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LEO Mega-Constellations for 6G Global Coverage: Challenges and Opportunities

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ABSTRACT Mega-constellations have the potential for providing 6G Internet owing to the unique advantage of global coverage. However, current satellite technologies are not omnipotent. There are still many challenging problems that need to be solved for mega-constellations to support 6G, e.g., efficient resource allocation, gratifying mobility management, and large-scale full-time TT&C (tracking, telemetry, and command). This paper starts with a novel definition of LEO mega-constellations and a brief review regarding the current typical mega-constellations, discussing the development direction of the mega-constellation air interface. Then, the key technologies development status of satellite networks is illustrated and analyzed from five aspects: network protocol, multiple access, satellite handover, TT&C, and interference mitigation, especially their adaptability in mega-constellations for 6G global coverage. Finally, considering the features and requirements of 6G, future challenges for mega-constellations and some potential solutions are proposed.

INDEX TERMS Mega-constellations, air interface, network protocol, multiple access, satellite handover, TT&C, interference mitigation.

I. INTRODUCTION

To satisfy the requirements of mobile communications of the future in 2030 and beyond, research on the critical technologies of sixth-generation (6G) have begun in full swing [1], [2]. In the next-generation 6G wireless networks, the system must simultaneously deliver more bits, more reliability, high energy efficiency for heterogeneous devices, across uplink and downlink. The performance requirements for various types of 6G applications are depicted in Table 1, including *mobile broadband reliable low latency communication (MBRLLC)*, *massive URLLC (mURLLC)*, *human-centric services (HCS)*, and *Multi-Purpose services (MPS)*. It is noted that the main distinguishing feature of 6G is no longer a single breakthrough in capacity and transmission rate but to achieve ubiquitous and fair connectivity, reducing the digital divide.

For the vision of 6G, it is generally recognized that terrestrial cellular networks alone cannot achieve. For example, in remote rural and barren areas, traditional terrestrial networks are still incapable of deploying and maintaining owing to their limitations of geographical location and operation cost [3]–[6]. According to the report of Global System for Mobile Communications assembly (GMSA), more than 40% of the Earth's area is still without network coverage, and nearly 4.6 billion Internet users are looking forward to a higher rate plus lower latency network [7]. Thanks to the advantages of ubiquitous coverage, immune to disaster, and low deployment complexity, satellite communication could be considered as a complementary design for global coverage, playing essential roles in 6G.

Actually, since the United States launched the satellite Synkom in 1963, people have shown intense interest in using satellites to communicate. The first satellite communication system is the geosynchronous mobile communication satellite system, but it has many shortcomings. First, geosynchronous satellites have high orbits plus long transmission delays, so it is challenging to meet the interaction needs of users. Besides, geosynchronous orbit resources are limited.

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TABLE 1. The performance requirements for various types of 6G applications.

Service	Performance indicators	Example application
MBRLLC	Energy efficiency Ubiquitous connectivity Stringent rate-reliability-latency	XR/AR/VR Autonomous drones Autonomous vehicular
mURLLC	Scalability Massive reliability Ultra-high reliability Massive connectivity	Blockchain Massive sensing Internet of Things Autonomous robotics
HCS	High reliability QoPE guarantees Ubiquitous connectivity	BCI Haptics Human communication
MPS	High control stability Wide-area connectivity Low computing latency	Telemedicine Robotics System Environmental imaging

* Retrieved from "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems" by W. Saad, M. Bennis and M. Chen, no. 3, pp. 134-142.

Therefore, the system cannot serve many users. Furthermore, it is difficult for geosynchronous orbit satellites to achieve global coverage veritably. Most importantly, the cost of satellite manufacturing and launching is high. As a result, users need to pay a costly fee.

In the 1990s, low-orbit mobile communication satellite constellations emerged, such as Iridium, Globalstar, and Teledesic. Although they have surmounted some problems of geosynchronous satellites, e.g., the typical transmission round trip time (RTT) is over 250∼350 ms in GEO satellite but less than 30 ms RTT in LEO constellations, the cost of service and maintenance is still high. Therefore, the low-orbit mobile communication satellite constellation was unsuccessful, and some were even canceled before launch. From the late 1990s to 2012, satellite communication entered a relatively uneventful period.

In recent years, with the rise of 6G, people have shown intense interest in low-orbit satellite communication constellations once again. Only in 2014 and 2016, 11 companies were applying to the FCC for the deployment of low-orbit mega-constellations, hoping to use them to provide global broadband access services [8]. As the number of satellites boom, an open question is where do the traditional satellite communication technology should go from here, including network protocol, multiple access, satellite handover, etc.

This paper focuses on the future development of key technologies and possible challenges for LEO mega-constellations for 6G global coverage. The rest of this paper is organized as follows: Section II first reviews three well-known mega-constellations: Telesat, OneWeb, and SpaceX, then defines mega-constellations afresh and finally points out the development trend of air interface technology for mega-constellations. Section III illustrates and summarizes the development status of key technologies of satellite networks from five aspects: network protocol, multiple access, satellite handover, TT&C, interference mitigation, and provides the analysis of their adaptability in mega-constellations for 6G.

TABLE 2. Classification of LEO satellite constellations (1997).

Constellation type	Satellite mass	Number of satellites	Data type
LEO Small-constellations	< 100 lb	<50 pcs	message
LEO Large-constellations	< 300 lb	<100 pcs	voice call
LEO Mega-constellations	>1,000 lb	>200 pcs	Broadband network

In Section IV, according to the characteristics and requirements of mega-constellations and 6G, future challenges and research directions plus preliminary solutions are given. Section V summarizes the full paper.

II. THE CONCEPT AND DEVELOPMENT STATUS OF THE MEGA CONSTELLATION

This section first defines mega-constellations and then briefly reviews the three typical mega-constellations of SpaceX, OneWeb, and Telesat. Finally, the development trend of the LEO mega-constellations air interface is analyzed.

A. THE CONCEPT OF MEGA CONSTELLATION

Up to date, there is still no clear definition of mega-constellations in academia. When the idea of mega-constellations was first proposed, scholars classified LEO satellite constellations in the light of Table 2 [9]. Recent research is still discussing how many satellites should be in mega-constellations [10]. Although the numbers of mega-constellations defined in different papers vary due to assuming different orbit altitudes, orbit types, satellite capabilities, user requirements, etc., we can observe a general trend in the definition of the number of mega-constellations satellites is constantly increasing. However, how many LEO satellites are needed to be called mega-constellations in the end?

We believe that the definition of a mega constellation should not be limited to satellite mass or the number of satellites. Combined with the current universal knowledge on mega-constellations in academia, the mega constellation can be defined as a constellation that comprises a series of low-cost, miniaturized low-orbit communication satellites; reaching the capacity of more than Gbit/s plus a transmission delay of less than 50 ms; and achieving global coverage by inter-satellite links or on-board processing. Mega-constellations are expected to aim at the following scenarios, including dead zones of terrestrial networks, such as deserts and mountains; disaster areas, such as earthquakes and typhoons; aerial platforms, such as airliners and hot air balloons; and ocean areas, such as liners, oil rigs, as well as and marine sensors.

B. THREE TYPICAL MEGA-CONSTELLATIONS PLAYERS

1) ONEWEB [11]–[14]

OneWeb's goal is to provide seamless broadband Internet access services worldwide. At the beginning of the

TABLE 3. The orbit characteristics of Starlink Gen2.

Sub-constellation	Altitude	Inclination	Planes	Satellites per plane	Number of satellites
1	328	30	1	7,178	7,178
2	334	40	1	7,178	7,178
3	345	53	1	7,178	7,178
4	360	96.9	40	50	2,000
5	373	75	1	1,998	1,998
6	499	53	1	4,000	4,000
7	604	148	12	12	144
8	614	115.7	18	18	324
Total			75	/	30,000
-	km	°	-	-	-

project, the OneWeb constellation was designed to distribute 716 satellites among 12 and 8 circular orbital planes at 1,200 km, inclined at 87.9° and 55°, respectively. Currently, OneWeb has applied to the FCC, hoping to expand its constellation by adding 5,656 satellites, aiming to extensively cover the Earth populated regions.

In OneWeb, each satellite carries a bent-pipe payload with 16 identical, fixed, highly elliptical user beams (may form up to 32 steerable user beams in the future) to ensure that any user with an elevation angle greater than 55° will be within the line-of-sight (LOS) of at least one satellite. Despite OneWeb having the lowest satellite utilization among the three typical constellations, it is estimated that the system has more than 50 gateway earth stations with antennas between 2.4 and 3.5m, and user terminals can achieve at a speed of 100 Mbit/s.

2) SPACEX [15]–[18], [19], [20]

Initially, SpaceX prepared to use 4,409 satellites to deploy the core constellation in the Ka and Ku bands (first stage) and use 7,518 satellites to achieve global high-speed and low-cost Internet services in the V band (second stage). Currently, due to the data of the test satellite plus various factors, SpaceX began to take 75 orbital planes at an altitude between 328 and 614 km as the target orbit and hope to add 30,000 satellites plus E bands to obtain better performance, including narrower beams, shorter delays, better reliability, as well as and greater capacities - named ‘‘Starlink Generation 2 (Gen 2)’’. The orbit characteristics of Starlink Gen2 are summarized in Table 3.

SpaceX plans to deploy a vast number of gateways worldwide with 1.5 m antennas, and one gateway can connect to four satellites concurrently.

3) TELESAT [21], [22]

The satellites of the Telesat constellation are distributed in two sets of orbits: the first set has six circular orbital planes (polar orbits) with an altitude of 1,015 km and an inclination of 98.98°. Each plane has at least 13 satellites, which can provide global coverage; the second set has 20 circular orbital planes (inclined orbits), at 1,325 km, inclined at 50.88°, with at least 11 satellites per plane, focusing on populous areas. Like OneWeb, most of Telesat’s capacity is concentrated in populated regions.

Telesat is designed with several gateways worldwide, and each gateway is equipped with multiple 3.5 m antennas. Because of this, it has achieved a similar throughput to SpaceX despite having the fewest satellites among the three typical constellations.

According to the FCC filing, Telesat intends to increase from 6 polar planes to 27, and from 20 inclined planes to 40, while trebling the number of satellites on the inclined planes.

4) BRIEF SUMMARY

Although the three typical mega-constellations have different orbit altitudes, eccentricity, and inclinations, it is obviously found that they all allocate some satellites in polar orbits; that is, the three typical mega-constellations are capable of realizing the vision of 6G. Meanwhile, The idea behind the three typical mega-constellations is the same: use a minority of satellites to cover the poles while focusing their capacity on populated regions.

In addition to the aforementioned contents, we also summarize the other characteristics of the three typical mega-constellations in Table 4, including capacity, the number of users, peak data rate, frequency band, polarization mode, etc.

C. THE AIR INTERFACE OF MEGA-CONSTELLATIONS

With the rapid growth of wireless communications, mega-constellations require an excellent air interface to advance spectral efficiency and energy efficiency, providing 6G wireless communication networks worldwide. In this section, we will first analyze the development trend of mega-constellations air interface from frequency bands and coded modulation scheme, followed by AI based on Inter-satellite Links and On-board Processing.

1) HIGHER FREQUENCY BANDS

According to the frequency division of ‘‘Radio Regulations’’, satellite communication services only are authorized in the S-band, C-band, Ku-band, and Ka-band, as depicted in Figure 1. It is challenging to satisfy the stringent requirements of near future 6G for 10Gbps $\sim$ 100Gbps on peak data rate due to the limited frequency resources. Moving the spectrum of the mega constellation to a higher frequency band is considered a promising solution, e.g., mmWave operating between 30 GHz and 300 GHz, THz, as well as and laser. Currently, three well-known LEO mega-constellations also seem to have set this new trend. In March 2017, they all submitted applications to the FCC, hoping to provide services in the higher frequency band.

As the favorite of the intersatellite link (ISL), laser communication has the advantages of low transmission loss, long transmission distance, high communication quality, and large capacity. mmWave can effectively alleviate many problems of high-speed broad access, and thus it has been extensively studied in short-distance wireless communication. THz is the

TABLE 4. Summary of the other characteristics of OneWeb, Telesat, and SpaceX.

		SpaceX	*OneWeb*	*Telesat*
Capacity		17∼23 Gbit/s	8 Gbit/s	10∼38 Gbit/s
Users		-	4 million	-
Peak Data Rate		-	Uplink: 375 Mbps Downlink: 750 Mbps	-
Frequency Bands	G-to-S[1]	27.5∼29.1 GHz[2,3] 29.5∼30.0 GHz[2,3] 47.2∼52.4 GHz[2] 81.0∼86.0 GHZ[3]	27.5∼29.1 GHz 29.1∼29.5 GHz[4] 29.5∼30.0 GHz	27.5∼28.35 GHz 28.35∼28.6 GHz 28.6∼29.1 GHz 29.5∼30.0 GHz
	S-to-G[1]	17.8∼18.6 GHz[2,3] 18.8∼19.3 GHz[2,3] 37.5∼42.5 GHz[2] 71.0∼76.0 GHz[3]	17.8∼18.6 GHz 18.8∼19.3 GHz 19.3∼19.7 GHz[4] 19.7∼20.2 GHz[4]	17.8∼18.3 GHz 18.3∼18.8 GHz 18.8∼19.3 GHz 19.7∼20.2 GHz
	U-to-S[1]	12.75∼13.25 GHz[3] 14.0∼14.5 GHz[2,3] 28.35∼30.0 GHz[3] 47.2∼52.4 GHZ[2]	12.75∼13.25 GHz[4] 14.0∼14.5 GHz	27.5∼28.35 GHz 28.35∼28.6 GHz 28.6∼29.1 GHz 29.5∼30.0 GHz
	S-to-U[1]	10.7∼12.75 GHz[2,3] 17.8∼19.3 GHz[3] 19.7∼20.2 GHz[3] 37.5∼42.5 GHz[2]	10.7∼12.7 GHz	17.8∼18.3 GHz 18.3∼18.8 GHz 18.8∼19.3 GHz 19.7∼20.2 GHz
polarization	G-to-S[1]	LHCP/ RHCP	LHCP/ RHCP	LHCP/ RHCP
	S-to-G[1]	LHCP/ RHCP	LHCP/ RHCP	LHCP/ RHCP
	U-to-S[1]	LHCP	LHCP	LHCP/ RHCP
	S-to-U[1]	LHCP	RHCP	LHCP/ RHCP
Beams		Flexible	Fixed (Flexible)[6]	Flexible
InterSatellite Link (ISL)		✓[5]	× (✓)[6]	✓
On-Board Processing		✓	× (✓)[6]	✓

[1] "G-to-S" indicates "Gateway-to-Satellite", "S-to-G" indicates "Satellite-to-Gateway", "U-to-S" indicates "User Terminal-to-Satellite", and "S-to-U" indicates "Satellite-to-User Terminal".
[2] Frequency Bands used by the SpaceX System in Generation 1.
[3] Frequency Bands will be used by the SpaceX System in Generation 2.
[4] OneWeb has the capacity in these bands, but FCC authorization is not being requested at this time.
[5] SpaceX plans to use optical ISL and has completed on-orbit testing.
[6] OneWeb will not use these technologies for the time being, but they claim that at some point in the deployment of the system.
[*] At the time of writing, SpaceX and Telesat have not released public FCC filings about their number of users and peak data rate; thus, no information regarding their system is included in this Table.

transition zone from electronics to photonics. Compared with laser communication, THz communication is much easier to track and align the beam, reducing the requirements for the stability and accuracy of the equipment. In addition, it is slightly affected by atmospheric conditions,[1] including rain, fog, snow, dust, and so on. In contrast with mmWave frequency bands, THz communication has more frequency resources and is easier to achieve high-speed transmission. In other words, the THz band can be regarded as a compromise between mmWave and optical. From the perspective of 6G application scenarios, it is the most desirable frequency band.

However, there are many new challenging problems for THz to be employed in the LEO mega-constellations for 6G global coverage. First, wireless channels are the foundation of any new communication system, but we are kept

[1] Atmospheric molecules such as oxygen, nitrogen, carbon dioxide, as well as and water vapor will absorb light; atmospheric molecules such as dust, smoke, ice crystals, salt particles, microorganisms as well as and tiny water droplets will scatter light.

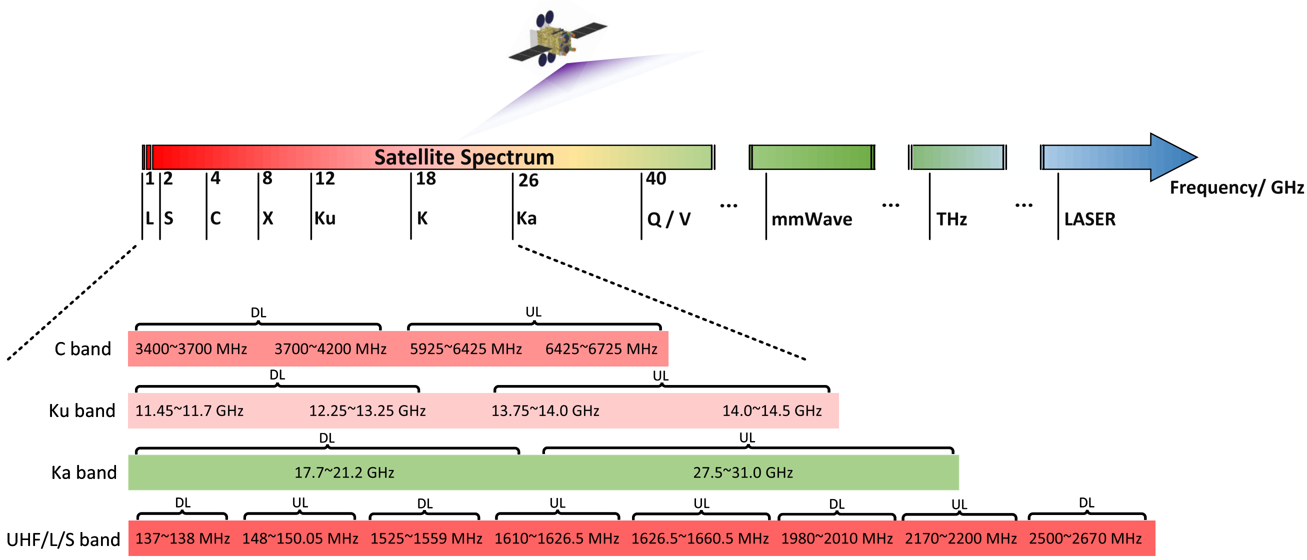

FIGURE 1. Diagram of satellite spectrum.

in the dark about the channel propagation characteristics above 300 GHz. Second, the severe atmospheric propagation losses of electromagnetic waves at THz frequencies need to be overcome. Last but not least, it is challenging to achieve high-power transceivers at THz frequencies based on the existing technology.

2) ADVANCED CODED MODULATION SCHEME

There are two key ways to provide ultra-high capacity for users in the 6G systems: utilizing larger frequency bandwidth and improving spectral efficiency. Although we are able to exploit much more spectrum resources in the higher frequency bands, improving spectral efficiency is still essential to achieve ultra-high capacity.

Currently, for channel coding, the principal methods are low-density parity-check code (LDPC), polar code, and Turbo code. Among them, LDPC and Turbo code have been adopted by 3G and 4G communication standards and Wi-Fi standards, respectively. Compared with the other two coding schemes, LDPC is much easier to satisfy the delay requirement and has excellent performance among almost all channels. Most importantly, it has a lower error floor. Although the error floor of the Turbo code is relatively high, it has notable advantages in complexity, area efficiency, as well as and energy efficiency. As a novel code, Polar code is the only encoding method that can reach the Shannon limit, but it only has excellent performance for short data due to its complexity.

As the decoding mechanism of Turbo code is iterative decoding between two-component decoders, using Turbo code in LEO mega-constellations may cause many problems in meeting the targets of 6G. With the explosive growth of short data traffic in wireless communication systems, Polar code could be envisioned as a promising candidate code scheme for signaling and burst data in the near future LEO mega-constellations. Specifically, compared with the other two coding schemes, Polar code has lower signal-to-noise ratio requirements, that is, higher reliability and coding gain, which immensely appealed to the application like Ultra-Low-Power IoT (ULP-IoT). Thanks to the low complexity and increased flexibility of LDPC, it could be envisioned as a promising candidate code scheme for long data in the near future LEO mega-constellations.

For modulation modes, APSK modulation combines the advantages of both MPSK modulation and MQAM modulation, realizing a constant envelope, high spectral efficiency, and low complexity. Currently, well-known mega-constellations like SpaceX, OneWeb, and Telesat all exploit APSK to balance peak-to-average ratio (PAPR) and BER. Still, to ensure the excellent performance of 6G services in LEO mega-constellations, data traffic characteristics also should be considered. In contrast with APSK modulation, GMSK modulation seems to be more suitable for burst communication systems. Meanwhile, GMSK modulation also has good spectrum and power characteristics and performs well in nonlinear, fading, and large Doppler channels. Therefore, GMSK modulation can be envisioned as a promising candidate modulation scheme for the near future LEO mega-constellations.

3) AI BASED ON ISL AND ON-BOARD PROCESSING

Generally speaking, the air interface in the LEO mega-constellations system for 6G services will be more complicated in the new era, which poses many new challenges. First, wireless channels are the foundation of any communication system, which tends to be built as an accurate mathematical model before communication. However, as mentioned above, it is hard to precisely describe an LEO mega-constellations communication system because of its distinctive propagation properties, e.g., low-rank, time-variant, and nonlinear. Second, to achieve the goal of 6G, Internet of everything, the existing barriers between different facilities, systems, and protocols must be removed through cooperation. Third, global coverage will drastically increase environmental diversity, and a dynamic air interface scheme is required to ensure excellent transmission performance.

Currently, three well-known mega-constellations all have benefited from the usage of ISL (intra- and cross-plane ISL) plus on-satellite processing, forming a space network to realize data exchange and data routing between satellites. Therefore, some AI technologies applied to terrestrial networks can be considered to solve the above challenges. The most prominent benefit of AI over traditional methods is that it can optimize complex and even unknown scenarios, unknown frameworks, and unknown frequency bands communication systems, building a universal signal processing framework to achieve compatibility with various communication systems.

AI has two modes: model-driven and data-driven. Thanks to the power of big data, both of them in terrestrial networks have shown the potential of AI to air interface. For the data-driven option, scholar Huang *et al.* were surprised to find that some machine learning (ML) algorithms (e.g., ANN, CNN, and GAN) can be applied to channel measurements and modeling [23]; Scholar Xu *et al.* proposed to adopt deep neural networks to realize channel estimation of MIMO systems [24]. For the model-driven option, scholar Ye *et al.* utilize deep neural networks to develop a low-complexity and high-accuracy multi-user detection network framework [25]; Scholar Gao *et al.* combined deep neural networks with expert knowledge to develop an OFDM receiver [26].

In the future, potential opportunities for AI can also be utilized for LEO mega-constellations and some unnoticed modules, such as encoding, decoding, and detection modules. However, it's worth noting that though AI can help address some challenges, it will suffer from the satellite resource limitations of computing and storage, especially for a large-scale satellite internet. Therefore, developing an efficient hardware implementation algorithm is essential to reduce the gap between theory and practice. More importantly, we have to pay attention to the balance between the training efforts and performance.

III. ENABLING TECHNOLOGIES OF THE SATELLITE CONSTELLATIONS

This section illustrates the development status of key technologies of satellite networks from five aspects: network protocol, multiple access, satellite handover, tracking, telemetry and command (TT&C), and interference mitigation. For each technology, different solutions were compared. Aiming at the characteristics and requirements of 6G, relevant analyses of their adaptability in mega-constellations are given.

A. NETWORK PROTOCOL

The early network protocols of satellite communication systems are generally based on ATMs. However, with the development of technologies such as coding and interleaving, ATM's complex QoS mechanism no longer has obvious advantages. As an important extension of the terrestrial network, the current satellite network protocol mostly adopts TCP/IP suites [28].

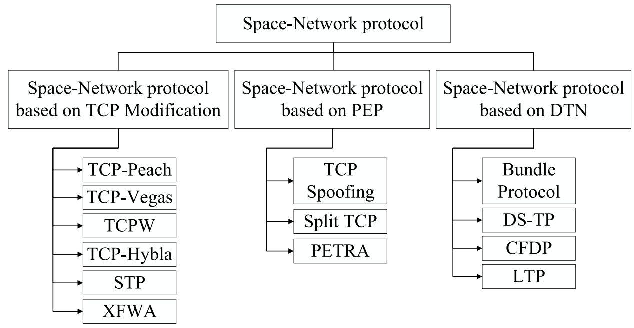

FIGURE 2. The current major satellite network protocols.

Taking into account the differences between satellite networks and terrestrial networks, traditional TCP/IP suites generally need to be improved in satellite communications, as depicted in Figure 2, mainly including the following directions: (1). end-to-end modification; (2). introduction of performance enhancement proxy (PEP); (3). application of delay tolerant networks (DTN); (4). cross-layer design; and (5). Addition of novel mechanisms to routers.

1) END-TO-END MODIFY

The simplest end-to-end modification is optimizing TCP operating parameters, such as expanding the initial congestion window [29], using a fine-grained timer [30], applying the TCP timestamp [31], as well as and path MTU (Max Transmission Unit) discovery [32]. However, optimizing TCP operating parameters has limited performance improvement, especially for RTT fairness and link asymmetry.

Except for optimizing TCP operating parameters, Modifying the standard TCP is also an effective means. Here are some typical improved protocols.

- TCP Reno (1990)
  TCP Reno includes three classic mechanisms of the TCP Tahoe [33]: slow-start (SS), congestion avoidance (CA), and fast retransmit algorithms (FSs), plus a new mechanism: fast recovery (FR). Since TCP Reno is currently the most well-known TCP version, this paper uses it as a traditional TCP [34].
- TCP Vegas (1994) / TCP Vegas+ (2016)
  TCP Vegas utilizes the round-trip time to calculate the difference between the expected throughput and the actual throughput, then compares the difference with the threshold to adjust the size of congestion window. It is easy to find that the CA of TCP Vegas is not based on the loss of data segments but changes of surplus data in the network. Therefore, TCP Vegas can predict congestion and adjust the transmission rate in time [30].

- TCP New Reno (1999)
TCP New Reno modifies the FS of TCP Reno, which enables the terminal to distinguish between the situation of losing several packets at a time and congestions many times. TCP New Reno considerably improves TCP robustness and throughput [35].
- TCP Peach (2001) / TCP Peach+ (2002)
TCP Peach uses virtual segments to explore network resource availability and then sets the appropriate congestion window. Although TCP Peach does not recognize the cause of packet loss, it can quickly increase the transmission rate through virtual segments, solving the impact of long delays plus high error rates in satellite channels [36].
In TCP Peach+, virtual segments are not only used to detect the availability of network resources but also carry unconfirmed information [37].
- TCP WESTWOOD (2001) / TCP WESTWOOD+ (2002)
According to the ACK arrival rate, TCP Westwood (TCPW) calculates the available network resources, then uses it to determine packet loss reason, avoiding overreacting to packet loss caused by random errors [38]. In practice, a variant of TCPW, TCP Westwood+, is usually used [39].
- MPTCP (2011)
MPTCP (multipath TCP) is an enhancement of traditional single-path TCP that runs between applications and TCP sub-flows, utilizing multiple available communication links to increase the reliability and throughput [40]. For satellite channels, combining the MPTCP and PBNC (network coding), the system can still have good robustness when link interrupts or packet losses occur [41].

Compared to modifying the standard TCP, a better way is to design a novel TCP for satellite networks. Several novel TCPs are outlined below.

- STP (1999)
The main difference between the STP and traditional TCP is the data confirmation mechanism. In STP, the sender only requests the receiver to periodically confirm the received data, which is exceptionally suitable for asymmetric links. Compared with the standard TCP, when transferring large files, the bandwidth used by the reverse path can be reduced by one to two orders of magnitude [42].
- XFWA (2004)
XFWA is a novel TCP specially designed for multihop satellite networks, which utilizes the ''multihop'' feature to estimate the RTT and the bandwidth-delay product of connections. Through explicit and fair control of the congestion window, XFWA achieves high link utilization plus low packet loss rates simultaneously. Most importantly, XFWA maintains good fairness between competing TCP streams and maintains excellent stability when the load changes [28].
- TCP Hybla (2004)
The basic idea of TCP Hybla is to provide a long RTT connection with the same transmission rate as the reference connection ($RTT = RTT_0$), ensuring fairness between TCP streams with different RTTs. TCP Hybla is particularly suitable for scenarios with high BDP and high packet loss rates. Compared with most TCP variants, TCP Hybla considerably improves the performance of connections with long RTTs while achieving higher throughput of the entire network [43].
- TCP Noordwijk (2009)
TCP Noordwijk (TCPN) replaces the traditional ''window-based'' transmission with ''burst-based'' transmission, aiming to specifically optimize the performance of web traffic [44].

2) INTRODUCTION OF PERFORMANCE ENHANCEMENT PROXY (PEP)

End-to-end solutions require modifying terminal equipment, which is challenging to popularize and deploy on a large scale. Using the TCP performance enhancement proxy (PEP) is an alternative solution, which can be divided into the following three categories [45]:

- TCP Spoofing: When PEP receives the data packet from the sender, it acts as the receiver and sends ACK to the sender at the appropriate time, which lets the sender believe that the data packet has been successfully received, thereby accelerating the growth of the congestion window properly.
- Split TCP: PEP divides the satellite link into uplink and downlink. The ground is only responsible for acting as a transceiver while the satellite performs data forwarding.
- PETRA: PEP splits the end-to-end connection into a satellite transmission part and a non-satellite transmission part: the non-satellite transmission part adopts the standard TCP; the satellite transmission part adopts the optimized TCP for the satellite network.

TCP Spoofing enables to accelerate the SS process in the high BDP environment effectively, but it has higher requirements on PEP's storage capacity. Obviously, Split-TCP also has higher requirements on satellite storage plus processing capabilities. Although PETRA reduces the impact of high BER and asymmetric links, the main problem of large transmission delay in satellite networks has not been solved. Most importantly, they all violate the end-to-end semantics of TCP, causing some applications to be unusable. In other words, Some specific services will plunge the performance of the protocol. For example, when communication is encrypted through High Assurance Internet Protocol Encryptions (HAIPE), PEPs must be forbidden, and thus the transmission performance will be reduced by 50% to 70% [46]. In addition, PEPs need to save all data for each connection until receiving the ACK from the receiver. Most importantly,

TABLE 5. Comparison of the major satellite network protocols and some TCP enhancement technologies.

Mechanism	Throughput*	High BER**	Fairness*	High BDP**	Asymmetric**	Transparent*	Friendliness*	Recommended
TCP Vegas	✓						✓	
TCP New Reno	✓						✓	
TCP Peach	✓	✓		✓				
TCP Hybla	✓	✓	✓	✓			✓	✓
TCP Noordwijk	✓	✓	✓	✓			✓	✓
TCP Westwood	✓	✓					✓	
MPTCP	✓	✓					✓	
STP	✓				✓		✓	
XFWA	✓		✓	✓		✓	✓	✓
PEP	✓	\	\	\	\	✓	\	✓
DTN	✓	✓		✓			\	✓
Cross-Layer	✓	✓		✓			\	✓
Novel-AQM	✓	✓	✓	✓		✓	\	✓
Novel-ECN	✓	✓		✓		✓	\	✓

\ : Not sure under a wide definition.
* represents the mechanism has this feature
** represents the mechanism can work well under this condition

once a PEP is out of the gear, all data packets routed through the PEP will be lost. Therefore, research in this area has attracted increasing attention in recent years [47], [48].

3) APPLICATION OF DELAY TOLERANT NETWORKS (DTN)

The basic idea of delay tolerant networks (DTNs) is to divide a large, hybrid network into homogeneous areas and to introduce a new layer between the application layer and the transport layer: the bundle layer. In DTN, the end-to-end transmission protocol is limited to use in homogeneous areas, and the interoperability between different regions is realized through the DTN gateway; that is, the bundle layer is responsible for the true end-to-end reliability across heterogeneous networks [49].

Compared with PEP, DTN has obvious superiority. First, DTN can avoid violating the end-to-end semantics of TCP. After that, since the sender can distinguish the confirmation between the receiver and intermediate node, the reliability of the system is greatly improved. Finally, DTN can implement security mechanisms. However, due to the existence of the bundle layer, DTN will bring additional overhead.

4) CROSS-LAYER DESIGN

Cross-layer design can sufficiently consider the interaction between layers in the network and enable the upper layer to acquire network status in real-time. Therefore, many researchers have developed designs for this. In SaclTCP, the physical layer feeds back the effective link bandwidth to the transport layer so that the transport layer can accurately set the threshold of the congestion window; the data link layer notifies the transport layer of packet loss reason, avoiding reduction of the congestion window due to packet loss caused by random error [50]. SCPS-TP transmits link congestion or interruption messages through ICMP; the sender can take different measures in different situations (congestion, burst error, link interruption) to avoid unnecessary window reduction [51].

However, unscheduled cross-layer interactions may adversely affect the performance of the entire system. In addition, the cross-layer design makes it possible to redesign and replace the whole protocol for each update. Therefore, unlimited cross-layer design should be banned.

5) ADDITION OF NOVEL MECHANISMS TO ROUTERS

The most significant impact on TCP congestion control in routers is the packet discard strategy. Traditional strategies tend to make the discarding of packets more synchronized between different window sizes so that congestion windows with shorter RTTs always grow faster than with longer RTTs, which exacerbates RTT unfairness. Suter *et al.* developed a fair queue mechanism combined with a new buffer management scheme: FQ-LQD and FQ-RND [52]. By giving a higher drop rate for connections with long queues, the new mechanism provides RTT fairness plus nearly perfect TCP isolation at the expense of extremely low complexity.

In addition to new active queue management (AQM) mechanisms, routers can also implement novel explicit congestion notification (ECN) schemes, helping the sender determine the cause of packet loss clearly [53]. The initial explicit congestion notification is binary feedback, which allows the sender to realize the current network status and adjust the congestion window appropriately. However, although initial ECN can effectively reduce the packet loss rate, binary feedback is not enough to reflect the degree of network congestion; that is, fine-grained adjustments cannot be made. Therefore, Gerla *et al.* proposed generalized window advertising (GWA), aiming to achieve better congestion control through more feedback [54]. Grazia *et al.* also developed passive inverse feedback (PINK), which allows the network elements between the TCP source and TCP destination to determine the optimal transmission rate of the TCP source through the number of active connections, RTTs, as well as and channel bandwidth [55].

6) BRIEF SUMMARY

The different TCP enhancement technologies are summarized in Table 5. In addition to taking the link characteristics of mega-constellations and requirements of 6G as evaluation criteria, considering different versions of the protocol may coexist in the system during the evolution process of 6G, we also add TCP friendliness and TCP transparency. TCP friendliness can ensure that different versions of the protocol compete fairly for link capacity. TCP transparency can be used to evaluate the feasibility of popularization and deployment. In mega-constellations, we sharpen our focus on the performance of different algorithms in the High BDP scenario. In addition, because the TCP friendliness is crucial to the heterogeneous devices, which directly determines the holistic performance of the system, e.g., QoS and QoE, it is also considered the primary indicator. We believe that regardless of how the network protocol of mega-constellations for 6G global coverage is designed in the future, the ideas of recommended enhancement technologies in Table 5 are worth adopting.

B. MULTIPLE ACCESS

Multiple access can be divided into random multiple access (RA), Orthogonal multiple access (OMA), and Non-orthogonal multiple access (NOMA), as depicted in Figure 3. The development of OMA spanned five decades, and its success in the last century is mainly owing to the fact that it can be implemented in a low complexity way. However, Shannon's theoretical work pointed out that the spectrum efficiency of OMA is sub-optimal [56]. NOMA is a shift for the critical idea of multiple access, which encourages spectrum sharing among users. Compared with OMA, NOMA users can be served at the same time, frequency, and spreading code. Thanks to the spectral efficiency of NOMA is significantly superior to that of OMA, and it has been extensively studied in recent 20 years.

For intermittent traffic, popular protocols mostly rely on random access techniques, including synchronous RA protocols, quasi-synchronous RA protocols, and asynchronous RA protocols, as depicted in Figure 4. Currently, the Internet of Things (IoT) has been a great success story via 5G terrestrial networks and satellite constellations are envisioned as a promising way to support dense IoT devices in 6G [57]. It is obvious that one of the challenging problems in LEO

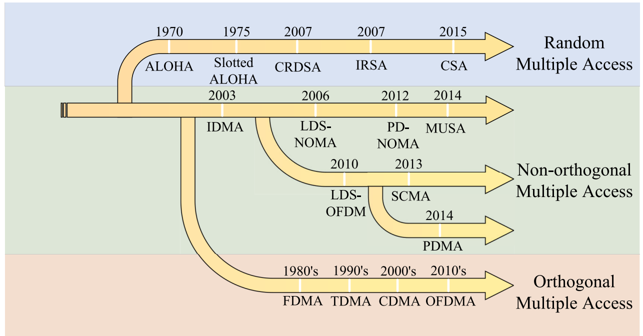

FIGURE 3. Diagram of multiple access timeline.

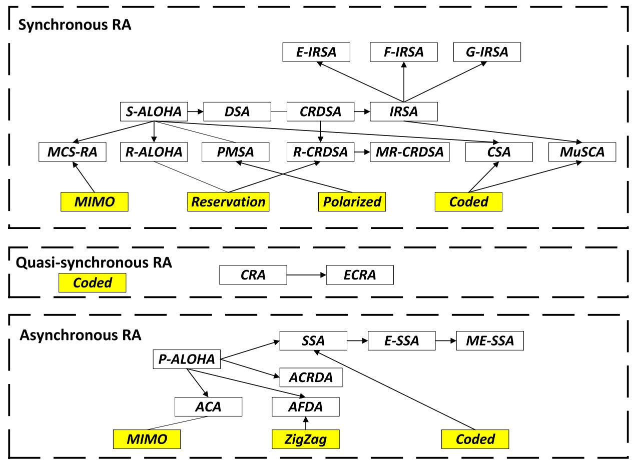

FIGURE 4. Diagram of random access protocol development.

mega-constellations will be related to the massive multiple access, especially for sporadic (brief) traffic [58].

1) SYNCHRONOUS RA PROTOCOL

If the pure ALOHA is not classified as an asynchronous RA protocol, the synchronous RA was a pioneer in the field of random multiple access. The solid foundation in synchronous RA protocol is Slot ALOHA (SA) and Diversity ALOHA (DSA). SA reduces the probability of data collisions by dividing time into synchronous time slots [59]. The maximum normalized throughput increases from 0.18 (pure ALOHA) to 0.36. On the basis of SA, DSA realizes time diversity gain by sending the same data packet twice in different random time slots in a frame [60]. However, although DSA can increase throughput and reduce transmission delay under low load, due to the existence of duplicates, there are a large number of retransmissions under high load conditions, which results in increased delay and packet loss ratio (PLR).

In SA and DSA, the system considers that conflicting data packets are unusable and thus directly discards them. With the development of successive interference cancellation (SIC) technology, scholars have begun to make use of conflicting data packets. Contention Resolution Diversity Slotted

ALOHA (CRDSA) solves the interference between data packets by eliminating replicas of successfully decoded data packets, whose maximum normalized throughput can reach 0.55 [61]. CRDSA++ is considered an enhanced version of CRDSA, extending the CRDSA concept to more than two replicas. By optimizing the number of replicas and exploiting power fluctuations in the received signal, the system can reduce the probability of the so-called "loop" phenomenon,[2] and boost the performance of CRDSA remarkably. When CRDSA++ adopts three replicas, the maximum normalized throughput can reach 0.68 [62]. Irregular Repetition Slotted ALOHA (IRSA) is also an extension of the concept of CRDSA, which establishes a bridge by a bipartite graph between SIC and the iterative erasure decoding of graph-based codes. In IRSA, the number of each packet replica follows a given probability distribution rather than the fixed repetition rates in CRDSA. By optimizing the probability distribution, the maximum normalized throughput of IRSA can reach 0.97. It is noted that if PLR $< 10^{-3}$ is required, its throughput will slump. In addition, the complexity of IRSA is many high [63].

Based on the considerations above, many scholars have proposed a series of variants. G-IRSA jointly designed the distribution of repetition rates for all users, which can not only completely control the distribution of users' degrees but also determine the number of replicas and the connectivity in each time slot. Compared to IRSA, the G-IRSA packet loss rate is much lower [64]. Feedback-aided IRSA (F-IRSA) uses feedback to cut the useless replicas, avoiding the waste of transmission resources, reducing the energy consumption of mobile terminals [65]. Intra-Slot Interference Cancellation for Collision Resolution in IRSA(E-IRSA) performs SIC at the slot level, named intra-slot SIC, which can improve throughput and reduce average delay remarkably [66].

Coded Slotted ALOHA (CSA) further extends IRSA and CRDSA through channel coding. On the sender's side, CSA does not simply send replicas in different time slots but divides each data packet into k sub-data packets before transmission and performs linear block code encoding. Then are transmitted in different slices in a slot, respectively. At the receiver's side, CSA uses SIC to decode data packets. Obviously, compared with IRSA and CRDSA, CSA has excellent energy efficiency [67].

Please note that the aforementioned protocols all rely on "clean" replicas in a time slot. However, detecting "clean" replicas will make protocols challenging to work under high load. Using forward error correction (FEC) and the capture effect can alleviate the reliance on "clean" replicas [68]. In addition, the further development of synchronous ALOHA includes a combination of ALOHA, reservation mechanisms / MIMO technology, which are compatible with different CRDSA and IRSA schemes [69], [70].

[2] "loop" phenomenon refers to all replicas of a set of packets being unrecoverable.

2) QUASI-SYNCHRONOUS RA PROTOCOL

Although synchronous RA protocols have good performance, they all rely on the synchronization of the whole network at a slot level.

Paolini *et al.* proposed a quasi-synchronous RA protocol: Contention Resolution ALOHA (CRA), which can send several replicas at any time within a frame and apply SIC technology. Compared with CRDSA and IRSA, CRA relaxes the timing requirements and removes the restriction on data packet size. Most importantly, since partial interference is more likely than complete interference, CRA can benefit from FEC and power balance, which significantly improves throughput [71].

Clazzer *et al.* further extend Contention Resolution ALOHA, Enhanced Contention Resolution ALOHA (ECRA), which innovatively attempts to decode conflicting replicas. Specifically, ECRA combines the conflict-free parts of each replica to form a new data packet. If some parts of the data packet interfere in all replicas, ECRA selects several replicas with minor interference to create a new data packet. Through decoding the higher SNR combined data packet, ECRA can realize the recovery of conflicting data packet [72].

CRA and ECRA are still not genuinely asynchronous protocols, which need to be synchronized at the frame level. Still, relative to slot-level synchronization, the requirements for timing are immensely relaxed.

3) ASYNCHRONOUS RA PROTOCOL

In recent years, the asynchronous RA protocol has begun to be proposed.

Asynchronous Contention Resolution Diversity ALOHA (ACRDA) is a genuinely asynchronous version of CRDSA, which deletes the frame structure that still exists in CRA. Compared to CRDSA, ACRDA requires fewer replicas to achieve the same "loop" probability. Although ACRDA only realizes slightly better throughput and delay performance, it is vital that it doesn't have to need global time synchronization [73].

Zheng *et al.* proposed an asynchronous RA protocol that is different from the existing diversity transmission method: Asynchronous Flipped Diversity ALOHA (AFDA). Each AFDA data packet and copy are transmitted back-to-back using Zigzag decoding technology to recover conflicting data packets. In the absence of time synchronization or handshake, the performance of AFDA is not affected by changes in propagation delay. Compared with the existing asynchronous RA protocol, AFDA achieves better throughput and PLR performance. In addition, AFDA can transmit data packets of different sizes without segmentation, which is more attractive for burst traffic with various sizes and ACMs [74]. However, the Zigzag decoding algorithm is easy to suffer from error propagation under noisy conditions. Especially when the data packet is large, the performance of AFDA will slump. Fortunately, Shahriar Rahman *et al.* developed an iterative Zigzag decoding algorithm, which effectively overcomes error propagation and further improves system performance in the presence of collisions [75], [76].

In contrast to the aforementioned protocol evolution process, spread-spectrum access (SSA) applies spectrum spreading technology to RA, which is similar to the CDMA system in terrestrial cellular networks [77]. To overcome the problem that SSA is sensitive to signal power imbalance, Herrero *et al.* combined SSA and SIC, proposing enhanced spread-spectrum access (E-SSA). Compared with the existing RA protocol based on the time slot, E-SSA can achieve better delay performance and service more users with bursty traffic (such as M2M data packets), while reducing peak power and synchronization overhead [78]. ME-SSA exploits an approximately linear minimum mean square error (MMSE) detector instead of the single-user matched filter (SUMF) detector used in E-SSA. In most typical scenarios, the spectrum efficiency of ME-SSA is 50% higher than that of E-SSA [79].

4) BRIEF SUMMARY

The different random access protocols are compared in six indicators, as depicted in Table 6. Among the above six indicators, throughput and delay aim to evaluate the maximum service capacity of the protocol; the critical load point is used to characterize the difficulty of load control in satellite networks and the stability of the capacity when the 6G traffic load increases rapidly in coming years. In the future, with densely deployed Internet of Things (IoT) devices, the challenging problem is related to the life of battery-powered equipment and adaptability of the protocol in a heterogeneous environment. Thus, both energy consumption and adaptability serve an essential role in appraising protocol performance. It should be noted that: 1) to compare different protocols, limit the normalized load to be between 0 and 1; 2) the energy consumption in Table 6 is the energy consumption of user terminal; and 3) +/− only represents relative superiority/inferiority.

C. SATELLITE HANDOVER

There are various types of mobility introduced in the satellite Internet by vehicular devices, marine devices, and aerial devices, especially the high-speed LEO satellites. Generally, there are three reasons for satellite handover: 1) For seamless mobility services. Since the maximum service time of a single satellite to users is limited, to maintain communication, it is necessary to switch to the next servicing satellite horizontally within the homogeneous segment or vertically between heterogeneous network segments. 2) For link interference mitigation. Due to link loss, link interference, and other factors, users need to automatically switch to the next servicing satellite when normal communication is impossible. 3) For load balancing. Owing to the randomness of user arrival and the inhomogeneity of traffic distribution, some users connecting to congested satellites need to be switched to idle satellites.

Handovers in satellite networks can be divided into beam handovers and intersatellite handovers. User terminal switching from one spot beam of a satellite to another spot beam is called beam handover, and switching from one satellite to another is called intersatellite handover. Since the coverage area of spot beams is relatively tiny to satellites, beam handover is more frequent than intersatellite handover.

1) SPOTBEAM HANDOVER

In beam handover, all spot beams are provided by the same satellite. Therefore, the selection of satellites is not involved in the switching process, and the critical issue is the allocation of channel resources [80]. With limited satellite network resources, the beam handover strategy requires a degree of compromise between call blocking probability (CBP) and forced termination probability (FTP).[3]

The nonpriority handover strategy treats handover users and new call users indiscriminately. However, since forced termination caused by handover failure is more intolerable than new call blocking, the nonpriority handover strategy is not commonly used in reality.

The adaptive dynamic channel allocation strategy uses the protection channel during the switching process, and thus, it must timely track the changes in traffic. According to user location information, ADCA dynamically adjusts the number of protection channels, achieving a compromise between protection channels and normal channels [82].

The queue handover strategy initially determines the priority of various types of requests and then classifies them into different queues, waiting for network services. Currently, there are three typical queuing mechanisms: first in first out (FIFO), last useful instant (LUI), as well as and measurement-based prioritization scheme (MBPS) [83]. FIFO services users in the order of arrival time; LUI queues according to each handover request's maximum remaining waiting time and prioritizes the most urgent handover request; MBPS queues according to the received signal power and prioritizes the requests with the fastest decline in terms of link quality.

The channel reservation strategy utilizes the orbit information of the satellite network to reserve channels in advance for handover users. Its pioneering research is the guaranteed handover (GH) strategy proposed by Maral *et al.*, which is capable of eliminating service interruption due to handover failure [84]. However, in the GH scheme, the system allocates channels for new calls only when there are surplus channels; that is, the GH scheme does not make full use of precious network resources. As the number of users gradually increases, most new calls will be rejected, and thus CBP will rise sharply.

Based on the considerations above, scholars have proposed some improved GH schemes: elastic channel locking (ECL) [85], time-based channel reservation algorithm (TCRA) [86], as well as and dynamic Doppler-based

[3]There are two classic indicators for evaluating the performance of a handover strategy: call blocking probability (CBP) and forced termination probability (FTP). CBP refers to the probability of a new call service being blocked due to a lack of channel resources. FTP refers to the probability of service interruption due to handover failure [81].

TABLE 6. Comparison of different random access protocols.

	Throughput	Delay	Energy Consumption	Complexity	Critical Load	Adaptability in Heterogeneous Environment
PA*	\	\	\	\	\	✓
CRDSA	+	-	++	+	+	×
R-CRDSA	++	- -	+	+	++	×
MR-CRDSA	++	- - -	+	+	++	×
IRSA	+++	- -	++	++	+++	×
E-IRSA	≈ *1*	- - -	+	+++	≈ *1*	×
F-IRSA	+++	- -	+	++	+++	×
G-IRSA	+++	- -	++	+++	+++	×
CSA	+++	- -	+	++	+++	×
CRA	+	- -	+	+	+	✓
ECRA	++	- - -	+	++	++	✓
SSA	+	- -	+	++	++	×
E-SSA	≈ *1*	- -	+	+++	≈ *1*	✓
ACRDA	++	- -	++	++	++	✓
AFDA	+	- -	++	++	+	✓

* All Protocols use Pure ALOHA (PA) as a reference.

handover prioritization (DDBHP) [87]. They are all based on the prediction of handover requests. The main difference is how to determine the timing of channel reservation, thereby reducing the idle time of channel resources. In ECL, new calls will not send channel lock requests to the next servicing unit at the beginning but delay the request for a while. By adjusting the delay time of the request, ECL can balance between CBP and FTP, thereby satisfying the quality of service (QoS). The delay time of TCRA is not determined by FTP but is based on user status and certain satellite orbits. Different from ECL and TCRA, DDBHP eliminates the dependence of GPS, exploiting the Doppler effect to calculate the remaining service time and trades of the share of precious channel resources between handover users and new calls by defining the threshold. However, when all channels in networks are busy, there is still a waste of channel resources in reserved time. Chen *et al.* developed an adaptive probabilistic reservation strategy (APRS), lending reserved channel resources to new connection requests under certain probability, through which the system can serve as many users as possible, utilizing channel resources efficiently [88].

2) INTERSATELLITE HANDOVER

The intersatellite handover also involves channel resource allocation, but compared to beam handover, satellite selection strategies need to be considered more. Common satellite selection strategies are mainly divided into the following four types:

- Maximum service time [89]: Under the condition of satisfying the lowest elevation angle, the user preferentially chooses the satellite that can provide the longest service time. To a certain extent, this strategy can significantly reduce the number of user handovers and FTP. The minimum hop strategy is equivalent to the maximum service time strategy in effect. Both of them can minimize the number of handovers. The difference is that the minimum hop strategy generally knows the handover path beforehand. Therefore, it is possible for a minimum hop strategy to reserve channel resources in advance for handover users, through which the system can achieve lower FTP [90].
- Maximum number of available channels [91]: The user preferentially selects the satellite with the minimum load among all visible satellites as the target satellite for handover. This strategy makes the satellite network traffic tend to be balanced, avoiding affecting the system's performance due to the overload of a satellite node, through which the system can remarkably reduce both CBP and FTP.
- Maximum elevation [92]: The user preferentially selects the satellite with the most prominent elevation to switch. This strategy can satisfy the better quality of service (QoS) but increase the number of handovers. Most papers use elevation to reflect the communication link quality between users and satellites. Still, some papers point out that elevation does not truly reflect the quality of the wireless link yet. For example, Yang *et al.* proposed exploiting the received signal strength RSS) to judge the link quality exactly [93]. However, regardless of whether the link quality is judged by elevation or RSS, the maximum elevation strategy signifies an emphasis on channel quality.

Due to different objective functions, different strategies have their emphasis. Users will often choose the standard according to actual scenarios in reality. For example, during emergency communications such as earthquakes and typhoons, the maximum service time strategy is preferentially used to reduce the number of handovers and delays [94]. However, if only a single standard is used for switching, it will make users shortsighted. In addition, the randomness of user terminal access and the unbalanced distribution of satellite network traffic will also make a single strategy unable to satisfy the quality of service (QoS) requirements. Thus, people have shown interest in using a different set of satellite selection criteria to access the next satellite. For example, Zhao *et al.* developed a handover strategy with the linear weighting of various indicators, and simulation results show that this strategy realizes relatively low FTP. Compared to simple linear weighting, Miao *et al.* adopted a multiple attribute decision algorithm to make handover decisions, comprehensively considering the received signal strength, remaining service time, as well as and satellite idle channels [95]. To avoid the influence of artificial prior information and improve the flexibility of the strategy, Xu *et al.* exploit AI to overcome multicriteria optimization problems [96].

With the increasing popularity of GPS, users can effectively predict the visible satellites and their service time. Wu *et al.* proposed a graph-based satellite handover framework and modeled the satellite handover process as finding a path in the directed graph [97]. Although the conventional strategy is used in that paper, the graph-based satellite handover framework can support different handover strategies; that is, different link weights can be set according to different handover strategies, which has good flexibility. Based on the weighted bipartite graph, Feng *et al.* adopted the Kuhn-Munkres (KM) algorithm to achieve multi-order maximum weight matching, which can balance a load of satellite networks effectively [98]. Different from scholar Wu and scholar Feng, who performed satellite handover prediction in a static and stable satellite link, Hu *et al.* extended the handover to dynamic scenarios, alleviating the failure of handover prediction [99].

The aforementioned handover strategies are mainly from the perspective of a single user instead of the system. In fact, game theory is an excellent tool for calculating both users' behavior and strategic interactions among users. Yang *et al.* proposed a satellite handover strategy based on the potential game, in which users choose the best strategy by maximizing their utility function through multiple rounds of games. Finally, the system will reach the Nash equilibrium [100].

3) BRIEF SUMMARY

At present, the scale of the communication satellite constellation is still relatively small, and most users are only covered by double stars. When users perform handover, the system only needs a good channel allocation strategy. For satellite selection strategies, most of them are determined based on the designer's ideas, and their weight factors are also set based on experience. Mega-constellations for 6G global coverage bring unprecedented challenges to traditional satellite handover. First, mega-constellations have multi-satellite coverage, short LOS time, and large elevation, making it difficult for designers to choose the best handover strategy according to traditional methods. In addition, frequent handover is required to satisfy the stringent requirements of 6G for 10Gbps $\sim$ 100Gbps on peak data rate. However, the existing handover algorithms do not pay attention to the algorithm complexity, which may bring a severe computational burden to the system. In the future, it is urgent to design suitable satellite handover strategies and algorithms for mega-constellations according to their characteristics.

D. TRACKING, TELEMETRY AND COMMAND

Tracking, telemetry and command (TT&C) systems mainly include mission control centers (MCCs), terrestrial stations, ocean TT&C ships, relay satellite systems, global satellite navigation systems, as well as and corresponding communication support systems. The following tasks need to be completed:

- Orbit determination
  Through long-term tracking and measurement, the satellite TT&C system obtains satellite parameters such as distance, azimuth, as well as and elevation; determines the instantaneous position of the satellite; extrapolates orbit; uploads the orbit information to satellites regularly.
- Transmission and monitoring of telemetry data
  The satellite TT&C system receives the operational status of each satellite subsystem and external space environment parameters; monitors the operating and health status of the satellite; warns when the value of the parameter exceeds the specified threshold.
- Command
  The satellite TT&C system uploads remote commands to the satellite, controlling satellite movement plus working status. When a satellite works abnormally or fails, the TT&C system uploads emergency schemes or self-destruction commands.
- Clock synchronization
  The satellite TT&C system compares satellite time with the standard time and sends the difference to the satellite system, ensuring the time synchronization between satellite and terrestrial stations.

Over the last four decades, the TT&C system has evolved from a ground-based TT&C system to a space-based TT&C system. Currently, the concept of networked TT&C systems has begun to be proposed, aiming to mitigate the status of insufficient TT&C resources.

1) GROUND-BASED TT&C SYSTEM

Considering the cost of construction and maintenance, the earliest satellite TT&C system was built on the ground platform [101]. The ground-based TT&C system consists of satellites and terrestrial TT&C stations, as well as and a mission center, as depicted in Figure 5. When the satellite

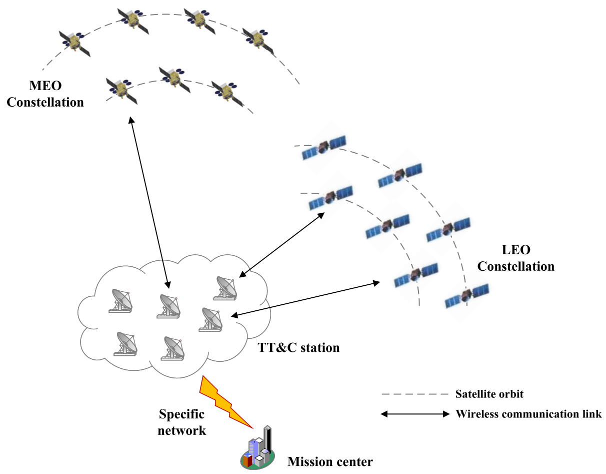

FIGURE 5. Diagram of the ground-based TT&C system.

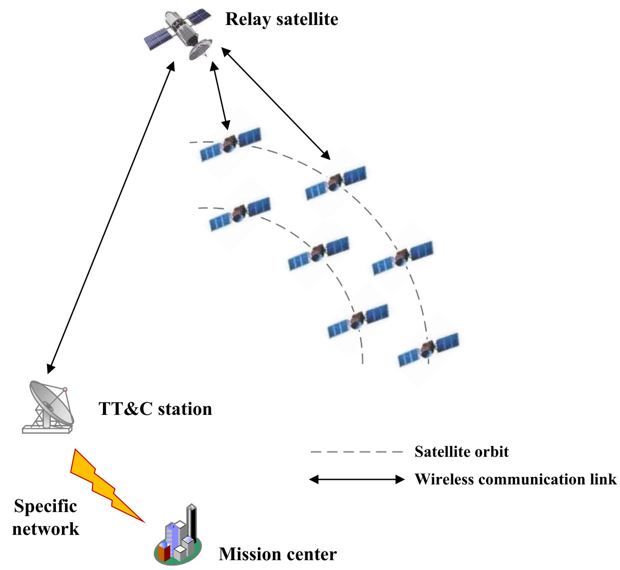

FIGURE 6. Diagram of the space-based TT&C system.

is visible to the terrestrial TT&C station, it transmits telemetry data through the space-ground TT&C link. The mission center is connected to the terrestrial TT&C station through a private network, analyzing the received telemetry data and uploading remote commands when necessary. The broadly defined ground-based TT&C system also includes ocean TT&C ships and terrestrial TT&C mobile stations, which can increase the TT&C coverage of some critical arcs in the satellite launch process, such as separation of satellites and rockets, the establishment of injection attitudes, and deployment of solar panels.

It is worth noting that the United States has established massive terrestrial TT&C stations worldwide to receive telemetry data from satellite constellations at all times. However, it is unrealistic to deploy terrestrial TT&C stations in most regions of the world for other countries; that is, most countries still have many TT&C blind areas, and it is impossible to achieve full-time TT&C. Although renting other countries' TT&C stations can rapidly solve this problem, their safety needs further consideration. Still, the ground-based TT&C system has been the primary way to perform satellite and spacecraft TT&C tasks for a long time.

2) SPACE-BASED TT&C SYSTEM

Since 1980, TDRS satellites have become an important part of the TT&C system, effectively improving the real-time performance and reliability of TT&C [102]. The space-based TT&C system as depicted in Figure 6. In this mode, TDRS acts as a repeater, through its higher orbit(geostationary Earth orbits) and stronger data transmission ability(equipped with high-gain trackable intersatellite antennas), allowing the mission center to communicate with satellites that are invisible to terrestrial TT&C stations, realizing full-time TT&C.

Although three TDRSs with intersatellite links can already provide full-time TT&C support for the entire satellite constellation in theory. Still, it should be noted that relay is a point-to-point process. With the increase in active elements in orbit and the limitation of multiple access, the number of TDRSs needs to continue to increase to meet the needs of TT&C. However, the available position of the relay satellite is running out. Meanwhile, owing to different launch times, the TT&C conditions by TDRS for different satellites are also different, which aggravates the difficulty of space-based TT&C. In addition, because the TDRS system works in the geostationary Earth orbit, the real-time performance of TT&C will be hard to guarantee; that is, abnormal situations may not be dealt with in time. Most importantly, once a relay satellite cannot operate reliably, the entire satellite system may incur irreparable losses.

3) NETWORKED TT&C SYSTEM

With the development of on-board processing technology, satellites can already transmit information through intersatellite links and complete various complex tasks, such as ranging, timing, and coordinated control. Gradually, the concept of a networked TT&C system began to propose, as depicted in Figure 7 [103]. The key idea of networked TT&C is to integrate the traditional TT&C architecture with the communication satellite network and treat TT&C as a communication service. Unlike conventional satellites that complete TT&C alone, networked TT&C places more emphasis on coordination and dependence. The satellite network exchanges TT&C information through intersatellite links and exploits intelligent plus automated cooperation to realize self-management, self-monitoring, self-diagnosis, and exception handling.

In the networked TT&C system, TT&C not only can be implemented to the satellite constellation itself through the intersatellite link but can also be performed through the medium/high orbit communication satellite network. Regardless of the TT&C mode, we call the satellites that TT&C other satellites as TT&C satellites. Moreover, TT&C core

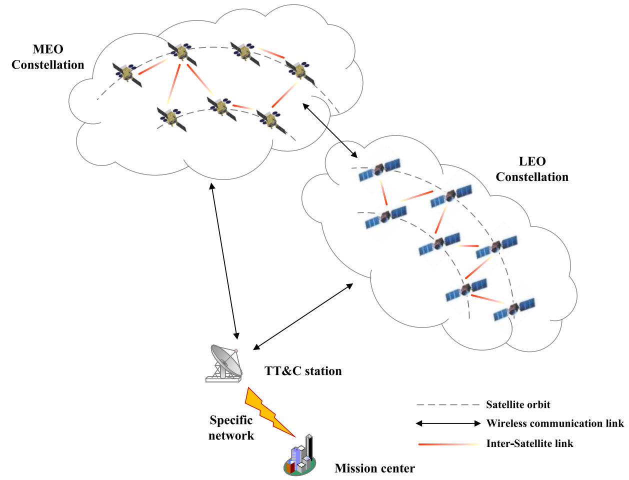

FIGURE 7. Diagram of the networked TT&C system.

network functions will further sink to the edge of the network. As a "central logic controller", the terrestrial TT&C station collects the TT&C information of the entire network, uploads remote commands from the mission center, and transmits accurate time plus space references. TT&C satellites will be an "edge core" for networked TT&C systems, leveraging edge computing to form a multi-center architecture and making lightweight decisions in orbit. With the decision control sinking to the edge, the constraints of system "centralization" will be cast off, network management flexibility will be improved, and the delay will be reduced.

4) BRIEF SUMMARY

It is clear that neither the ground-based TT&C system nor the space-based TT&C system can undertake the huge TT&C tasks of mega-constellations for 6G global coverage. Compared with the ground-based TT&C system and space-based TT&C system, the networked TT&C system has the following superiorities: 1) Surmount the shortage of TT&C resources. Using existing TT&C equipment, the system does not have to build additional terrestrial TT&C stations or launch more TDRSs; 2) Realize full-time TT&C; 3) The intersatellite link delay is relatively low, ensuring the real-time performance of TT&C information, especially important in an emergency; 4) Cooperative control brings considerable autonomy to the satellite; 5) With numerous satellite network nodes, there are several transmission paths for TT&C information, remarkably improving the robustness. Based on the considerations above, we believe that the networked TT&C system is more attractive for TT&C tasks of hundreds and thousands of satellites. Table 7 shows the comparison of the ground-based TT&C system, space-based TT&C system, and networked TT&C system.

E. INTERFERENCE MITIGATION

In the near future, the 6G network will be an integrated network that the satellites and terrestrial wireless networks simultaneously access tens of thousands of connections. When higher frequency bands and more satellites are needed to satisfy the 6G needs, mega-constellations face severe challenges in improving coverage and reducing interference. The following frequency interference needs to be overcome.

TABLE 7. Comparison of different TT&C systems.

	Ground-based TT&C system	Space-based TT&C system	Networked TT&C system
TT&C main part	Ground station	TDRSs	SATNET
Relay link	Null	Single-hop	Multihop
Transmission delay	Low	High	Medium
Resource requirements	High	Medium	Low
Full-time TT&C	No	Yes	Yes
Autonomy	No	No	Yes
Robust	Medium	Low	High

- Interference within the satellite constellation
  Multibeam satellites have been widely adopted in satellite communication systems as they can generate multiple isolated beams within the coverage area to increase wireless data rates [104]. Although a more aggressive full frequency reuse scheme has been adopted to improve the system capacity of satellite communications further, they also cause serious co-channel inter-beam interference.[4] The closer orbital positions of two adjacent satellites are, the greater the possibility of intersatellite interference.
- Interference between the satellite constellation and geosynchronous orbit(GEO) satellites
  Most satellites and GEO satellites are in different orbital planes. A vital issue to be considered is collinear interference and quasi-collinear interference, which occur whenever non-geosynchronous orbit (NGEO) satellites, GEO satellites, and terrestrial users are in a straight line. Since this interference tends to affect the normal communication of the GEO system severely, it is essential to find an appropriate spectrum sharing method between the NGEO satellite and the GEO system [105].
- Interference between the satellite constellation and the terrestrial network
  The terrestrial network and the satellite network form an enormous communication system together, but the actual occupancy of the satellite spectrum is much lower than 100% in general. Therefore, in the United States, Europe, and other places, spectrum legality has authorized terrestrial networks to use satellite spectra. China has also authorized some satellite C-band frequencies for 5G signals [106]. The 17∼30 GHz frequency band that has been partially licensed to satellites is even one

[4]Co-channel interference refers to beams separated by a restricted physical distance using carriers of the same frequency that will interfere with each other.

of the candidate frequencies bands for next-generation cellular networks (6G) [107]. It is clear that reusing satellite frequencies in terrestrial networks is an effective way to optimize precious spectrum resources. However, this frequency reuse will inevitably lead to co-frequency interference between satellite users and ground users.

Since the emergence of radio communications, significant effort has been devoted to spectrum sharing. There are the following interference mitigation methods:

- Larger antenna aperture: Adopting a larger aperture antenna, the system will significantly reduce the transmit power and obtain a smaller equivalent isotropically radiated power (EIRP) without loss of SNR, which is beneficial to alleviate interference to other satellites.
- Geographical isolation: The definition of the protected area guarantees the performance of the primary receiver, and thus many papers point out the necessity of establishing protected areas [108]. Currently, determining the scope of protected areas is still an open issue.
- Adaptive power control: When frequency interference occurs between the terrestrial network and the satellite network, the system can comprehensively consider the channel estimation error, channel resource constraints, the maximum transmission power of satellite users, and the interference threshold of the base station. Through adaptive power control and channel allocation, the capacity of the terrestrial network can be optimized while satisfying the specified outage probability of the satellite link.
- Cognitive Radio: Cognitive Radio (CR) is a promising solution to alleviate interference caused by spectrum sharing [109], [110]. By perceiving the surrounding spectrum environment, it dynamically alters the transmission power, modulation mode, communication protocol, as well as and other parameters of the wireless communication system to realize intelligent spectrum sharing and accessing in both licensed and unlicensed bands [111], [112]. Currently, AI is becoming an effective enabler to support Cognitive Radio to tackle interference caused by spectrum sharing. For example, through learning WiFi traffic by deep reinforcement learning (DRL), LTE networks can coexist fairly with WiFi in unlicensed frequency bands.
- MIMO: Under the same data rate, adopting MIMO technology, the system can work with lower transmit power. In other words, under the same data rate, the potential interference from the MIMO system to the SISO system will be much lower than that from the SISO system to the SISO system. Therefore, taking advantage of MIMO technology, the communication constellation can achieve higher data rates with minor interference or work with smaller satellite spacing/ground terminal antenna aperture.
- Smart antenna: Smart antenna enables multiple users to use the same frequency resources in the same geographic area simultaneously. Specifically, beamforming technology can be used to operate the output of the antenna array to form the required pattern, alleviating interference to adjacent receivers. The adaptive antenna can point the zero point of the antenna lobe toward the unintended transmitter all along, reducing the degree of interference.
- Beam hopping: Adopting beam-hopping technology, the system can rapidly switch beams over time. It is worth noting that only a tiny part of the beams will be activated at the same time according to actual needs, and the remaining beams will be in an idle state. Therefore, compared to traditional satellite systems, beam-hopping satellite systems can make better use of frequency resources.
- Database: Generally, the database contains carrier frequency, channel bandwidth, policies, polarization mode, antenna gain, antenna radiation pattern, transmission power, etc., information of each region [113]. Using the database, different systems can access other spectra beyond their own. If it is connected to the network management unit, the overall frequency resource allocation can also be optimized. Tang *et al.* proved that using the database plus CR in the UK, which has the densest BSS network, more than 98% of the area can add an additional 400 MHz bandwidth [114].

The different interference mitigation solutions mentioned above are compared in Table 8. For the trend of miniaturization and the low cost of mega-constellations, it is challenging to increase satellite antenna aperture. Of course, it is also difficult to equip users with a larger antenna aperture. For satellites with special missions, geographic isolation is appropriate. However, for commercial satellite constellations such as mega-constellations for 6G global coverage, geographic isolation will remarkably affect its goal of providing high-speed Internet services to worldwide users. For the integrated satellite and terrestrial networks, if we believe that in areas with developed terrestrial networks, the first choice for users accessing the network is still terrestrial networks, then adaptive power control and cognitive radio are all worth recommending. With the explosive growth of mega-constellations, smaller satellite spacing will further exacerbate the interference between satellites. Through MIMO and smart antenna, it can effectively suppress interference in the spatial domain. To date, more than ten mega-constellation plans have been proposed. It is conceivable that there will be several mega-constellations to serve users simultaneously in the future. If different mega-constellations can exploit databases and beam hopping technology to share frequency resources by friendly consultation, this will substantially improve the service capabilities of the global satellite Internet.

Based on the considerations above, the recommended interference mitigation solutions include the following: adaptive power control, cognitive radio, MIMO, smart antenna, beam hopping, as well as and databases.

TABLE 8. Comparison of different interference mitigation solutions.

Technique	Advantage	Risks
Larger antenna aperture	Reduce transmit power and EIRP without loss of SNR	The modification of user or satellite equipment is challenging.
Geographical isolation	Guarantee the performance of the main receiver.	Reduce the spectrum utilization.
Adaptive power control	Achieve global optimization.	Exist aggregate interference.
Cognitive Radio	Preeminent spectrum utilization.	Require advancements in device manufacturing processes.
MIMO	Enable satellites to work with smaller satellite spacing or ground terminal antenna aperture.	More antennas need to be deployed.
Smart antenna	Realize space isolation.	The location information of the satellite and user terminal is required.
Beam hopping	Superior flexibility and resource utilization efficiency.	The complexity of on-board processing is increased.

IV. SUGGESTIONS AND FUTURE RESEARCH DIRECTIONS OF MEGA-CONSTELLATIONS

Considering the characteristics and requirements of mega-constellations and 6G, combined with some emerging technologies proposed in recent years, appropriate recommendations and future research directions are given for the aforementioned technologies.

A. NETWORK PROTOCOL

Over the last four decades, significant effort has been devoted to researching network protocol of satellite Internet in different directions. Still, as the TCP/IP protocol suite was initially designed to support the terrestrial networks, it still has some limitations when applying to the future satellite Internet for 6G. First, network protocols based on TCP/IP are appropriate for random topologies on the Internet essentially, but LEO mega-constellations for 6G global coverage in the near future will have dynamic but deterministic topologies. As a result, taking advantage of the preliminary topological information to design a more effective network protocol is necessary. In addition, LEO mega-constellations for 6G global coverage will be confronted with the datasets generated by extremely diverse communication scenarios, heterogeneous networks, and new service requirements, which will deviate even more from the Internet. Further research needs to consider how to exploit an intelligent network protocol with the aid of artificial intelligence (AI) and ML technologies. Finally, with the emerging network virtualization technology such as network slice, the future satellite Internet may support private networks to ensure QoS requirements such as bandwidth, delay, jitter, etc. Under the network slicing framework, mobile operators need to consider a new pricing pattern, and game theory is an excellent tool for calculating both users' behavior and strategic interactions among users. In the future, significant research effort is needed to resolve the following issues to make them viable for 6G.

- Inaccurate RTO estimation
  In mega-constellations for 6G global coverage, the high mobility of LEO satellites may cause inaccurate RTO estimation. More importantly, an unsatisfactory satellite handover algorithm may exacerbate this phenomenon. The significant variations of RTT will trigger timeout retransmissions erroneously (retransmit earlier or wait longer), degrading the TCP performance tremendously.
- Low channel utilization
  Mega-constellations for 6G global coverage are dominated by burst traffic. When the length of the TCP stream is much shorter than the time required for the TCP congestion window to extend to saturation, it is difficult for the system to fill the entire network, leading to poor channel utilization. More importantly, the transmission rate asymmetry in satellite Internet uplink and downlink channels will reduce the increase of the TCP sending rate further, degrading the channel utilization.
- RTT fairness and TCP friendliness
  Faced with heterogeneous networks, different propagation delays, and diverse communication scenarios, mega-constellations for 6G global coverage need a network protocol with excellent TCP friendliness and RTT fairness to ensure different protocol versions and connections with varying communication delays compete fairly for link capacity. However, the existing network protocols are limited in their performance to satisfy fairness and friendliness.

B. MULTIPLE ACCESS

The massive connections, large dynamic channels, and sporadic data of satellite Internet for 6G service bring the characteristics of random and time-frequency asynchronous non-orthogonal access. On that account, the widely used synchronous RA protocol does not appear to be more attractive on the satellite Internet in the future. First, synchronous RA protocols generally require global time synchronization and precise location of the sender, which is almost unrealistic for a significant number of low-cost devices. After that, using a synchronous RA protocol, a large amount of signaling overhead will remarkably shorten the life of battery-powered equipment. More importantly, it is a heterogeneous network that the satellite Internet faces in the future, which has different and varying propagation delays, making it difficult for synchronous RA to work effectively. We believe that asynchronous RA protocol will be more appropriate for mega-constellation. However, significant research effort is needed to resolve the following issue to make it viable for 6G.

- Asynchronous protocol performance

Although the asynchronous RA protocol can better meet the needs of mega constellation users, compared to the synchronous RA protocol, even if interference cancellation technology is used, its throughput is still unsatisfactory. Fortunately, Massey *et al.* studied the capacity boundary of an asynchronous RA protocol without feedback [115]. He pointed out that with an unlimited number of users, the capacity of the asynchronous RA protocol is the same as that of the synchronous RA protocol, implying that an effective asynchronous RA protocol also has outstanding throughput, which provides theoretical indicators and motivation for the design of future asynchronous protocols.

C. SATELLITE HANDOVER

As mentioned in section III, mega-constellations for 6G global coverage bring many new challenges to satellite handover. For satellite handover in mega-constellations, here are some suggestions.

- Satellite selection criteria
  Compared with traditional satellite constellations, there are more satellites and smaller spacings in mega-constellations, so the RSS and elevation of adjacent satellites may be the same. In addition, the mega constellation has a low orbit and short LOS time. In other words, selecting a star based on the maximum service time may result in a high probability of handover failure and extended access waiting time. Therefore, considering the number of users and frequent handovers in mega-constellations, channel resources and signaling overhead should become crucial in satellite handover.
- AI-assisted satellite handover
  Considering the diversified objectives, changeable service scenarios, and personalized user requirements in mega-constellations, satellite handover is not only required to have a low call blocking probability and forced termination probability but also the ability to self-decide. In fact, some AI technologies have been successfully applied to the global optimization of ground network handover in recent years, such as Q-learning [116], recurrent neural networks (RNNs) [117], as well as and convolutional neural networks (CNNs) [118]. For mega-constellations handover, users also seem incapable of selecting the next servicing satellite well through a model in most cases. The results of machine learning may be a good reference. In addition, a critical task of satellite handover is to perceive and predict the variations of service requests, mobility, network traffic, resource utilization in systems.AI has great potential in these areas.

D. TRACKING, TELEMETRY AND COMMAND

Based on the analysis in section III, the networked TT&C system is more attractive for mega-constellations. To achieve real networked TT&C, some suggestions are given. First, embedded a rapid self-cure mechanism for fault satellites and a fast self-reconstruction mechanism for new satellites. Currently, the operation control center (OCC) is responsible for analyzing and maintaining the status of all satellites in satellite networks, but achieving troubleshooting in seconds by OCC in mega-constellations is immensely challenging. Joint decision-making in orbit with prior information of fault diagnosis and associated topology can be envisioned as a promising candidate scheme for intelligent TT&C in mega-constellations, including fault early warning, fault source tracing, fault location, and fault cure. Second, design a fine-grained and multi-dimensional TT&C resource allocation mechanism under multiple constraints. It is noted that resource allocation poses one key challenge in satellite TT&C systems, especially for mega-constellations. To begin with, when resources are limited, such as available spectrum, computing power, energy, communications channels, etc., resource allocation is a typical multi-objective performance optimization problem, and multi-objective performance optimization is usually a non-deterministic polynomial NP-hard problem. Besides, satellites would be divided into different clusters changeably with different functions in mega-constellations; that is, there are numerous different and time-varying TT&C requirements in the satellite Internet. Regarding the above problems, with the development of ML, especially Deep Learning (DL), the system could model resource allocation as a Markov decision process and carry out relevant learnings to allocate resources efficiently to achieve performance close to the optimum in any status. To satisfy the requirements of future 6G, many key technologies still need to be broken through, including the following aspects.

- Transmission security
  In addition to real-time, the system's accuracy and reliability of TT&C information are also critical factors. There is almost no relay link between satellites and the mission center in the ground-based TT&C system and the space-based TT&C system. However, for the networked TT&C system, the communication between satellites and the mission center requires multihop inter-satellite TT&C links and single-hop satellite-to-ground TT&C links, making it easier for malicious entities to interfere or attack. At the same time, the open mega constellation makes it possible to interconnect satellites in different countries and institutions, which also brings unprecedented challenges to traditional security strategies. Therefore, it is necessary to carry out extensive research into transmission security, such as authentication, data encryption, etc.
- Data compression
  In actual engineering applications, most of the valuable telemetry data only account for less than 10% of the total; that is, existing satellite TT&C data are redundant. In the future, with the increasing diversity and scale of

information, it is necessary to reduce the redundancy of mega-constellations telemetry data through practical data compression algorithms.

E. INTERFERENCE MITIGATION

Currently, the existing satellite constellations have not been troubled excessively by frequency interference only because they are not massive enough yet. However, it is usually not straightforward to extend some widely used interference mitigation approaches to the near future LEO mega-constellations for 6G global coverage due to the obviously different channel properties and the satellite payload limitations. To this end, it is necessary to batten down the hatches, and here are some suggestions. First, establish interference protection standards and interference evaluation methods suitable for mega-constellations. Until now, there are no mature ITU standards, and the applicability of traditional interference assessment methods, protection standards, and simulation methods still need to be further studied. Second, adopt the SDN architecture in mega-constellations for 6G global coverage. In the future 6G system, with programmable, agile, and cost-effective, the hybrid SDN[5] can be envisioned as a promising candidate means for alleviating the frequency interference, which is capable of transforming heterogeneous satellite networks and terrestrial networks into integrated networks with reconfigurability and interoperability and thus can configure, control, change, and manage frequency resources together to different degrees for avoiding frequency collision in mega-constellations. For more details on SDN, please refer to the literature [119] and literature [120]. In the future, significant research effort is needed to resolve the following issues to make them viable for 6G.

- Inherent contradictions between high-speed Internet services and interference mitigation
  Traditional interference mitigation measures such as adjusting the antenna direction and limiting the transmission power will become challenging to implement for mega-constellations. In many cases, the above method means reducing the data transmission rate remarkably, that is, running counter to its goal of providing high-speed Internet services to users around the world, which is unacceptable for commercial satellite constellations, e.g., mega-constellations.
- The deployment of MIMO in mega-constellations
  As mentioned in section III, with high spectral and energy efficiency, MIMO is promising for a core ingredient of mega-constellations to alleviate the frequency interference effectively. However, The deployment of massive MIMO in mega-constellations is immensely challenging due to, e.g., weight, size, power consumption restrictions, etc.

[5]Hybrid SDN refers to a networking architecture that is consisted of the traditional network and the pure SDN network.

V. CONCLUSION

Painstaking efforts from both academia and industry are still required over the next decade to meet technical challenges towards developing the 6G system based on LEO mega-constellations. Considering the development trend of 6G, combined with some new technologies proposed in recent years, some appropriate recommendations and future research directions for mega-constellations have been proposed in this paper. Five aspects, including network protocol, multiple access, satellite handover, TT&C, and interference mitigation, have been discussed. For the network protocol, different TCP enhancement technologies are compared in terms of throughput, RTT fairness, TCP friendliness, etc. Some ideas worth adopting for the future network protocol design of mega-constellations for 6G global coverage are pointed out. For the multiple access, it is difficult for the wide-area users to maintain accurate time synchronization. Compared with the synchronous RA protocol, the asynchronous RA protocol appears to be more attractive in the initial access of satellite Internet for 6G global coverage. For satellite handover, none of the existing satellite handover strategies and algorithms can perform well. In the future, it is necessary to design new processes and algorithms suitable for the characteristics of both mega-constellations and 6G. For the TT&C, neither the ground-based TT&C system nor the space-based TT&C system can undertake the huge TT&C tasks of the mega-constellations. Networked TT&C is a potential solution. Still, there are many critical technologies of networked TT&C that need to be broken through yet. For interference mitigation, the recommended solutions include the following: adaptive power control, cognitive radio, MIMO, smart antenna, beam hopping, as well as and databases.

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