Integrated Communication and Navigation for Ultra-Dense LEO Satellite Networks: Vision, Challenges and Solutions

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ABSTRACT

Next generation beyond 5G networks are expected to provide both Terabits per second data rate communication services and centimeter-level accuracy localization services in an efficient, seamless and cost-effective manner. However, most of the current communication and localization systems are separately designed, leading to an under-utilization of radio resources and network performance degradation. In this paper, we propose an integrated communication and navigation (ICAN) framework to fully unleash the potential of ultra-dense LEO satellite networks for optimal provisioning of differentiated services. The specific benefits, feasibility analysis and challenges for ICAN enabled satellite system are explicitly discussed. In particular, a novel beam hopping based ICAN satellite system solution is devised to adaptively tune the network beam layout for dual functional communication and positioning purposes. Furthermore, a thorough experimental platform is built following the Third Generation Partnership Project (3GPP) defined non-terrestrial network simulation parameters to validate the performance gain of the ICAN satellite system.

Index Terms

Integrated communication and navigation, multi-beam LEO satellite, ultra-dense networks, positioning accuracy, beam hopping.

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I. INTRODUCTION

Accommodating ubiquitous connectivity and high data rate communication services is one of the main goals for communication networks. To complement this goal, satellite communication has gained a renewed upsurge in the New Space era [1] due to its ability to provide global wireless coverage and continuous service guarantee especially in scenarios not optimally supported by terrestrial infrastructures. In particular, a new work item has recently been initialized by the Third Generation Partnership Project (3GPP) to study a set of necessary adaptations enabling the operation of 5G New Radio (NR) protocol in non-terrestrial network (NTN) with a first priority on satellite access [2]. In the NTN context, compared with conventional geostationary earth orbit (GEO) and medium earth orbit (MEO), low earth orbit (LEO) based satellite networks stand out as a promising solution considering the lower propagation delay, power consumption and launch cost. As such, numerous companies have announced ambitious plans to provide broadband Internet access over the globe by deploying LEO satellite mega-constellations, e.g., OneWeb, Kuiper and Starlink [3].

In parallel to legacy communication services, the rapid proliferation of location-based services, e.g., smart transportation, augmented reality and autonomous driving, brings great value-added opportunities to communication networks. In this regard, it is much anticipated to provide high precision positioning and navigation information through communication networks [4]. As specified by NR Release-16, a positioning accuracy of 3-meter within 1 second end to end latency should be achieved for commercial use cases [5], and subsequent releases are expected to further targeting sub-meter accuracy and millisecond level lower latency. To circumvent this issue, the vision of integrated communication and navigation (ICAN) is proposed to fully reap the benefits of next generation wireless networks [6], [7]. With ICAN, it becomes possible to exploit co-design and optimization of communication and localization aspects for best utilization of shared network infrastructures and radio resources.

Specifically, in ultra-dense LEO satellite networks, the ICAN paradigm exhibits some distinct advantages, such as navigation improvement with stronger signal strength and better network geometry, and user equipment (UE) self-localization enhanced network access and mobility management. To the authors’ best knowledge, this is the first in-depth study on applying ICAN

\[1\] Navigation can be considered as a set of continuous and dynamic positioning/localization procedures. In this paper, we use navigation and positioning/localization interchangeably when no ambiguity occurs.
concept in the context of LEO satellite mega-constellations. Particularly, we present a through analysis on the benefits, feasibility and challenges for ICAN enabled ultra-dense satellite networks. A novel beam hopping (BH) based solution is then proposed to facilitate flexible ICAN satellite network operation, such that the satellite system can adaptively tune its physical beams for dual-functional communication and positioning purposes. The associated measurement signal structure, physical layer control procedures and practical BH algorithm are elaborated for the integrated satellite system. To validate the performance gain brought by ICAN satellite system, we have conducted a set of experiments following 3GPP NTN satellite simulation assumptions. The numerical results demonstrate that the proposed BH solution can dramatically improve the positioning accuracy from approximate 200-meter to 20-meter. Next, some future research directions are investigated. Finally, we conclude our work.

II. ICAN Satellite Network Vision Overview

A. ICAN Satellite Network: Concepts and Benefits

Traditionally, although localization systems can reuse communication infrastructures like cellular networks cost-effectively to some extent, the localization and communication systems are mostly designed in separation. This inevitably results in a waste of precious radio resources and network performance degradation. To this end, the ICAN concept is proposed to support both communication and positioning services with optimized network infrastructure design and radio resource utilization for dual purposes. An illustrative example of ICAN enabled satellite system is shown in Fig. 1. An ICAN UE can simultaneously receive a set of integrated signal blocks (ISBs) from multiple satellites possibly operating at different orbits. ISBs are utilized for both communication and localization purposes. Besides, to alleviate inter-satellite interference, a color reuse pattern, e.g., 4-color reuse, is employed to broadcasting ISBs originated from different satellites/beams, wherein a color refers to a combination of polarization and frequency. Last but not the least, an integrated ICAN UE receiver structure can be customized to encompass channel estimation, information decoder and location measurement [6], such that both services can be provisioned in a seamless manner.

Especially in the context of ultra-dense LEO satellite networks, ICAN paradigm exhibits some distinct benefits as follows.

**Location based communication optimization:** Due to the prevalent frequency/polarization reuse pattern, a UE can simultaneously measuring positioning reference signals at different
frequencies/polarizations from multiple satellites. Through the range measurements and available broadcasting satellite ephemeris, creditable self-localization can be attained by computing location results at the UE side. The acquired location information can be exploited to simplify network mobility management, improve Doppler compensation and timing advance maintenance, and facilitate location enhanced network access over the globe in the highly dynamic LEO satellite scenario. As a consequence, network signaling overhead can be significantly reduced.

**Communication for enhanced localization:** Compared with traditional global navigation satellite system (GNSS) operating at MEO and GEO, LEO satellite network offers several advantages such as lower propagation delay, 300 to 2400 times stronger signals and threefold improvement in satellite geometry [8]. Through exploitation of LEO satellite communication capabilities, e.g., satellite-air-ground cooperative transmission, inter-satellite link augmented communication, and satellite communication signals of opportunities, positioning/navigation accuracy can be significantly improved and both multiple-satellite searching complexity and time to first fix can be decreased to some extent.

In summary, the adoption of ICAN can bring additional potential to LEO satellite networks.

**B. Feasibility Analysis**

One fundamental prerequisite towards realizing ICAN satellite system is feasibility analysis. To this end, we highlight several conditions and technical advances that accelerate the pace to
a truly functional integrated network.

- **Satellite network densification:** Driven by advanced manufacturing technology and cheaper launch costs, the LEO satellite network scale has tremendously expanded from traditionally tens of satellites to thousands or even tens of thousands of satellites in the last few decades. For instance, Amazon has recently gained the approval of its Kuiper constellation with 3236 satellites from the U.S. Federal Communications Commission (FCC) [9]. Meanwhile, SpaceX tends to build its magnificent Starlink constellation composed of nearly 12000 satellites, with more than 500 satellites already deployed on orbit by June 2020 [10]. As a matter of fact, a UE in a dense satellite network generally can have tens or even hundreds of satellites in view simultaneously. This greatly boosts the communication and navigation capability through multi-satellite cooperation technique.

- **Satellite communication characteristics:** Unlike the aggressive full frequency reuse in cellular networks, satellite communication typically adopts a frequency/polarization reuse pattern with reuse factor larger than one to mitigate inter-beam interference. This fact is consistent with the localization requirement, as a UE can receive multiple signals at the same time by monitoring different frequencies/polarizations. On the other hand, different from terrestrial networks where the location of base stations is confidential and not informed to UEs, satellite ephemeris are commonly available to UEs in coverage. Therefore, in the satellite scenario, it is feasible and convenient to compute location at the UE side without incurring much complexity and signaling overhead.

- **Flexible onboard payload:** Owing to the development of flexible satellite payload technique, satellite communication has evolved from previous bent-pipe/transparent architecture to current regenerative one with powerful onboard processing functions, e.g., beam steering and resource orchestration ability [11]. As a consequence, multiple functions can now be implemented within the satellite itself rather than the ground stations. For example, an Iridium-Next satellite is equipped with communication payload, navigation enhancement payload and earth observation sensors. On the basis, intelligent payload operation for multifarious services can be performed.

C. Challenges

Despite the above advantages, it is technically challenging to design an ICAN satellite system.
• Flexible system architecture: Currently, a communication system is designed mainly for communication purpose with proprietary payload and protocols. As an integrated network, the network is expected to intelligently reconfigure its architecture, e.g., network geometry, reference signal structure and control procedure, such that differentiated services can be optimally supported. Unfortunately, the dynamic network topology variation and constrained multi-dimensional heterogeneous resources induce difficulties in system architecture design.

• Quality of Service (QoS) provisioning: Communication services and positioning services have distinct QoS requirements. Regarding communication services, it is sufficient to have good coverage and signal quality purely from the serving satellite. While for positioning services, acceptable signal quality and network geometry of multiple satellites are essential. The aforementioned two goals are contradictory in general, because a good signal quality for the serving satellite normally means low interference as well as signal strength from neighboring satellites.

• Beam management: Next generation satellites are expected to carry several tens of narrow spot beams. Those beams can be manipulated over complex dimensions, e.g., space, time, power and frequency domain. Multi-dimensional resource joint optimization should be performed for beam management to deal with the extremely non-uniform traffic distribution. To make matter worse, with the fast mobility of satellites, i.e., approximate 7.5 km/s for a typical LEO satellite, beams should be shut on and off from time to time for interference reduction. This leads to extra non-negligible complexity in satellite beam management.

III. Beam Hopping based ICAN Satellite System

Herein, we mainly elaborate on the novel BH based ICAN satellite system framework, which includes the system workflow, detailed BH algorithm design and performance evaluation.

A. System Workflow

First, both the downlink measurement signal structure and physical layer control procedures are designed to facilitate the ICAN satellite system operation.

1) New Measurement Signal Structure: In NR, the downlink measurement signals for UEs during initial access and idle mode are termed as synchronization signal blocks (SSBs). While in the ICAN enabled NTN environment, a new measurement signal structure is required to enable both cell search and UE passive localization process. Specifically, the ISBs consist of two logical
parts, namely communication reference signal blocks (CRSBs) and positioning reference signal blocks (PRSBs). We use the term logical because the actual realization of CRSBs and PRSBs can be the same in uniform broadcasting signal design case or different in separate broadcasting signal design case. An example measurement signal structure for the above two cases are depicted in Fig. 2(a) and Fig. 2(b), respectively. Hereafter, the separate design case is taken as an example to show the concrete functions of CRSBs and PRSBs.

**CRSBs:** The CRSBs are used for UEs to acquire time and frequency synchronization with a cell and to detect its physical layer cell ID. The CRSBs last for a time duration of $T_{CRSB}$ within a periodicity of $T_{per}$. To some extent, one can view CRSBs as conventional SSBs, except that CRSBs have a more general meaning and can span over frequency/time/space domain. Notably, a UE can acquire the PRSB configurations for multiple neighboring satellites by extracting the system information (SI) contained in the CRSBs of the accessed cell.

**PRSBs:** The PRSBs are dedicated for ranging purpose, and span for a time duration of $T_{PRSB}$...
within a periodicity of $T_{\text{per}}$. The pseudo-random quadrature phase shift keying (QPSK) sequence with diagonal pattern defined in Release-9 is an example PRSB design. A UE can receive PRSBs from multiple satellites on demand and perform related measurements, e.g., time of arrival (ToA), frequency of arrival (FoA), and angle of arrival (AoA), to calculate self location. Note that both CRSBs and PRSBs can be turned on and off for the aim of interference reduction and service provisioning. Furthermore, the time duration of $T_{\text{CRSB}}$ and $T_{\text{PRSB}}$ can be tuned dynamically to strike a good balance between communication and localization performance.

2) Physical Layer Control Procedures: The physical layer control procedure is tailored for ICAN satellite system. A concrete flow diagram of the control procedure is given in Fig. 3. To be specific, a UE during initial access or in the idle mode should first search for the CRSBs from its serving satellite. Based on the received signal quality and CRSB configuration information, the UE can then perform random access or cell reselection procedure. Note that the aforementioned procedures are completed purely based on signal quality measurements, e.g., reference signal receiving power (RSRP). If there is positioning requirement for mobility management or cell access, the UE should then measure PRSBs from multiple neighboring satellites besides the serving satellite. The configuration information of the PRSBs can be obtained from the serving satellite’s SI. Through adequate number of range measurements, e.g., ToA/FoA/AoA, the UE is able to calculate its own location and then utilize the location information for various usage, e.g., location enhanced network access.

B. Beam Hopping Scheme

Due to the payload weight and volume limitations, it is essential to employ only a small subset of transmitters/beams for serving extensive satellite coverage area. As an appealing solution, BH has been proposed accordingly. Assuming that a satellite intends to achieve a coverage of $N$ beams by $K$ transmitters/beams with $K < N$. For this aim, at each time stamp, a maximum number of $K$ beams are assigned to illuminate a portion of the whole satellite coverage area, and time-division multiplexing approach is implemented to manipulate the set of $K$ beams into different portions within the coverage area of $N$ beams. Through flexible beam allocation, full satellite coverage service can be eventually obtained.

Herein, we exploit the BH mechanism to efficiently broadcast ISBs, i.e., CRSBs and PRSBs, in ICAN enabled satellite systems. More specifically, CRSBs are transmitted using communication beams, while PRSBs are transmitted by positioning beams. To support the beam sharing over
a common physical transceiver, BH is applied to adaptively tune the physical beams between communication beams and positioning beams in a time-division multiplexing manner. Besides, an efficient UV plane based BH algorithm (UVBHA) is devised for beam transformation, where UV plane is defined as the perpendicular plane to the satellite-earth line on the orbital plane [2]. In UVBHA, a hexagonal beam layout is defined on the UV plane with UV coordinate of the nadir of the reference satellite setting to (0,0) for communication beams. For positioning beams, there are two different configuration situations. Firstly, to perform localization in its own service area, the satellite can simply reuse the communication beams as positioning beams. Secondly, to assist localization for a neighboring satellite, the satellite needs to translate the beams centered
at (0,0) to the center of the neighbor satellite’s nadir in the UV plane denoted by \((u, v)\). We can derive \(u = \sin \theta \cos \varphi\) and \(v = \sin \theta \sin \varphi\), where \(\theta\) and \(\varphi\) represent beam bore-sight steering angle and azimuth, respectively.

An example beam layout of 4 satellites for the proposed UVBHA in geodetic plane is shown in Fig. 4. As can be seen, each satellite is equipped with 61 beams. The set of communication beams are pointed at the origin, i.e., (0,0) in the UV plane, of the reference satellite. In addition, Sat-1 in Fig. 4(b) still uses the set of communication beams as positioning beams. For neighboring satellites, i.e., Sat-2, Sat-3 and Sat-4, the set of beams are redirected to the nadir of Sat-1 to enable UE localization in its service area. Consequently, with UVBHA, the physical beams can be shared for dual purposes, i.e., communication and positioning beams. There are several aspects to be noted in BH algorithm design. First, the beam layout for positioning beams are generally not hexagonal as beams deviates from the nadir. Second, the coverage of positioning beams after BH is larger than that of communication beams, and thus further optimization, e.g., turn off some edge beams, can be investigated.

C. Performance Evaluation

In this part, to validate the performance gain brought by ICAN satellite system, a thorough simulation platform is built based on 3GPP NTN simulation assumptions and parameters. The
set of key parameters used for simulation are summarized in Table I. Particularly, the satellite network comprises a total of 2400 satellites, with an orbit height of 1200 km and inclination of 87.5 degree. For dynamic simulation, the orbit period is divided into 100 snapshots of equal time duration. A total of 500 stationary UEs are randomly deployed in the target area with longitude and latitude setting to [-70,-60] and [-5,5], respectively. The time differential of arrival (TDOA) based positioning algorithms adopted by 3GPP technical specifications are taken as the benchmark and the corresponding Cramer-Rao lower bound (CRLB) for positioning performance is theoretically derived. The CRLB results for different schemes in the example network are given in Fig. 5. It can be observed that the proposed BH method significantly outperforms traditional method using communication beams (TMCB) in terms of CRLB. This is because in TMCB, although the received signal quality from the serving satellite is favorable,

<ref>Since the communication beams in conventional system and ICAN satellite system are identical, there is no difference in communication related performance, e.g., signal quality. We thus only consider positioning related performance comparison in this paper.</ref>
the signal quality from neighboring satellites is very poor due to the long distance between UE and beam center location. Nonetheless, in the proposed BH method, neighboring satellite beam center is directed to cover UEs of interest, and thus multiple signals with good quality can be measured to facilitate high accuracy positioning. Besides, as the number of positioning satellites increases from 6 to 8, the CRLBs for both algorithms improve as well. This phenomena can be expected, because more signals and better network geometry are obtained by exploring satellite diversity. Furthermore, both the TMCB and proposed BH method exhibit CRLB fluctuation as time snapshots change. The variation tendency is quite complicated, due to the intertwined influence by time varying inter-beam interference and dynamic geometric dilution of precision (GDOP).

IV. OPEN RESEARCH ISSUES

In this section, we identify several open research directions related to the ICAN system design.

A. Intelligent Multi-Resource Allocation

With multi-dimensional resources, e.g., power, time, frequency and beam, presented in the integrated network, intelligent resource allocation scheme is highly required. However, due to
the highly dynamic network topology evolution, the multi-resource availability varies accordingly. Besides, the non-uniform traffic distribution in both space-time domain makes the optimal match between resource and differentiated services challenging. To make matter worse, the use of massive satellites and dense beams exacerbates the prevalent inter-beam interference problem in satellite networks. This issue needs to be carefully tackled in the resource allocation schemes. One viable solution is to apply the promising machine learning technique, e.g., deep learning and reinforcement learning, because more cognition and intelligence can be exploited to improve network performance under complex and dynamic radio conditions [12], [13].

B. Integrated Broadcasting Signal Design

To fully reap the benefits of the envisioned ICAN satellite network, a fundamental issue lies in the ISB design for dual communication and navigation usage. As for communication waveform design, several key parameters including peak-to-average power ratio (PAPR), out of band leakage, error performance and spectral efficiency should be considered. With respect to navigation waveform design, it is crucial to take autocorrelation/cross-correlation properties and ranging resolution requirements into account. However, traditional orthogonal frequency division multiplexing (OFDM) communication signal is suboptimal in the satellite environment, due to the high PAPR, large Doppler shift and long delay presented in ICAN satellite system. Further investigation is highly demanded to solve the aforementioned problem.

C. Theoretical Performance Analysis Framework

Theoretical performance analysis can provide important guidance for ICAN satellite system design. However, it is a nontrivial task to conduct theoretical performance analysis for ultra-dense LEO satellite networks considering the following aspects. On the one hand, the network is dynamic in terms of both channel connectivity and quality, a tractable analysis framework dealing with those dynamics is troublesome. Moreover, the complicated interaction between communication and navigation should be captured in the performance analysis framework. On the other hand, numerous imperfect stochastic effects should be accounted in the ICAN satellite network for accurate analysis, such as large delay, nonlinearity, orbit perturbation, atmospheric environment and so on. A possible solution is to leverage both the stochastic geometry and dynamic graph theory [14], [15], such that both the dynamic and stochastic effects are elegantly modeled. Overall, in-depth research efforts are expected to tackle this issue.
D. Multi-Layer Heterogeneous Network Cooperation

It is widely acknowledged that a single standalone network infrastructure is not sufficient and economic to support diverse service requirements, e.g., Terabits per second data rate and centimeter-level positioning accuracy. For instance, terrestrial cellular network is generally not available in remote and disaster-striking areas, while satellite/aerial communication experiences heavy attenuation in indoor environments. In this regard, it is imperative to construct a multi-layer heterogeneous network architecture integrating satellite, air, and ground counterparts. However, due to the various characteristics and capacity of the above three network segments, network cooperation scheme with context-awareness becomes quite complex and remains to be studied.

V. CONCLUSION

This article addressed the issue of exploiting ICAN techniques for ultra-dense LEO satellite networks. The beam hopping based framework encompassing reference signal structure, physical layer control procedure, algorithm design, and performance evaluation was comprehensively studied. Significant CRLB performance gains are achieved through the integrated system. Since ICAN enabled satellite system is still in its infancy, we expect that this study could open up a new research direction for the design of next-generation LEO satellite networks.

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