Frontiers of Information Technology & Electronic Engineering
www.jzus.zju.edu.cn; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Review:

Satellite Internet of Things: challenges, solutions, and development trends*

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Received Dec. 18, 2022; Revision accepted Feb. 26, 2023; Crosschecked Mar. 31, 2023; Published online June 16, 2023

Abstract: Satellite Internet of Things (IoT) is a promising way to provide seamless coverage to a massive number of devices all over the world, especially in remote areas not covered by cellular networks, e.g., forests, oceans, mountains, and deserts. In general, satellite IoT networks take low Earth orbit (LEO) satellites as access points, which solves the problem of wide coverage, but leads to many challenging issues. We first give an overview of satellite IoT, with an emphasis on revealing the characteristics of IoT services. Then, the challenging issues of satellite IoT, i.e., massive connectivity, wide coverage, high mobility, low power, and stringent delay, are analyzed in detail. Furthermore, the possible solutions to these challenges are provided. In particular, new massive access protocols and techniques are designed according to the characteristics and requirements of satellite IoT. Finally, we discuss several development trends of satellite IoT to stimulate and encourage further research in such a broad area.

Key words: Internet of Things; Satellite communications; Low Earth orbit (LEO); Massive connectivity; Random access

https://doi.org/10.1631/FITEE.2200648 **CLC number:** TN929.5

1 Introduction

With the upcoming era of the Internet of Everything (IoE), a massive number of devices want to access wireless networks to provide various wireless services, e.g., smart traffic, smart industry, smart medicine, and smart agriculture (Xu et al., 2014; Zanella et al., 2014; Islam et al., 2015; Ahmed et al., 2018; You XH et al., 2021). It is predicted that the number of wireless devices will exceed 41.6 billion in 2025, and reach hundreds of billions in 2030 (Statista Research Department, 2016; Cisco, 2019). In this context, 3GPP takes massive Internet of Things (IoT) or massive machine-type communication (mMTC) as one of three use cases of fifth-generation (5G) wireless networks (Chen XM, 2019). From the perspectives of construction costs and economic profits, 5G wireless networks are deployed in population-intensive areas, e.g., urban and rural areas, but these population-intensive areas are only a small part of the world. In fact, most of the world has no human population, e.g., forests, oceans, mountains, and deserts. Nowadays, more and more IoT devices are deployed in these unpopulated areas. For instance, security cameras have been installed in forests to predict wildfires (Kaur and Sood, 2020), and many sensors have been deployed in the sea to monitor ocean resources (Qiu et al., 2020). To this end, satellite IoT has been widely recognized as an enabling solution to worldwide coverage.

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Satellite IoT has received considerable interests from academia and industry (Briskman, 1984; De Sanctis et al., 2016; Hassan et al., 2020; Caus et al., 2021; Cao et al., 2023). Some companies and organizations such as SpaceX have launched tens of hundreds of satellites to realize global Internet service. Generally speaking, satellite IoT takes low Earth orbit (LEO) satellites as access points (APs), which orbit between 400 and 2000 km above the Earth (Qu et al., 2017; Di et al., 2019; Kodheli et al., 2019). Hence, the propagation delay from the device to the AP is $<$ 10 ms, which is a key metric of IoT. In fact, LEO satellite communications have been used for many years in multiple fields. In traditional applications, LEO satellite communications need only to admit very few devices. Therefore, multi-beam techniques combining random access protocols are usually employed in LEO satellite communications (Joroughi et al., 2017). In particular, the LEO first determines the admissible devices based on a grant-based random access protocol such as ALOHA, and then the gateway (GW) on Earth designs the beams and sends them to the LEO satellite via the feeder link. Hence, the LEO satellite has low implementation cost and power consumption. Considering the rate constraint of the feeder link, multi-GW techniques are also adopted in some scenarios. Multi-beam techniques may lead to co-channel interference, especially at the edge of beams. To reduce the co-channel interference, multi-beam techniques are used with frequency division multiple access (FDMA), such as four-color frequency reuse (Vázquez et al., 2016). Intuitively, FDMA reduces the available bandwidth, resulting in performance degradation.

Recently, with the increase in LEO satellite processing capability, multi-beam precoding techniques with full frequency reuse have been applied to further improve the performance (Zheng et al., 2012). In particular, GW conveys channel state information (CSI) related to the admissible devices to the LEO satellite, and then the LEO satellite carries out precoding to transmit beams according to available CSI. Intuitively, if the LEO satellite has full CSI, the precoding techniques can cancel co-channel interference completely. However, due to feedback delay, transmission error, and rate constraints, CSI at the LEO satellite is usually imperfect. In this context, to guarantee the performance of satellite communications, it is desired to conduct robust precoding based on the available CSI. You L et al. (2019) provided a CSI error model according to the characteristics of LEO satellite channels. Based on such a CSI error model, a robust precoding scheme was designed with the goal of minimizing the power consumption at the LEO satellite subject to outage rate constraints. Moreover, the average rate constraints in the presence of CSI uncertainty were considered in the design of a robust precoding scheme in Wang et al. (2018). You L et al. (2020) proposed statistical precoding based on statistical channel information for situations when instantaneous CSI is unavailable at the LEO satellite.

Although multi-beam precoding techniques can improve the performance of LEO satellite communications, it is possible to admit only a limited number of devices. As the number of devices increases, multi-beam precoding techniques lead to severe co-channel interference. Moreover, precoder design for a large number of devices has a high computational complexity. Therefore, traditional LEO satellite communication techniques are not applicable for satellite IoT with a massive number of devices. In this context, it is necessary to design protocols and techniques that satisfy the requirements of satellite IoT. In this paper, we first give an overview of satellite IoT networks, with an emphasis on the characteristics of satellite IoT. Then we investigate the satellite IoT design issues, point out the fundamental challenges for fulfilling these design requirements, and provide possible solutions to these challenges. Finally, we analyze and discuss the development trends of satellite IoT.

2 Satellite Internet of Things (IoT) networks

Satellite IoT is a new kind of network. On one hand, unlike traditional IoT networks, satellite IoT takes LEO satellites as APs, resulting in new network architectures. On the other hand, unlike traditional satellite communication networks, satellite IoT has to support various IoT services, resulting in new service characteristics. In this section, we briefly introduce the satellite IoT network architectures and service characteristics, which lay a foundation for the design of satellite IoT.

2.1 Network architecture

In general, satellite IoT has four components: IoT devices, GWs, access networks, and core networks (De Sanctis et al., 2016; Qu et al., 2017), as shown in Fig. 1. IoT devices are various sensors, cameras, and controllers. These devices are distributed over different regions, including forests, oceans, mountains, and deserts. Most of these devices are simple nodes with limited processing capabilities. GWs build a feeder link from the devices to the LEO satellite and have two main functions. One is CSI conveyance from the devices to the LEO satellites. The other is signal processing for the LEO satellite. For example, a GW may design a precoder for the LEO satellite if the LEO satellite has limited processing capability. Currently, precoders are usually designed on board according to the received CSI. Note that multiple GWs are usually employed to support a large amount of information feedback. The access networks consist of multiple LEO satellites, namely APs. With technical progress, LEO satellites have a strong processing capability. Hence, LEO satellites can process the received signals on board directly. LEO satellites move very fast, to provide global coverage, and tens of hundreds of LEO satellites are required. In particular, LEO satellite constellations or swarm satellites are usually designed as APs. Active IoT devices that have information exchange access the satellite IoT networks via these LEO satellites using two procedures: access identification and information transmission. The core networks are formed by geosynchronous orbit (GEO) satellites. The GEO satellites orbit at an altitude of 36 000 km and remain static with respect to the Earth. On one hand, GEO satellites connect APs via high-throughput millimeter waves or even lasers. On the other hand, GEO satellites connect the IoT servers via one or multiple hops.

For IoT applications, the information exchange between IoT devices and IoT servers should pass the access network and the core network. As mentioned above, because the core network transfers the data packets using high-throughput millimeter waves or lasers, it is possible to support high-speed transmission. However, for the access network, APs have to communicate with a massive number of simple IoT devices, which is a bottleneck of the satellite IoT network. The channel is the most important factor determining wireless access performance, e.g., rate and delay. For satellite IoT, the LEO satellite usually works at the Ka-band, and the channel from the LEO satellite to the device can be expressed as (Chu et al., 2021)

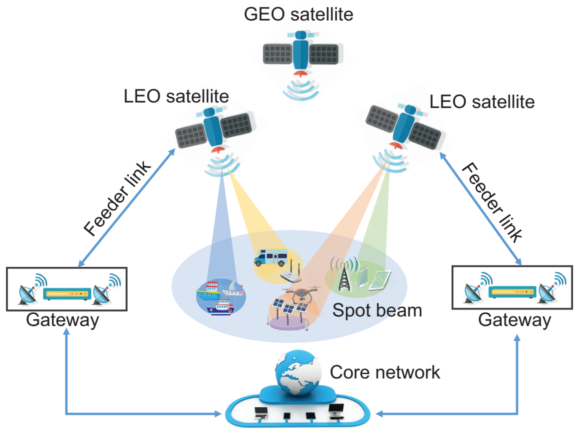

Fig. 1 A typical network architecture of satellite Internet of Things (IoT) (LEO: low Earth orbit; GEO: geosynchronous orbit)

$$\boldsymbol{h} = \sqrt{C}\boldsymbol{b}^{1/2} \odot \boldsymbol{r}^{1/2} \odot \exp(\mathrm{j}\boldsymbol{\theta}), \tag{1}$$

where "$\odot$" denotes the Hadamard product, $\boldsymbol{h}$ is the N-dimensional channel vector with N being the number of antennas at the LEO satellite, C is the large-scale fading coefficient, $\boldsymbol{b}$ is the beam radiation pattern vector, $\boldsymbol{r}$ is the rain attenuation coefficient vector, and $\boldsymbol{\theta}$ is the channel phase vector. Given the position of the LEO satellite, the large-scale fading coefficient, the beam radiation pattern, and the rain attenuation coefficient are constant, but the channel phase is random. As a result, channel phase error may occur at the LEO satellite due to CSI conveyance from the device to the LEO satellite via the GW, which is a main factor affecting the performance of satellite IoT.

2.2 Service characteristics

Satellite IoT networks are used mainly to provide wireless coverage to devices over remote areas, e.g., forests, oceans, mountains, and deserts. Most devices in these areas carry out sensing, monitoring, and controlling, but not voice communications in traditional wireless networks. In other words, satellite IoT provides mainly machine-type communication (MTC) services, which are very different from conventional human-centric communication (HCC) services. To design an effective satellite IoT, the service characteristics of satellite IoT must be understood. Generally speaking, the MTC services in satellite IoT have the following characteristics (Chen XM et al., 2021):

1. Sporadic traffic. IoT services are usually event-driven, resulting in extreme randomness. In other words, at a given time slot, only a portion of the devices have data to send. According to statistics, 10%–15% of devices are active at a given time slot. To save energy, inactive devices without data transmission do not access the satellite IoT.

2. Small data. Unlike HCC services, MTC services in general generate a small volume of data, e.g., tens or hundreds of bits. To improve the spectral efficiency and reduce the transmission delay, satellite IoT should adopt short-packet transmission.

3. Massive packets. The satellite IoT should support access by a massive number of devices, which generate a massive number of short data packets. It is predicted that the number of wireless devices will reach hundreds of billions, most of which are IoT devices for MTC services.

4. Heterogeneous requirements. IoT services are various, e.g., sensing, monitoring, and controlling, resulting in diverse quality of service (QoS) requirements in rate, latency, and reliability.

These distinct network architectures and service characteristics lead to a tremendous difference between satellite IoT networks and traditional wireless networks. Hence, it is necessary to design effective satellite IoT schemes to support a variety of advanced services.

3 Challenges in satellite IoT

As mentioned above, satellite IoT is a new kind of wireless network, which is very different from traditional wireless networks, e.g., territorial 5G wireless networks and general satellite communication networks. Hence, traditional wireless techniques cannot be applied to satellite IoT directly. It is imperative to design wireless techniques according to the characteristics and requirements of satellite IoT. Prior to providing possible solutions to satellite IoT, we first analyze and discuss the challenging issues in the design of satellite IoT.

3.1 Massive connectivity

With widespread applications of IoT in forests, oceans, mountains, and deserts, the number of IoT devices experiences explosive growth. Although only a portion of IoT devices are active at a given time slot, the number of active devices is still very large. For satellite IoT, it is not a trivial issue to support massive connectivity. First, to save energy, only active devices access the satellite IoT. Hence, LEO satellites must identify active devices from a massive number of devices. Generally, LEO satellites identify active devices by multiple negotiations, resulting in prohibitive signalling overhead. Second, the admissible devices generate a large number of short data packets. Traditionally, orthogonal multiple access (OMA) techniques, e.g., FDMA, are used for data transmission. However, it is difficult for OMA to transmit a large number of data packets simultaneously over a limited radio spectrum. Thereby, massive connectivity is a critical issue for satellite IoT.

3.2 Wide coverage

A main advantage of satellite IoT with respect to territorial IoT networks is wide coverage with a low cost by using multi-beam techniques at the LEO satellites. However, wide coverage based on multi-beam techniques is not trivial. First, due to the hardware constraints, the number of beams is very limited. To avoid co-channel interference, a beam serves only one or multiple devices with the same services. Hence, even though the active devices are covered by satellites, they cannot access the satellite IoT. Second, IoT devices are distributed over different areas, e.g., forests, oceans, mountains, and deserts, which have different propagation environments. As a result, the precoder design for beams becomes very complex. Furthermore, because LEO satellites obtain only partial CSI, robust precoding for beams is extremely difficult. In other words, wide coverage in satellite IoT leads to high computational complexity.

3.3 High mobility

LEO satellites, as APs of satellite IoT, move very fast. It is well known that high mobility is a challenging issue of wireless communications, especially in the scenarios of simple nodes. In satellite

IoT, a high-mobility LEO satellite leads to fast time-varying of the channel. Consequently, on one hand, CSI obtained at the LEO satellite from the GW may be outdated, which severely degrades the performance of multi-beam techniques. On the other hand, it is impossible to carry out complex wireless techniques to improve the quality of the received signal. However, because the Ka-band signals are weak caused by path loss and rain attenuation, the resulting performance may be unsatisfactory. Moreover, high mobility of LEO satellites means that an LEO satellite can serve a device for only a short time duration. Therefore, for some services with a long time duration, the services must be completed with multiple LEO satellites. Frequent handoff among multiple LEO satellites inevitably leads to performance degradation.

3.4 Low power

Unlike territorial IoT networks, satellite IoT requires low power consumption at both the transmitters and the receivers. First, the LEO satellites harvest solar energy, which is not reliable or stable. Due to the size constraint, they cannot store much energy. In this case, they cannot adopt high-power-consumption algorithms, which significantly limits the processing capability of the LEO satellites. Second, IoT devices have much more stringent low power consumption requirements. Intuitively, it is impossible to replace the batteries of IoT devices frequently. An IoT device battery must be used for >10 years. Accordingly, the transmit power of an IoT device needs to be <23 dBm. Because the satellite channel undergoes severe path loss and rain attenuation, the received signal is weak. If the transmit power is too low, it is difficult to satisfy the QoS requirements.

3.5 Stringent latency

Compared to territorial IoT networks, satellite IoT has a large delay. Although LEO satellites are used as APs, the transmission delay is >1 ms. Considering the processing delay, the total delay is high. For example, the commonly used grant-based random access protocol requires four transmissions between an AP and the devices to complete the access identification. In other words, the delay is 4 ms at least. In fact, some IoT services have stringent delay constraints, e.g., wildfire monitoring in forests. Hence, it is necessary to reduce the latency of satellite IoT by some means.

Satellite IoT faces many challenging issues that cannot be solved by traditional IoT techniques. In this context, effective techniques must be designed according to the characteristics and requirements of satellite IoT.

4 Solutions to satellite IoT

In the above, we analyzed and discussed the characteristics and requirements of satellite IoT, and revealed the corresponding challenging issues in the design of satellite IoT. In this section, we provide possible solutions to the design of satellite IoT. As analyzed above, the main bottleneck of satellite IoT lies in wireless access. Hence, we focus on the design of wireless access from access protocols to access techniques.

4.1 Access protocol

The first step of wireless access is to determine the devices that can access the wireless network based on a predetermined access protocol. Due to the burst characteristics of IoT services and to save IoT device energy, only active devices access the wireless network. In traditional IoT networks, grant-based random access protocols, e.g., ALOHA, are adopted to manage IoT device access (Centenaro et al., 2017). As shown in Fig. 2a, grant-based random access includes four transmissions to complete the access identification. First, an active device randomly selects a preamble from a preamble pool and uses the selected preamble to inform the AP that is active. Then, the AP responds to each preamble and allows the corresponding device to take an action at the next step. Next, the active device sends a connection request to the AP. Finally, if a preamble is selected by one active device, the AP sends a contention-resolution message to inform the active device about the allocated resource; otherwise, the access request is denied. Grant-based random access has a large signaling overhead and a high access failure probability, especially in the case of massive connectivity. Importantly, for satellite IoT, four transmissions between the device and the AP lead to significant delay. Hence, grant-based random access protocols are not appropriate for satellite IoT. In this context, satellite IoT has to adopt grant-free random access protocols (Zhang ZY et al., 2016; Zhang ZJ et al., 2020; Ying et al., 2023), as shown in Fig. 2b. Specifically, each device is allocated to a unique preamble. After sending the preamble, the active device transmits its data packet without the grant of the AP. Therefore, the signalling overhead and the access delay can be reduced significantly.

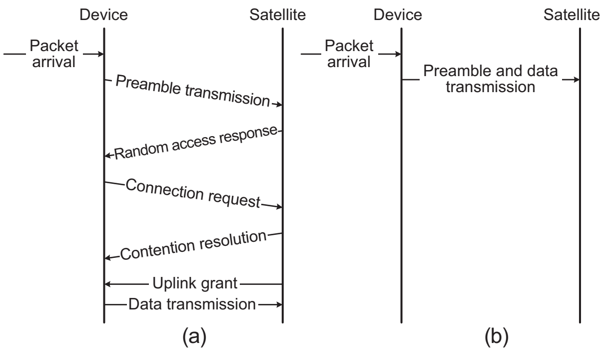

Fig. 2 Random access protocols: (a) grant-based; (b) grant-free

The key to grant-free random access is to detect active devices based on the received preambles. In the context of massive connectivity, the preambles are non-orthogonal to each other, resulting in high complexity of active device detection. Because only a portion of devices are active at a given time slot, active device detection is a typical sparse signal recovery problem. To solve such a problem, there are two approaches. In what follows, we briefly introduce these two approaches:

1. Compressive sensing (CS) based approaches. Active device detection is a sparse signal recovery problem that can be solved by using CS-based approaches, wherein approximate message passing (AMP) is a commonly used method for active device detection (Liu et al., 2018). AMP iteratively conducts denoising and updates the residual until the mean square error (MSE) of the desired signal is minimized. Moreover, to reduce the computational complexity of active device detection, a dimension reduction based detection algorithm was proposed in Shao et al. (2020). Specifically, the received signal was first reduced to a low-dimensional version based on its rank, and then Riemannian optimization was employed to obtain the desired signal. Generally, the CS-based approaches use the sparsity of the instantaneous received signal.

2. Covariance-based approaches. Active device detection can also be performed based on the covariance of the received signal (Chen ZL et al., 2019). Because active device detection is a 0–1 problem, it is possible to derive the likelihood function of the desired signal based on the covariance of the received signal. By maximizing the likelihood function, one can judge the state of an arbitrary device.

Because satellite IoT adopts short-packet transmission, grant-free random access must use short preambles. Note that in the context of massive connectivity, short preambles lead to poor detection performance. Hence, it is necessary to design an effective detection algorithm to improve the performance in the case of short preambles. In Fig. 3, we compare the average error rate (AER) of multiple typical CS-based detection algorithms (Shao et al., 2020). It is found that for a given AER requirement, the dimension reduction based algorithm needs a short preamble, which is appealing in satellite IoT.

Moreover, for some IoT services, if the AP does not need to know who sends the data packet and is concerned only with the information, a new unsourced random access protocol can be employed (Fengler et al., 2019). Specifically, all devices share a common codebook. The active device maps its information bits to a codeword in the codebook. Then, the AP recovers the information bits from the mixed received signal based on the same codebook. Unsourced random access avoids active device detection, and detects the transmitted signal directly. Hence, the delay can be further reduced.

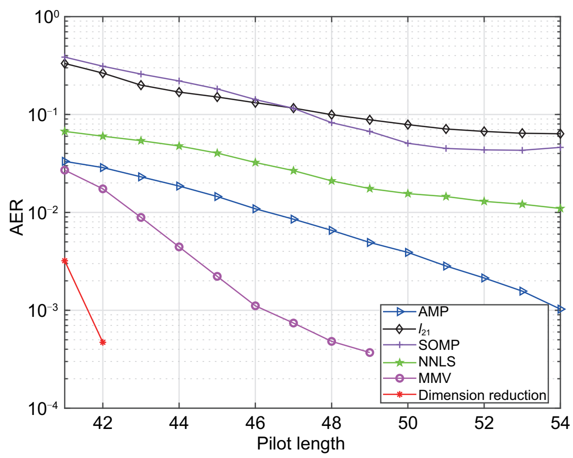

Fig. 3 Performance comparison of several typical CS-based detection algorithms (CS: compressive sensing; AER: average error rate)

4.2 Multiple access techniques

After sending the preamble for active device detection, the active devices exchange information with the APs. Due to massive connectivity, a huge number of short packets are transferred over a limited radio spectrum. Therefore, traditional multiple access techniques, e.g., multi-beam precoding techniques, are not applicable. To solve this challenging issue, we introduce two kinds of effective multiple access techniques:

1. OMA techniques (Fig. 4a). To support the transmission of a huge number of packets and enhance the quality of the received signal with low transmit power, a feasible approach is the use of a large number of narrow beams. For satellite IoT, if the LEO satellite is equipped with a large-scale antenna array, the beam can match the channel and the co-channel interference asymptotically approaches zero (You L et al., 2020). A major problem of the deployment of a large-scale antenna array at the LEO satellite is the high cost and power consumption.

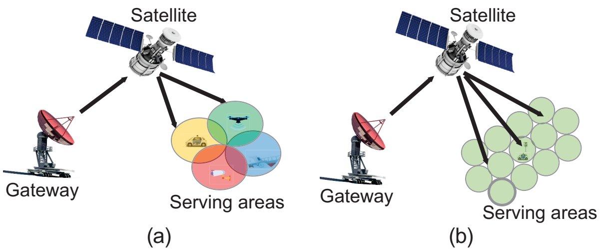

Fig. 4 Multiple access techniques: (a) orthogonal; (b) non-orthogonal

2. Non-orthogonal multiple access (NOMA) techniques (Fig. 4b). To avoid the use of a large-scale antenna array, satellite IoT can adopt NOMA techniques (Jiao et al., 2020). Specifically, a beam admits transmissions from multiple devices. NOMA results in severe co-channel interference. To solve this problem, interference mitigation schemes should be combined with NOMA. For example, precoders for the beams are designed according to the CSI related to the devices sharing the same beam. Moreover, successive interference cancellation (SIC) can be employed to further reduce the interference (Chen XM et al., 2018; Tian and Chen, 2019). However, these schemes may lead to high computational complexity.

Generally, OMA and NOMA techniques have their advantages, but also have some extra problems. Hence, one should choose multiple access techniques according to the characteristics and requirements of the satellite IoT network. Fig. 5 compares the performance of the OMA technique and NOMA technique in satellite IoT. We choose FDMA as a typical OMA technique. It is found that for a given required minimum signal-to-interference-plus-noise (SINR) requirement, NOMA consumes much less total transmit power than FDMA, which is quite appealing for satellite IoT. However, NOMA has a higher implementation complexity than FDMA.

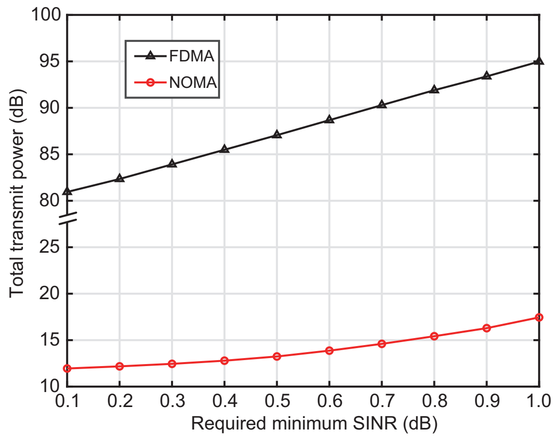

Fig. 5 Performance comparison of orthogonal frequency division multiple access (FDMA) and non-orthogonal multiple access (NOMA) techniques (SINR: signal-to-interference-plus-noise)

5 Development trends of satellite IoT

The research on satellite IoT has just begun, and many critical issues have not been well addressed. Currently, satellite IoT is a simple network that cannot fully satisfy the requirements of IoT services. Academia and industry in multiple countries are developing satellite IoT, which means fast development of satellite IoT. In this section, we list some development trends in satellite IoT.

5.1 Satellite-territorial integrated IoT

So far, there have been many IoT networks, especially low-power wide-area networks (LPWANs). In space, we have satellite IoT. On the ground, we have 5G narrowband IoT (NB-IoT). These IoT networks have their respective advantages. Satellite IoT can provide wide coverage at low cost, while 5G NB-IoT can support massive connectivity with performance guarantees. Traditionally, these two IoT networks provide services in different areas, i.e., satellite IoT in urban and rural areas and satellite IoT in remote areas such as forests, oceans, mountains, and deserts. By combining these two IoT networks, the integrated IoT network is capable of providing seamless coverage across the world, and thus realizes the goal of IoE (Kuang et al., 2018).

5.2 Multi-LEO satellite cooperation

A challenging issue of satellite IoT is the high mobility of LEO satellites, resulting in performance degradation and frequent handoff. A possible solution is the cooperation among multiple adjacent LEO satellites. On one hand, multi-LEO satellite cooperation can improve the performance by using multi-point cooperative transmission techniques. On the other hand, multi-LEO satellite cooperation can conduct soft handoff, and thus avoids service interruption. To realize effective multi-LEO satellite cooperation, corresponding cooperation protocols and techniques must be designed.

5.3 Joint LEO and GEO satellite access

Currently, satellite IoT takes LEO satellites as APs and GEO satellites as nodes of core networks. LEO and GEO satellites have respective advantages and disadvantages. LEO satellites have low transmission delay but move fast. GEO satellites remain static with respect to the Earth but have high transmission delay. In fact, LEO satellites also can be used as APs. This is because some IoT services are delay-insensitive, but have stringent reliability requirements. Thereby, joint LEO and GEO satellite access is a development trend of next-generation satellite IoT.

5.4 Convergence of satellite IoT and deep-space communication networks

In recent years, the international community began a new round of deep-space exploration, e.g., lunar and Mars explorations. To realize effective deep-space exploration, several big powers have constructed deep-space communication networks, which build transmission links between the exploration rover and the Earth stations via the relay of multiple satellites. In the future, exploration bases will be built on the moon and Mars. Hence, there is a large transmission requirement that the current deep-space communication network cannot fulfill. If satellite IoT and deep-space communication networks are combined, it is possible to build a high-throughput space network, which further broadens the coverage of satellite IoT from the Earth to the space.

6 Conclusions

We presented a review of satellite IoT, focusing on radio interface techniques. First, we provided an introduction to satellite IoT networks, with an emphasis on the characteristics of IoT services, including massive packets, sporadic traffic, small data, and heterogeneous requirements. Then we analyzed various challenging issues in the design of satellite IoT, i.e., massive connectivity, wide coverage, high mobility, low power, and stringent delay. We also presented an example of the design of satellite IoT from access protocols to access techniques, and showed the performance through numerical simulations. Finally, some development trends of satellite IoT were discussed.

Contributors

Xiaoming CHEN performed the simulations and drafted the paper. Zhaobin XU and Lin SHANG helped organize the paper. Xiaoming CHEN, Zhaobin XU, and Lin SHANG revised and finalized the paper.

Compliance with ethics guidelines

Xiaoming CHEN is a corresponding expert of *Frontiers of Information Technology & Electronic Engineering*. Xiaoming CHEN, Zhaobin XU, and Lin SHANG declare that they have no conflict of interest.

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