with Multi-Constellation LEO Satellite Signals of Opportunity," Aug. 2023.

[94] T. Mortlock and Z. M. Kassas, "Assessing machine learning for LEO satellite orbit determination in simultaneous tracking and navigation," in *2021 IEEE Aerospace Conference*, 2021, pp. 1–8.

[95] Q. Wei, X. Chen, Z. Ni, C. Jiang, Z. Huang, and S. Zhang, "Integrated Doppler Positioning in a Narrowband Satellite System: Performance Bound, Parameter Estimation, and Receiver Architecture," *IEEE Internet of Things Journal*, vol. 11, no. 6, pp. 10 893–10 910, Mar. 2024.

[96] A. Al-Hourani and B. Al Homssi, "Doppler Shift Distribution in Satellite Constellations," *IEEE Communications Letters*, vol. 28, no. 9, pp. 2131–2135, Sep. 2024.

[97] A. J. R. Lopez-Arreguin and S. Montenegro, "Signals of opportunity for space navigation: An application-oriented review," *Results in Engineering*, vol. 21, p. 101778, Mar. 2024.

[98] L. Morichi, A. Minetto, A. Nardin, S. Zocca, and F. Dovis, "Pseudorange and Doppler-based state estimation from MEO to LEO: A comprehensive analysis of maximum-likelihood estimators," *2024 International Technical Meeting of the Institute of Navigation (ION ITM 2024)*, Long Beach, CA, USA, Jan. 2024, pp. 677–691.

[99] F. Van Graas, "Doppler processing for satellite navigation," *2023 IEEE/ION Position, Location and Navigation Symposium (PLANS 2023)*, Monterey, CA, USA, Apr. 2023, pp. 365–371.

[100] J. Du, X. Dai, Y. Lou, Y. Qing, Y. Peng, and X. Li, "An improved method for LEO orbit prediction using predicted accelerometer data," *GPS Solutions*, vol. 28, no. 3, p. 132, May 2024.

[101] V. K. Srivastava, P. Mishra, and B. N. Ramakrishna, "Satellite ephemeris prediction for the Earth orbiting satellites," *Aerospace Systems*, vol. 4, no. 4, pp. 323–334, Dec. 2021.

[102] Tan Zizhong, Qin Honglei, Cong Li, and Zhao Chao, "New method for positioning using IRIDIUM satellite signals of opportunity," *IEEE Access*, vol. 7, pp. 83 412–83 423, 2019.

[103] H. Benzerrouk, X. Fang, R. Landry, A. Amrhar, A. Q. Nguyen, and H. Rasaee, "Iridium next LEO satellites as an alternative PNT in GNSS denied environments–Part 1," *Inside GNSS*, vol. 14, no. 3, pp. 56–64, 2019.

[104] Chen Xi, Wang Menglu, and Zhang Lei, "Analysis on the performance bound of doppler positioning using one LEO satellite," in *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, 2016, pp. 1–5.

[105] J. J. Khalife and Z. M. Kassas, "Receiver design for doppler positioning with leo satellites," in *ICASSP 2019 - 2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2019, pp. 5506–5510.

[106] M. Orabi, J. Khalife, and Z. M. Kassas, "Opportunistic navigation with doppler measurements from iridium next and orbcomm LEO satellites," in *2021 IEEE Aerospace Conference*, 2021, pp. 1–9.

[107] J. Khalife, M. Neinavaie, and Z. M. Kassas, "Navigation with differential carrier phase measurements from megaconstellation LEO satellites," in *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, 2020, pp. 1393–1404.

[108] L. Ye, Y. Yang, X. Jing, J. Ma, L. Deng, and H. Li, "Single-satellite integrated navigation algorithm based on broadband LEO constellation communication links," *Remote Sensing*, vol. 13, no. 4, p. 703, 2021.

[109] K. Shen, J. Zuo, Y. Li, S. Zuo, and W. Guo, "Observability Analysis and Optimization of Cooperative Navigation System With a Low-Cost Inertial Sensor Array," *IEEE Internet of Things Journal*, vol. 10, no. 11, pp. 9863–9877, Jun. 2023.

[110] Z. Kassas, J. Morales, and J. Khalife, "New-age satellite-based Navigation–STAN: Simultaneous tracking and navigation with LEO satellite signals," *Inside GNSS Magazine*, vol. 14, no. 4, pp. 56–65, 2019.

[111] C. T. Ardito, J. J. Morales, J. Khalife, A. Abdallah, Z. M. Kassas *et al.*, "Performance evaluation of navigation using LEO satellite signals with periodically transmitted satellite positions," *2019 International Technical Meeting of the Institute of Navigation*, 2019, pp. 306–318.

[112] P. Enge, B. Ferrell, J. Bennett, D. Whelan, G. Gutt, and D. Lawrence, "Orbital diversity for satellite navigation," in *Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2012)*, 2012, pp. 3834–3846.

[113] L. Wang, R. Chen, D. Li, G. Zhang, X. Shen, B. Yu, C. Wu, S. Xie, P. Zhang, M. Li, and Y. Pan, "Initial assessment of the LEO based navigation signal augmentation system from luojia-1A satellite," *Sensors*, vol. 18, no. 11, 2018.

[114] "Orbit of QZSS," https://qzss.go.jp/en/technical/technology/orbit.html.

[115] L. Bofeng, G. Haibo, G. Maorong, N. Liangwei, S. Yunzhong, and S. Harald, "LEO enhanced Global Navigation Satellite System (LeGNSS) for real-time precise positioning services," *Advances in Space Research*, vol. 63, no. 1, pp. 73–93, 2019.

[116] J. Ren, D. Sun, D. Pan, M. Li, and J. Zheng, "Cost-efficient LEO navigation augmentation constellation design under a constrained deployment approach," *International Journal of Aerospace Engineering*, vol. 2021, p. 5042650, 2021.

[117] M. Guan, T. Xu, F. Gao, W. Nie, and H. Yang, "Optimal Walker Constellation Design of LEO-Based Global Navigation and Augmentation System," *Remote Sensing*, vol. 12, no. 11, p. 1845, Jan. 2020.

[118] Z. Deng, W. Ge, L. Yin, and S. Dai, "Optimization design of two-layer Walker constellation for LEO navigation augmentation using a dynamic multi-objective differential evolutionary algorithm based on elite guidance," *GPS Solutions*, vol. 27, no. 1, p. 26, Nov. 2022.

[119] F. Yang, C. Zheng, H. Li, L. Li, J. Zhang, and L. Zhao, "Continuity Enhancement Method for Real-Time PPP Based on Zero-Baseline Constraint of Multi-Receiver," *Remote Sensing*, vol. 13, no. 4, p. 605, Jan. 2021.

[120] Xingxing Wang, C. Sheng, B. Yu, Z. Zhang, J. Zhang, and Q. Yi, "Rapid Re-Convergence of Real-Time Dynamic Precise Point Positioning by Adding Velocity Constraints," *Gyroscopy and Navigation*, vol. 13, no. 4, pp. 283–293, Dec. 2022.

[121] M. Ke, J. Lv, J. Chang, W. Dai, K. Tong, and M. Zhu, "Integrating GPS and LEO to accelerate convergence time of precise point positioning," in *2015 International Conference on Wireless Communications & Signal Processing (WCSP)*, 2015, pp. 1–5.

[122] M. Joerger, L. Gratton, B. Pervan, and C. E. Cohen, "Analysis of Iridium-augmented GPS for floating carrier phase positioning," *Navigation*, vol. 57, no. 2, pp. 137–160, 2010.

[123] S. Zhu, C. Reigber, and R. König, "Integrated adjustment of CHAMP, GRACE, and GPS data," *Journal of Geodesy*, vol. 78, no. 1, pp. 103–108, 2004.

[124] T. G. R. Reid, T. Walter, P. K. Enge, and T. Sakai, "Orbital representations for the next generation of satellite-based augmentation systems," *GPS Solutions*, vol. 20, no. 4, pp. 737–750, 2016.

[125] L. Meng, J. Chen, J. Wang, and Y. Zhang, "Broadcast ephemerides for LEO augmentation satellites based on nonsingular elements," *GPS Solutions*, vol. 25, no. 4, pp. 1–11, 2021.

[126] W. Kan and E.-M. Ahmed, "LEO satellite clock analysis and prediction for positioning applications," *Geo-spatial Information Science*, pp. 1–20, 2021.

[127] C. Günther, "Kepler–satellite navigation system description and validation," in *9th Workshop on Satellite Navigation Technologies (NAVITEC 2018)*. Noordwijk, The Netherlands: European Space Research and Technology Centre (ESTEC), 2018.

[128] S. Oak, S. Pullen, S. Lo, I. Colobong, J. Blanch, T. Walter, M. Crews, and R. Jackson, "GNSS Augmentation by Low-Earth-Orbit (LEO) Satellites: Integrity Performance Under Non-Ideal Conditions," *The 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023)*, Sep. 2023, pp. 1436–1453.

[129] J. Qin, X. Li, X. Ma, X. Guo, and J. Yang, "Cross-Domain Fusion Constellation Design of Communication, Navigation and Remote Sensing," *Applied Sciences*, vol. 13, no. 5, p. 3113, Jan. 2023.

[130] J. Wu, S. Su, X. Wang, J. Zhang, and Y. Gao, "Accelerating Handover in Mobile Satellite Network," in *IEEE INFOCOM 2024 - IEEE Conference on Computer Communications*, May 2024, pp. 531–540.

[131] L. Wang, Z. Lü, X. Tang, K. Zhang, and F. Wang, "LEO-Augmented GNSS Based on Communication Navigation Integrated Signal," *Sensors*, vol. 19, no. 21, p. 4700, Jan. 2019.

[132] X. Li, F. Ma, X. Li, H. Lv, L. Bian, Z. Jiang, and X. Zhang, "LEO Constellation-Augmented Multi-GNSS for Rapid PPP Convergence," *Journal of Geodesy*, vol. 93, no. 5, pp. 749–764, 2019.

[133] P. A. Iannucci and T. E. Humphreys, "Fused Low-Earth-Orbit GNSS," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 60, no. 4, pp. 3730–3749, 2024.

[134] L. Zhen, A. K. Bashir Kashif, K. Yu, Y. D. Al-Otaibi, C. H. Foh, and P. Xiao Pei, "Energy-efficient random access for LEO satellite-assisted 6G internet of remote things," *IEEE Internet of Things Journal*, vol. 8, no. 7, pp. 5114–5128, 2021.

[135] X. Lin, S. Cioni, G. Charbit, N. Chuberre, S. Hellsten, and J. F. Boutillon, "On the path to 6G: Low orbit is the new high," *CoRR*, vol. abs/2104.10533, 2021.

[136] "Solutions for NR to support non-terrestrial networks (NTN)," 3GPP, Tech. Rep. TR 38.821, Jan. 2020.

[137] D. Krystal and A. Matthew, von, "LEO constellations and tracking challenges."

[138] G. Giorgi, B. Kroese, and G. Michalak, "Future GNSS constellations with optical inter-satellite links. Preliminary space segment analyses," in *2019 IEEE Aerospace Conference*, 2019, pp. 1–13.

[139] "The Almanac, Time to First Fix and Satellite Health," https://www.e-education.psu.edu/geog862/node/1739.

[140] D. Akopian and J. Syrjarinne, "A Fast Positioning Method Without Navigation Data Decoding for Assisted GPS Receivers," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, pp. 4640–4645, Oct. 2009.

[141] C. S. Burrus, J. W. Fox, G. A. Sitton, and S. Treitel, "Horner's Method for Evaluating and Deflating Polynomials," *DSP Software Notes, Rice University, Nov*, vol. 26, 2003.

[142] D. Li, X. Zhou, and K. Li, "Centimeter-Level Orbit Determination of Grace-c Using IGS-RTS Data," *Remote Sensing*, vol. 15, no. 7, p. 1832, 2023.

[143] D. Racelis, B. Pervan, and M. Joerger, "Fault-free integrity analysis of mega-constellation-augmented GNSS," in *Proceedings of the 32nd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2019)*, 2019, pp. 465–484.

[144] P. Tavella and G. Petit, "Precise time scales and navigation systems: Mutual benefits of timekeeping and positioning," *Satellite Navigation*, vol. 1, no. 1, p. 10, Mar. 2020.

[145] M. Dassié and G. Giorgi, "Relativistic Modelling for Accurate Time Transfer via Optical Inter-Satellite Links," *Aerotecnica Missili & Spazio*, vol. 100, no. 3, pp. 277–288, Sep. 2021.

[146] W. Guo, W. Song, X. Niu, Y. Lou, S. Gu, S. Zhang, and C. Shi, "Foundation and performance evaluation of real-time GNSS high-precision one-way timing system," *GPS Solutions*, vol. 23, no. 1, p. 23, Jan. 2019.

[147] B. Jaduszliwer and J. Camparo, "Past, present and future of atomic clocks for GNSS," *GPS Solutions*, vol. 25, no. 1, p. 27, Jan. 2021.

[148] M. Motzigemba, H. Zech, and P. Biller, "Optical Inter Satellite Links for Broadband Networks," in *2019 9th International Conference on Recent Advances in Space Technologies (RAST)*, Jun. 2019, pp. 509–512.

[149] D. Muhire, D. Stepanova, S. Santra, P. Baranwal, M. Romero, R. Amrutkar, S. Bonnart, D. Jha, and A. Zucherman, "Optical Communications for Small Satellites: A Review of Pointing Strategies & Requirements Optimization," Oct. 2020.

[150] R. Wolf, "Satellite orbit and ephemeris determination using inter satellite links," Ph.D. dissertation, München, Univ. der Bundeswehr, Diss., 2001, 2001.

[151] N. Zhu, J. Marais, D. Bétaille, and M. Berbineau, "GNSS Position Integrity in Urban Environments: A Review of Literature," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 9, pp. 2762–2778, Sep. 2018.

[152] J. Song, T. Liu, X. Chen, and Z. Wu, "Satellite Navigation Message Authentication in GNSS: Research on Message Scheduler for SBAS L1," *Sensors*, vol. 24, no. 2, p. 360, Jan. 2024.

[153] D. Lawrence, D. Bunce, N. G. Mathur, and C. E. Sigler, "Wide Area Augmentation System (WAAS) - Program Status," *The 20th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2007)*, Sep. 2007, pp. 892–899.

[154] F. Ullah, M. Ahmad, M. Habib, and J. Muhammad, "Analysis of security protocols for Wireless Sensor Networks," *2011 3rd International Conference on Computer Research and Development*, vol. 2, Mar. 2011, pp. 383–387.

[155] N. Li, D. Liu, and S. Nepal, "Lightweight Mutual Authentication for IoT and Its Applications," *IEEE Transactions on Sustainable Computing*, vol. 2, no. 4, pp. 359–370, Oct. 2017.

[156] R. Tian, Z. Cui, S. Zhang, and D. Wang, "Overview of the development of navigation enhancement technology based on leo communication constellation," *Navigation, positioning and timing*, vol. 8, no. 01, pp. 66–81, 2021.

[157] P. K. Enge, "The Global Positioning System: Signals, measurements, and performance," *International Journal of Wireless Information Networks*, vol. 1, no. 2, pp. 83–105, Apr. 1994.

[158] D. Zou, X. Li, and R. Ma, "A signal optimization strategy for next generation navigation and communication integration applications," *Physical Communication*, vol. 50, p. 101510, 2022.

[159] J. Cui and H. Shi, "Satellite communication and navigation integrated signal," *TELKOMNIKA Indonesian Journal of Electrical Engineering*, vol. 11, no. 8, pp. 4351–4356, 2013.

[160] X. Huang and G. Ou, "MC-BOC: A new modulation technology for integrated navigation and communication system," *Journal of radio science*, vol. 35, no. 05, pp. 762–768, 2020.

[161] P. K. Enge, "The Global Positioning System: Signals, Measurements, and Performance," *International Journal of Wireless Information Networks*, vol. 1, no. 2, pp. 83–105, Apr. 1994.

[162] R. Chen, X. Lu, and K. Yang, "Joint resource allocation based on F-OFDM for integrated communication and positioning system," in *Communications and Networking*. Cham: Springer International Publishing, 2022, pp. 91–101.

[163] X. Luo, X. Lu, B. Yin, and K. Yang, "Resource Allocation for Joint Communication and Positioning in mmWave Ad Hoc Networks," *IEEE Transactions on Vehicular Technology*, vol. 73, no. 2, pp. 2187–2201, Feb. 2024.

[164] S. Ma, X. Li, and D. Zou, "A CCSK based navigation and communication integrated satellite signal," *2021 International Wireless Communications and Mobile Computing (IWCMC)*, 2021, pp. 1079–1082.

[165] F. Davarian, S. Asmar, M. Angert, J. Baker, J. Gao, R. Hodges, D. Israel, D. Landau, N. Lay, and L. Torgerson, "Improving small satellite communications and tracking in deep Space—A review of the existing systems and technologies with recommendations for improvement. Part II: Small satellite navigation, proximity links, and communications link science," *IEEE Aerospace and Electronic Systems Magazine*, vol. 35, no. 7, pp. 26–40, 2020.

[166] Q. Feng, H. Zhou, K. Zhao, and N. Zhang, "Sparse inverse fast Fourier transform-based channel estimation for millimetre-wave vector orthogonal frequency division multiplexing systems," *IET Communications*, vol. 11, no. 11, pp. 1732–1740, 2017.

[167] Z. Deng and L. Yin, "Indoor positioning system based on TC-OFDM system," *Information and Communication Technology and Policy*, vol. 3, pp. 32–35, 2015.

[168] W. Liu, X. Bian, Z. Deng, J. Mo, and B. Jia, "A novel carrier loop algorithm based on maximum likelihood estimation (MLE) and kalman filter (KF) for weak TC-OFDM signals," *Sensors*, vol. 18, no. 7, 2018.

[169] J. Liu, Z. Deng, K. Luo, S. Tang, and X. Deng, "An unambiguous acquisition algorithm for TC-OFDM signals based on BOC modulation," *China Satellite Navigation Conference (CSNC 2021) Proceedings*. Singapore: Springer, 2021, pp. 435–444.

[170] L. Yin, J. Cao, T. Jiang, and Z. Deng, "Joint Power Allocation for a Novel Positioning-communication Integrated Signal," *2020 IEEE/CIC International Conference on Communications in China (ICCC)*, Aug. 2020, pp. 923–928.

[171] Yin Lu, Jiang Tianrun, Deng Zhongliang, Sun Shihua, and Wang Ziyang, "Joint uplink power allocation method in wireless communication and positioning integrated system," *IEEE Access*, vol. 9, pp. 53 669–53 678, 2021.

[172] Yin Lu, Cao Jiameng, Ni Qiang, Ma Yuzheng, and Li Song, "Design and performance analysis of multi-scale NOMA for future communication-positioning integration system," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 4, pp. 1333–1345, 2022.

[173] S. Dai, L. Yin, W. Ge, and N. Djuric, "A PSO-Based Power Allocation Strategy for D2D and MS-NOMA Signals in Positioning-Timing-Communication Integration System," in *China Satellite Navigation Conference (CSNC 2024) Proceedings*, C. Yang and J. Xie, Eds. Singapore: Springer Nature, 2024, pp. 530–540.

[174] M. Wang, G. Liu, R. Ma., W. Zhao, and W. Kang, "A Novel Navigation-Communication Integrated Waveform for LEO Network," *GLOBECOM 2022 - 2022 IEEE Global Communications Conference*, Dec. 2022, pp. 747–752.

[175] Y. Li, G. Zhang, J. Yu, G. Li, and Y. Li, "OTFS-Based Communication and Navigation Integrated Signal Transmission for LEO Satellites," *2022 IEEE 22nd International Conference on Communication Technology (ICCT)*, Nov. 2022, pp. 451–457.

[176] D. Borio, F. Dovis, H. Kuusniemi, and L. Lo Presti, "Impact and Detection of GNSS Jammers on Consumer Grade Satellite Navigation Receivers," *Proceedings of the IEEE*, vol. 104, no. 6, pp. 1233–1245, Jun. 2016.

[177] P. Madhani, P. Axelrad, K. Krumvieda, and J. Thomas, "Application of Successive Interference Cancellation to The GPS Pseudolite Near-Far Problem," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 39, no. 2, pp. 481–488, Apr. 2003.

[178] M. Amin and W. Sun, "A Novel Interference Suppression Scheme for Global Navigation Satellite Systems Using Antenna Array," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 5, pp. 999–1012, May 2005.

[179] T. Oyedare, V. K. Shah, D. J. Jakubisin, and J. H. Reed, "Interference Suppression Using Deep Learning: Current Approaches and Open Challenges," *IEEE Access*, vol. 10, pp. 66 238–66 266, 2022.

[180] R. Hadani and A. Monk, "OTFS: A New Generation of Modulation Addressing the Challenges of 5G," Feb. 2018.

[181] Y. Wang, H. Luo, Y. Chen, J. Wang, R. Li, and B. Wang, "Integrated Communication and Navigation for Ultra-Dense LEO Satellite Networks: Vision, Challenges and Solutions," 2021, *arXiv:2105.08985*.

[182] J. Li, B. Liu, and M. Peng, "Joint Beamforming Design and Satellite Selection for Integrated Communication and Navigation in LEO Satellite Networks," 2024, *arXiv:2410.19358*.

[183] L. You, X. Qiang, Y. Zhu, F. Jiang, C. G. Tsinos, W. Wang, H. Wymeersch, X. Gao, and B. Ottersten, "Integrated Communications and Localization for Massive MIMO LEO Satellite Systems," *IEEE Transactions on Wireless Communications*, vol. 23, no. 9, pp. 11061–11075, 2024.

[184] "Study on new radio (NR) to support non-terrestrial networks," 3GPP, Tech. Rep. TR 38.821, 2021.

[185] *Digital Video Broadcasting (DVB); Second Generation Broadcast Satellite System (DVB-S2X); Part 2: Lower Layers for Physical Layer and DVB-S2 Extensions (DVB-S2X)*, Std. EN 302 307-2, 2014.
[186] J. Iyengar and M. Thomson, "QUIC: A UDP-based multiplexed and secure transport," 2021.
[187] "Interface control document (ICD) for L2 civil (L2C)," US DoD, Tech. Rep. IS-GPS-200D, 2013.
[188] European GNSS Supervisory Authority, *Galileo Open Service: Signal in Space Interface Control Document (OS SIS ICD), Issue 2.1*. Luxembourg: Publications Office of the European Union, 2023. [Online]. Available: https://data.europa.eu/doi/10.2878/39727
[189] *RTCM Standard for Differential GNSS Services, Version 3.3, SC-104*, Std. 10 403.1, 2019.
[190] *CCSDS PNT-EPH-01: Packet Telemetry Standard for PNT Data*, Std. PNT-EPH-01, 2020.
[191] "WAAS Interface Control Document," Federal Aviation Administration, Tech. Rep., 2020.
[192] S. Sörensen and S. Rauch, "Networked Transport of RTCM via Internet Protocol (NTRIP)," 2007.
[193] S. Burleigh and A. Hooke, "Bundle Protocol Specification (bpv7)," 2022.
[194] "System Architecture for The 5G System: Stage 2," 3GPP, Tech. Rep. TS 23.501, 2022.
[195] "Management and Orchestration; Network Slicing Management and Orchestration," 3GPP, Tech. Rep. TS 28.531, 2021.
[196] *CCSDS Mission Operations Services Draft Recommended Standard*, Std. 520.0-B-2, 2018.
[197] Q. Chen, L. Yang, J. Guo, X. Liu, and X. Chen, "Optimal Gateway Placement for Minimizing Intersatellite Link Usage in LEO Megaconstellation Networks," *IEEE Internet of Things Journal*, vol. 9, no. 22, pp. 22 682–22 694, Nov. 2022.
[198] A. Nardin, A. Minetto, O. Vouch, M. Mariani, and F. Dovis, "Snapshot Acquisition of GNSS Signals in Space: A Case Study at Lunar Distances," *The 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022)*, Sep. 2022, pp. 3603–3617.
[199] L. Meng, L. Yang, W. Yang, and L. Zhang, "A survey of GNSS spoofing and anti-spoofing technology," *Remote Sensing*, vol. 14, no. 19, 2022.
[200] A. Al-Hourani, "Session duration between handovers in dense LEO satellite networks," *IEEE Wireless Communications Letters*, vol. 10, no. 12, pp. 2810–2814, 2021.
[201] Z. Li, Z. Xie, and X. Liang, "Dynamic channel reservation strategy based on DQN algorithm for multi-service LEO satellite communication system," *IEEE Wireless Communications Letters*, vol. 10, no. 4, pp. 770–774, 2021.
[202] H. Liu, J. Lai, J. Zhu, L. Gan, and Z. Chang, "Enabling High-Throughput Routing for LEO Satellite Broadband Networks: A Flow-Centric Deep Reinforcement Learning Approach," *IEEE Internet of Things Journal*, pp. 1–1, 2024.
[203] C.-Q. Dai, M. Zhang, C. Li, J. Zhao, and Q. Chen, "QoE-Aware Intelligent Satellite Constellation Design in Satellite Internet of Things," *IEEE Internet of Things Journal*, vol. 8, no. 6, pp. 4855–4867, Mar. 2021.