Optimizing Spectrum Sensing in Cognitive GEO-LEO Satellite Networks: Overcoming Challenges for Effective Spectrum Utilization

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***Abstract*—The rapid growth of wireless and satellite technologies has increased the demand for efficient use of the electromagnetic spectrum. Cognitive satellite networks offer a promising solution, with spectrum sensing being crucial for optimal utilization of radio frequency resources. However, in cognitive satellite networks, characterized by excessive propagation delays, the effectiveness of spectrum sensing depends on the strategic placement of sensing nodes. This paper represents the first endeavor in the literature to investigate optimal spectrum sensing locations considering propagation delay for effective spectrum utilization in cognitive satellite networks. We begin by examining the geostationary (GEO) satellite downlink spectrum availability for cognitive technology through observations of the Inmarsat-4 F1 satellite downlink activities. We then analyze the impact of propagation delays on spectrum sensing in cognitive dual satellite networks, where low Earth orbit (LEO) satellites share the spectrum allocated to GEO satellites. Additionally, we address a critical design consideration: tracking GEO frequencies against Doppler shifts at LEO satellites, which significantly affects the effectiveness of spectrum sensing by LEO satellites. Finally, we explore future research directions in spectrum sensing within cognitive GEO-LEO satellite networks.**

***Index Terms*—Cognitive GEO-LEO satellite networks, spectrum sensing, GEO frequency tracking, propagation delay, Doppler shift.**

I. INTRODUCTION

The evolution of 6G and upcoming wireless networks has embraced satellite communications as a vital component to achieve worldwide connectivity. This integration of satellite communication has sparked a significant shift in our communication methods and access to information, resulting in an unprecedented surge in demand for the electromagnetic spectrum. As the number of wireless devices and applications continues to grow, efficiently and reliably utilizing the limited radio frequency resources has become a significant challenge. In this context, cognitive networks have emerged as a promising solution to address the issue of spectrum scarcity. Cognitive networks empower secondary users to autonomously sense and opportunistically exploit underutilized frequency bands of primary users, thereby enhancing the overall spectrum efficiency.

Incorporating cognitive technologies into satellite communications offers a viable approach to overcome the challenges associated with limited spectrum resources. Unlike terrestrial bands, the spectrum bands reserved for satellites, particularly those designated for geostationary (GEO) satellites, have not experienced the same level of congestion, making them an attractive option for spectrum sharing. A recent area of research that has garnered attention is cognitive dual satellite networks (CDSNs), wherein two satellite systems share the same spectrum. Specifically, CDSNs involve a low Earth orbit (LEO) satellite system utilizing the unused spectrum of a GEO satellite system. To ensure the effective and efficient operation of CDSNs, various techniques are currently under development, including spectrum sensing, interference mitigation, and spectrum accessing. However, it is worth noting that these techniques tailored for satellite networks are still in their early stages compared to their counterparts designed for terrestrial networks. Despite this, spectrum sensing remains a critical aspect of CDSNs. Its effectiveness is influenced by several factors, with the placement of sensing nodes being one of the key considerations. The strategic placement of these nodes significantly impacts the accuracy, reliability, and overall performance of spectrum sensing in CDSNs, primarily due to the excessive propagation delay experienced in comparison to terrestrial networks. When the sensing nodes are strategically located closer to the primary users, the propagation delay is minimized. This reduction in propagation delay allows for faster detection of spectrum availability and improves the system's responsiveness to dynamic changes in the spectrum environment.

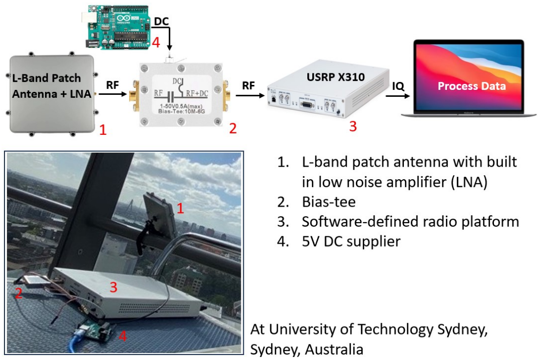
In CDSNs, spectrum sensing can take place either on the ground by LEO users or via LEO satellites. Currently, the prevailing method involves ground users conducting the sensing. This preference stems mainly from the ease of integrating established spectrum sensing technologies from terrestrial networks into satellite networks, given that GEO satellites remain relatively stationary to ground users. However, this approach falls short in maximizing spectrum utilization. When sensing is carried out by secondary users who are farthest from GEO satellites, it leads to increased sensing and communication times, thereby diminishing the available secondary spectrum usage time for LEO satellite systems. Conversely, when sensing is conducted by LEO satellites, it brings the sensing nodes closer to GEO satellites, resulting in shorter sensing and communication times. Nonetheless, spectrum sensing technology tailored for LEO satellites is still in its early stages of development, primarily due to the integration complexity involved. One significant challenge specific to LEO satellites is the presence of Doppler shift effects caused by their movement. These effects induce frequency shifts in received signals, posing complications for spectrum sensing efforts.

Overcoming Doppler shift and reliably detecting signals amid frequency variations present notable technical hurdles in this domain. Only few studies, [1]–[3], have explored the use of LEO satellites for spectrum sensing. In [1], spectrum sharing challenges were explored in a cognitive satellite network with a GEO satellite and a pair of LEO satellites. One LEO satellite performed spectrum sensing for the GEO spectrum, while the other engaged in secondary transmission, leveraging insights from the sensing LEO satellite. However, the transmission protocol introduced additional latency for ground users due to the segregation of sensing and transmission satellites. Moreover, the optimization problem primarily focused on maximizing the throughput of the data transmission LEO satellite, neglecting solutions for mitigating Doppler shift from LEO satellite movement. A radio environment map within a cognitive GEO-LEO network was established in [2]. LEO satellites conducted spectrum sensing but did not make the final decision. Instead, they transmitted sensing data to a ground-based fusion center for decision-making. However, this approach prolonged sensing duration due to the time required for data transmission and decision-making, leading to insufficient utilization of the available GEO spectrum. Contrarily, [3] presented a machine learning-driven cyclostationary spectrum sensing algorithm specifically designed for LEO satellites in a CDSN. While this algorithm accounted for Doppler shift experienced by LEO satellites, it lacked sufficient measures to tackle the GEO frequency tracking issue. Additionally, [3] solely investigated a scenario where the LEO satellite operates under a single beam from the GEO satellite, which might not accurately represent real-world operational conditions.

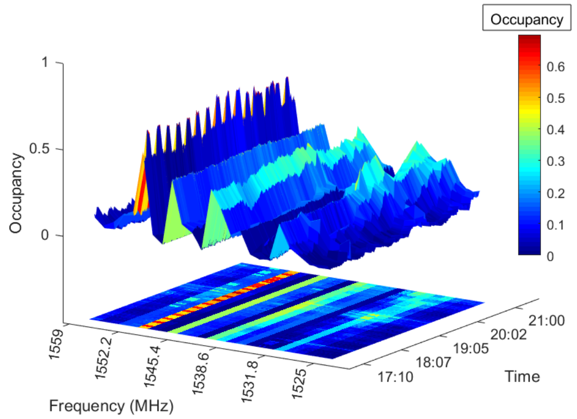
This article explores the opportunities and challenges of spectrum sensing in cognitive GEO-LEO satellite networks. It begins by assessing the available downlink spectrum of the Inmarsat-4 F1 GEO satellite to evaluate the feasibility of cognitive technology adoption. It then explores strategies for deploying spectrum sensing nodes and examines the impact of propagation delay on spectrum sensing by ground users and LEO satellites. Findings show that LEO satellites can achieve over 90% effectiveness in utilizing available GEO spectrum, compared to 20% when conducted on the ground. The article also addresses the crucial design challenge of maintaining frequency tracking at LEO satellites for GEO signals, considering the Doppler effect caused by LEO satellite movement. By highlighting these key aspects, the article aims to enhance understanding of spectrum sensing at LEO satellites and promote efficient electromagnetic spectrum utilization in cognitive satellite networks.

II. How Much Spectrum Is Available for Sharing

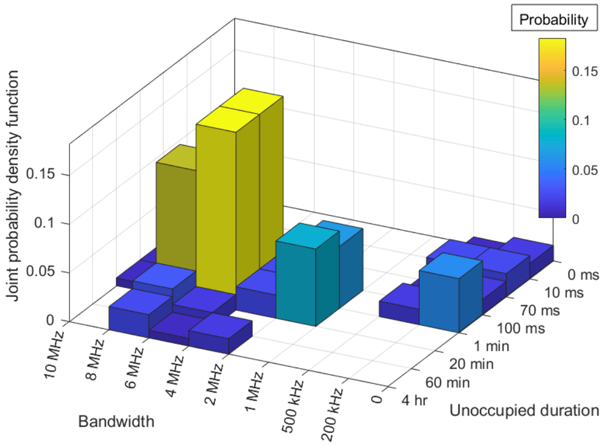
In order to assess the amount of unused spectrum within the GEO satellite system, we undertook the task of capturing and analyzing signals from GEO satellites. This effort aimed to identify potential opportunities for cognitive technology in both the frequency and time domains. Our primary focus was on capturing signals from the Inmarsat-4 F1 Broadband Global Area Network satellite, positioned at a longitude of 143.5° East, which is received in Sydney, Australia.



(a) Measurement setup.



(b) Spectrum occupancy.



(c) Joint probability density function of bandwidth and unoccupied duration.

Fig. 1. Measurement platform and spectrum availability results for Inmarsat-4 F1 L-band downlink.

The measurements, illustrated in Fig. 1a, were conducted within the Inmarsat downlink L-band, spanning a frequency range of 1525 to 1559 MHz. A USRP X310 software-defined radio (SDR) was used to capture the signals continuously for four hours. The SDR was connected to an L-band patch antenna equipped with a built-in low noise amplifier and a bias tee for the measurement. A detailed description of the measurement platform can be found in [4]. To evaluate the spectrum occupancy, we measured the power levels of the detected signals.

The results shown in Figs. 1b and 1c illustrate a significant amount of accessible spectrum within the Inmarsat downlink band of the Sydney beam. Fig. 1b presents the spectrum occupancy, which indicates the percentage of time the received signal power exceeds a predefined threshold of -40 dB throughout the total measurement period. We observe that most of the L-band exhibits low occupancy levels, with only the subband from 1550.84 MHz to 1552.2 MHz exceeding an occupancy level of 0.5.

Fig. 1c displays the joint probability density function of available bandwidth and unoccupied duration, revealing a range of unoccupied durations ranging from 10 ms to over 60 minutes across different bandwidths. Notably, only 8% of the spectrum was in use for over 99% of the measured duration, indicating a substantial portion of untapped spectrum. Almost half of the spectrum remained accessible for 99% of the time, highlighting a strong potential for the implementation of cognitive technologies.

The duration of unoccupied spectrum plays a critical role in enhancing spectrum reuse efficiency within cognitive GEO-LEO satellite networks. For shorter unoccupied durations, such as 10 ms or 20 ms, the time required for sensing and communication to and from LEO satellites may exceed these brief intervals. This mismatch can lead to wasted spectrum, as the process of identifying and utilizing available spectrum may not be completed in time to capitalize on these fleeting opportunities. Moreover, current spectrum sensing technologies that detect GEO satellite signals from the ground often require additional time to accurately identify and switch to available frequencies, limiting their effectiveness for such short durations.

III. IMPACT OF PROPAGATION DELAY ON SPECTRUM SENSING IN CDSNS

A. Propagation Delay and Spectrum Sensing

Consider a CDSN with a LEO satellite network utilizing the downlink spectrum resources of a GEO satellite network as shown in Fig. 2. In this CDSN, the primary network consists of a GEO satellite, denoted as S_{GEO}, and a GEO satellite user, labeled as SU_G. The secondary network comprises a LEO satellite, referred to as S_{LEO}, along with a LEO satellite user, denoted as SU_L. Due to the high altitude of GEO satellite, the difference in propagation delay from S_{GEO} to SU_L and SU_G is negligible.

We analyze two distinct case studies in the spectrum sensing scheme, which depend on the location of S_{LEO}:

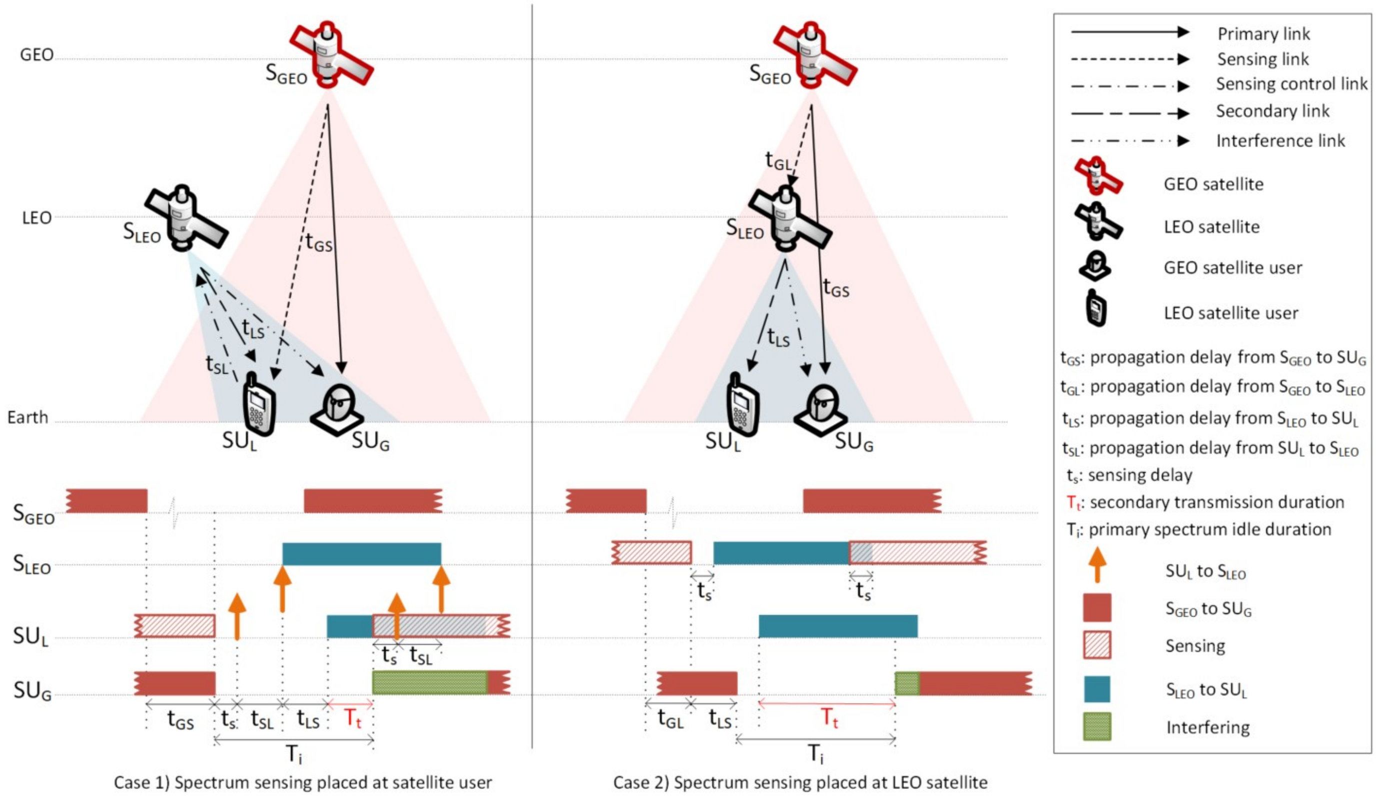
- **Case 1**: When S_{LEO} is positioned outside the transmission range of S_{GEO}, the determination of spectrum usage relies on the sensing outcome conducted by SU_L, which is then forwarded to S_{LEO}.
- **Case 2**: When S_{LEO} is within the transmission range of S_{GEO}, the determination of spectrum usage is based on the sensing outcome performed by S_{LEO}.

We use the proportion of borrowed spectrum, denoted as f_b, from the GEO satellite network as the criterion for selecting the optimal location of the sensing node within the LEO satellite network. This approach involves assessing time delay to identify the location that maximizes f_b, thereby ensuring efficient spectrum sharing between the GEO and LEO networks. Let T_i represent the duration of idle spectrum of S_{GEO} and T_t indicate the transmission time of S_{LEO} without causing any interference to the transmission of S_{GEO} at SU_G. The proportion of the spectrum that S_{LEO} can borrow from S_{GEO} is defined as the ratio between T_t and T_i. Let t_{LS} and t_{SL} correspond to the propagation delays from S_{LEO} to SU_L and from SU_L to S_{LEO}, respectively. Finally, t_s refers to the sensing delay.

When the spectrum occupancy pattern of S_{GEO} is random, the potential for the LEO satellite network to effectively utilize the unoccupied spectrum of the GEO network exists only when the duration of idle spectrum exceeds the combined duration of sensing and the propagation delay from S_{LEO} to SU_L, i.e., $T_i > t_s + t_{LS}$. This holds true when the LEO satellite performs the sensing. Similarly, in the scenario where the user undertakes the sensing, the duration of idle spectrum must surpass the total of the sensing duration and the round-trip propagation delay from S_{LEO} to SU_L, yielding $T_i > t_s + t_{LS} + t_{SL}$.

The propagation delay, i.e., t_{LS}, when the receiver is stationary is calculated as the ratio between the distance the signal travels from the transmitter to the receiver within the received time-frame and the speed of light. However, when the receiver is in motion, as for the propagation delay T_{SL} from SU_L to S_{LEO}, the movement of S_{LEO} must be factored in. The sensing delay t_s includes the duration required to make sensing decisions. This time can vary depending on the sensing technology employed in the decision-making process at the sensing nodes. In general, the time for decision making in spectrum sensing can range from microseconds to milliseconds.

To provide a numerical illustration, we consider the Inmarsat-4 F1 and Iridium 914 satellites as representations of S_{GEO} and S_{LEO}, respectively, with their orbital parameters sourced from Space-track [5]. Additionally, we place a SU_L at the geocentric coordinate of $(3.749, -0.070, -5.145)$ km, with a SU_G in close proximity. The propagation delay t_{LS} and t_{SL} were acquired by sampling every two minutes while S_{LEO} had communication capability with SU_L during its one cycle of orbiting. The average propagation delay of t_{LS} and t_{SL} result in 7.50 ms. t_s is set to 1 ms. The proportion of borrowed spectrum f_b with various S_{GEO}'s idle channel duration is depicted in Table I with T_i results from the measurement in Section II. The results demonstrate that over 90% of the GEO satellite's spectrum can be accessed for Case 2, whereas significantly lower proportions of the spectrum can be accessed in Case 1. According to our measurement, various bands of Inmarsat satellite are available for sharing for a duration of up to 10 ms. However, if the spectrum sensing is conducted on the ground, the LEO satellite network cannot utilize these spectra. Tasking the sensing at a LEO satellite results in a notably increased utilization of shared spectrum resources. Nevertheless, there exists a technical challenge in tracking GEO satellite signals' frequencies, given the Doppler effect experienced by the swiftly moving LEO satellite. Conversely, assigning the sensing responsibility to a ground user does



Case 1) Spectrum sensing placed at satellite user

Case 2) Spectrum sensing placed at LEO satellite

Fig. 2. An illustration of spectrum sensing in cognitive GEO-LEO dual satellite network.

TABLE I
PROPORTION OF BORROWED SPECTRUM FOR SECONDARY USAGE FROM GEO SATELLITE

$\mathbf{T_i}$ (ms)		10	15	20	30	40	50	60+
Total delay (ms)	**Case 1**	16(0)	16(0)	16(4)	16(30.67)	16(44)	16(52)	16(57.33+)
	Case 2	1(9)	1(14)	1(19)	1(29)	1(39)	1(49)	1(59+)
	Case 3	12.5 (0)	12.5(2.5)	12.5(7.5)	12.5(17.5)	12.5(27.5)	12.5(37.5)	12.5(47.5+)
$\mathbf{f_b}$ (%)	**Case 1**	NA	NA	20.00	46.67	60.00	68.00	73.33+
	Case 2	90.00	93.33	95.00	96.67	97.50	98.00	98.33+
	Case 3	NA	16.67	37.50	58.33	68.75	75.00	79.17+

Case 3 refers to the constellation case in Fig. 3.
16(4): total sensing and control communication delay is 16 ms, and secondary transmission time is 4 ms.
NA: Cannot do secondary transmission.

not result in a significant utilization of borrowed spectrum. However, it effectively sidesteps the technical complexity associated with frequency tracking. This is due to the GEO satellite's relative stationary position when observed from ground users, simplifying the process.

Incorporating a hybrid approach that combines the strengths of both ground users and LEO satellites for spectrum sensing can yield even more benefits. By strategically deploying ground sensors in areas of high network activity and utilizing LEO satellites for broader coverage, we can achieve an optimized sensing ecosystem. This approach not only maximizes spectrum resource utilization but also mitigates the challenges associated with LEO satellite movement. Moreover, it offers a scalable solution where the deployment of ground-based sensors can be tailored to specific network demands, ensuring efficient spectrum sharing and accurate data collection across diverse geographical regions. In an era where the demand for wireless connectivity continues to grow, this dual strategy holds the promise of not only addressing technical intricacies but also providing a flexible and adaptable framework for future spectrum management.

B. Leveraging Satellite Constellations for Spectrum Sensing

In Case 2, the proportion of borrowed spectrum for secondary usage is significantly higher. As LEO satellites commonly operate within constellations, the satellite constellations can be leveraged for spectrum sensing when the LEO satellite is positioned outside the transmission range of a GEO satellite, thereby enhancing the proportion of borrowed spectrum. Let us introduce Case Study 3, where we designate an additional LEO satellite within the same constellation as $S_{LEO'}$, situated within the transmission range of S_{GEO}. As illustrated in Fig. 3, the task of spectrum sensing can be performed by $S_{LEO'}$ if an intersatellite link exists between these two LEO satellites, and the propagation delay $t_{LL'}$ between them is shorter than t_{SL}. For the establishment of an intersatellite link, two conditions related to the visibility between the two satellites need to be satisfied: geometric visibility and antenna visibility. Geometric visibility places a constraint on the distance between the two satellites, while antenna visibility mandates that the satellites fall within the scanning range of each other's antennas.

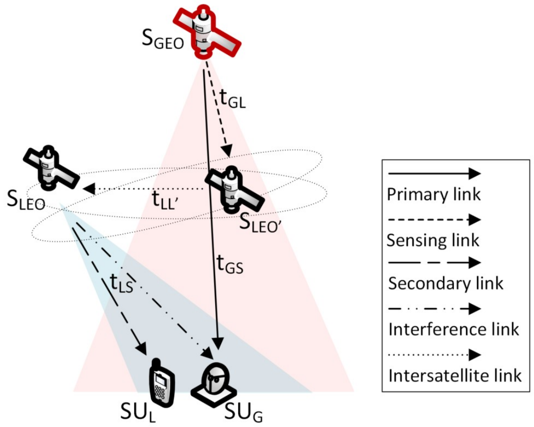


Fig. 3. An illustration of spectrum sensing with LEO satellite constellations in CDSNs.

As an illustration, we can leverage the Iridium constellations to augment the proportion of borrowed spectrum for the Iridium 914 satellite in Case 1. This constellation encompasses 66 satellites orbiting at an altitude of 780 km above the Earth's surface, distributed across six orbital planes, with each plane housing 11 satellites. It is stipulated that adjacent satellites within the same orbital plane maintain a minimum distance of approximately 30° of longitude between each other, as indicated in [5]. Consequently, the minimum separation between Iridium 914 and its neighboring satellite $S_{LEO'}$ is roughly 189 km. We make the assumption that $S_{LEO'}$ lies within the transmission range of Inmarsat-4 F1 and that an intersatellite link exists between Iridium 914 and $S_{LEO'}$. The average propagation delay between these two LEO satellites is constrained between 0.63 ms to 7.50 ms. The maximum enhanced proportion of borrowed spectrum for Case 1 can be expressed as in the constellations case in Table I. In practical applications, the selection of a specific LEO satellite within the constellation for spectrum sensing necessitates the consideration of additional factors. These factors include the current workload of the chosen LEO satellite, the system overhead, and the overall system efficiency, in addition to the two fundamental conditions regarding intersatellite link establishment and propagation delay.

IV. IMPACT OF DOPPLER SHIFT ON SPECTRUM SENSING AT LEO SATELLITES

When performing spectrum sensing with LEO satellites, it is crucial to address errors caused by Doppler shift due to their high velocity. The rapid motion of LEO satellites relative to GEO satellites leads to variations in the received signal frequency, which presents a significant challenge for accurate spectrum sensing, particularly when detecting multiple frequency channels of GEO satellites.

In a typical LEO satellite system, predicting Doppler shift involves a multi-step process. Ground stations continuously monitor and update precise orbital parameters of LEO satellites. Algorithms then estimate expected Doppler shift based on current satellite positions and user terminal locations. With accurate predictions, the system adjusts signal frequency to compensate, ensuring optimal communication.

In cognitive GEO-LEO satellite networks, Doppler shift estimation and compensation are performed entirely onboard LEO satellites during spectrum sensing of GEO signals. This process is technically challenging due to the need for precise determination of satellite positions and velocities. The complexities are compounded by factors such as atmospheric drag, gravitational forces, and the dynamic nature of LEO satellite orbits, making real-time data acquisition for both LEO and GEO satellite positions difficult. Tracking GEO satellites from LEO further adds to the inaccuracies and complexities involved. Moreover, the deployment of these systems on LEO satellites is particularly challenging due to limited onboard processing capability, power constraints, and restricted spectrum resources [6]. These limitations necessitate a careful balance between accuracy and efficiency in Doppler shift estimation and compensation techniques.

A. *Doppler Shift Estimation at LEO Satellites*

Doppler shift estimation for LEO satellites is typically conducted by ground-based satellite users. This approach is necessitated by the fact that accurate Doppler shift estimation requires knowledge of the orbital positions of LEO satellites, which is determined through tracking performed by ground-based satellite stations. When LEO satellites undertake sensing tasks, it becomes crucial for them to be capable of tracking their positions in relation to GEO satellites. Recently, a navigation technique known as angles-only navigation, which involves determining the relative position and velocity of spacecraft by measuring line-of-sight angles, has been validated as an effective means of establishing the orbits of LEO satellites. This is achieved through optical tracking of GEO satellites, as discussed in [7].

Upon achieving the relative position and velocity, estimating the Doppler shift at S_{LEO} while receiving a signal from S_{GEO} involves considering the propagation direction of the signal, represented by a unit vector derived from the satellite coordinates. The relative velocities and angles between the satellites and this vector play crucial roles in determining the observed Doppler shift.

Fig. 4 illustrates the observed Doppler shift and rate experienced by the Iridium 914 satellite while receiving signals from the Inmarsat-4 F1 satellite over a complete orbital cycle of the Inmarsat satellite. The signals analyzed correspond to the Inmarsat L-band downlink at a carrier frequency of 1530 MHz. It is important to note that Doppler shift and rate values are not available during periods when direct communication between the two satellites is not established, which can limit the data captured during certain segments of the orbit.

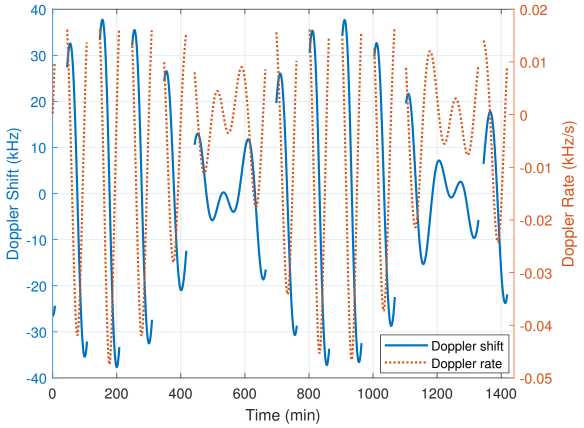


Fig. 4. Doppler effect observed at Iridium satellite, during an orbit cycle of Inmarsat satellite.

The Iridium satellite experiences a significant Doppler shift, as evident from Fig. 4, reaching a maximum Doppler shift of ±37.730 kHz with a rate of 0.065 kHz/s. This becomes particularly significant when considering the bandwidth of the L-band downlink channels of Inmarsat-4 F1. Each spot beam in the Inmarsat-4 F1 has a bandwidth of 200 kHz, comprised of multiple sub-bands, with each sub-band having a width of 42 kHz [8]. The substantial Doppler shift experienced by the Iridium satellite raises concerns about accurate band sensing, leading to potential incorrect decisions about the frequency band in use by Inmarsat. Moreover, to enable cognitive spectrum sharing without compensating for Doppler shift, at least three sub-bands of the Inmarsat satellite need to be available for one sub-band sensed as idle by the Iridium satellite. This results in a significantly low proportion of spectrum borrowed by the Iridium satellite in the frequency domain compared to more than 90% borrowed in the time domain (as shown in Table I). To address this challenge, it becomes imperative for the Iridium satellite's receiver to have the capability to handle and compensate for the observed Doppler shift. By doing so, effective and accurate spectrum sensing can be maintained, ensuring seamless communication and optimal performance for the cognitive network.

B. Doppler Compensation Techniques for LEO Satellites

Currently, Doppler compensation techniques implemented onboard LEO satellites are primarily designed for precompensating Doppler shift in downlink communication with ground users. However, in CDSNs, if the Doppler shift can be estimated accurately, these techniques can still be leveraged to compensate for Doppler and track GEO signal frequency. Existing Doppler compensation techniques for LEO satellites are summarized in Table II.

In [9] and [10], traditional phase-locked loop (PLL) methods for accurate carrier tracking were employed, enhanced by adaptive sweeping and pilot techniques, respectively. The compensating technique proposed in [9] was implemented for spacecraft in deep space networks. An onboard Doppler compensation unit was developed for LEO satellites in [11] to precompensate for Doppler effects when relaying signals through GEO satellites. In [12], a cost-effective Doppler emulation and compensation technique using a LoRa chipset for LEO satellite communication was introduced. [13] designed an SDR receiver for Doppler correction in satellite networks. A blind Doppler shift estimation and compensation method with hardware implementation was proposed in [14], using a cascading algorithm that combines a time-varying Burg (TV-Burg) spectral analyzer with an alpha-beta filter to provide recursive Doppler estimates at each sampling point. [15] utilized an orthogonal time frequency space (OTFS) modulation scheme, leveraging modulating information to average out Doppler shifts.

Existing Doppler compensation techniques, while effective for ground-based processing of LEO satellite signals, face feasibility challenges for direct implementation on LEO satellites due to limited computational power and energy constraints. Evaluating the processing demands of these methods is essential to identify those deployable within typical satellite hardware capabilities, as summarized in Table II. Additionally, LEO satellites must sense GEO satellite signals, which often employ distinct modulation schemes, complicating the application of standard compensation techniques. Furthermore, LEO satellites need to anticipate and adjust for Doppler shifts in real time to avoid interfering with ground-based GEO users, a task made more difficult by the lack of precise GEO user location data. Addressing these feasibility, practical, and implementation challenges is critical for advancing Doppler shift compensation in GEO-LEO cognitive satellite networks.

V. RESEARCH DIRECTIONS AND CHALLENGES

Spectrum sensing by LEO satellites within CDSNs offers superior mitigation of propagation delay compared to traditional ground-based sensing, leading to enhanced secondary spectrum utilization. Conducting sensing at LEO satellites presents several research directions and associated challenges as follows.

(1) **Sensing Techniques**. Future research in this area will focus on the development of advanced sensing techniques specifically designed to meet the unique requirements of LEO satellites. These techniques must be capable of effectively detecting signals originating from GEO satellites while simultaneously accurately tracking their frequencies. This entails devising algorithms and signal processing methods that can mitigate the impact of Doppler effects resulting from the rapid movement of LEO satellites. Additionally, addressing the limitations posed by onboard computing resources will necessitate the exploration of innovative approaches.

(2) **Interference Management**. A key research area is mitigating interference for primary GEO users during secondary transmissions by LEO satellites. The main challenge is the lack of coordination between GEO and LEO systems, leading to LEO satellites not knowing GEO user positions. This requires innovative techniques to avoid or mitigate interference, enabling LEO satellites to protect GEO users without explicit coordination. Another critical research focus is managing inter-beam interference for LEO users in multibeam

TABLE II
EXISTING DOPPLER COMPENSATION TECHNIQUES FOR LEO SATELLITES

Research work	Technique	Compensated Doppler shifts	Carrier frequency	Signal type	Hardware requirement	Cost	Deployability to CDSNs
[9]	PLL & Adaptive sweeping	±20 kHz	X-band	QAM/QPSK	Analog electronic system	Low	✓
[10]	Pilot & PLL	±200 kHz	8.4 GHz	8-PSK	Analog electronic system	Low	✓
[11]	Incremental Doppler shift characterization	±60 kHz	Ka-band	QPSK	FPGA, SDR	High	✓
[12]	Clock manipulation-based	±20 kHz	868 MHz	LoRa	LoRa chipset	Medium	
[13]	Coarse Doppler cross-correlation search	±30.72 kHz	S-band	BPSK, GMSK	FPGA, SDR	High	✓
[14]	TV Burg & $\alpha - \beta$ filter	±382 kHz	20 GHz	DVB-S2	FPGA	High	
[15]	OTFS	±480 kHz	30 GHz	OTFS	FPGA	High	

transmission modes. The challenge here is optimizing LEO beams to minimize inter-beam interference while ensuring adequate Doppler compensation for users at beam edges. This involves exploring beamforming strategies, beam shaping techniques, and adaptive algorithms to adjust beam parameters dynamically based on LEO users' spatial distribution and the communication environment.

(3) **Dynamic Spectrum Access**. Research in dynamic spectrum access for LEO satellites within cognitive GEO-LEO satellite networks is crucial for optimizing spectrum utilization while minimizing interference with primary users, including GEO satellites and terrestrial systems, across varying network conditions. To meet the unique operational requirements of LEO satellites, dynamic spectrum access algorithms must be developed to adapt to different network environments. These algorithms should be capable of dynamically adjusting sensing parameters and transmission strategies in response to real-time spectrum availability, fluctuating user demands, and diverse network conditions such as varying levels of congestion, interference, and propagation characteristics. Key challenges in this research include the dynamic nature of spectrum usage, the limited sensing and processing capabilities of LEO satellites, and the lack of direct coordination between GEO and LEO systems. Addressing these challenges requires innovative approaches that combine advanced signal processing techniques with adaptive decision-making algorithms, enabling efficient spectrum utilization and management under varying network conditions in satellite networks.

(4) **Cross-Layer Optimization**. In cognitive GEO-LEO satellite networks, cross-layer optimization becomes crucial for maximizing the efficiency and reliability of communication systems. Research efforts should focus on developing cross-layer optimization approaches that seamlessly integrate spectrum sensing with higher-layer protocol design and resource allocation strategies. By jointly optimizing sensing, access, and transmission parameters across multiple protocol layers, LEO satellites can improve spectral efficiency and quality of service provisioning in dynamic and heterogeneous communication environments. This entails leveraging real-time spectrum sensing information to dynamically adapt modulation and coding schemes, power control policies, and routing protocols based on the current spectrum availability and channel conditions.

(5) **Security and Privacy**. Future research in CDSNs should focus on enhancing security and privacy to address the unique challenges posed by these systems. As cognitive satellite networks dynamically access and share spectrum, they become vulnerable to various cyber threats such as jamming, eavesdropping, and spoofing. Developing robust encryption techniques and secure communication protocols tailored for satellite environments is crucial. Additionally, incorporating machine learning algorithms can help in detecting and mitigating security threats in real-time. Privacy-preserving methods, such as homomorphic encryption and differential privacy, should be explored to protect user data during transmission and processing.

VI. CONCLUSION

This article has thoroughly investigated the impact of propagation delay on spectrum sensing within GEO-LEO CDSNs. The result highlighted that locating the sensing nodes on LEO satellites can yield over 90% effectiveness in utilizing borrowed spectrum. However, it also unveiled the complexity introduced by implementing effective Doppler shift estimation and compensation technique on LEO satellites. By scrutinizing critical factors such as propagation delay and Doppler shift compensation for LEO satellites, this article underscored their profound influence on the success of spectrum sensing. Drawing insights from GEO satellite spectrum usage and potential LEO spectrum utilization, valuable guidance for sensing node placement in CDSNs was presented.

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