A review on non-terrestrial wireless technologies for Smart City Internet of Things

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Abstract
Smart City Internet of Things will become a fundamental infrastructure to support massive machine-type communications between the widely deployed sensors serving big cities. Since there exists many location constraints for the existing terrestrial Internet of Things, the non-terrestrial Internet of Things sheds light on breaking these limits. Therefore, this article conducts a comprehensive survey on non-terrestrial Internet of Things technologies for Smart City, which is an important complement to terrestrial Internet of Things. We first present the application scenarios of Internet of Things and point out where the existing terrestrial Internet of Things cannot work perfectly. Two non-terrestrial Internet of Things technical proposals are then introduced, namely satellite Internet of Things and unmanned aerial vehicle Internet of Things. However, the focuses of these non-terrestrial Internet of Things are distinct, that is, the major problems of satellite and unmanned aerial vehicle Internet of Things are the high dynamic nature of channel and high maneuverability of unmanned aerial vehicles, respectively. The key technologies for satellite and unmanned aerial vehicle Internet of Things are then reviewed separately. Both physical and non-physical layer technologies are surveyed for satellite Internet of Things, and the route planning is mainly investigated for the unmanned aerial vehicle Internet of Things. Finally, we draw a conclusion and give some potential research directions of non-terrestrial Internet of Things.

Keywords
Internet of Things, Smart City, non-terrestrial, satellite, unmanned aerial vehicle

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Introduction
With the digital transformation of traditional economy, Internet of Things (IoT), as a new generation of communication infrastructure, is the key enabling factor of ubiquitous connectivity. It realizes ubiquitous social services, builds a beautiful vision of a Smart City, and creates a brand new network environment for human development and civilization evolution through ubiquitous access and information sharing. By 2025, IoT applications are projected to grow dramatically, reaching 27 billion connections worldwide. Therefore, as an IoT application scenario, Smart City is bound to become the direction of future urban development. The deployment of Smart City in large cities will eliminate the information islands and information chimneys.

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Wireless communication technology is the core technology of enabling IoT. As a summary of existing technologies, Table 1 summarizes the current research directions of IoT, which mainly focuses on the standards, security, scenarios, protocols, data computing, and other aspects of terrestrial IoT, and the research has been very extensive. However, with the emergence of some new type of business for the IoT, such as hydrological monitoring and environmental protection, terrestrial wireless communication has been unable to meet requirements. Therefore, new ideas are urgently needed to supplement the deficiency of terrestrial wireless communication. The wide coverage and low cost of non-terrestrial wireless communications complement terrestrial wireless communications. However, there is little research literature on non-territorial IoT.

Different from existing literature, this article starts with the IoT-oriented application scenarios, and leads to non-territorial IoT for scenarios that are not suitable for territorial IoT deployment. Then, we conducted an extensive survey, as given in sections “Physical layer technologies of satellite IoT,” “Non-physical layer technologies of satellite IoT,” and “Communication technologies of UAV IoT,” by dividing the non-territorial IoT into satellite IoT and UAV IoT. Finally, this article summarizes the whole article and looks forward to the possible future development directions. Figure 1 illustrates the broad outline of this review.

**Overview on Internet of Things**

IoT is primarily for device-to-device (D2D) communication. Different from cellular communication, IoT requires a lower transmission rate, a higher number of device connections, and requires low-power transmission due to limited power of the terminal device. In general, IoT application scenarios can be divided into two parts in Smart City: (1) small range and short-distance transmission scenarios, (2) large range and long-distance transmission scenarios. For the terminals in the first scenario, they are usually covered by local area network (LAN), such as WiFi, ZigBee, and so on. The terminals in the latter scenario are covered by low-power wide-area network (LPWAN). Typical applications of these scenarios are shown in Table 2.

IoT technologies for different scenarios have different characteristics. Figure 2 illustrates the relationship between coverage and throughput for different technologies. Figure 3 shows the relationship between coverage and equipment life for LAN and LPWAN. As can be seen from these two figures, LPWAN has low throughput but long terminal battery life, and LAN requires higher throughput and does not require strict power dissipation limits. Since this article focuses on Smart City, LPWAN is the key point.

![Figure 1. The outline of this article.](image-url)

IoT: Internet of Things; UAV: unmanned aerial vehicle.

![Figure 2. The relationship between coverage and throughput for different technologies.](image-url)

IoT: Internet of Things; UAV: unmanned aerial vehicle.

![Figure 3. The relationship between coverage and equipment life for LAN and LPWAN.](image-url)

LAN: local area network; LPWAN: low-power wide-area network.

**Table 1. Summary of existing surveys about IoT.**

| Classification          | Direction                                      |
|-------------------------|------------------------------------------------|
| Territorial IoT         | Standard$^1$, Overview$^2,3$, Security$^4,6$, Data collection$^7,9$, Scenarios$^{10,12}$, Protocols$^{13,14}$, Data calculation$^{15,17}$, Integrating with 5G$^{18}$ |
| Non-territorial IoT     | UAV$^{19}$, Satellite$^{20}$                   |

IoT: Internet of Things; UAV: unmanned aerial vehicle.

**Table 2. Typical applications of scenarios.**

| Scenarios                               | Typical application                       | Appropriate technology |
|-----------------------------------------|-------------------------------------------|------------------------|
| Small range and short-distance transmission | Smart Home, E-health                    | LAN                    |
| Wide range and long-distance transmission | Smart City, smart grid, disaster warning | LPWAN                  |

LAN: local area network; LPWAN: low-power wide-area network.
Table 3. Technical indicators of LPWAN.

| Feature            | LoRa       | NB-IoT (R13 +) | LTE-M (R13) |
|--------------------|------------|----------------|-------------|
| Modulation         | Chirp SS   | OFDMA          | OFDMA       |
| Rx bandwidth       | 500–125 KHz| 200 KHz        | 20–1.4 MHz  |
| Max output power   | 20 dBm     | 20 dBm         | 23/30 dBm   |
| Data rate          | 290 bps to 50 Kbps | ~ 20 Kbps       | 200 Kbps to 1 Mbps |
| Link budget        | 154 dB     | 150 dB         | 146 dB      |
| Power efficiency   | No.1       | No.2           | No.3        |

LPWAN: low-power wide-area network; OFDMA: orthogonal frequency-division multiple access; LoRa: long range; SS: spread spectrum; NB: narrowband; LTE-M: long-term evolution for machines.

Table 4. Subdivided scenes of LPWAN.

| Scenarios                                      | Application               |
|-----------------------------------------------|---------------------------|
| Small number of terminals and large-scale distribution | Tsunami warning, Landslide warning |
| Small number of terminals and small range distribution | Military application |
| Large number of terminals and large-scale distribution | Warehousing, dock |
| Large number of terminals and small range distribution | Gas, water |

Figure 2. Relationship between coverage and throughput.
LAN: local area network; LPWAN: low-power wide-area network.

Figure 3. Relationship between coverage and life duration.
LAN: local area network; LPWAN: low-power wide-area network.

Table 3 shows the relevant typical technologies and important indicators contained in LPWAN.

The application scenario of LPWAN can be divided into four parts, as shown in Table 4. To cover a wide range of scenario with a small number of terminals in some big mountain cities, considering the relatively limited coverage of the terrestrial base station, the complex geographical conditions, and the limited and dispersed equipment, the base station is not only difficult to implement, but also can only access fewer IoT equipment, which makes the construction and communication costs surge. Significant contrast with the terrestrial wireless communications, the non-terrestrial wireless communications has unique advantages, as follows:

- Wide coverage, which can realize global coverage, and sensor laying is not limited by space;
- Not affected by extreme terrain;
- Strong destruction resistance of the system.

These advantages totally fit into the scenario of large coverage and few terminals. In General, non-terrestrial IoT communication platforms can be considered to include satellite platforms and UAV platforms. However, the characteristics of satellite IoT and UAV IoT are different, and so are the technical requirements. Therefore, we will study these two technical approaches separately in the following article.

Satellite IoT

Since the features of satellite orbit make different kinds of satellites having different characteristics, it is very important to choose the right kind of satellites to meet the needs of IoT. The geostationary Earth orbit (GEO) satellite is stationary to the Earth and can provide continuous service to an area. However, it is in a higher orbit resulting in large round-trip delay and signal attenuation. In contrast to GEO, The low Earth orbit (LEO) satellite moves relative to the Earth, has a lower orbit, lower signal delay, and relatively small signal attenuation.
Due to the low cost and small size of terrestrial terminals facing Smart City, compared with GEO satellites, LEO satellites have less signal attenuation and are easier to meet the characteristics of terrestrial terminals. Therefore, there is more extensive research on the LEO satellite IoT. On the other hand, GEO satellites have the advantage of ensuring continuous service within designated coverage and providing global access beyond the polar regions with just three satellites.

However, to meet IoT requirements, satellite IoT still faces many problems:

- As IoT requires a large number of terminal access systems, wireless access technologies that avoid/tolerate collisions are required;
- Low power consumption and high energy efficiency design;
- Designed for coping with large dynamic channels;
- Deal with the scarcity of spectrum;
- Design the antenna required by satellite IoT;
- Satellite IoT protocols, standards, and so on.

Oriented by requirements, the following sections describe technologies of satellite IoT in two parts: physical and non-physical, with an emphasis on technologies of physical layer.

**UAV IoT**

UAVs are highly maneuverable. Therefore, the flexible layout and mobility of UAVs are the most important features of UAV IoT. However, there are still many problems to overcome:

- Flexible UAV deployment to achieve efficient coverage and data collection;
- Low power consumption design;
- Coping with data collision;
- Design for dynamic channel characteristics such as Doppler frequency shift;
- Others: such as throughput optimization, low delay design, and so on.

In the section “Communication technologies of UAV IoT,” we focus on the flexible deployment of UAVs and summarize the technical status quo of UAV IoT oriented by requirements.

### Physical layer technologies of satellite IoT

A typical satellite IoT system model is shown in Figure 4. The terrestrial IoT device first uploads data to a satellite relay, which then sends the data to a terrestrial data processing center for unified processing. Based on this typical system model, this article summarizes the current research achievements on physical layer of the satellite IoT in Table 5 according to the technical requirements mentioned in the previous section. These technologies of physical layer mainly focus on modulation, multiple access, channel coding, frame structure design, resource scheduling, spectrum, and so on, which are subsequently described in the sections “Physical layer technologies of satellite IoT” and “Non-physical layer technologies of satellite IoT” later.

#### Wireless access technologies

To deal with the large number of terrestrial terminals access to satellites, related scholars put forward a variety of access technologies to avoid or tolerate collisions. For IoT based on GEO satellite, Hofmann et al.21
proposed a new chirp-spread spectrum (CSS)-based modulation and signaling scheme. Unipolar codes are used in the proposed transport structures in a new way, which allows a large number of devices to access a common channel randomly.

Non-orthogonal multiple access (NOMA) is an important means of terrestrial wireless access and a hotspot of 5G/6G research and standardization. Furthermore, in IoT access for integrated air-ground network, it is still a key research direction. Ding et al. proposed a multiple input multiple output (MIMO)-NOMA scheme for IoT, which uses precoding to make one user strictly meet the service quality, and the other user gets the services through NOMA opportunistically. Hu et al. proposed constellation coding for multiuser reuse, which improves spectral efficiency and the number of users’ access by transmitting multiple users signals simultaneously on the same frequency band. Specifically, Hu et al. first give each user a specific number and corresponding constellation, and then they map each combination of user constellation points to a higher-order constellation point, and the schematic diagram is shown in Figure 5. At the receiver, after the user detects the high-order modulation signal, each user applies the corresponding constellation decoding to get its own signal.

Random access technology is a kind of multiple access technology based on competition. Multiple users can occupy channel resources in a competitive way without signaling scheduling, which is an access method suitable for the IoT. ALOHA is the first random-access technology proposed by Abramson, which has the problem of low channel utilization. Later, Roberts introduced the concept of “time slot” based on ALOHA and proposed the slotted ALOHA, which reduced the collision probability of packets. On the basis of slotted ALOHA, researchers in recent years have studied the repeated transmission of packets to find the optimal balance between packet collision and reliability. They introduced the idea of time/frequency diversity and interference cancelation, and proposed diversity slotted ALOHA (DSA), resolution DSA (RDSA), and so on. Irregular repetition slotted ALOHA (IRSA) improved RDSA to further increase throughput. In addition, asynchronous contention resolution diversity slotted ALOHA (ACRDSA), spread slotted ALOHA (SSA), and coded slotted ALOHA (CSA) is also an improved scheme based on ALOHA. ACRDSA overcomes the disadvantage of multi-terminal synchronization based on CRDSA. SSA introduces spread spectrum technology in slotted-ALOHA; CSA introduces the combination of packet erasure correcting codes and successive interference cancelation (SIC) into slotted ALOHA. Irregular repetition spatially coupled slotted ALOHA (IRSC-SA) introduces the concept of spatial coupling in slotted ALOHA and applies a new density evolution (DE) method to address the unequal protection of different users. Subsequently, R-CSA further improved CSA to cope with the ALOHA collision problem in the multi-receiver satellite IoT. Bai and Ren proposed a new adaptive packet-length assisted slotted ALOHA scheme to cope with the large dynamic satellite channel environment. Ren’s team introduced the ideas of non-orthogonal multi-access and polarized transport into slotted ALOHA, and proposed two random-access methods, namely non-orthogonal slotted ALOHA (NOSA) and polarized MIMO slotted ALOHA (PMSA), to achieve higher throughput. Zhao et al. proposed a random-access method called random mode multiplexing, which implements multi-user random mode access by mapping packets to a resource block (RB) composed of multiple resource elements (REs). Herrero and De Gaudenzi proposed a multi-access scheme to provide machine-to-machine (M2M) communication services for a large number of low-cost satellite-borne terminals, which improved the spectrum efficiency in the case of power imbalance. Zhao et al. proposed a cooperative random-access scheme for multiple satellites. By using a packet structure based on single-carrier interleave frequency division multiple access (SC-IFDMA), the influence of user transmission delay on received signals of satellite nodes was overcome and the synchronization of received signals was ensured. Zhen et al. proposed an enhanced spatial group-based random-access scheme from the perspective of preamble design to accommodate massive and concurrent M2M random access requests and ensure human-to-human communication, which significantly reduces the collision probability. Time/frequency ALOHA, a random-access scheme suitable for ultra narrow band (UNB), is introduced by Anteur et al. Due to the large number of devices in IoT, an overloaded random-access channel (RACH) may cause a service outage. Therefore, based on the background of satellite IoT system, Chelle et al. proposed a dynamic calculation method of load.
control parameters based on access class barring (ACB). In the article by Gan et al., the performance of an uncoordinated code domain NOMA protocol as shown in Figure 6 is discussed to solve the pilot collision of massive machine type communications (mMTC) in space information network (SIN). In addition, SIC and successive joint decoding (SJD) were used to recover collision information under the satellite and ground channel model of shadow fading and path loss. Due to the characteristics of non-terrestrial IoT business, signaling interaction is reduced and grant-free transmission is required. To solve the collision problem caused by grant-free transmission, a rate-adaptive multiple access (RAMA) scheme was proposed.

Aiming at the problem that a large number of territorial IoT terminals upload data that may easily lead to data collision, Kawamoto et al. divided IoT terminals into groups and allocated satellite bandwidth control access in a divide and conquer manner. In the article by Cluzel et al., an abstract estimation method of bit error rate (BER) and packet error rate (PER) using physical layer is studied under a time-frequency random scheme.

**High efficacy**

Based on the modified Zadoff-Chu sequence, Doré and Berg proposed an efficient channel synchronization frame structure, which has low-level peak-to-average power ratio (PAPR) and is suitable for large levels Doppler.

It is worth noting that the power resources and storage resources of the satellite are limited, inefficient resource allocation may lead to interruption events, and the limited storage resources may overflow. For the communication between satellite and ground station, a low-cost source coding scheme is needed to compress the image information efficiently. Distributed source coding of hyperspectral images based on low-complexity discrete cosine transform (DCT) can effectively reduce the complexity of the coding side and is suitable for on-star signal processing. In the article by Sun et al., the authors first established a long-term joint power distribution and rate control scheme for satellite IoT NOMA downlink system. The optimal SIC decoding sequence is difficult to express because queue states and channel states constantly change from one slot to another. Therefore, deep-learning-based long-term power allocation (DL-PA) is adopted to approximate SIC decoding order by training a large amount of data. The framework of the DL-PA scheme is shown in Figure 7, where $Q_i(t)$ represents the queue backlog status of UE; $g_i(t)$ at slot $t$, $s_i(t)$ at time slot $t$, and $p_i(t)$ represents the transmit power allocated to UE at time slot $t$.

**Large dynamic channel**

Regarding the Doppler effect, since LoRa has not established relevant standards for the Doppler effect of fast-moving satellite communications, Doroshkin et al. discussed the feasibility of LoRa modulation in CubeSat radio communication systems. Since chirp signal has good anti-Doppler shift performance, Qian et al. studied the application of LoRa technology in LEO satellite, placing emphasis on CSS modulation and introduced symmetry CSS (SCSS) into LEO satellite IoT. Asymmetric chirp signal (ACS) is therefore more applicable to LEO satellite IoT. Similarly, Qian et al. proposed ACS. Compared with symmetric chirp
signal (SCS), ACS has better auto-correlation and better cross-relation in time domain and frequency domain. Yang et al. proposed a folded chirp-rate shift keying (FCrSK) modulation technique, which has a strong ability to resist Doppler shift. Compared with traditional chirp-rate shift keying, its bandwidth and symbol length are consistent among chirp-rate.

Since the traditional fixed rate coding is difficult to satisfy the communication service of high-speed moving objects, the rateless coding can solve this problem to some extent. Spinal codes are a kind of rateless codes, which first converts message bits into pseudo-random sequences using a hash function and maps them to dense constellation points for transmission. The coding process of spinal codes is shown in Figure 8, where $M_i(t)$ represents a message block, $h$ is a random hash function, and $s_j$ represents a v-bit state.

Based on the NB-IoT standard of 3GPP, Sylvain Cluzel et al. designed a kind of IoT for LEO satellite, and proposed a set of detection algorithms for Doppler shift. Similarly, Colavolpe et al. mainly studied LoRa waveform characteristics and signal detection for LEO satellite IoT application. Then, Colavolpe et al. proposed a new receiver structure that exploits interference cancelation to deal with the Doppler shift.

NB-IoT was used to enable LEO satellite IoT. In this system, Kodheli et al. found the problem of high differential Doppler between different user channels. Aiming at this problem, Kodheli et al. put forward a resource allocation scheme. In addition, Kodheli et al. proposed an uplink scheduling technique to keep differential Doppler within NB-IoT acceptable limits.

**Figure 8. Encoding process of spinal codes.**

High efficacy

As the current IoT protocol is not suitable for LEO satellite IoT, Wang et al. introduced the millimeter-wave (mm-Wave) frequency band. Combined with the massive MIMO assisted by beamforming, Wang et al. proposed an effective adaptive random-selected multi-beamforming (ARM) estimation scheme. For hybrid satellite-terrestrial relay network (HSTRN), X Liang et al. analyzed the system performance of mm-Wave, and further studied the influence of rainfall on mm-Wave communication under non-line-of-sight conditions. In view of the common channel interference between systems caused by the spectrum sharing of terrestrial IoT and non-terrestrial IoT, Xu et al. analyzed various situations of common channel interference.

**Other enabling technologies**

Sanil et al. studied and discussed the use of satellite facilities in C-band and X-band in IoT, and designed a multi-band microstrip antenna with three different frequencies in C-band and X-band. In order to respond flexibly to traffic demand, Takahashi et al. used beamforming technology to allocate power resources, and introduced a new power resource allocation method based on transmit power and multi-beam directivity fusion control. Jin et al. analyzed the special application scenarios and traffic distribution characteristics of LEO satellite IoT, and then proposed a traffic simulation method based on LEO satellite IoT. To solve the satellite downlink replanning problem, Song et al. proposed a combination method based on improved genetic algorithm, and took advantage of back propagation (BP) neural network to optimize the initial population of genetic algorithm. In addition, Roy et al. proposed a symmetric chirp signal for LEO satellites, namely symmetric chirp with multi-chirp rate (SC-MCR), which improved the cross-correlation level of SC waveform and achieves better anti-interference performance than symmetric chirp (SC) signals. In addition, time domain multiplexing (SC-MCR) waveform is designed to improve the transmission rate.

**Non-physical layer technologies of satellite IoT**

This section summarizes the contribution of network protocol, MAC layer protocols, network architecture, and satellite constellation model to technical requirements of satellite IoT.
data from IoT gateways via LEO satellites using an energy-saving method under time-varying uplink. In LoRa-based satellite IoT, Qian et al.\textsuperscript{71} made a critical study on how to capture SCS, and proposed a new SCS acquisition method that can balance complexity and performance.

**Network architecture**

From the perspective of network architecture, considering the future development direction of satellite network, IoT network and mobile network, Wei-Che Chien et al.\textsuperscript{72} proposed a potential heterogeneous space and terrestrial integrated network (H-STIN) architecture for the purpose of integrating various system architectures and different wireless communication protocols. To achieve a satellite-ground integrated network, network function virtualization (NFV) and software defined network (SDN) can be used to improve the capacity of wireless communication systems.\textsuperscript{73} To cope with the problem of unbalanced traffic demand and frequent link congestion of satellite IoT, Z Liu et al.\textsuperscript{74} proposed a routing scheme for low-earth orbit satellite network, aiming to maintain global and local load balance and optimize the data transmission of IoT. To reduce the connection delay of nanosatellite constellation, Marcano and Jacobsen\textsuperscript{75} studied random linear-network coding (RLNC) and proposed an RLNC transmission scheme. Chelle et al.\textsuperscript{76} analyzed M2M communication extensively from the perspective of satellite, and defined a new traffic modeling for M2M communication from the perspective of the satellite.

**Other enabling technologies**

The European Space Agency considered the constrained limited application protocol (CoAP) as the IoT application protocol suitable for collecting IoT data through satellites in machine-type communication satellite networks. Therefore, Soua et al.\textsuperscript{77} studied the effective configuration of CoAP, and put forward the relevant optimal design according to the characteristics of satellite link. Similarly, Bacco et al.\textsuperscript{78} compared two common protocol stacks, CoAP and MQTT, based on the DVB-RCS2 standard. Based on the satellite VHF data exchange system (S-VDES) MAC protocol, the detection probability of ships was analyzed and derived from the Satellite VDES by Wong et al.\textsuperscript{79} Furthermore, this team also proposed an asynchronous multichannel pure collective ALOHA MAC protocol based on a decollision algorithm (MC-CA-SA).\textsuperscript{80} In order to improve energy efficiency and reduce the network delay, Wang et al.\textsuperscript{81} proposed a joint TDMA MAC protocol (SL-MAC) applicable to LEO satellite IoT. Bacco et al.\textsuperscript{82} analyzed the main problems hindering M2M interconnection, and proposed a M2M/IoT communication protocol stack based on oneM2M standard.

**Communication technologies of UAV IoT**

UAVs are now widely used in many scenarios as low-altitude platforms. However, as a low-altitude communication platform, UAV is different from traditional terrestrial communication, such as high dynamic channel environment and severe non-stationarity.\textsuperscript{83} In view of the technical requirements faced by UAV IoT, this article makes a list of related technologies as shown in Table 6.

| Requirements                                | References |
|---------------------------------------------|------------|
| Flexible deployment                         | 84–96      |
| Low power consumption design                | 97–105     |
| Data collision elimination                  | 106–110    |
| Large dynamic channel                       | 111–116    |
| Other enabling technologies                 | 117–119,133|
| M2M interconnection, and proposed a M2M/IoT communication protocol stack based on oneM2M standard. |

**Flexible deployment and route planning**

Due to the high maneuverability of UAV, trajectory planning is an important optimization point for UAV to achieve air-to-ground communication. For wireless sensor network scenario, as in the article by Yang and Yoo,\textsuperscript{84} UAV first obtains data collection points from the whole sensor network and then uses the proposed joint genetic algorithm and ant colony optimization algorithm to determine the best route between adjacent collection points. For the task of selecting an appropriate UAV for a specific IoT task, Motlagh et al.\textsuperscript{85} designed two solutions based on the standard of optimal energy consumption, called energy-aware selection (EAS) of UAVs and delay-aware selection (DAS) of UAVs. Similarly, Mozaffari et al.\textsuperscript{86} mainly considered saving energy for IoT devices and realizing reliable uplink communication. Therefore, a new method for optimal mobility of UAV is proposed, which reduces the total transmission power by 56%. In terms of system construction, according to the limited energy characteristics of UAVs, Liu et al.\textsuperscript{87} established a multi-hop D2D link in Figure 9 to extend the coverage. Lyu and Zhang\textsuperscript{88} attempted to realize UAVs’ uplink and downlink communication in three-dimensional (3D) space by using cellular networks. Therefore, a new 3D system model for UAVs is constructed, and a framework for
analyzing UAVs’ uplink/downlink 3D coverage performance is proposed. Shi et al. proposed a 3D UAV trajectory design idea: multiple DC periodically fly over the IoT devices and forward the data of the IoT to base stations (BSs). Compared with static UAV deployment, the proposed scheme reduces the average road loss by 10–15 dB. Qi et al. developed a 5G IoT network based on the imagination of future Smart City. The article particularly emphasized the UAV enabling the IoT in the air to achieve 3D connectivity and connected the whole world through heterogeneous intelligent devices. Technically, a layered multi-UAV architecture for team coordination and trajectory tracking is proposed. In order to integrate different UAVs into 5G network, Huo et al. proposed a multi-layer and distributed UAVs hierarchical structure. Jiang et al. focused on cache-enabled UAVs. In order to meet the requirements of multimedia data transmission scenario on system throughput, a collaborative IoT network structure assisted by cache-enabled UAV was proposed. Ye et al. studied the UAV-assisted full duplex wireless IoT network under the scenario of sparse sensor distribution, in which UAV is equipped with full-duplex hybrid access point (HAP). It is assumed that the signals sent by UAV can only be received by neighboring sensors. Therefore, the Ye et al. proposed a new UAV-assisted IoT network line model to optimize system throughput. The model structure is shown in Figure 10. The model shows a dynamic time division multiple access (TDMA) frame structure, which means that each sensor can only transmit information in its allocated time slot thereby avoiding interference from other sensors. Abouzaid et al. proposed an analysis model of the UAV flying mesh network, which works cooperatively in multi-hop mode to provide connectivity, data acquisition and forwarding for the terminal system, balancing end-to-end throughput, and stability. Liu et al. proposed a system model for UAV-enabled wireless sensor network data acquisition. In order to maximize the uplink decoding success ratio and minimize the flight time of UAV, Farajzadeh et al. adopted the power domain NOMA in the uplink, and proposed an optimization framework to determine the trade-off between numerous network parameters.

**Low power consumption design**

Al-Turjman et al. took UAV as the aerial base station in a specific dangerous area to enable 5G network. By optimizing the number and location of UAV, higher energy efficiency can be achieved when considering data rate, delay, throughput, and other parameters. Considering the low cost and long service life of IoT devices, battery-free sensing devices based on scattering communication are a possible choice. From the perspective of the system framework, a new framework was proposed by Mozaffari et al. for the joint optimization of UAVs, device–UAV association, and uplink power control, which enables the uplink reliable transmission of IoT devices with the minimum comprehensive transmission power. In the case of multi-user overlay transmission, the mutual interference is reduced and the receiving performance is improved by designing multi-user constellation map under the simple serial interference elimination technology. Du et al. studied a kind of UAV as a marginal cloud to minimize UAV energy by optimizing UAV’s hovering time, scheduling, and resource allocation. Feng et al. adopted multi-antenna UAV and multi-antenna IoT device cluster communication to form virtual MIMO link. The transmission duration and transmission power of all devices in the system are designed jointly, which greatly improves the efficiency of data acquisition of the whole flight. Considering the energy consumption and operation time of UAVs to ensure the efficient operation of value-added IoT services (VAIoTSs), Motlagh et al. proposed three complementary solutions, namely energy-sensing UAV selection (EAUS), delay sensing UAV selection (DAUS) and fair weighing UAV selection (FTUS). Zhan and Lai studied the data collection of IoT system enabled by UAV with limited energy. In order to meet the energy budget of UAV, Zhan and Lai focused on the energy of mobile propulsion system of UAV, and introduced the energy propulsion model of UAV to minimize the maximum energy consumption of all IoT devices. Aiming at the requirement of efficient data collection in dense wireless sensor networks, Ebrahimi et al. proposed a projection-based compressive data gathering (CDG) method. This method aggregates data on selected projection nodes, reducing the number of data-required transmissions.
consequently, reducing energy consumption and extending network life.

Collision resolution design

The access of a large number of IoT devices in the region leads to a large amount of data traffic, and the spectrum is also very crowded, which makes data collisions occur from time to time. Almasoud and Kamal\textsuperscript{106} studied cognitive UAV for data transmission, and data collision is effectively avoided by using spectrum sensing technology. Introducing controllable interference between multiple users to realize the increase of the number of access users is the core idea of NOMA technology.\textsuperscript{107} Therefore, the application of NOMA technology in UAV IoT is a feasible solution to deal with multi-user collision. Liu et al.\textsuperscript{108} used the characteristics of tolerating data collision of power domain NOMA (PD-NOMA), introducing PD-NOMA into UAV-assisted heterogeneous IoT emergency communication, so that air-to-ground (A2G) and ground-to-ground (G2G) communication are compatible in the same spectrum, which solved the data collision problem and further proposed a distributed SIC-free NOMA (DSF-NOMA) solution. Also using the power domain NOMA, buffering-aided (BA) relay selection was applied to the uplink of NOMA network where both user and device exist by Nomikos et al.\textsuperscript{109} and a relay selection strategy based on dynamic decoding sequence was proposed, namely flex-NOMA. This strategy avoided the need for transmitter channel state information (CSI) and reduced the probability of packet collision and delay. In addition, Duan et al.\textsuperscript{110} combined UAV and NOMA to build a high-capacity uplink transmission system that can tolerate collisions. By jointly optimizing UAV flight height, transmission power and sub-channel allocation, the system capacity is maximized.

Large dynamic channel

Xu et al.\textsuperscript{111} introduced coherent/incoherent spatial modulation (SM) and space-time block coding using index shift keying (STBC-ISK) to deal with Doppler correspondence, where coherent SM and coherent STBC-ISK structure diagrams are shown in Figure 11. In the complex channel environment, NOMA can be used to optimize access efficiency, reduce mutual interference, and improve transmission robustness.\textsuperscript{112} In terms of channel modeling, with the introduction of von-mises-fisher (VMF) scattering distribution, a new 3D MIMO channel model was proposed by Bi et al.\textsuperscript{113} Simulation results have shown that the model can accurately evaluate A2G UAV channel. Ding and Xiu\textsuperscript{114} proposed a scheme called block turbo-coded orthogonal frequency-division multiplexing (OFDM) for high-speed UAV data link, which combines block turbo codes (BTCs) with OFDM. The traditional channel
coding relies on the estimation of CSI and the active bit rate selection, which cannot adapt to the rapidly changing channel conditions. Rateless codes can achieve almost optimal bit rates under rapidly changing channel conditions without CSI estimation and explicit rate selection. Zhang and Hranilovic\textsuperscript{115} and Pang et al.\textsuperscript{116} studied the applications of rateless raptor codes and spinal codes in UAV IoT, respectively. In addition, polar codes are also a promising channel-encoding method for higher throughput performance in UAV IoT systems.\textsuperscript{117}

**Other enabling technologies**

In this subsection, the content is divided into four parts: low-latency design, joint optimization, data acquisition technology, and other technologies, which will be explained in turn below.

For the UAV cluster-service scenario, a UAV management system needs to be designed due to the system’s demand for real-time data delivery. Choi et al.\textsuperscript{118} designed a procedure that can realize real-time data transmission for oneM2M message flow. Aiming at the challenge posed by the high time-sensitive business of UAV IoT to effective routing, Zhang et al.\textsuperscript{119} proposed a layered UAV swarm network structure and designed a low-latency routing algorithm (LLRA) based on partial location information and network structural connectivity. Considering the ultra-low latency requirements of the tactile IoT, grant-free NOMA is a feasible solution that can take advantage of its non-orthogonal and unlicensed transmission to achieve low-latency access.\textsuperscript{120}

Based on the reinforced barriers and collision avoidance characteristics of the heterogeneous UAV, Kim and Ben-Othman\textsuperscript{121} conducted joint optimization of the UAV’s flight path without collision. Aiming at the problem that dense network signaling interactions may cause aggregation interference to terminal nodes, Ji et al.\textsuperscript{122} proposed a joint optimization scheme that can effectively improve system throughput, interrupt probability and lawlessness by considering such parameters as transmission power, scaling factor, and UAV relay selection. To ensure timely delivery of information, Abd-Elmagid and Dhillon\textsuperscript{123} constructed an optimization problem that takes into account UAV’s flight trajectory, energy allocation, and service time allocation for packet transmission, then proposed an effective iterative algorithm. Spectrum sharing in heterogeneous networks leads to cross-layer interference, which makes the power association problem in three-layer networks of satellite, UAV and macro-cellular become a key problem. A two-stage joint hovering altitude and power control scheme was proposed by Wang et al., which effectively improved the system throughput. In the UAV-assisted IoT communication system, Wang et al.\textsuperscript{125} maximized the sum rate by jointly optimizing UAV altitude, user equipment uplink transmission power, and user equipment–UAV scheduling.

Chakareski\textsuperscript{126} investigated the immersive data acquisition technology under the remote virtual reality scene based on UAV IoT, and designed the scalable source channel viewpoint coding, so as to maximize the reconstruction fidelity of the data captured at each UAV position at the ground convergence point. To realize accurate and efficient data sampling and reconstruction, Yu et al.\textsuperscript{127} proposed a spatial data sampling scheme of UAV using a denoising autoencoder (DAE) neural network. Autoencoder (AE) is a neural network model for feature extraction, which has the ability to process nonlinear data. DAE evolved from basic AE, which can extract features from corrupted data and reconstruct the original data. The structure of DAE is shown in Figure 12, where $x$ represents original data, $\tilde{x} = q_D(x)$ represents the data corrupted by $x$, $q_D$ is corruption function. As shown in Figure 12, $y = f_0(\tilde{x})$ is coded data from $\tilde{x}$, $z = g_p(y)$ represents decoded data form $y$. Qin et al.\textsuperscript{128} designed a novel protocol using

![Figure 11. Schematics of SM (a) and STBC-ISK (b).\textsuperscript{111}](image-url)
existing ultra-low-power physical and asynchronous media access control mechanisms, as well as a light-weight application layer for data collection.

To realize the communication among various systems that may not contain the available electrical volume to support the traditional transmission of required signals, Santos et al. proposed a new small electric antenna realized by direct antenna modulation (DAM). Handouf et al. studied the problem of activity energy optimization of UAV, introduced the constraint optimization method of activity cycle adjustment, finally improved the system coverage and rate performance. Jingcheng et al. proposed a UAV-positioning method, which uses the range resolution ability of wide-band radar to infer the target position, and uses time-frequency analysis to analyze the Doppler effect generated by rotor rotation to determine whether it is a UAV. Gaur et al. proposed an efficient vertical handover mechanism between different networks, which improves the communication reliability of beyond line of sight (BLOS) and reduces the cost. In order to achieve the optimal summation rate of UAV, Wang et al. conducted joint optimization of IoT equipment-UAV scheduling, uplink transmission power of IoT equipment and UAV altitude. Yuan et al. mainly studied the super-reliable communication system of UAV swarm, designed the software protocol stack and radiofrequency (RF) hardware, and developed the open-source UAV cluster platform, namely Easy-Swarm. In the UAV-assisted IoT communication network, it is necessary to study the access selection of UAVs and the bandwidth allocation of BS to balance the network performance. Therefore, Yan et al. proposed a layered game framework, in which they modeled the bandwidth allocation problem as a non-cooperative game. According to the ergodic rate analysis, this article proposed a game framework, that is, a hierarchical Stackelberg game framework. The framework consists of the follower evolution game for UAVs access selection and the leader non-cooperative game for BS bandwidth allocation, as shown in Figure 13.

**Conclusion and future prospects**

As a complement to the territorial IoT platforms in extreme geographic environments, non-territorial IoT platforms can effectively improve IoT coverage and enhance network reliability and availability. The article mainly discusses two non-territorial IoT technical paths, satellite IoT, and UAV IoT. This article studies and sorts out the status quo of both technologies according to the perspective of technical requirements. In terms of satellite IoT, we divide existing technologies into physical and non-physical layers. For UAV IoT, there is relatively little research on physical layer technology. In general, the research on physical layer technology for large dynamic and low power consumption is still insufficient, and the research on networking technologies for non-territorial IoT platform is relatively superficial.

Specifically, according to the current technological progress, some possible future research directions are as follows:

- In order to achieve the integration of the non-territorial IoT and the territorial IoT in the B5G era, we need to unify the two systems. In terms of physical layer, the waveform of non-territorial link and territorial link will be unified. Considering that territorial IoT adopts OFDM waveform, and OFDM is easy to be combined with other multiple access methods, OFDM waveform is a possible development direction. In terms of network layer, it is a possible research
direction to combine non-territorial and territorial IoT systems considering the large link delay and space link instability of non-territorial IoT.

- In order to cope with the high dynamic channel of non-territorial communication, there may be two technical approaches as follows: In terms of channel coding, we could consider using the rate-less characteristic of spinal codes to automatically adjust the code rate according to the real-time channel characteristic to cope with the large dynamic characteristic of satellite channel. In terms of multi-access, asynchronous multi-access is also a possible research direction considering the problem of multi-user time-frequency asynchrony easily caused by large dynamic channels.

- To solve the problem of frequent switching of user connection relation, which arises from the change of network topology caused by the rapid movement of non-territorial platform, we can consider simplifying the user access, registration signaling process, and corresponding signal design of physical layer at the signaling process level. In addition, in the physical layer, multi-user multi-satellite/multi-station non-orthogonal connection communication system is also a feasible research direction.

- Considering that the hardware resources of non-territorial platform are severely limited, we can consider the antenna and power constraints on the transmitting side to study the NOMA scheme with low peak average power ratio and high energy efficiency. The receiving side should be based on the general platform to realize the multi-user equalization and receiving technology with low complexity and updating. In addition, the neural network can be introduced to optimize the problem that cannot be expressed in closed form by data-driven method, and offline training is used to realize intelligent updates.

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