LEO Satellite Constellations for 5G and Beyond: How Will It Reshape Vertical Domains?

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***Abstract*—The rapid development of communication technologies in the past decades has provided immense vertical opportunities for individuals and enterprises. However, conventional terrestrial cellular networks ranging from 1G to 5G have unfortunately neglected the huge geographical digital divide, rather than positively reduce it. To fully meet the ambitious goal of "connecting the unconnected", integrating low Earth orbit (LEO) satellites with the terrestrial cellular networks has been widely considered as a promising solution. In this article, we first introduce the development roadmap of LEO satellite constellations, including the early attemps in LEO satellites and the emerging LEO constellations. Further, we discuss the unique opportunities and challenges of employing the LEO satellite constellations. Specifically, we discuss the potential impacts of applying LEO satellite communications on the typical 5G use cases and then present their key performance indicators, which offer important guidelines for the design of the associated enabling techniques. Moreover, the involved key techniques are further illustrated in details. Finally, we conceive the future vision of various vertical domains reshaped by LEO satellite constellations.**

***Index Terms*—Low Earth orbit (LEO) satellites, satellite constellation, 5G Vertical.**

I. INTRODUCTION

THE unprecedented development in communication technology has been witnessed in the past few decades, where the overall transmission rate of wireless systems has experienced an exponentially growth [1], [2]. However, in recent years, the further development of communication technology faces severe challenges as the ultra-dense networks and massive nodes become mobilized and ubiquitous. Unlike previous mobile communications ranging from 1G to 4G, 5G networks aim for industrial communications to help digitize the economy and contribute towards the global digital transformation, rather than barely improving the overall data rate. Correspondingly, the driving force that urges further research of beyond 5G (B5G) even 6G is the demand-intensive vertical industries, which can be classified as one or a mix of the following usage scenarios: enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra reliable low latency communications (URLLC) [3].

Affected by the impact of the COVID-19 global epidemic, vertical applications such as online education, remote working, online conferences, and eHealth have attracted widespread attention, and are expected to become a new normality in the near future. The advanced terrestrial networks make it possible for us to attend work, school, and meetings at home. However, according to the report of the international telecommunication union (ITU), only 48.6% people in the world have access to the Internet [4]. The huge dead zone of coverage can be eliminated by deploying more terrestrial base stations (BSs), which is, nevertheless, impractical and unaffordable under current situation. Additionally, the required ubiquitous connectivity can be challenging due to severe propagation fading of complex terrains and poor penetration feature of millimeter-wave communications to be employed in 5G. Against the aforementioned constraints, space-based satellite constellations emerge as the times require.

With the emerging concept referred as mega-constellations [5], the era of seamless connectivity is around the corner. Hundreds of satellites in low Earth orbit (LEO), medium Earth orbit (MEO), and geostationary orbit (GEO) collaborate together forming satellite constellations, which completely change the static topology in conventional terrestrial networks and enable flexible network deployment. Despite the fact that only ultilizing 3 GEO satellites can provide seamless coverage of the globe, the associated latency and small throughput are generally intolerable in most 5G application scenarios. Hence, LEO satellites attract more and more attention as it can operate on a lower orbit with shorter latency and provide wide band Internet access.

In recent years, low-cost rocket launching and advanced manufacturing technologies have paved the way for the deployment of mega constellations, especially for LEO satellites. For LEO, the lower orbit altitude leads to a shorter latency for delay-sensitive tasks such as media and entertainments, while the high density constellation guarantees the seamless coverage globally. Therefore, the amalgamation of satellite access and conventional terrestrial networks is an inevitable trend for B5G and even 6G in meeting the increasing demands.

The rest of the article first introduces the roadmap of LEO satellite constellations development, after which the opportunities of employing LEO satellite constellations are discussed. We further discuss the technique challenges and highlight the research directions, and finally come to future vision.

II. DEVELOPMENT ROADMAP OF LEO SATELLITE CONSTELLATIONS

In the early 1990s, the idea of communicating via commercial LEO satellites has gradually materialized. The earliest satellite was launched in 1957. Since then, satellites used for data transmission are mainly high Earth orbit (HEO) satellites and the majority of them served as data broadcasting satellites, whose applications include satellite TV programs, positioning, etc. With the increasing demands for higher system capacity

TABLE I
COMPARISON OF SELECTED CONSTELLATION OPERATORS

Constellation	Regime	Orbit height	Quantity	Bands	Latency	Services	Est. data rate
Iridium Gen. 1	LEO	781 km	77	L	40 ms	Voice, data	2.4 Kbps
Globalstar	LEO	1414 km	48	S, L	60 ms	Voice, data	(up to) 9.6 Kbps
Orbcomm Gen. 1	LEO	700 $\sim$ 800 km	36	VHF	40 ms	IoT & M2M* communication	2.4 Kbps
Skybridge	LEO	1457 km	64	Ku	40 ms	Broadband internet	60 Mbps
Teledesic	LEO	1375 km	288(840)	Ka	-	Broadband internet	64 Mbps
Iridium Gen. 2	LEO	781 km	66	L, Ka	40 ms	Voice, data	1.5 Mbps, 8 Mbps
Orbcomm Gen. 2	LEO	700 $\sim$ 800 km	18	VHF	40 ms	IoT & M2M communication	4.8 Kbps
O3b	MEO	8063 km	20	Ka	140 ms	Broadband internet	500 Mbps
Oneweb	LEO	1200 km	648	Ku	30 ms	Broadband internet	400 Mbps
Starlink	LEO	550 km	42000	Ku, Ka, V, E	20 ms	Broadband internet	100 Mbps
Hongyan	LEO	1100 km	320	L, Ka	-	Voice, broadband internet	100 Mbps
Kuiper	LEO	590 $\sim$ 630 km	3236	Ka	-	Broadband internet	-

* : Internet of things and machine to machine

and shorter latency, the concept of seamless constellation composed of LEO satellites has been proposed. Early designs of LEO satellites typically included a small amount of satellites to ensure every corner on the Earth could be served by at least one satellite. In this section, we provide a comprehensive overview and comparision on the existing satellite constellations. Table I gives a brief summary of the most well-known satellite communication systems that utilize constellations to support wide-area coverage.

A. *Overview of Early LEO Satellites*

In the late 20$^{\text{th}}$ century, network operators and companies have made their initial attempts in LEO constellations. Although most of the early attemps ended up with bankruptcy, their experiences fortunately have guided the way for the newcomers.

1) **Iridium:** Iridium went into operation by Motorola in 1998 as one of the earliest LEO constellations adopting the Walker constellation pattern. The constellation consists of a group of satellites that are in circular orbits and have the same period and inclination. 11 satellites are uniformly distributed on 7 orbit planes (6 planes in the 2$^{\text{nd}}$ generation of Iridium) with a height of 780 km, and are able to work in both time division multiple access (TDMA) and frequency division multiple access (FDMA) mode. The Walker star constellation has the best coverage diversity at poles, while the worst at Equator. Due to the unaffordable costs, Iridium eventually went bankrupt in 1999.

2) **Globalstar:** Globalstar became commercially available in later 1998. Different from Iridium, Globalstar constellation adopted the Walker Delta pattern, which is also known as Rosette, achieved the best coverage diversity at mid-latitudes, but no coverage at poles. Globalstar constellation is designed to deploy 48 LEO satellites at the altitude of 1414 km adopting code division multiple access (CDMA) mode for satellite phone and low-speed data communication services. Unfortunately, Globalstar also went bankrupt due to huge economic losses in 2002.

3) **SkyBridge***:* SkyBridge is a broadband access system that utilizes a constellation of LEO satellites. Unlike the aforementioned constellations that only provide voice and low-speed data services, SkyBridge provides broadband internet access that can be up to 60 Mbps adaptively in increments of 16 Kbps. The constellation of SkyBridge can be divided into 2 symmetrical Walker pattern constellation at an altitude of 1457 km, which can seamlessly cover gateways and user terminals (UTs) over the globe.

4) **Teledesic***:* Teledesic started its operation on 1998, and it initially attempted to build the largest constellation with 840 satellites at the altitude of 700 km for supporting the space-based broadband internet access, while was scaled down to 288 satellites later. After several reorganizations and merging, Teledesic eventually suspended its operation in 2002 owing to the commercial failure similar to other service providers.

Despite the setbacks at the early exploration of LEO constellations, its development still continues and the related technologies become mature and relatively affordable.

B. *State-of-the-Art Emerging Constellations*

The Iridium NEXT and Second-generation Globalstar are reconstructed from bankruptcy, and slightly expanded their scopes of business aiming at offering higher data rate and larger user capacities. Instead of supporting the voice and low-speed data services, the remaining and emerging companies target at global broadband Internet access.

OneWeb[1] targets at seamless global coverage with customer demonstrations and commercial services in the upcoming future, and has launched 74 of 648 planned satellites to date. OneWeb constellation is expected to provide up to 400 Mbps downlink and 30 Mbps uplink rate through special UTs or gateways. Note that different types of UT are tailored to multiple vertical cases such as aero, maritime, and cellular scenarios.

Apart from OneWeb, several developing or designing LEO satellite constellations are in progress. **Starlink** is another emerging constellation which has planned to launch around 42000 satellites, the largest constellation ever, on several

[1]OneWeb also went bankrupt in March 2020 due to the hight cost of manufaturing and launching satellites, while sought to expand the constellation up to 48000 satellites after taken over by the new owners.

TABLE II
TYPICAL 5G USE CASES AND CORRESPONDING KPIS

Verticals	Latency	Reliability*	Data rate	Cost	Positioning Accuracy	Mobility	Density**
Industry 4.0	100 ms	$\sim 10^{-6}$	10 Mbps	High	High	Medium	High
eHealth	10 ms	$\sim 10^{-9}$	10 Mbps	Medium	High	High	High
Energy	100 ms	$\sim 10^{-6}$	10 Mbps	Medium	Medium	High	Low
Education	100 ms	$\sim 10^{-5}$	1 Gbps	Medium	Low	High	High
Finance	10 ms	$\sim 10^{-9}$	100 Mbps	High	Low	Low	Low

* : Bit error rate (BER).
** : Devices per km^2.

different altitudes of orbits, and is the first constellation that has applied for the use of V-band and E-band to support its advanced services in broadband Internet access globally. On the other hand, project **Kuiper** is an initiative that proposes to build an LEO constellation with 3236 satellites for providing broadband connectivity to the unserved users. Other constellation competitors such as O3b and Hongyan whose related details can also be found in Table I.

In recent years, integrating 5G with LEO satellite constellations becomes a trending topic. The low altitude characteristics of LEO constellations provide the convenience of low latency, and the massive deployment achieves global coverage. These features of LEO constellations perfectly cover the flaws of current terrestrial 5G networks, which can be a brand new attempt in the field of wireless communications.

III. OPPORTUNATIES OF LEO SATELLITE CONSTELLATION FOR 5G AND BEYOND

In this section, we will give a brief introduction to the motivation of adopting LEO constellations, and analyze the impact on B5G use cases.

A. Motivation of Using LEO Satellite Constellations

5G has specified new KPIs for typical use cases. Therefore, to further explore the unique advantages of applying LEO satellite constellations to terrestrial 5G, we first discuss the KPIs of space-based network as shown in Table II. The unique advantages of LEO satellite constellations motivate us to integrate space-based network with the future B5G and even 6G to achieve a better performance. Specifically, these KPIs include

1) Latency: The altitude of orbits determines the end-to-end communication latency. Extremely high altitude may bring wide coverage, while the introduced physical round-trip latency (e.g., up to 240 ms via GEO satellites) is obviously intolerable under the requirements of current 5G standard. By contrast, the altitude of LEO is lower than 2000 km, whereas some of the latest constellations such as Starlink are as low as 500 km. As a result, the corresponding round-trip latency is around 3 ms physically, which can well meet the control plane round-trip latency requirements for eMBB and URLLC usage scenarios requiring lower than 20 ms [3].

2) Reliability: The reliability generally represents the error rate of communication links that is one of the most important KPIs in communication systems. Reliability is crucial to various vertical applications (e.g., eHealth and finance), and is expected to approach 10^{-5} or lower BERs. In addition to error rate, interruption time is another manifestation of reliability, which is defined in eMBB and URLLC usage scenarios. As the scale of constellations increases, each user can be servered by several satellites simultaneously to improve the communication reliability benefited from the spatial diversity gains.

3) Data rate: Achieving both of the throughput and reliability is generally infeasible due to the limited system resources. Satellite-ground links used to be low-speed links, i.e., supporting several Kbps, which cannot well meet the demands set by 5G eMBB. Fortunately, the emerging LEO mega-constellations are expected to be a game changer. Huge number of satellites exploiting large bandwidth and the high-quality line-of-sight (LoS) links can support much higher data rate than ever before, and are expected to reach the demand of mMTC and eMBB.

4) Cost: Cost is the biggest challenge to profitability and long-term viability. Due to the financial burden from manufacturing, launching, operating, and so on. Several companies have gone bankruptcy in the early 21st century. Fortunately, the recently developed and advanced satellite technologies and the soaring demand for ubiquitous broadband Internet access with promising market profits have fueled the development of affordable and healthy operation of LEO constellations.

5) Positioning and navigation: As the demand for positioning and navigation service has upsurged in recent years, LEO constellations serve as a viable solution to meet these requirements and enhance the current services. In fact, the unprecedented number of LEO satellites can provide much more measurements simultaneously to support higher positioning accuracy, while the lower altitude reduces the physical latency in the meantime. Additionally, shorter orbital period contributes to the time decorrelation, which will accelerate the convergence process in high-precision positioning tasks.

6) Mobility: At the micro level, the frequent migration via public transportations, high-speed rail, airplanes, and even ships remain a mobility issue to be solved. Against this background, LEO satellites will well support the aforementioned high mobility vehicles, whose velocity reach as high as 1000 kmph in the air, or 300 kmph on rails, without deploying much more BSs. Therefore, the supported mobility is an important KPI for LEO satellite constellations.

7) Connection density: An unprecedented number of satellites can be exploited to support high density of services. Other than users, the number of machine-type nodes increases rapidly, which makes the connection density as a KPI. Networks are required to support higher density of services for the increasing number of nodes, and the LEO satellites can be the solution. The reduction in mass and production

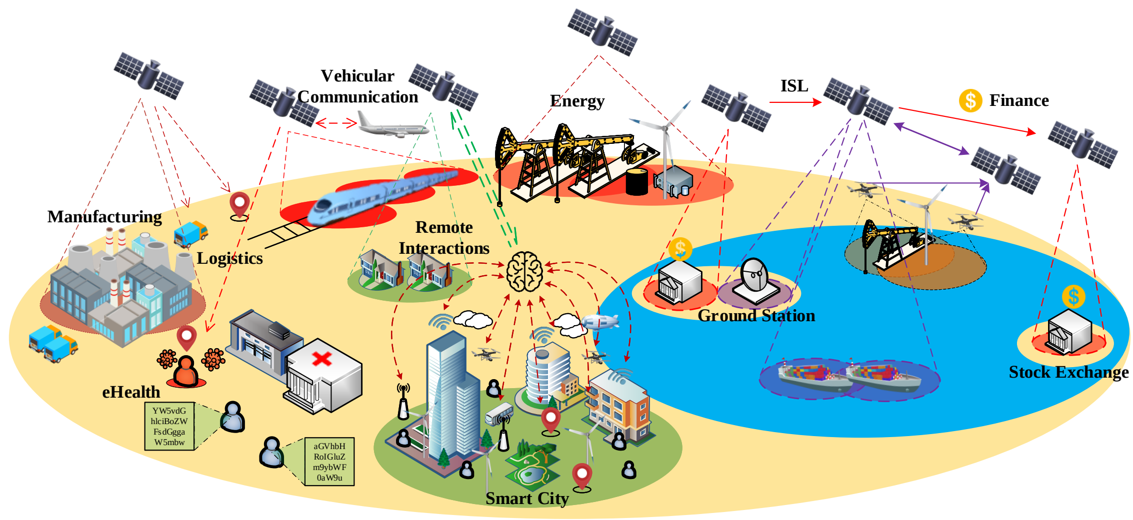

Fig. 1. Ambitious vision of various vertical domains reshaped by LEO satellite constellations.

cost of LEO satellites make it possible to construct mega-constellations, therefore the service density of networks is expected to increase continously.

B. Impact on B5G Use Cases

As mentioned before, the huge geographical digital divide [6] is non-negligible in conventional terrestrial cellular networks caused by harsh terrain environments. Against this background, future B5G or even 6G integrated with the space-based LEO constellations is envisioned to bridge the digital divide, which can be achieved by reshaping the traditional vertical domains and promising a myriad of opportunities for rising industries. Here we present the impact of future LEO satellite constellations on B5G use cases which are shown in Fig. 1 as follows:

1) Industry 4.0: Traditional industry focused on the digitization of manufacturing, while industry 4.0 is an era that promotes the industrial revolution by digitization technologies including saving energy and resources, minimizing waste production, and customizing products. The highly customized industry requires quick reaction from customers, suppliers, and logistics providers to dynamically modify the process of planning, producing, shipping, and selling.

2) eHealth: Public heath emergencies have stimulated global attention on medical services and the integrated medical security scheme should be perfected for all countries. The eHealth is envisioned to provide individualized health care and ubiquitous connectivity by monitoring and tracking health data of patients, which will encourage the integration of LEO satellite-based infrastructures for globally wider coverage.

3) Energy: The newly discovered fossil energy is generally distributed in remote areas and maritime areas, which are usually far from the 5G terrestrial cellular coverage. Nevertheless, LEO constellation is the most suitable solution to support intelligent and remote operations. Most of the operation environment, such as the offshore plaform and the radioactive environment, is not suitable for long-term onsite in person operations. Therefore full information and necessary control acquired by LEO constellations will greatly promote the development of energy fields.

4) Education: Education undoubtedly plays an important role in the society and still remains one of the most noticed vertical domains in the world. However, the form and content have been reshaped significantly during the global pandemic. Remote education emerged as a promising alternative solution and is envisioned to be the direction of future education. It not only redistribute the educational resources, which leads to a higher profit and flexibility in resource allocation, but also robust against other emergencies. Moreover, seamless coverage of satellite network can expand the coverage of remote education, which reshapes the future education paradigm, opens on new markets, and furthur promotes digitization.

5) Finance: Financial applications such as asset tracking (AT) and high-frequency trading (HFT) are typical scenarios for LEO satellites. AT requires one-way communication to achieve physical tracking, which is implemented by terrestrial networks and global positioning system. LEO satellites will improve the unreliability of terrestrial network and the positioning accuracy of GPS, therefore achieveing better performances. HFT can be prcessed by computer algorithms rapidly in fractions of seconds and is sensitive to latencies. Space-based transmissions are expected to offer lower latency than undersea fiber, which may promote financial profit in the long term.

IV. Technique Challenges and Research Directions in LEO Satellite Constellations

In this section, we introduce some key technologies that support various vertical solutions mentioned above. The challenging techniques are presented from the following three aspects.

A. Network Architecture

Currently, shown in Fig. 2, there are 2 types of methodologies that establish the constellation-based network architecture:

- User equipments (UE) directly communicate with LEO satellites.
- The UE communicates through a terrestrial BS, and the satellite-ground link serves as backhaul for data exchange.

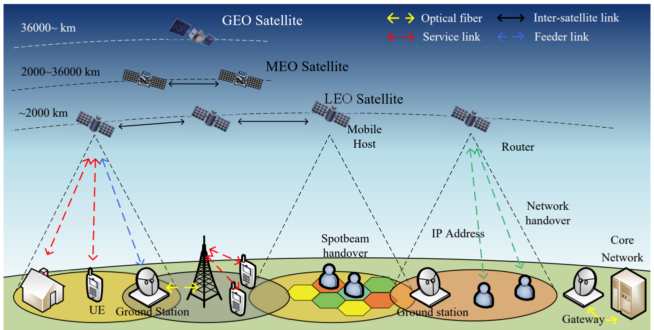

Fig. 2. Schematic diagram of network architecture and mobility management in LEO satellite constellations.

The former strategy is adopted by Iridium, Globalstar, and some other operators by promoting their satellite UTs in the early stages, which has caused inconvenience and financial burden on both subscribers and operators practically. In contrast, the latter strategy still depends highly on the terrestrial stations to complete the network topology. On the other hand, LEO constellations are not the only space-based networks that have been imposed the duty of communication. Various standardization processes have been carried out on different satellite altitudes [9], respectively. However, jointly optimizing resource allocation and signal processing on different altitude satellites (e.g., GEO, MEO, and LEO satellites) is envisioned to be a promising topology for future heterogeneous cellular network, where the satellites complement each other on computation capacity, location accuracy, and seamless coverage.

B. Mobility Management

Mobility management was firstly proposed in cellular networks for supporting continuous communication applications. In fact, LEO constellation communication scenarios are rather similar to the cellular scenarios, while the mobility of satellites will produce frequent relative movements unlike the fixed BSs. High mobility triggers more frequent randomness for continuous communications, hence the handover techniques for link layer and network layer are urgely required for LEO satellite communication systems [7], [8].

1) Link layer: Link layer handover occurs when one or more links between the communication nodes have changed due to the dynamic connectivity patterns caused by high mobility of LEO satellites. This can be further classified into spotbeam handover, satellite handover, and inter-satellite link (ISL) handover scenes:

- **Spotbeam handover** happens when terrestrial nodes actively or passively cross the boundary between 2 adjacent spotbeams of one satellite.
- **Satellite handover** happens when a node is no longer served by the previous satellite.
- **ISL handover** happens when an ISL is interrupted due to the change in distance or field-of-view angle, where new ISL establishes and causes rerouting issues.

2) Network layer: Network layer handover occurs when a satellite or terrestrial node needs to change its IP address. When satellites operate as mobile hosts that exchange data with terrestrial stations for different communication terminals, the IP address of the satellite is bonded with the terrestrial stations. When the satellite leaves the coverage area of the previous terrestrial station and starts to bond with another terrestrial station, the IP address of the satellite has to be updated, which requires network layer handover. Additionally, when the satellite operates as a router, users covered by these satellites may require a handover in the case of switching between spotbeams or satellite routers.

Similar to terrestrial networks, there are two main types of network layer handover techniques that can be adopted to deal with handover issues, which are respectively referred to as hard handover and soft handover. In particular, hard handover would first disconnect the current link and then establish a new handover link, while the soft handover will not initiatively disconnect the link before a new link is stably established. However, most existing handover solutions for mobility management only focus on voice services, while ignore the characteristics of data traffic. Furthermore, the scale of constellations and terrestrial nodes has become larger than ever before. The great amount of satellites lead to excessive overlapping of seamless coverage areas, thereby causing new handover issues to be solved.

C. Physical Layer Transmission

Experiments for LEO mega-constellations are underway [5], while the integration of satellite access in terrestrial 5G still remains unsettled. Commercial solutions for mobile satellite communication includes setting up several terrestrial gateways, densely deploying special antennas, and using specified UTs. Integating satellite access with 5G network will bring the unprecedented convenience to wireless systems and finally achieve the seamless network coverage by a unified protocol.

According to the current 5G technology and non-terrestrial network status [9], several incompatibilities still need to be investigated in future integrations.

1) **Spectrum planning:** 5G has scheduled dozens of new frequency bands, which has further squeezed the idle bands in sub-6G frequencies, and the unexpectedly arrangement of over 40000 satellites in the near future will accelereate the exhaustion of limited spectrum. Most of the LEO constellations have planned the frequency bands in Ka band as shown in Table I, where the detailed spectrum allocation schemes require further discussion.

2) **Terahertz and free space optical based ISL:** Terahertz (THz) and free space optical (FSO) are two of the most promising techniques to support ISL due to their extremely high directional transmission, ultra-wide band, and security characteristics. In a turbulence-free outer space scenario where the coordinate of each satellite can be precisely calculated, THz or FSO based ISLs can be accurately established for routing or data exchanging. According to the current research situation, the stable ultra-high speed electro-optic modulation and signal processing techniques remain to be further explored.

3) **Multi-beam technique:** As manufacturing and launching proceed as planned, the Earth will be covered by several layers of LEO satellite constellations with different altitudes. The trend is that the number of beams from multi-beam antennas will increase continuously as the distributed IoT nodes increase, whereas the full frequency reuse (FFR) scheme rather than 4 color frequency reuse (FR4) will be considered to fully utilize the spectrum reuse gain. However, FFR leads to serious inter-beam interference (IBI), where the advanced precoding [11], dynamic beam shut off [12], and non-orthogonal multiple access (NOMA) [13] techniques should be adopted for better interference management. Additionally, energy consumption and power control are also key challenges, where the hybrid multiple-input-multiple-out arrays [14] with flexible beam configuration and low resolution analog-to-digital converters will become promising research trends in future non-terrestrial networks.

4) **Modulation for fast-varying satellite channel:** Unlike terrestrial cellular systems, propagation channel in satellite communication is generally a LoS channel which is Rician distributed. Although multipath effect is no longer the main issue, the altitude and the corresponding mobility of LEO satellites introduce other technical issues. Preserving current standards, cyclic prefix in orthogonal frequency division multiplexing or single carrier frequency domain equalization systems should be further extended to compensate delay spread and jittering for satellite signal, while on the other hand, unnegligible Doppler effect may further affect the aforementioned subcarrier spacing scheme. To mitigate the effect of delay-Doppler impairments, new modulation scheme should be proposed for efficient Doppler compensations.

5) **Access protocols for low latency:** Among the potential latencies in different layers, the physical latency due to the propagation is inevitable, thus the focus falls on the protocols and signal processing techniques. Novel mechanism named as grant-free random access (GFRA) addresses the challenge of low-latency transmission in IoT networks. GFRA allows active nodes to transmit their pilots and data to the BS without waiting for permissions, which cuts down the overall latency, while still requires further research in satellite communication scenes [15].

V. Future Vision of Verticals Reshaped by LEO Constellations

In this section we highlight the productivity enhancements and functionality enrichments of future verticals reshaped by LEO constellations.

A. Intelligent Vehicular Networks

As the constellations become popularized thanks to the advanced manufacturing and low-cost launching techniques, elimination of coverage dead zones in air lines, sea lanes, and high-speed rails is an obvious trend. Employing new antennas tailored for LEO constellation, the airplanes, vessels, and high-speed trains can instantaneously become new dynamic nodes in satellite network topology. Network coverage can be unprecedentedly wide, whereas the link performance such as reliability, capacity, and latency will be much better than ever before. The enhanced vehicular network can fulfill the requirements raised by eMBB, and further makes it possible to deal with trading, streaming, and monitoring.

B. Industrial IoT

Industrial IoT, also known as Industry 4.0, is the combination of massive IoT nodes with industry applications, mostly manufacturing. Deploying LEO constellations can be a better solution to solve the problems such as distributed manufacturing, personalized assembling, and cognitive supply networks, which require fine-grained connectivity and high-accuracy positioning services provided by countless terrestrial BSs, and is an enabling technology for business-to-business (B2B) promotion.

C. Intelligent Agriculture

Compared with industry, agriculture relies more on the convenience brought by the LEO constellations. The cultivated land typically located in the vast and sparsely populated areas, which brings the burden of cost for optical cables deployment. As more machine-type nodes are utilized in agriculture practice, deploying LEO satellites for crops and livestock monitoring or even unmanned operations is an inevitable trend, and will significantly contribute to the productivity in agriculture.

D. Intelligent Living and Business via Remote Interactions

Remote interactions including education, online-work, online-entertainment and shopping for isolated and rural areas is not a novel idea, while it is not until the pandemic emergency that these remote interactions have once again attracted public attention. Globally seamless coverage with considerable low latency and wide bandwidth paves the way for people in rural areas to interact remotely, and our vision is that through allocating satellite resources, we can effectively promote the remote interactions as a safe and efficient solution in emergencies, a daily lifestyle, and even driving forces which conform to the unmanned fashion for labor-intensive industries.

E. Smart City

The dominated issues of constructing smart city are the technically outdated infrastructure, imperfect coordination mechanism, insufficient resources, etc. In a typical smart city, massive IoT sensors distributed in cities can be directly connected to the “City Brain”, where the cross-system aquired multi-mode data are processed in real time. LEO satellites will play an important role in synchronization, and dynamic resource allocation with fast response and high concurrency, and is envisioned to play a role in traffic management, large-scale activity flow monitoring, smart tourism, and cloud-edge integrated infrastructure management.

VI. Conclusions

In this article, we have investigated the development roadmap of LEO satellite constellations, and introduced opportunities and key technologies of integrating LEO constellations with future cellular networks. We further prospects the future vision of reshaping verticals by LEO constellations. In a sum, as shown in Fig. 3, the key techniques are the pillars for achieving the superior KPIs and supporting various service requirements, superior KPIs are the foundations for breeding and

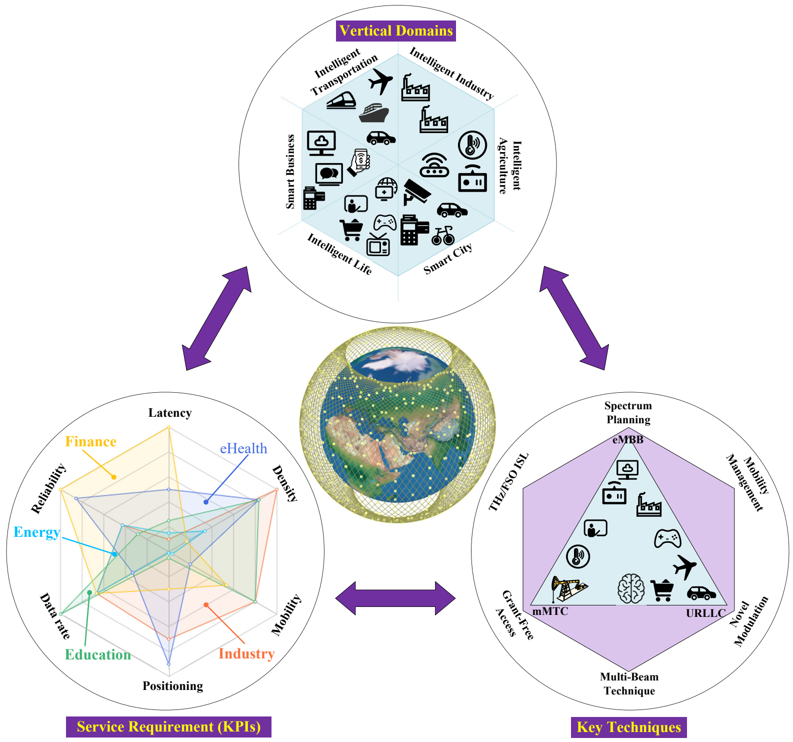

Fig. 3. Relationship between vertical domains, service requirements, and key techniques.

reshaping the various vertical applications, and revolutionary vertical applications will further bring profits for promoting the technique innovations of LEO constellations.

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