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LEO Satellite Constellation for Internet of Things

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ABSTRACT Internet of Things (IoT) is one of the evolutionary directions of the Internet. This paper focuses on the low earth orbit (LEO) satellite constellation-based IoT services for their irreplaceable functions. In many cases, IoT devices are distributed in remote areas (e.g., desert, ocean, and forest) in some special applications, they are placed in some extreme topography, where are unable to have direct terrestrial network accesses and can only be covered by satellite. Comparing with the traditional geostationary earth orbit (GEO) systems, LEO satellite constellation has the advantages of low propagation delay, small propagation loss and global coverage. Furthermore, revision of existing IoT protocol are necessary to enhance the compatibility of the LEO satellite constellation-based IoT with terrestrial IoT systems. In this paper, we provide an overview of the architecture of the LEO satellite constellation-based IoT including the following topics: LEO satellite constellation structure, efficient spectrum allocation, heterogeneous networks compatibility, and access and routing protocols.

INDEX TERMS Internet of things (IoT), LEO satellite constellation, low-power wide-area network (LPWAN), long range (LoRa), machine-to-machine (M2M) communications, narrow band internet of things (NB-IoT).

I. INTRODUCTION

The Internet of Things (IoT) is a burgeoning paradigm that points out a novel direction of future internet, in which numerous heterogeneous networks containing different user data will be integrated transparently and seamlessly through appropriate protocol stacks [1], [2]. This integration aims to enable anything with a transceiver to access Internet at all times and places. Moreover, through those easy accesses, various kinds of IoT devices such as, environmental monitoring sensors, smart household electrical appliances, actuators, vehicles, etc., can exchange data with the IoT networks and provide unprecedented services for private users, business users, government users, army and anyone who utilize IoT. The obvious applications of the IoT will be visible for individual needs such as e-health, home automation, and elderly assistance as well as for industrial needs like smart grid, business management, environmental monitoring and smart city [1]–[3]. Connection types under different IoT scenarios are listed in Table 1.

TABLE 1. Connection types under different scenarios.

Scenario	Devices	Connection type
E-health	Health monitoring devices	Short-range, cellular
Home automation	Smart household electrical appliances	Short-range
Smart city	Vehicles, lighting, monitoring cameras, smart parking devices, air quality monitor	Cellular
Smart grid	Power meters	LPWAN
Environmental monitoring	Wild environmental sensors	LPWAN
Geologic disaster forecasting	Crustal movement monitor	LPWAN

Machina Research, a global leading provider of market intelligence and strategic, predicts 27 billion connected devices and USD 3 trillion in revenue in 2025. It highlights the direction of connections using Low Power Wide-Area Network (LPWAN) [4]. Comparing to short-range connections based on WiFi, Zigbee, Near Field Communication (NFC), Bluetooth or in-building power line communication (PLC) and cellular connections, the wide range ones are more capable for remote industrial scenario like smart grid and environmental monitoring. However, terrestrial-based LPWAN still cannot cover remote areas like desert, coastal waters and forests due to the commercial and engineering difficulties of constructing LPWAN in those areas.

To solve the aforementioned covering problem, satellite communication for IoT comes into view. The potential necessities of constructing satellite IoT system are listed as follows:

1) Firstly, the extreme topographies, such as cliff, valley, and steep slope, are places where geologic disasters are more easily to happen while terrestrial networks cannot access due to engineering difficulties. Satellite IoT system can make a breakthrough in the limits of topography with its covering advantages.
2) For IoT application in remote areas, satellite IoT system provides a cost-efficient solution with respect to other terrestrial technologies to their interconnection and communication with ‘‘the rest of the world’’ [5], [6].
3) For terrestrial IoT network, which mostly depends on wireless access, a communication network consisting of enough base stations is indispensable. However, constructing terrestrial base stations and connecting network is constrained by several limitations. For instance, terrestrial communication infrastructures are fragile that may be easily damaged by natural disasters like earthquake and flood. Meanwhile, terrestrial IoT can provide effective coverage only in a relatively small range (currently, terrestrial wireless network can only cover around 20% of territory in China and the U.S [7]). As a supplement and extension to the terrestrial IoT network, satellite IoT system is the only approach to achieve global IoT service covering.

Furthermore, aiming at the necessities of satellite IoT system, LEO satellite constellation technology has unique advantages comparing to GEO systems:

1) Due to the lower orbit altitude of LEO satellite constellation (normally lower than 2000km), it is more time efficient than GEO systems. In terms of propagation delay, quantified by a round trip time (RTT), LEO satellite constellation has a RTT less than 100ms while GEO systems’ RTT is over 600ms [6].
2) Most satellite IoT terminals are designed to be small-sized, long-life, and low power consumption. Benefiting from the relatively shorter propagation distance of LEO satellite constellation, the signal loss due to propagation shall be smaller, which helps the terminal design to reach the ideal pattern.
3) Communication via GEO satellite is constrained by extreme topographies because of the relatively static position between terminals and GEO satellite. If there is an obstacle (tree, cliff, etc.) in the line of sight (LOS) from terminal to satellite, this terminal is unable to communicate with the satellite unless the obstacle is removed. Comparing to GEO satellite, LEO satellite is connectable even if an obstacle locates near the terminal due to the satellite movement.

As a matter of fact, LEO satellite constellation-based IoT system is a realizable and powerful supplement to the terrestrial IoT networks. The global market for satellite IoT services is going to reach 1.7 billion dollars in 2017, and will rapidly dilate in coming years [8]. However, the IoT services requirements cannot be fully satisfied by simply combining the current satellite proprietary standard and terrestrial IoT protocol stacks. For example, plenty of IoT services tend to be short-burst data (SBD) transmission. In terrestrial IoT systems, based on complete access networks and high base stations density, applications can inherit the wireless communication protocol with a little refinement to suit their requirements. NB-IoT protocol, for instance, simplifies the structure of long term evolution (LTE) by deleting physical uplink control channel (PUCCH) [9], [10], narrowing the channel bandwidth [11], and predigesting the process. The core of NB-IoT, however, persists in the form of LTE that uninterrupted connection between user equipment (UE) and the Evolved Node B (eNodeB) during the whole communication process. If such protocol are deployed in its intact type, considering the limited communication resources over satellite and required low power consumption for terminals, the interactive overhead is a phenomenal burden that SBD services and satellite IoT terminals cannot afford.

In this work, we particularly focused on the following issues: 1) design of LEO satellite constellation for IoT services; 2) anti-interference measures for satellite IoT system; and 3) refinement of terrestrial IoT protocols for suiting satellite communication.

The reminder of this paper is organized as follows. Section II describes several typical application scenarios for LEO satellite constellation-based IoT system. Section III presents the thinking of design about LEO satellite constellation. Section IV illustrates existing interference environment between terrestrial and satellite-based network, and demonstrates potential anti-interference measures for satellite IoT system. Section V demonstrates the compatibility between satellite-based and terrestrial systems. Finally, Section VI concludes this work.

II. TYPICAL APPLICATION SCENARIOS FOR LEO SATELLITE CONSTELLATION-BASED IoT SYSTEM

In this section, we divide typical LEO satellite constellation-based IoT application scenarios into two groups: 1) delay-tolerant applications (DTAs) (for instance, monitoring and forecasting applications); 2) delay-sensitive applications (DSAs) (for instance, enhanced supervisory control and data acquisition (SCADA) and military applications). For each group, we present one or two specific applications to illustrate the current capabilities and potential possibilities which LEO constellation-based IoT system owns.

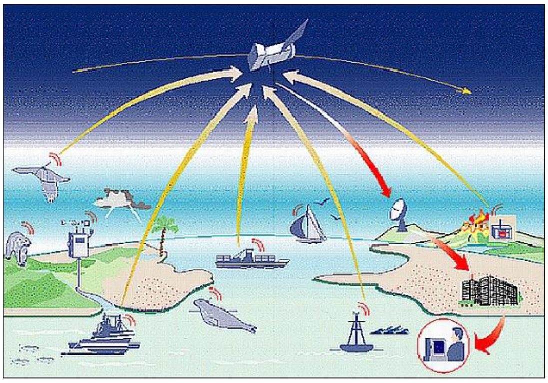

FIGURE 1. Satellite-based DTN system.

A. DELAY-TOLERANT APPLICATIONS

The concept of DTA is a part of delay-tolerant networking (DTN), which is a novel communication structure to provide automated store-and-forward data communication services in networks [12]. Fig. 1 shows an overview of a satellite-based DTN system. In general, those applications have common characteristics of frequent and prolonged temporary disconnections, and long propagation delay [13]. One of the typical DTAs is water monitoring.

Water is the source of life, and over 70 percent of earth surface is water covered. Water monitoring aims to secure the water quality from human activities and human safety from natural disasters. The main category of water monitoring includes temperature monitoring, tide monitoring, pollution monitoring, etc. The use of satellite could be irreplaceable for remote waters monitoring (for example, wetland and ocean), which terrestrial system cannot make implementation.

Currently, satellite-based monitoring remains in the way of remote sensing including satellite imagery [14], on-board satellite sensors [15], and on-board satellite Synthetic aperture radar (SAR) systems [15], [16]. Those traditional techniques have limits listed as follows:

1) Weather influence: Both aforementioned sensing techniques, especially the optical sensing by satellite imagery, are impacted by weather conditions. Fog, cloud or brume will lead to inaccuracy of satellite imagery. Meanwhile, when comparing selected data on the timeline, different weather conditions will eliminate the comparability.
2) Indirect results: The results from sensing need to be analyzed by specialists to get underlying information. This indirect approach will increase the difficulty of using analyzing algorithms as well as reduce analyzing efficiency.
3) System cost: Usually, remote sensing satellites are designed for specific purpose. Therefore, to gather different kinds of water information, the whole system needs to launch corresponding satellites, which certainly will increase the constructing and operating costs.

Aiming at the above disadvantages of remote sensing, LEO constellation-based IoT system may offer a replaceable solution for water monitoring, as it would obtain direct monitoring information through different kinds of sensors. In this solution, LEO satellites only play the role of communication platform, which can sharply reduce the cost of a single satellite. Furthermore, LEO constellation can ensure more frequent data-collection than a single remote sensing satellite to improve the accuracy of prediction and forecasting.

Though LEO constellation seems an ideal plan for water monitoring, several challenges arise. For example, interference from terrestrial IoT systems will affect the monitoring performance, especially in wetlands or coastal waters. Moreover, to meet the requirement of energy efficient, it requires specific concern on protocols and media access control (MAC) mechanism. Those issues are discussed in Section V.

B. DELAY-SENSITIVE APPLICATIONS

DSAs are quite different scenarios that have stringent requirements (i.e., lower latency and higher reliability) from the DTAs. Smart grid and Internet of Battle Things (IoBT) are representative application scenarios for civil and for military, respectively.

Current grid, for instance, is under the SCADA scheme, in which remote monitoring and automated control of substations are implemented through a slow central network [17]. However, the novel concept of smart grid [18] requiring the power grid to be able to react and adapt to the grid dynamics can be defined as a DSA. Currently, parts of smart grid elements are already available, and existed wired/wireless communication networks can support smart grid in urban/suburban areas. Apart from the densely populated regions, for implementing smart grid in remote locations including offshore wind farms and solar energy systems in desert, LEO constellation-based IoT system could present a viable and cost-effective solution. In [19], a LEO satellite constellation-based power manage solution is illustrated in detail including LEO satellite network, delay analysis and simulation experiments for typical traffic scenarios, which cover the main concerning points of smart grid.

Modern war is mainly in the form of information-based war, and United States Forces proposed the concept of network centric warfare (NCW) [20]. The key of NCW is that things can communicate with each other and can better serve humans involved in warfare. Similarly, the intelligent devices that populate in warfare is referred to as the IoBT [21]. During warfare, ground access system would be vulnerable as a result of enemy actions so that satellite-based access system is of great significance. However, GEO satellite cannot meet the safety requirements of IoBT for different reasons:

1) GEO satellite is relatively static to the ground, which makes it easy to be located and blanket jammed by enemies.

2) GEO satellite is easy for signal tracking due to its wide beam coverage. Once characteristic parameters have been seized, using deception jamming or coherent jamming will significantly raise the interference level.

Due to the aforementioned drawbacks of GEO satellite in IoBT, LEO constellation based system become a better choice. Meanwhile, in IoBT region, DSAs such as unmanned combat robot and unmanned aerial vehicle can be only satisfied by LEO constellation based network due to the strict requirements on latency.

Comparing to DTAs, DSAs require different design in LEO satellite constellation, e.g. implementing inter-satellite links (ISLs). At the same time, satellites are required to have the ability of on-board processing and on-board routing. The detailed demonstrations are illustrated in Section III and Section V.

III. DESIGN OF LEO SATELLITE CONSTELLATION

Generally, a LEO satellite constellation consists numbers of satellites in orbits of 500-2000 km. In constellation designing, following main factors should be taken into consideration:

1) Global coverage
2) Target application scenarios
3) Cost of single satellite and constructing the whole constellation

Aiming at above factors, LEO constellation can be categorized into two classes, i.e. constellation with/without ISLs. Meanwhile, there are differences in network architecture characteristics between two constellation designs.

A. LEO CONSTELLATION WITHOUT ISLs

LEO constellation without ISLs is more suitable for DTAs due to its low cost and complexity. At the beginning of designing a constellation, the orbit eccentricity, altitude and inclination should be considered.

As an important parameter in orbit designing, orbit eccentricity will have influence on satellite's covering area and time. When the satellite is near the apogee, covering area and time becomes relatively wider and higher, respectively. On the contrary, when the satellite is near perigee, the two quotas will decrease at same time. To get constant satellite overhead pass times and power levels needed for communication, the satellite orbits in the constellation are all round orbit. Meanwhile, in order to be convenient for controlling satellites during operation, the orbits are designed as recursive orbit, e.g. satellites will pass the same point after a certain time interval in days. Therefore, the satellite orbit period T_s can be calculated by following equations:

$$\frac{T_s}{T_e} = \frac{k}{n} \tag{1}$$

$$h = \frac{T_s^{\frac{2}{3}} \mu^{\frac{1}{3}}}{(2\pi)^{\frac{2}{3}}} - R \tag{2}$$

(1) ensures that the orbit is quasi-recursive, T_e where is equinoctial day with length of 86164 s, and k, n are integers, which represent orbit period in days and recursive cycles, respectively. (2) is the Kepler's third law, in which μ is the Kepler constant defined by, $\mu = 3.986 \times 10^{14} m^3/s^2$, h is orbit altitude, and R is the radius of earth with 6371 km. In this work, we pick $k/n = 1/14$, e.g. orbit period is one day and recursive cycles are 14, to calculate out $T_s = 6155s$ and $h = 887km$.

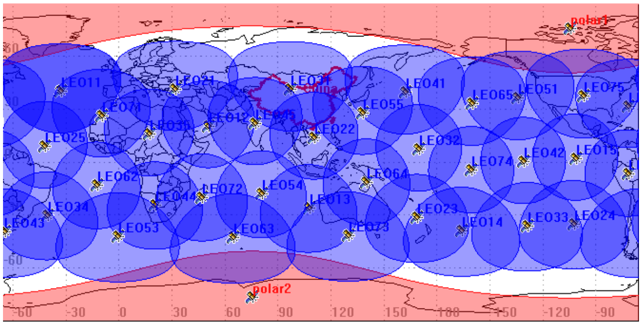

FIGURE 2. 2-D LEO constellation without ISLs coverage diagram.

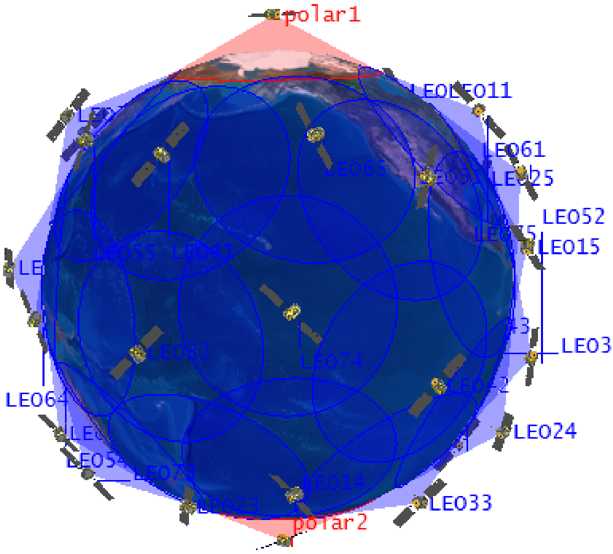

FIGURE 3. 3-D LEO constellation without ISLs coverage diagram.

To realize global seamless covering, Rosette Constellations are recommended due to their coverage properties [22]. Commonly, a shorthand notation (N, P, m) named Walker code is used to designate a rosette constellation having N total satellites, P orbit planes, and a harmonic factor m. In general, reasonable inclination of orbit is supposed to range from 30° to 50° for the covering goal. In this work, a Rosette Constellation which inclination of orbit is 42° and walker code (35, 7, 1) is proposed. Meanwhile, in order to optimize polar area coverage, the whole constellation design adds two polar satellites to cover polar areas periodically. The 2-D and 3-D coverage diagrams are shown in Fig.2 and Fig. 3 by simulating in System Tool Kit (STK).

B. LEO CONSTELLATION WITH ISLs

To implement ISLs and realize global seamless coverage, LEO constellation tends to accept polar orbit planes instead

TABLE 2. Orbit plane satellite parameters for LEO constellation with ISLs.

Orbit Plane	Perigee Altitude/km	Apogee Altitude/km	Inclination	Right Ascension of Ascending Node	Argument of Perigee	True Anomaly
A	887	887	86°	0°	0°	0°
B	887	887	86°	38°	0°	333°
C	887	887	86°	76°	0°	353°
D	887	887	86°	114°	0°	328°
E	887	887	94°	151°	0°	351°

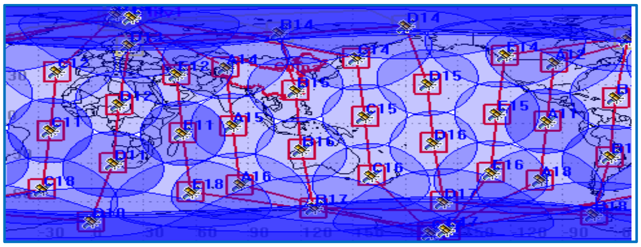

FIGURE 4. 2-D LEO constellation with ISLs coverage diagram.

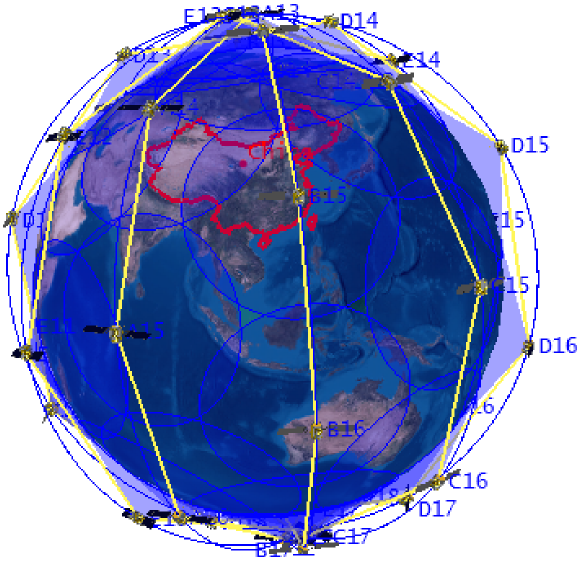

FIGURE 5. 3-D LEO constellation with ISLs coverage diagram.

of inclining orbit planes. However, to avoid satellites crashing at poles when there are two or more polar orbit planes, near polar orbits with inclination ranging from 80° to 100° (except 90°) are used to replace the standard polar orbit. Meanwhile, to reduce constructing cost, the constellation needs minimum satellites to realize global coverage. ISLs between orbit planes, which dramatically increase the system complexity (for instance, on-board processing, satellite antenna pointing, and system routing), are ignored by common LEO constellation based IoT system for same reason. To be notified, in IoBT, ISLs between different planes and on-board routing are necessary for strictly real-time application. Therefore, method of combining coverage zones of different orbit planes is used to design LEO constellation. The orbit planes consisted in the constellation have the same orbit altitude, and the satellites in each plane have the same inclination and angular spacing.

Here, a constellation design with 40 satellites in five orbit planes is proposed. In this plan, each satellite has two bidirectional ISLs with its two vertically adjacent satellites in the same plane. The initial orbit parameters, 2-D, and 3-D coverage diagrams are shown in Table 2, Fig.4, and Fig.5, respectively.

IV. LEO CONSTELLATION-BASED IoT INTERFERENCE ANALYSIS

Commonly, current satellite operating frequency tends to deploy in higher frequency bands such as Ku and Ka band, which can improve system capacity. However, operating on those bands cannot meet the requirements of IoT UE (e.g. small size and low power consumption) due to the severe propagation impairments including path loss and rain attenuation [23]. Meanwhile, dedicated lower frequency bands for mobile satellite system are rare that only a few companies, e.g. Orbcomm and Iridium, have registered for licensed radio spectrum. Despite operating on licensed frequencies, those systems need to negotiate with local radio administration since there is not a global pattern for frequency allocation. Therefore, sharing the same frequency bands with terrestrial IoT systems spontaneously becomes a considerable option for LEO constellation-based IoT. There are two existed frequency plans corresponding to LoRa and NB-IoT, respectively. LoRa alliance [24] suggests operating on unlicensed Industrial Scientific Medical (ISM) band referring to local radio standard. On the contrary, NB-IoT operates on licensed radio spectrum with three different operation modes: (1) stand-alone as a dedicated carrier, (2) in-band within the occupied bandwidth of a wideband LTE carrier, and (3) within the guard-band of an existing LTE carrier [10].

Unfortunately, sharing the same frequency band between terrestrial and satellite networks may lead interference to both satellite and terrestrial cells [25]. Usually, a LEO satellite spot beam diameter can be over a thousand kilometers, which can accumulate from a large area including highly populated

TABLE 3. **Interference analysis parameters.**

Satellite altitude	780 km
Satellite uplink TX EIRP	33 dBm -38.5 dBm
Satellite RX antenna gain	17dBi (noise figure 8dB)
RX G/T	-5dB/K
Interference source TX power	0 dBm

Abbreviations

EIRP	equivalent isotopically radiated power
TX	transmitter
RX	receiver

TABLE 4. **Interference analysis of elevation angle.**

TX EIRP (dBm)	Maximum Elevation Angle (degree)	Bearable TISs (BER 10^{-3})
33	47	4,320,000
36	60	3,376,000
38.5	72	2,900,000

TABLE 5. **SRRC table of allocations in LoRa ISM bands.**

Frequency bands	China Mainland
470-510 MHz	Broadcasting Space operation (space-earth) Space research (space-earth) [Fixed services] [mobile services]
779-787 MHz	Broadcasting [Fixed services] [mobile services]

cities crowed by terrestrial cells. Even though using multibeam antenna and designing LEO and terrestrial networks to cover different areas, the satellite beams can drift and cause overlapping in the satellite and terrestrial cells.

In [25], an analysis on satellite uplink transmission with terrestrial network interference has been proposed. The simulated parameters are listed in Table 3. The received signal power P_R at satellite antenna can be calculated as

$$P_R = P_T + G_R - L_{path} \tag{3}$$

where P_T is the transmitter power in dBm, G_R is the gain of satellite antenna, and L_{path} is propagation loss calculated by

$$L_{path} = 20 \times 10\log_{10}(4\pi df) \tag{4}$$

where d is the link distance in meters and f is the carrier frequency in Hertz. The signal-to-interference ratio (SIR) can be expressed in decibels by

$$SIR = P_R - P_I \tag{5}$$

where the calculation of is

$$P_I = P_{I_{TX}} + 10\log_{10}(N_{usr}) + G_R - L_{path} \tag{6}$$

where N_{usr} is the number of terrestrial interference sources (TISs). To be noticed that The TISs increase with the decrease of elevation angle due to the increase of satellite spot center distance. Meanwhile, it assumes that the interference signals are added together and then multiplied with $(1/\sqrt{SIR_{\text{lin}}})$ considering the numerous interference sources, where is defined by

$$SIR_{\text{lin}} = 10^{(SIR_{\text{dB}}/10)} \tag{7}$$

City Toulouse, France and Dusseldorf, Germany are taken into analysis in [25]. Though the number of TISs in Toulouse at the elevation angle of 23.4° is 435,180 and is 10 times larger than that at the elevation angle of 87.5°, the former one's SIR is 20dB higher than the later one's, which is because the simultaneously increasing propagation loss counteract the accumulated interference. Therefore, performance of a satellite-terrestrial hybrid system depending on population density and elevation angle. Analysis results for Dusseldorf referring to elevation angle and TISs are shown in Table 4. The analysis proves the potential feasibility for a satellite-terrestrial hybrid system sharing the same frequency band. However, the results show that satellite link is not immune to terrestrial interference especially for areas with high population density. Meanwhile, several assumptions in [25] are not available considering the LEO constellation-based IoT system; for instance, uplink TX ERIP is too high to meet the UE requirement of low power consumption. Therefore, the hybrid system cannot be designed solely on spectrum sharing, and further anti-interference measures should be taken into consideration.

Two topics are worth considering in the framework of potential anti-interference measures: 1) technology of cognitive radios (CRs) dealing with interference mitigation in satellite networks; 2) spread spectrum (SS) techniques, namely direct sequence (DS) and frequency-hopping spread spectrum (FHSS), in satellite communication (SATCOM). These topics are discussed below.

A. COGNITIVE RADIOS MECHANISMS FOR INTERFERENCE MITIGATION

CRs, from its definition, is a radio system that is able to sense its operating electromagnetic environment and adjust the radio parameters to optimize system performance dynamically and automatically [26]. In order to utilize shared frequency bands, CRs is needed while relieving interference from the terrestrial services and guaranteeing acceptable interference to the incumbent users [27].

With special focus on Chinese Mainland, LoRa can be used in 470-510 MHz band and 779-787 MHz band in line with LoRa alliance regulations [28] and State Radio Regulation of China (SRRC). Table 5 provides the SRRC allocations of the aforementioned frequency bands, where the services expressed in bracket are less important. As can be seen from Table 4, LEO constellation-based IoT deploying in LoRa frequency plan is sharing frequency bands with other radio services, which means in downlink, UEs need to manage interference received from the incumbent users, and in uplink, UEs need to ensure their transmission does not impact the incumbent receivers. Therefore, CRs mechanisms is necessary to mitigate the interference issues.

A spectrum utilization system with CRs mechanisms consists spectrum awareness (SA) unit and spectrum exploitation (SE) unit. The SA unit aims to gather knowledge about the incumbent users with the cooperation between databases and spectrum sensing.

1) *Databases:* The purpose of databases is to incorporate satellite broadcasting links and terrestrial services characteristics in order to determine terrestrial interference levels at any location and carrier frequency. Once received interference level is deemed to exceed threshold, CRs mechanisms then ought to mitigate the interference.
2) *Spectrum Sensing:* Spectrum sensing provides the essential information to enable this interweave communications in which primary and secondary users are not allowed to access the medium concurrently [29], including spectral energy, cyclostationary detection and SIR estimation [30], and shares information with databases to update the real-time interference scenario.

The core function of SE unit is dynamic channel assignment (DCA), which directly has respect to interference mitigation. Synthesizing the cognitive information collected by SA unit, DCA is necessary to allocate the determined cognitive resources, particularly the frequency channels, to UE. [27] proposes two allocating approaches focus on maximizing overall system throughput and system availability, respectively. In the allocating process, to ensure efficiency, factors such as channel priorities and aggregation need to be considered. With respect to channel priorities, DCA is designed to evaluate the channel interference level in an adjustable time interval. Suitable channels are prioritized in terms of interference power expected on the next scan, which bases on SIR estimation implemented in spectrum sensing. Meanwhile, SE unit also performs power control in the downlink, which keep interference to the incumbent users below a specific threshold on the premise of maintaining the system throughput.

Apart from aforementioned techniques, several methods including compressive sensing (CS) and beamforming are used in CRs mechanisms. In [31], CS is suggested to operate channel estimation due to the sparsity inherent in wireless channels. Since the active transmitting UE cannot be predicted in advance, the sparsity condition in CS theory can be justified. Beamforming, as an essential technique in 5G, can be implemented on satellite for interference detection and improving SIR of UEs [32].

B. SS TECHNIQUES IN SATCOM

SS technique is a common method implemented in wireless communication systems to resist interference from same frequency band. In current IoT standards, LoRa adopt DS/CDMA for its physical layer transmitting protocol due to the unlicensed frequency plan. Therefore, DS/CDMA can be also considered for LEO constellation-based IoT. In [33], total capacity in a shared CDMA/LEO environment is calculated, which presents a theoretical base for implementing DS/CDMA in LEO constellation-based IoT. Furthermore, to improve system efficiency, an adjustable spreading factor (SF) scheme is recommended by LoRa alliance [34]. Under the circumstance of LEO constellation-based IoT, basing on the channel state information broadcasted by satellite, UE can adaptively adjust SF and data rate in order to increase system throughput and maintain UE power efficiency.

FH is another approach of SS and extensively used in military satellite systems to resist intentional and unintentional interference. A fixed pseudorandom noise (PN) sequence is used in traditional FH operation, known to both transmitter and receiver, to switch a carrier among available channels. The limitation of traditional FH, however, is that PN sequence will inevitably switch a carrier that is persistently occupied by other users since both transmitter and receiver have no channel state information. To solve the limitation of static FH scheme, [35] proposes a dynamic frequency hopping (DFH) scheme combining with CRs techniques. In this approach, FH sequence is no longer a fixed PN sequence but depending on the spectrum sensing information. Basing on proactive sensing, DFH could mitigate both intended and unintended interference.

V. COMPATIBILITY BETWEEN LEO CONSTELLATION -BASED AND TERRESTRIAL IoT SYSTEMS

As mentioned at the beginning, LEO constellation-based IoT system is a powerful supplementary to terrestrial system, which aims to cover remote or extreme areas where terrestrial system cannot reach. Therefore, the compatibility between two systems should be considered in order to generate an integrated IoT network. Unfortunately, though the third generation partnership project (3GPP) LTE air interface in satellite communication was evaluated in [36], up to now, the terrestrial IoT standards have not taken any satellite components into consideration. Hence, the compatibility remains an open area for researching.

The aspect of compatibility includes the following topics such as MAC protocols, network architecture and united service patterns. In literature, MAC protocols for satellite-based IoT system have been studied mainly focus on random access (RA) in the case where numerous terminals are deployed and the transmitting requests are generated arbitrarily. In [6], [37]–[39], different RA protocols are analyzed for their feasibilities in satellite-based IoT system. For instance, in [39], satellite uses a divide-and-conquer scheme to allocate time slots on demand to terminals under the assumption of using GEO satellite which means the whole system is time synchronous. However, in LEO constellation-based IoT system, high satellite dynamic makes system time synchronous difficult to realize due to the dramatic relative motion between satellite and UEs. Therefore, to adopt those

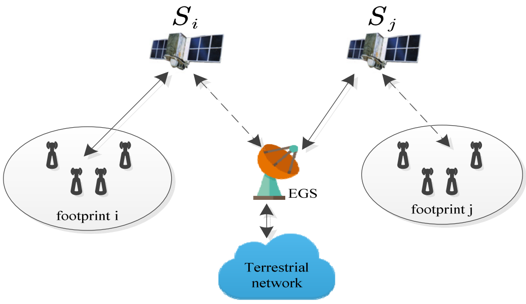

FIGURE 6. EGS-centralized network architecture.

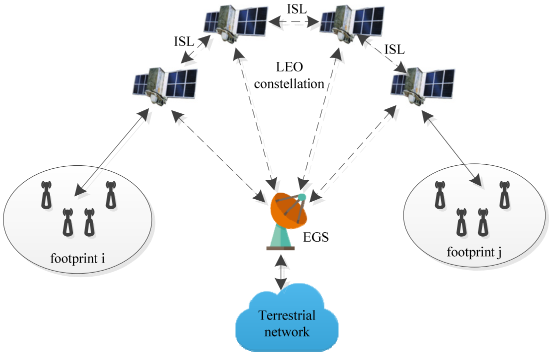

FIGURE 7. Dynamic satellite topology network architecture.

RA schemes in LEO constellation-based IoT system potentially, satellite dynamic problem needs to be mitigated.

The following of this section focuses on the other two topics: 1) network architecture of LEO constellation-based IoT and 2) the united higher layer design for integrated space-terrestrial (IST) IoT network.

A. LEO CONSTELLATION-BASED IoT NETWORK ARCHITECTURE

Combining illustrations in Section III and viewpoint of network, the LEO satellite design in a constellation is based on one of two fundamentally different approaches as follows [40]:

1) Each satellite is a transparent retransmitter to relay traffic received from IoT terminals and earth gateway station (EGS), and returning the traffic to the ground.
2) Each satellite with ISLs is a network switch for being able to communicate with neighboring satellites. In this approach, IoT terminals within a satellite visible area (called satellite's footprint) can exchange traffic with EGS and IoT terminals in other satellites' footprints without terrestrial infrastructures' support.

Corresponding to the two satellite design approaches, the LEO constellation-based IoT network can be depicted by EGS-centralized network and dynamic satellite topology network shown in Fig. 6 and Fig. 7, respectively. To be noticed that EGS-centralized network mainly cater to DTA and utilize constellation without ISLs. On the contrary, dynamic satellite topology mostly aims on DSA and adopts ISLs in constellation design.

IoT mostly depends on TCP/IP protocol suite where IP provides enough routing information and TCP guarantees reliable data transmission on top of IP. To ensure the compatibility between LEO constellation-based IoT network and terrestrial ones, and distinguish from M2M communications, TCP/IP should be implemented in the network design. Meanwhile, since the network architecture or topology is decided by satellite design, the routing strategies vary from one to another.

For EGS-centralized network, satellites are not always visible for all IoT terminals, which makes it difficult to design routing strategy. For instance, in Fig. 6, S_i and S_j are corresponding to footprint i and j, respectively. Since S_i and S_j may not be visible for EGS, routing to footprint i or j need to wait for the satellite recurrence. To deal with this problem, a proxy cache scheme can be implemented in the routing strategy, which EGSs store all routing information (e.g. terminals location and ephemeris) updated within each transmission process. When EGS receive a routing request, the route via an optimum satellite to the destination will be calculated basing on ephemeris. The recursive orbit also designed for this routing strategy to get relatively stable routing table. Moreover, proxy cache scheme is also considerable in united higher layer designing, which will be detailed in Section V-B.

Routing situation becomes more complex in dynamic satellite topology network (DSTN) due to the relative motion between each satellite. The topology is a variation of the Manhattan street network (MSN) [41], which is a regular, two-connected network, designed for packet communications. The fundamental difference in routing strategy of MSN from conventional loop network is that routing decisions must be made at every node (e.g., each satellite in LEO constellation network) in this network [42]. However, unlike terrestrial networks, where a fixed route between source and destination is available at any point in time, LEO ISL meshes can offer more than one path when the path is longer than one ISL hop. Thus, the requirements of routing strategies for DSTN are listed as follows: 1) avoiding choosing multiple routes that will lead to ISL congestion; 2) reducing the hops of route to increasing time efficiency; 3) providing QoS guarantee. Considering the first two points, a kind of routing strategies is the variations of Dijkstra algorithm, which utilize the topology snapshot method [43]. Topology snapshot is to divide continual dynamic topology of satellite constellation network into a series of static topology structure called "snapshot", which update while the ISLs changing. Therefore, at every arbitrary moment, the DSTN has a particular snapshot that remains stable until next changing appears, and routing strategies used frequently are minimum distance algorithm (MDA) and minimum hops algorithm (MHA) focusing on different ISL factors. For MDA, cost function of each ISL is defined as its physical distance, while cost function is defined as one for MHA. Clearly, MDA is to find out the route with minimum distance that aims to reduce the time delay of communication but ignore the whole system flux balance, which may lead to severe ISL congestion.

Correspondingly, MHA focuses on decreasing route occupancy on system resources but does not consider handover cost. In [43], an application of K-shortest path algorithm is proposed to avoid ISL congestion and reduce handover cost at the same time.

In [44], [45], routing strategies focusing on QoS guarantees are proposed. Unlike Dijkstra algorithm based routing strategies that pre-determine routes in EGS, in these ones, each satellite updates the local routing table according to its signaling without the assistance of the terrestrial gateway stations, which improve the viability of DSTN. Satellites forecasts the routing signaling earlier before disconnection of the ISL and broadcast the signaling once the ISL is connected. After receiving the routing signaling, each satellite updates the routing table according to the path state collected by its signaling without any acknowledgement. Each intermediate satellite fills the link state information between itself and its previous satellite in the signaling record, which is referred to as ''reverse detection''. When congestion occurred in one satellite, it will generate a warning signal and send it to next satellite. Then the destination satellite broadcast a detection request for searching a new route with low congestion level. Moreover, [46] proposes QoS mapping techniques over heterogeneous networks and an applicable solution called technological independent-service access point (TI-SAP), which are reliable solutions for LEO constellation-based IoT network.

B. UNITED HIGHER LAYER DESIGN FOR IST IoT NETWORK

Currently, in the field of LPWAN, there are several popular technologies such as NB-IoT, LoRa, Sigfox, Random Phase Multiple Access (RPMA), etc. However, with respect to higher layer design, NB-IoT has incomparable advantages than others since it bases on LTE, which has a complete higher layer structure. In 3GPP Rel-13 [47], NB-IoT has been introduced to provide LPWA IoT services by modifying LTE technology. Thus, the higher layer design for IST IoT network may refer to the structure of NB-IoT.

In NB-IoT, LTE functionalities are inherited with simplifications and optimizations that only essential features for small data transmission are supported in Rel-13 [48]. A typical optimization for small data transmission is Radio Resource Control (RRC) connection suspend/resume. A diagram of RRC resume operation is shown in Fig. 8. Both UE and eNodeB store the Access Stratum (AS) context together with Resume ID upon connection suspension. When UE turns into data transmission progress, it provides the stored Resume ID to be used by eNodeB to access the stored information required to resume the RRC connection.

However, several disadvantages can be seen from this RRC resume operation that NB-IoT's higher layer design cannot fully meet the LEO constellation-based IoT system's requirements:

1) Continually signaling interaction: In RRC resume operation, before eNodeB sending UE context resume request to mobility management entity (MME), there are five signaling interactions between UE and eNodeB. Unlike NB-IoT, in LEO constellation-based IoT, the functionality of eNodeB is shared by satellite and EGS. As mentioned in Section V-A, the connection between satellite UE and eNodeB is not stable physical connection but routing through a dynamic topology network, which means each signaling interaction may transmit via different route. Due to the limited resource of ISLs and retransmitters, continually signaling interaction is bound to affect the system throughput and efficiency.
2) Context information storage: If utilize NB-IoT's pattern, UE and satellite will store AS context and Resume ID upon connection suspension. However, the limited on-board memory cannot afford such cost.

To release space segment pressure, proxy cache scheme can be also implemented in the LEO constellation-based

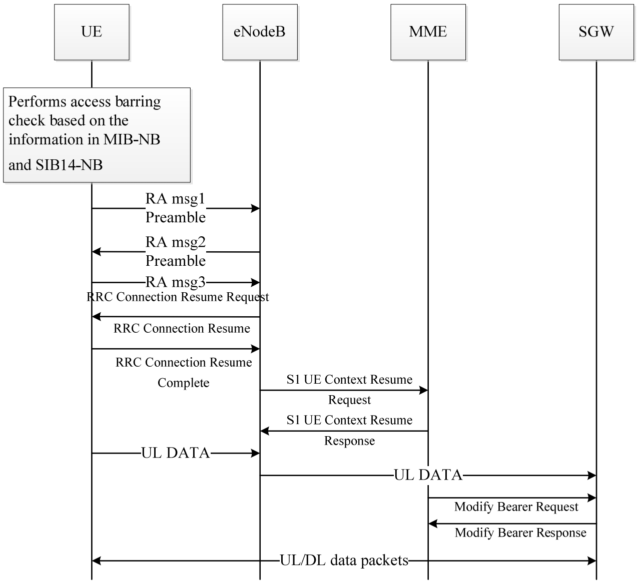

FIGURE 8. Data transmission using RRC resume operation.

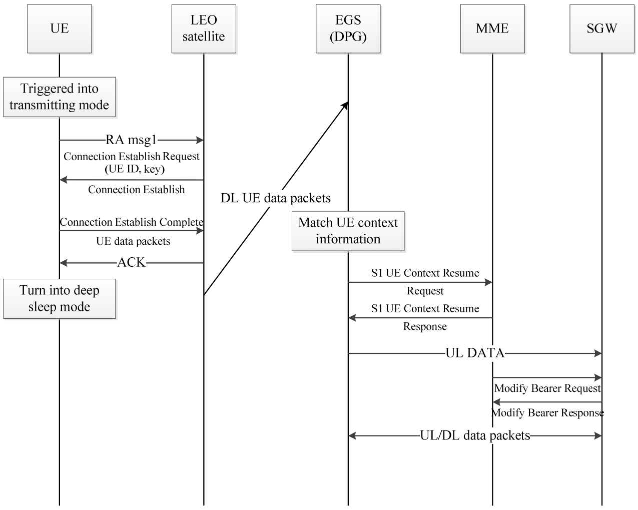

FIGURE 9. Data transmission operation in LEO constellation-based IoT.

IoT's higher layer design. The concrete measure is to separate UE-satellite segment as a pure transmission network from the terrestrial segment, e.g. the EGS. Data package oriented from UE contain the UE ID and corresponding key and satellite play the role of authentication. The UE-satellite segment is similar to the transmitting part of LoRa [24]. Upon finishing transmission, UE turns into deep sleep mode until next transmitting trigger. The data processing gateway (DPG) in EGS, which utilizes proxy cache scheme, stores all context information for establishing and resuming connection. After receiving the satellite downlink data, DPG will identifies different UE's data packages and then simulates corresponding UE to complete higher layer operation using stored information. The diagram is depicted in Fig. 9. By implementing DPG, space segment pressure can be sharply released.

VI. CONCLUSIONS

This paper presents an overview of LEO satellite constellation-based IoT system. Important issues that have been discussed are: constellation design, interference mitigation, constellation network architecture, routing scheme, and united higher layer design. For each of these topics, the authors report results of recent studies and post some specific thinking for system design.

As mentioned in [6], potential use of constellations of satellites for IoT applications is of growing interests. With booming development in IoT environment, as a powerful supplement to terrestrial systems, LEO constellation-based IoT is worth being focused and studied. To make this topic become a reliable cost-benefit solution, further researches are needed to be done including transmission scheme, system security and low power consumption design.

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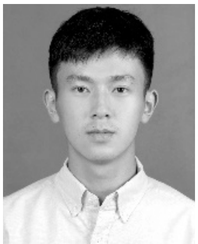

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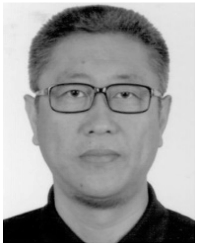

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