Grant-Free NOMA-OTFS Paradigm: Enabling Efficient Ubiquitous Access for LEO Satellite Internet-of-Things

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ABSTRACT
With the blooming of Internet-of-Things (IoT), we are witnessing an explosion in the number of IoT terminals, triggering an unprecedented demand for ubiquitous wireless access globally. In this context, the emerging low-Earth-orbit satellites (LEO-SATs) have been regarded as a promising enabler to complement terrestrial wireless networks in providing ubiquitous connectivity and bridging the ever-growing digital divide in the expected next-generation wireless communications. Nevertheless, the harsh conditions posed by LEO-SATs have imposed significant challenges to the current multiple access (MA) schemes and led to an emerging paradigm shift in system design. In this article, we first provide a comprehensive overview of the state-of-the-art MA schemes and investigate their limitations in the context of LEO-SATs. To this end, we propose a novel next generation MA (NGMA), which amalgamates the grant-free non-orthogonal multiple access (GF-NOMA) mechanism and the orthogonal time frequency space (OTFS) waveform, for simplifying the connection procedure with reduced access latency and enhanced Doppler-robustness. Critical open challenging issues and future directions are finally presented for further technical development.

INTRODUCTION
The Internet-of-Things (IoT) is envisioned to revolutionize our daily life by connecting massive heterogeneous terminals with diverse applications and has triggered the evolution of communication technologies in the past decades. Meanwhile, the flourishing fifth-generation (5G) communication systems have preliminarily paved the way for the development of IoT vertical domains including smart manufacturing, agriculture, e-health, smart city, and etc [1]. Driven by these demand-intensive vertical industries, the requirement for ubiquitous connectivity with guaranteed quality-of-service (QoS) is more prominent than ever.

Recently, the escalating data traffic of the IoT has imposed heavy burdens on the existing terrestrial cellular networks. As a direct result, the mismatch between the capabilities of 5G networks and the unprecedented IoT demands has been increasingly prominent, especially under the impact of the COVID-19 pandemic [1]. Moreover, the inherent limitations of terrestrial infrastructures severely restrict their capacity to achieve some anticipated key performance indicators (KPIs), such as access equality, availability, and reliability [2]. In this regard, low-Earth-orbit satellites (LEO-SATs) have emerged as a viable solution to supplement and extend terrestrial networks in the expected 6G networks. By virtue of their global footprints and relatively low round-trip latency, LEO-SATs are regarded as a promising enabler to support ubiquitous global access, bridge the ever-growing digital divide, and cater for increasingly stringent QoS requirements from a multitude of IoT applications, as illustrated in Fig. 1.

Despite the inviting outlook of LEO-SATs, technical innovations are in urgent need to enhance access efficiency at a reasonable cost. It is predict ed that the number of connected IoT terminals grows by 12 percent annually and will eventually reach hundreds of billions with a connection density of 10 million terminals per square kilometer by 2030 [1]. Against this background, to fully unleash the underlying potentials of LEO-SATs for accommodating the explosive growth of connections, one of the prerequisites lies in the design of efficient multiple access (MA) paradigms with limited radio resources. However, it is not straightforward to apply the conventional MA frameworks to LEO-SATs. On the one hand, conventional grant-based random access (GB-RA) protocols require complicated handshaking procedures, which would aggravate the access latency, and the induced exceedingly large signaling overheads can impose heavy burdens on the system resources [3]. On the other hand, due to the highly dynamic nature of the terrestrial-satellite link (TSL), traditional MA techniques, which allocate orthogonal or non-orthogonal resource blocks (RBs) in the time-frequency (TF) domain, are likely to suffer from severe orthogonality impairments due to the imperfect Doppler compensation that jeopardizes the system performance [2]. To this end, a paradigm shift in MA methodology is indispensible to realize efficient ubiquitous access for LEO-SATs in practice.

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The rest of this article is organized as follows. In the following sections, we first provide an overview of the state-of-the-art MA schemes and summarize their limitations for LEO-SATs. Then, we propose a novel next generation MA (NGMA) scheme, which combines grant-free non-orthogonal MA (GF-NOMA) with orthogonal time frequency space (OTFS) modulation to enable efficient ubiquitous access for LEO-SATs. Before concluding, important open research issues and future directions are discussed.

**Overview of the State-of-the-Art**

Distinguished by different connection procedures, there are mainly two categories of MA protocols, namely GB-RA and GF-RA. These two types of RA protocols have different merits and drawbacks, leading to distinct KPIs including reliability, access latency, and capacity. We commence this section by conducting a comprehensive survey of the state-of-the-art MA schemes and summarize them in Table 1. On this basis, we further elaborate their limitations on LEO-SATs and provide guidelines for subsequent research activities.

**GB-RA Protocols-Based Schemes**

The GB-RA protocols, which were originally conceived for human-type communication, have dominated the existing cellular networks’ standards nowadays, for example, long term evolution (LTE)/LTE-advanced (LTE-A) and 5G new radio (NR). Besides, they have been adopted by the standardized narrow-band IoT (NB-IoT) to support machine-type communications for co-existing with cellular networks [3]. These types of protocols stipulate that the active entities initialize the access procedures through a physical random access channel (PRACH) in a contention-based manner to set up the connection with the base station (BS). After the typical four-step handshake procedure is completed, the connected terminals are allowed to initiate a grant acquisition (GA) request for transmitting their payload data to the BS on the allocated orthogonal or non-orthogonal RBs.

In general, these solutions developed for terrestrial cellular networks are generally not applicable to LEO-SATs systems due to the harsh channel conditions in the TSLs, such as long propagation delay, severe Doppler effects, strong channel spatial correlation, and so on. For this purpose, some modifications have been made in recent endeavors [4–7]. For LEO-SATs employing massive multiple-input multiple-output (MIMO) and full frequency reuse techniques, [4] proposed a space angle-based user grouping algorithm to schedule the served terminals into different groups, where the terminals having different angles of arrival (AoAs) are assigned to the same group and share the same TF resources. Without requiring any modification to the current NB-IoT waveform, [5] addressed the issues of MA caused by the typical satellite channel impairments, including long round-trip delays, significant Doppler effects, and wide beams. Furthermore, [6–8] integrated the OTFS modulation with the GB-RA protocols and formulated new resource allocation schemes to accommodate the heterogeneous mobility demands of different IoT applications.

Despite the aforementioned efforts, some critical issues arise with the sophisticated access
TABLE 1. A summary of the typical MA schemes in the current literature.

| Solutions | Applicable Channel | MA Protocol | MA Technique | Waveform | Received Signal Processing¹ | Reasons for incompatibility with MA in the LEO-SATs |
|-----------|--------------------|-------------|--------------|----------|-----------------------------|--------------------------------------------------|
| LTE/NM    | Frequency selective and time-varying channels | GB-RA | OMA | (DFT-S)-OFDM² | ✓   | Complicated access procedures and susceptible to severe Doppler effect |
| [4]       | TSLs              | GB-RA | SOMA¹       | OFDM     | ✓   | Require the accurate Doppler and delay compensations at terminals, which is difficult to implement in practice |
| [5]       | TSLs              | GB-RA | Frequency-domain OMA | Single-carrier | ✓ | Complicated access procedures aggravate the access latency and the involved large signaling overheads |
| [6]       | Broadband time-varying channels | GB-RA | Path-domain OMA | OTFS     | ✓   | Require excessive orthogonal angle domain resources to assure that the observation regions for different terminals do not overlap |
| [7]       | Broadband time-varying channels | GB-RA | Power-domain NOMA | OTFS     | ✓   | Handshaking procedures and sophisticated SIC further deteriorate the access latency |
| [8]       | Broadband time-varying channels | GB-RA | Code-domain NOMA | OTFS     | ✓   | Handshaking procedures and complicated message passing MUD algorithm aggravate the access latency |
| Globalstar [9] | TSLs          | SSA       | Code-domain OMA | Single-carrier | ✓ | Only accommodate modest traffic and the packet collisions create potential network instability issues |
| DVB-RCS [9] | TSLs          | CRDSA | TDMA⁴ | Single-carrier | ✓   | Require complicated contention resolution at the receiver |
| [10]      | Broadband quasi-static channels | GB-RA | Code-domain NOMA | OFDM     | ✓   | Suffer from serious performance degradation over the time-varying channels due to the large interval of the beacon signals and outdated CSI |
| [11]      | Narrowband land mobile satellite (LMS) channels | GB-RA | Code-domain NOMA + SOMA | Single-carrier | ✓ | For narrowband systems only and suffer from low transmission rate |
| [12]      | Broadband block-fading channels | GB-RA | Code-domain NOMA + SOMA | OFDM     | ✓   | Severe Doppler effect leads to the orthogonality failures among OFDM sub-carriers |
| Proposed  | Broadband fast time-varying channels | GB-RA | Code-domain NOMA + SOMA | OFTS     | ✓   | — |

¹ SOMA: Spatial division MA; TDMA: Time division MA.  
² DFT-S-OFDM: Discrete Fourier Transform-Spread OFDM.  
³ ATI: Active terminal identification; CE: Channel estimation; SD: Signal detection.  
⁴ ATI: Active terminal identification; CE: Channel estimation; SD: Signal detection.

GF-RA Protocols-Based Schemes

In this case, the GF-RA protocols arise as a better option to cope with the escalating IoT traffic demand over satellite communications, where the representative case is ALOHA [2]. The original ALOHA protocol allows the terminals to transmit the data packets without any prior coordination, thus only performs well at modest traffic intensity. To alleviate the network congestion and the potential network instability issues, more advanced GF-RA techniques have been developed, such as Contention Resolution Diversity ALOHA (CRDSA) and Enhanced Spread Spectrum ALOHA (E-SSA), which integrates diversity or spreading techniques with successive interference cancellation (SIC) [9]. In fact, Globalstar has deployed the simplex data network based on the SSA-RA protocol along with the concept of sending multiple replicas of the same burst to increase reception probability [9]. Meanwhile, some satellite communication standards, such as digital video broadcasting return channel via satellite (DVB-RCS) and DVB-satellite services to handholds (DVB-SH), have widely adopted ALOHA-based GF-RA protocols. Nevertheless, the existing protocols commonly depend on OMA technique and require excessively increasing resources as the number of terrestrial IoT terminals to be connected grows exponentially.

Recently, an efficient GF-NOMA protocol has been proposed for terrestrial massive machine-type communication (mMTC) [13]. This protocol advocates to merge the RA process with data transmission by removing the GA request. For instance, when a terminal wakes up, it initializes the pre-configuration and synchronization by exploiting the beacon signals periodically broadcast from the BS. Before delivering the uplink payload data, the awak-
OTFS emerges as an alternative to OFDM to accommodate the channel dynamics via modulating information in the delay-Doppler domain and thus support more reliable services in high-mobility scenarios.

OTFS Waveform

Basic Principles: The essence of OTFS is to shift the data modulation and signal processing from the TF domain to the DD domain. Applying the two-dimensional (2-D) Fourier transformation to the TF domain channel impulse response (CIR) \( h(t, f) \) yields the DD domain CIR \( h(\tau, \nu) \). By parameterizing the channels with delay \( \tau \) and Doppler shift \( \nu \), the DD domain CIR can explicitly capture the underlying physics of radio propagation and directly separate multipath propagations from the delay and Doppler dimensions. In sharp contrast to the time-varying \( h(t, f) \), the quasi-time-invariant DD domain \( h(\tau, \nu) \) enjoys attractive characteristics, which can be exploited to facilitate efficient signal processing [6]. Besides, by attaching a pre-processing and a post-processing module to the conventional TF domain multi-carrier modulation, OTFS multiplexes data symbols in the DD domain lattices and spreads each one across the whole TF domain via a family of 2-D spreading functions. The mathematical structure of OTFS waveform indicates that the impairments caused by double-selective channels, that is, time- and frequency-shifts, can be represented by 2-D quasi-circular inter-symbol interference (ISI) patterns in the DD domain. In fact, the efficient utilization of the DD domain channels and the DD domain multiplexing have endowed OTFS with some unique virtues which render it eminently suitable for high-mobility scenarios [14].

Potentials for LEO-SATs: Incorporating the features of LEO-SATs, we detail the potentials of OTFS as follows.

Beneficial Features of TSLs in the DD Domain: Although the high mobility of LEO-SATs results in an extremely short coherence time for TSLs in the TF domain, the stability of the DD domain channels is still liable to maintain. This can be interpreted by the fact that their delay and Doppler parameters, which mainly hinge on the relative locations of satellites and IoT terminals, fluctuate more sluggishly compared with the channel gains in the TF domain. Besides, distinct from the terrestrial propagation environments, there are fewer scatterers in the TSL and the energy of multipath components (MPCs) could be relatively weak owing to the considerable path loss, both of which could substantially contribute to the sparsity of the TSLs in the DD domain. Furthermore, as a result of the relatively high altitude of satellite stations compared with the range of the scatterers located in the vicinity of the terminals, all MPCs for the same terminal undergo similar AoA, and thus the DD domain CIR tend to be concentrated along the Doppler dimension. In short, the TSLs preserve separable, stable, compact, and sparse patterns in the DD domain [14].

Robustness to Time-Varying Channel Components: The traditional modulation techniques do not consider the Doppler mitigation, and thus may suffer from severe performance degradation in the
time-varying channels. For instance, the popular OFDM modulation efficiently transforms a frequency-fading channel to multiple parallel flat frequency subchannels for low-complexity single-tap equalization. However, Doppler shift is treated as a hostile impairment in OFDM, whose orthogonality among different sub-carriers could be destroyed in this case, leading to the inter-carrier interference (ICI). By contrast, OTFS is initially conceived for double-selective channels and introduces an additional Doppler dimension to separate the time and frequency fadings in the DD domain, substantially mitigating the destructive effects of fadings' coupling [14]. Besides, it is not just the motion of LEO satellite that causes the Doppler shift. The higher frequency oscillators and mismatch between transmitter’s and receiver’s oscillators inevitably give rise to the issue of undesired phase noise, which introduces significant phase jitters and leads to the equivalently time-varying components. In this case, OTFS’s robustness against time-varying channels could also be taken as a pivotal enabler to combat the oscillator phase noise, which is critical for high-frequency satellite communications.
**Full Channel Diversity:** The channel diversity benefited from OTFS stems from multiplexing the data symbols in the DD domain and spreading them across the entire TF plane through cascaded OTFS transformations. In fact, in contrast to the traditional 1-D modulation scheme such as OFDM, the set of 2-D orthogonal spreading functions of OTFS spans the whole bandwidth and time duration of the transmission packet, which provides additional degrees of freedom in the Doppler (time) dimension. These spreading functions in conjunction with an elaborately designed equalizer in the TF or DD domain allow the exploitation of this full channel diversity gain, which is crucial for performance improvement.

**Other Potential Benefits:** Apart from the aforementioned pivotal features, OTFS also possesses some potential strengths over conventional modulation techniques. For example, OTFS boasts a lower peak-to-average power ratio (PAPR) than OFDM despite its multicarrier nature. Besides, OTFS can significantly reduce pilot and protection overheads, thereby enhancing transmission efficiency, both of which are crucial for resource-limited satellite communications.

**GF-NOMA-OTFS Paradigm**

As an amalgamation of the GF-RA mechanism with the OTFS waveform, the transmission procedure of the proposed GF-NOMA-OTFS paradigm can be summarized as follows:

**Step 1:** After initializing the pre-configuration and the time synchronization, the active IoT terminals are allowed to transmit RA uplink signals without complicated access and resource scheduling request.

**Step 2:** The satellite stations collect signals received from all active terminals and perform active terminal identification (ATI) and CE, where the estimated ATS and CSI are used for the following DD domain data demodulation in the absence of scheduling information.

**Step 3:** The satellite stations feedback the demodulated data through inter-satellite links (ISLs) and backhaul to the gateway and broadcast acknowledgment character to the active terminals. In order to achieve more efficient ATI and CE, we first propose an improved RA signal frame structure for OTFS waveform.

**RA Signal Frame Structure:** The widely adopted OTFS frame structure in the existing literature consists of the DD domain data symbols, guard intervals, and pilot symbols [14] as illustrated in Fig. 2. Since the pilots are directly placed in the sparsity domain (DD), the direct CE via the least-square (LS) or maximum likelihood (ML) approach are feasible and the most efficient schemes. However, its performance is severely restricted by the OTFS resolution (especially Doppler domain) [13]. To further enable compressive sensing (CS)-based and super-resolution CE approach, we propose a training sequence (TS)-aided OTFS (TS-OTFS) frame structure as shown in Fig. 2. Specifically, a TS-OTFS frame consists of two segments, corresponding to TSs and OTFS payload data, respectively. As for the OTFS payload data, the raw input bit streams generated by IoT terminals are firstly multiplexed in the DD domain, with delay and Doppler dimensions being denoted as M and N, respectively.

Then, the DD domain data is transformed into the time domain signal through a cascade of an OTFS pre-processing module and a multi-carrier modulator. As for the TSs, they are pre-allocated non-orthogonal random (e.g., pseudo-noise or complex Gaussian) sequences with low-correlation placed in the time-delay domain as unique identifiers for different terminals, whose length Mt is far smaller than the total number of served terminals (OMA cases). N identical TSs are embedded into OTFS payload data converted to the time domain as the substitute for the DD domain pilots to facilitate ATI and CE. Next, we leverage the TSs and the characteristics of TSL in the DD domain mentioned above to implement ATI and CE.

**ATI and CE Algorithm:** In the presence of propagation delay of MPCs, TSs are doomed to undergo severe ISI from the unknown payload data preceding it. In order to overcome the ISI impact on the ATI and CE, an effective approach is to utilize the non-ISI region of TSs as illustrated in Fig. 2, which is the tail-end of TSs and thereby merely depends on the known transmit TSs.

To begin with, by exploiting the 1-D convolutional relationship between the received TSs and the transmit TSs in the delay domain, and the superposition of TSs from different active terminals, the first stage of ATI and CE can be formulated as a typical sparse signal recovery problem, where the few non-zero elements of delay domain channels of active terminals are required to be recovered. In this way, by means of cutting-edge CS algorithms, the delay domain CIR vectors of all potential terminals can be recovered with the low-dimensional non-ISI region so that the length of TSs overhead can be substantially reduced. In line with the estimated channel gain, a power threshold detector could be further utilized to decide activity for each potential terminal, and thus acquire ATS [12].

As for CE, the accurate reconstruction of the DD domain CIR h(t, v) lies on the acquisition of key channel parameters, that is, delay, Doppler shift, and fading coefficients. Specifically, the support set of recovered delay domain sparse CIR vectors can straightforwardly map to the delay parameters. Furthermore, since the number of Doppler component L tends to meet L ≪ N, by collecting the recovered delay domain sparse CIR vectors corresponding to the N TSs (N different instants), the Doppler parameters can be estimated with super-precision in the time-domain resorting to the spatial spectrum estimation algorithm, for example, estimation of signal parameters using rotational invariance techniques (ESPRIT), and multiple signal classification (MUSIC). Eventually, the fading coefficients associated with each physical propagation path can be mathematically determined based on the LS criterion.

**Case Study**

To compare the existing MA schemes surveyed above and demonstrate the superiority of the GF-NOMA-OTFS paradigm and the frame structure design, we study a representative case in the LEO-SATs-based massive IoT access and provide
the on-board power and cost constraints.

On the other hand, low-resolution digital-to-analog conversion and simple hardware implementation, to meet significant performance loss regardless of pilot overhead. In contrast, the proposed GF-NOMA-OF5 paradigms enjoy performance superiority by handling the Doppler effect with their DD domain signal processing manner and the exploitation of the DD domain channel’s property. Unfortunately, due to the impact of discretization, the channel spreading and the limited resolution destroy the beneficial features of TSLs in the DD domain, degrading its optimal performance. The utilization of virtual oversampling lattice can compensate the performance loss to some extent while at the cost of higher computation complexity. Moreover, the proposed TSS enable the combination of CS-based estimation in the delay domain and super-resolution estimation in the time domain, ensuring superior performance while keeping lower pilot overheads.

On this basis, we further compare the performance of bit error rate (BER) in Fig. 3c based on the estimated ATS and CSI, where a straightforward DD domain LS multi-user signal detector is utilized to perform SD. The performance gain achieved by the proposed GF-NOMA-OTFS paradigm suggests the noticeable benefits from more accurate ATS and CSI, and the full channel diversity extraction provided by OTFS modulation. Furthermore, it is noteworthy that with the limited resolution ADC, that is, \( b_{\text{adc}} = 2, 3 \) bits, the performance of the GF-NOMA-OTFS paradigms degrades sluggishly in contrast to ideal ADC, which indicates the proposed schemes remain robust in this case, making hardware-efficient implementation possible for satellite payloads.

### Open Issues and Future Directions

As a fledgling concept, the GF-NOMA-OTFS paradigm not only unveils opportunities but also poses challenges. In this section, we discuss the challenges to be addressed and highlight the future research directions to spur more technological breakthroughs in the future.

### Terrestrial and On-Board Constraints Optimization

The IoT terminals are expected to be power-constrained for low carbon footprint and cost-efficient deployment, which yet may result in failure to close the path loss. At the cost of achievable data rate, the repetition code spreading specified in NB-IoT standard [5], and the direct sequence spread spectrum widely used in satellite communications [15], can be integrated with the OTFS modulation to improve link SNR and enhance robustness with low transmit power. In addition, imperfect hardware components remain another challenge. Practical satellite communication systems usually work within the saturation point of power amplifiers to provide the most efficient power output and compensate the significant path loss, yet results in severe non-linear behaviors. In particular, most multi-carrier waveforms are with inconstant signal envelopes, which is likely to lead to non-linear distortion in this case. On the other hand, low-resolution digital-to-analog conversion and simple hardware implementation, to meet the on-board power and cost constraints.

| Parameter                                      | Value               |
|------------------------------------------------|---------------------|
| Carrier frequency (GHz)                        | 10                  |
| System bandwidth (MHz)                         | 122.88              |
| Subcarrier spacing (MHz)                       | 480                 |
| OTS grid (delay × Doppler)                     | 236 × 8             |
| Satellite antenna array size                  | \( 32 \times 32 \)  |
| Terminal antenna array size                   | \( 32 \times 32 \)  |
| Quantizer precision (\( b_{\text{adc}} \))     | Lloyd-Max           |
| Number of potential terminals                  | 1000                |
| Activation probability                         | 0.01                |
| Satellite orbital altitude (km)                | 500                 |
| Azimuth angle range (°)                        | [–44, 44]           |
| Azimuth angle range (°)                        | [0, 360]            |
| Doppler shift range (kHz)                      | [–178.2, 178.2]     |
| Atmospheric loss (dB)                          | 0.07                |
| Scintillation loss (dB)                        | 2.2                 |
| Shadowing margin (dB)                          | 3                   |
| Free space path loss (dB)                      | 52.45 + 20\( \log_{10} (d_{\text{m}}) \) |
| Received signal-to-noise ratio (SNR) (dB)      | 15                  |
| Number of MTC's for each TSL                   | 2                   |

**TABLE 2.** Simulation parameter settings.
converters and ADCs, have attracted increasing research attention to be equipped for terminal and satellite apparatus. In the presence of non-ideal characteristics, undesired interference is often inevitable. It is suggested that the joint optimization of performance taking these on-board and terrestrial constraints into account is an underlying trend in the future research of MA paradigms [12].

**Interplay with Other NGMA Schemes**

In addition to SDMA, other cutting-edge NOMA paradigms, for example, power-domain NOMA [7] and sparse code MA [8], have been considered to integrate with OTFS waveform to enhance spectral efficiency and alleviate the spatial correlations caused by overloaded SDMA. Therefore, it is rewarding to investigate their amalgamation with the proposed MA scheme for more efficient payload data multiplexing, striking a trade-off between the spectral efficiency and transmission reliability. In this case, SIC and MUD algorithms are pivotal but challenging in the presence of more complicated multi-dimensional (Doppler, delay, spatial domains) interweaving and inter-users interference. In fact, under the framework of single-input single-output OTFS, a myriad of SD schemes have been proposed from different perspectives [14], including but not limited to execution in various domains, for example, the DD domain, the TF domain, and the cross-domain iteration; different optimization objective, for example, lower complexity and superior BER performance; and different techniques, for example, zero forcing, minimum mean square error, ML, and message passing. On this basis, their extension to more sophisticated multi-user NOMA systems should be further studied.

**NGMA for Cooperative Networks**

Benefiting from the ultra-dense network topology, the concept of multi-connectivity arises in LEO-SATs networks [2]. In this case, each terminal can be covered by multiple satellite stations simultaneously, and thus more available connection options arise: an IoT terminal may communicate with the preferred satellite for the shortest link or connect to multiple satellites concurrently with the aid of ISLs for exploiting diversity gain and avoiding frequent handover. Besides LEO-SATs, assortments of non-terrestrial infrastructures, such as high-altitude platforms and unmanned aerial vehicles are expected to be integrated with the terrestrial interfaces to constitute an integrated space-air-ground-sea network for 6G communications [12]. Therefore, how to coordinate the intra-network and inter-network cooperation with the NGMA scheme to facilitate the seamless integration of such multi-dimensional heterogeneous networks should be further investigated for QoS enhancement. To this end, key technologies, such as interference management, cognitive radio, and software-defined networking [2], which show promise to cope with more complicated interference scenarios among different interfaces and contribute to more flexible network architectures, are worthy of further exploration.

**Conclusions**

Efficient NGMA paradigms play a critical role for LEO-SATs in the expected 6G networks to fully unleash their potentials and support ubiquitous massive connectivity. We commenced this article by providing a comprehensive overview of the state-of-the-art MA schemes and highlighting their limitations in the context of LEO-SATs. By amalgamating the advantages of the GF-RA mechanism and the OTFS waveform, we proposed a GF-NOMA-OTFS paradigm to provide more efficient access and accommodate the high-mobility of TSLs. The case study validated that the proposed solution offered prominent gains for ATI and CE in the absence of scheduling information, while harvesting BER performance improvement by fully exploiting full channel diversity. Yet, there remain a plethora of open challenges to be addressed, encouraging more technological breakthroughs in the future.
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