Fetching Ecosystem Monitoring Data in Extreme Areas via a Drone-Enabled Internet of Remote Things

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***Abstract*—Ecosystem monitoring involves fully understanding the complex interactions of ecosystem progress and providing massive scientific data to answer research questions. Fetching data in extreme areas without a public network largely relies on human efforts. Along with the ongoing advances of the Internet of Things (IoT), the Internet of Remote Things (IoRT), as a new paradigm, is being pursued. In this article, we improve the previous drone-enabled IoRT system and innovatively integrate the system with ecological monitoring devices for wildlife, phenology and environmental monitoring, and the monitored data are remotely retrieved by drones. The experimental results indicate that the data transmission rate between the drone relay and the terrestrial terminal reaches up to 10–15 MB/s. Experiments further demonstrate that in terms of wildlife monitoring, the required time to retrieve an image cached on a terrestrial terminal is approximately 0.35 s, the time required to transfer a set of phenology data is 0.29 and 0.34 s, and in regard to environmental monitoring data, the average time consumption reaches approximately 0.0302 s. Moreover, we introduce a signal strength-based priority strategy that can reduce the time consumption of data transmission between the drone relay and the terrestrial terminal. The demonstrated applications reveal that monitoring devices deployed in remote extreme regions can be connected in the IoRT network, and the way to retrieve data from these deployed devices is being revolutionized by the drone-enabled IoRT network.**

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I. Introduction

ECOSYSTEM monitoring is essential for ecosystem science research, and long-term observation of key variables throughout the biosphere is required to better understand dynamic ecosystem processes in real time [1], [2]. This is achieved via the in situ deployment of monitoring devices, such as automatic weather stations for environmental variability monitoring, phenological cameras to monitor plant growth cycles and infrared cameras for wildlife population dynamics and behavior monitoring [3], [4], [5]. These devices conventionally transfer variable data to datacenters via ground public networks. However, the volume of data leads to an increase in the labor intensity of manual collection, resulting in a low efficiency and high cost. Therefore, innovative means of ecosystem monitoring have increased to facilitate the retrieval of challenging data such as images. In particular, data retrieval in extreme remote areas of interest remains a major challenge. These areas are typically defined as regions where the ground public network is absent or remote and hard to reach for humans.

Data fetching in these areas is conventionally accomplished through human efforts, resulting in a high difficulty or impossible deployment of a large number of devices for ecosystem monitoring. Moreover, access to extreme areas is difficult and often dangerous due to harsh conditions, thus threatening lives and safety. The emerging Internet of Things (IoT) offers promising potential to improve the hardness of data retrieval [6], [7]. Furthermore, the Internet of Remote Things (IoRT), which has been revolutionized by the IoT via satellites, tethered balloons, and drones, enables remote retrieval in remote areas via relays configured on corresponding mobile platforms to ferry data [8], [9], [10]. These advanced technology options facilitate a novel direction of future ecosystem monitoring in extremely harsh and unsafe areas.

Recently, the IoRT has evolved toward typical scenarios, including the Internet of Environmental Things (IoET) [11], the Internet of Underground Things (IoUT) [12], the Internet of Arctic Things (IoAT) [13], and the Internet of Smart Things (IoST) [14], for remote data retrieval via autonomous

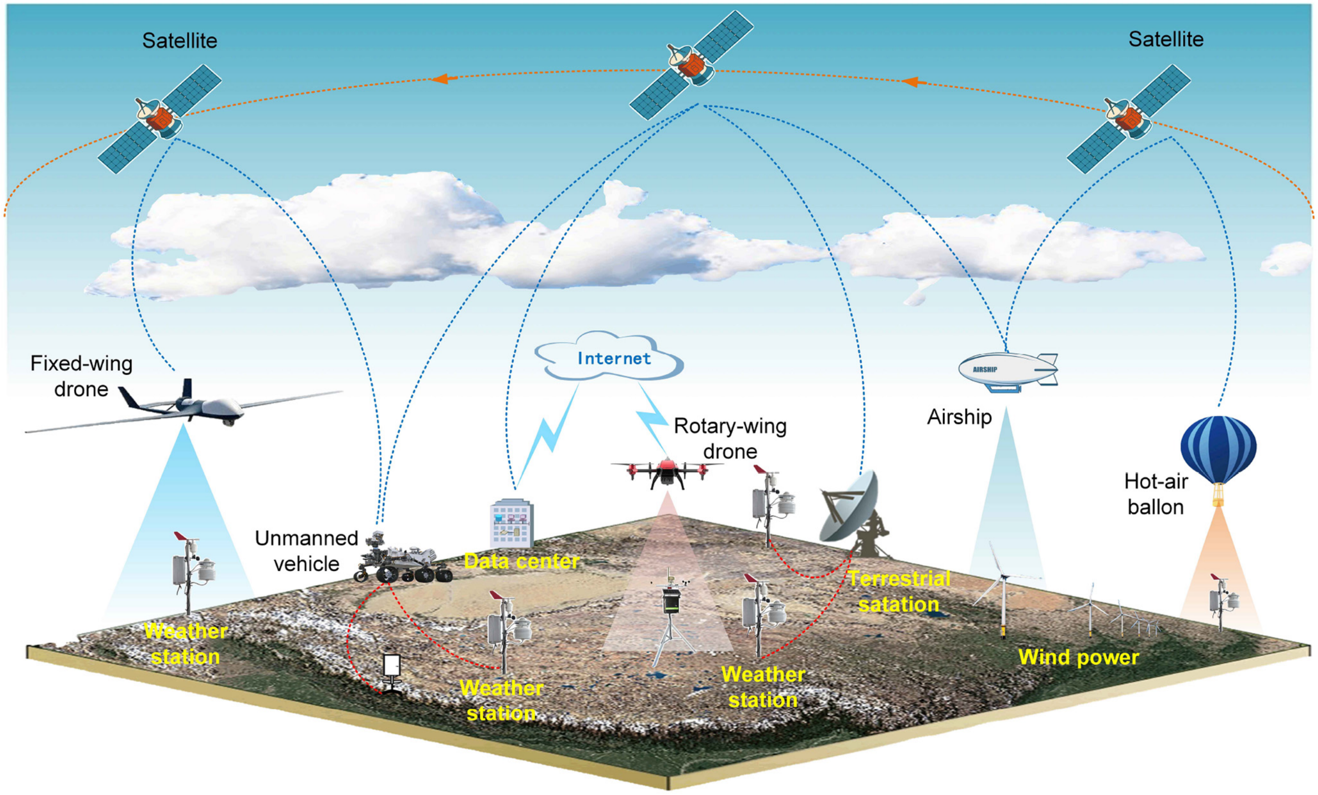

Fig. 1. Framework of the driverless-based IoRT network for ecosystem monitoring in extreme farmost environments.

unmanned vehicles, communication satellites, airships, and drones, as shown in Fig. 1, all of which have advanced and redefined our knowledge and understanding of ecosystem monitoring in extremely harsh areas. For example, satellite-enabled IoRT can facilitate data backhauling from any corner of interest on Earth due to its connection performance with large monitoring devices deployed in remote and inaccessible areas [15], [16]. While the IoRT network has proven that this driverless-based innovative approach is reliable and affordable, the state-of-the-art IoRT network recently assessed in [17], [18], and [19] has some limitations that still impede its widespread application. The application of the IoRT, such as satellite-enabled IoRT, to data retrieval must still be developed to transfer substantial amounts of data, especially for images collected by cameras deployed for monitoring wildlife animals and vegetation phenology. One challenge is that the limited bandwidth constrains the transfer of the massive volume of data collected by monitoring devices. In contrast, the current approach of data transfer, such as images and videos, via satellites is highly expensive. In fact, fetching data from remote extreme areas demands substantial bandwidth, meaning that the use of high-bandwidth long-distance networks maintain better performance, thus preventing the practical deployment of driverless-based IoRT networks in situ, in many cases, due to bandwidth and cost requirements.

Drone-enabled IoT network access of monitoring devices deployed in extreme areas was presented in our previous work [20] to provide a means to exploit an entirely new data retrieval strategy. This network access approach could enable real-time data fetching by drones in remote extreme areas. In this network, drones, considered a new burgeoning paradigm, provide the potential to address the above challenges: 1) first, drone-enabled IoRT assists satellite-enabled IoRT in achieving seamless coverage in farmost areas of interest in ecosystem monitoring applications; 2) in special applications, such as the backhauling of a large volume of monitoring data, the drone-enabled IoRT can address the difficulties of the monitoring data transfer process; and 3) a drone-enabled IoRT network is a promising data retrieval approach due to its advantages of high mobility, low cost, and flexible deployment. However, from a practical perspective, the communication link between the drone relay and the terrestrial terminal needs to be established at higher speed for collecting a large volume of data (e.g., image and video), and the terrestrial terminal needs to support various device integrations, such as wildlife monitoring (e.g., infrared camera), vegetation phenology monitoring, (e.g., phenological camera), environmental monitoring (e.g., general datalogger), and other monitoring. Additionally, using a cooperative priority strategy for a data fetching decision of a single drone to a multi terrestrial terminal is another important problem to be considered.

In this article, we optimize the drone-enabled IoRT system based on our previous work. The improved system yields a higher transmission rate while integrating with the most commonly used monitoring devices in a general-purpose method. We employ communication technologies in the proposed drone-enabled IoRT network, including 5-GHz Wi-Fi to transmit data between the drone relay and the terrestrial terminal at a high speed and an LoRa to remotely awaken high-power 5-GHz Wi-Fi modules embedded on terrestrial-monitoring devices. The design strategy considered in this proposed system aims to not only provide considerable bandwidth to support high-data-rate communication links but also to reduce the operating time of the 5-GHz Wi-Fi module. In addition, the Nginx server is deployed in the terrestrial terminal to optimize the data transmission approach between the controller and monitoring devices. In addition, the signal strength-based priority strategy is employed to improve the efficiency of data fetching between the drone relay and the terrestrial terminal. Moreover, this article aims to deliver the best possible scheme of integration with a diverse range of monitoring devices, seeking to rapidly fetch monitoring data from remote extreme areas. Finally, such a low-budget solution would foster its deployment in monitoring ecosystems of remote extreme areas, often even more deeply affected by the limitations of terrestrial public networks and expensive satellite communication. To this end, the primary contributions of this article are as follows.

1) An optimized drone-enabled IoRT system is proposed to address the requirements of fetching a large volume of data from remote extreme areas at high speed. A hardware system of drone relays and terrestrial terminals is developed to enable the transmission rate to reach up to 10 MB–15 MB/s.
2) The Nginx server is adopted in the developed terrestrial terminal for receiving monitoring data from deployed monitoring devices, such as an infrared camera, and each monitoring device can automatically upload monitored data to the terrestrial terminal via 2.4-GHz wireless, enabling an extensive deployment of monitoring devices in the extreme area of interest.
3) The implementation of a signal strength-based priority strategy can improve the efficiency of data fetching from all the terrestrial terminals. We rank the order of fetching data tasks from the terrestrial terminal according to the signal strength received by the drone relay, thereby saving a substantial amount of transmission time.
4) The developed system is innovatively integrated with different ecological monitoring devices via the general-purpose communication interface. The integrated system can be used to monitor wildlife, phenologies, and environmental variables and can contribute to obtaining field monitoring data at high efficiency and low cost.
5) Through demonstrating the application, we describe the implementation of a real system deployment on the Qilian Mountain and illustrate this potential with the demonstrated monitoring application targeting remote data retrieval via a drone-enabled IoRT network.

The remainder of this article is organized as follows. First, a summary of related work is presented in Section II. Next, we describe the drone-enabled IoRT network architecture focusing on improved system hardware in Section III. In Section IV, we illustrate the demonstrated application in wildlife animals, vegetation phenology, and environment monitoring and show the results of experimental tests conducted on the applied scenarios with different patterns. Finally, we present the conclusions and future perspectives in Section V.

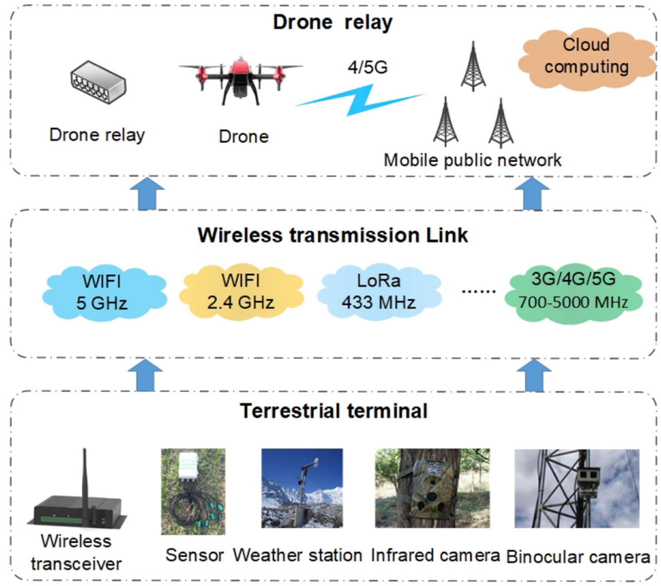

Fig. 2. Network architecture of the drone-enabled IoRT.

II. Related Work

Among many IoRT applications, drone-enabled IoRT networks have drawn a great deal of research attention for intelligent IoT monitoring. The drone-enabled IoRT network is considered a three-layer network structure, including a ground device layer, a drone-terrestrial transmission layer, and a drone application layer, as shown in Fig. 2. The bottom layer is the device level, which consists of multiple monitoring devices or nodes existing in the wireless sensor network (WSN) and can effectively monitor variables around surroundings and transfer data to the upper layer. The second layer is the link layer for data transmission, which is established between drones and terrestrials via widely used communication technologies, such as 3G/4G/5G LTE networks, narrow band IoT (NB-IoT), LoRa, ZigBee, Xbee, 2.4-GHz Wi-Fi, and 5-GHz Wi-Fi. These wireless technologies can apply protocols to transmit data from the bottom layer to the upper layer. The third layer is considered the application layer, which is near the drone side. Taking advantage of the data receiving module in the upper-layer relay, monitoring data cached terrestrial devices can be quickly fetched, and the final data can be returned to the user. Research shows that the impact of wireless communications technologies on drone-enabled IoRT networks is a key issue, and the system performance of controllers is an additional key driver in real system development [21], [22], [23]. Efficient data fetching using drones has been an attractive research topic due to its wide potentialities and synergies.

Deruyck *et al.* [24] designed UAV-aided emergency networks based on an LTE network for large-scale disaster scenarios. According to their work, a UAV configured with a femtocell base station hovers at a realistic disaster scenario in the city to provide full coverage of public wireless

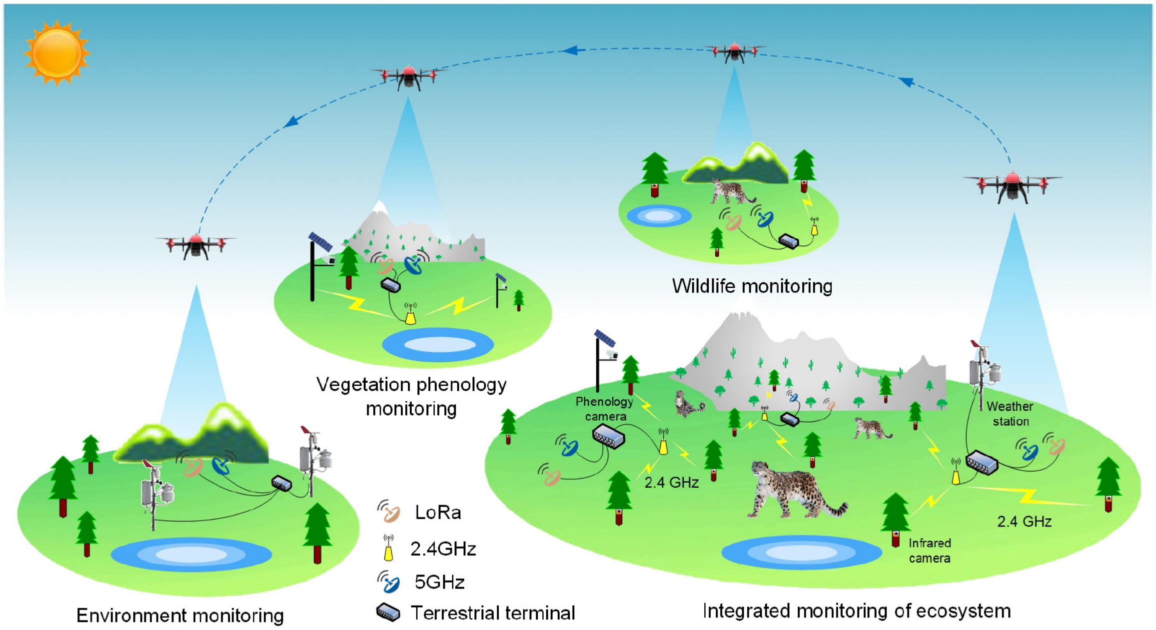

Fig. 3. Demonstrated application of the drone-enabled IoRT network.

communication networks. Khan *et al.* [25] proposed a UAV-aided 5G network using UAVs as a relay base station to assess the usage of UAVs in next-generation wireless networks in urban management. Additionally, Castellanos *et al.* [26] integrated NB-IoT technology and UAVs to design a novel UAV-aided network for collecting underground soil parameters in potato crops. Motlagh *et al.* [27] proposed a UAV-based IoT platform for crowd surveillance based on face recognition. Khan *et al.* [28] evaluated and implemented an aerial-terrestrial network that is based on terrestrial base stations and UAV relays for providing 5G services. However, the limitations of harsh conditions or less communication networks result in difficulty in backhaul data from monitoring devices deployed in remote fields via terrestrial public networks.

Therefore, wireless technologies, such as ZigBee, Wi-Fi, LoRa, and Xbee have been identified as an attractive solution, providing a means to exploit the drone-enabled IoRT network as an entirely new monitoring domain in diverse applications [29], [30]. Employing ZigBee as the communication link between UAVs and ground receiving systems to transmit image data was presented in [31] to experimentally investigate the performance of transmitting data via 2.4-GHz Wi-Fi and ZigBee technologies in geospatially large-scale structural health monitoring applications. Zhang *et al.* [32] presented a UAV-based network for an environmental monitoring system. The UAV was configured with a set of sensors to the monitoring environment and sent the data to a terrestrial monitoring station through Xbee. Moreover, Trasvia-Moreno *et al.* [33] introduced a UAV-based WSN for marine coastal environment monitoring. The proposed system uses a UAV as a mobile data collector to remotely fetch the data from a swarm of drifting buoys, and LoRa is used to establish communication links between the UAV and drifting buoys. Similarly, in [34], a UAV-assisted environmental monitoring system to achieve rapid acquisition of the environmental parameters of emergency sites was presented. According to their work, an LoRa-based mesh network that is used to establish the aerial-terrestrial network for emergency response can ensure rapid data collection in infrastructure-less areas. Moreover, Kalatzis *et al.* [35] proposed a UAV-enabled IoT network for early fire detection. The IEEE 802.11ac dual band Wi-Fi is employed in the proposed network instead of 4 G LTE for data transmission. Additionally, wireless backhaul strategies of using an IEEE 802.11ac Wi-Fi data link in a UAV-based aerial-terrestrial network to transmit data are presented in [36], [37], and [38].

In fact, to the best of our knowledge, the number of previous studies with experimental and practical results of using 5-GHz Wi-Fi to establish high-speed communication links between drone relays and terrestrial devices is still small, and this article is one of the first studies on the comprehensive application of drone-enabled IoRT while providing a new perspective in the ecosystem monitoring domain, such as wildlife animals, phenological rhythm, and environmental variable monitoring.

III. Drone-Enabled IoRT Network Framework

A. Drone-Enabled IoRT Network

In the drone-enabled IoRT network, we develop drone relays and terrestrial terminals to enable ecosystem monitoring devices to be networked. A drone is configured with a relay device, and as a mobile relay, to retrieve monitoring data from a terrestrial terminal. A terrestrial terminal comprising a wireless transceiver and monitoring devices, which is applied for target monitoring and data transferring, and a relay device mounted on the drone fetches monitoring data from the terrestrial terminal at a high speed. Fig. 3 shows the proposed application of the drone-enabled IoRT network to achieve comprehensive ecosystem monitoring, including wildlife, phenology, and environmental monitoring.

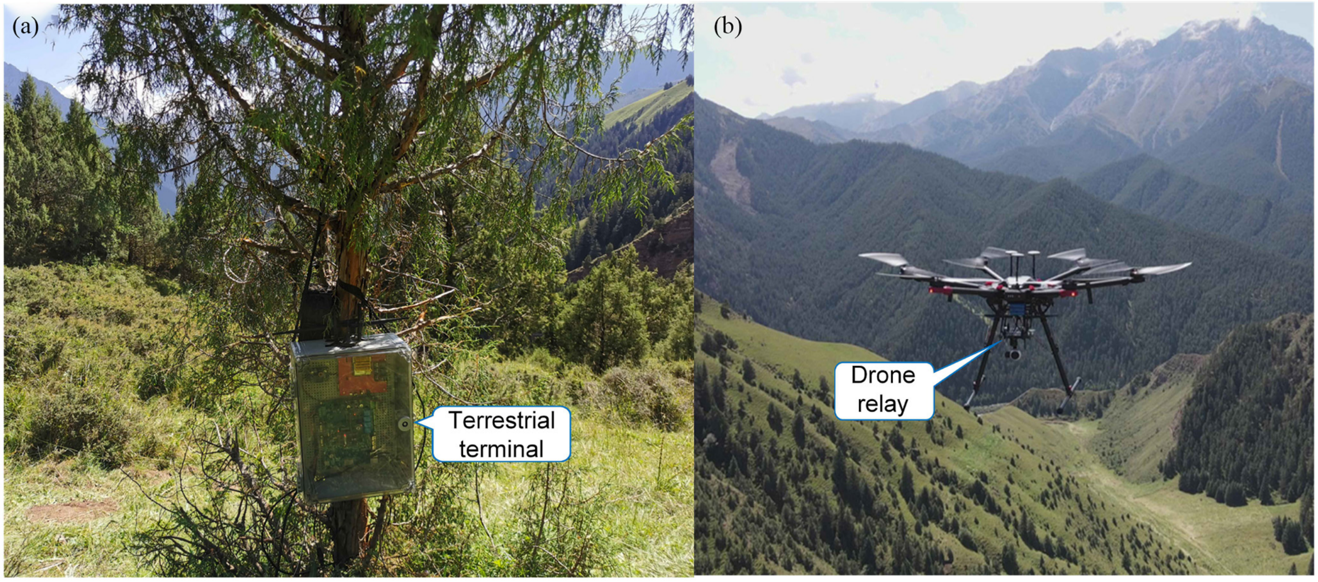

Fig. 4. Hardware system of the drone-enabled IoRT network, including (a) terrestrial terminal and (b) drone relay.

In summary, the process of remotely fetching monitoring data via the drone relay includes the following steps.

Step 1: A terrestrial terminal is deployed in the extreme farmost area of interest for real-time ecological environmental sensing. The data recorded by monitoring devices are transferred to a transceiver via a 2.4-GHz wireless link or RS232 wire communication link while locally caching the data into the storage memory.

Step 2: A drone performs the task of remotely fetching monitoring data cached on the terrestrial terminal deployed in the extreme area. The drone configured with a relay device hovers near the terrestrial terminal, thereby transmitting wake-up instructions to remotely activate a 5-GHz Wi-Fi transceiver via a wake-up link between the drone relay and the terrestrial terminal, as established by LoRa.

Step 3: Then, the drone hovers over the terrestrial terminal to establish a 5-GHz-based data transmission link between the drone and the terrestrial terminal to fetch data cached on the terrestrial terminal at a high speed. When the cached data is completely transferred, the drone flies to the next monitoring site for data fetching, and the 5-GHz transceiver is put into hibernation mode.

B. Drone-Enabled IoRT Hardware System

In the drone-enabled IoRT network, the drone relay is a device to collect monitoring data from the terrestrial terminal via a 5-GHz-based communication link, which is a high-speed communication technology with the IEEE 802.11ac protocol, and the transmission rate reaches up to 108 MB/s in theory. However, the transmission rate between the drone relay and terrestrial terminal is mainly limited by the performance of the system, such as the hardware system, in terms of the processor, antenna, I/O port, and software systems, including algorithm and program design. Thus, we improve the hardware system by replacing the processor and adopt a quad-core NXP Qual-Core i. MX8MM processor integrating an ARM Cortex-A53 processor with a 1.8-GHz operation frequency. The terrestrial terminal and drone relay are shown in Fig. 4. Fig. 5 shows details of the communication links between the controller board and monitoring devices with a system flow chart and an interface description of the controller.

C. Drone-Enabled IoRT Software System

1) Adopted Network in the Drone-Enabled IoRT: The communication link in the drone-enabled IoRT comprises of two parts, a drone relay-terrestrial terminal and a terrestrial terminal-monitoring device communication link, as shown in Fig. 6. The terrestrial terminal collects the monitored data from all deployed terrestrial-monitoring devices. Drone relay needs to fetch the data cached in the terrestrial terminal. All of the data transmission operations rely on the network. However, different communication technologies are used to address the data transmission requirements.

Many monitoring devices, such as an infrared camera and phenology camera, are deployed for sensing the targets of interest in the field. Therefore, the 2.4-GHz Wi-Fi wireless technology is utilized for data transmission between the terrestrial terminal and the monitoring device to reduce the human efforts for data collection. Likewise, the communication link of environmental monitoring devices is designed with extensibility in mind, the RS232 is a chosen duo to its steady performance and wide application. In addition to terrestrial communication, the communication link between the drone relay and the terrestrial terminal must transfer data with as high a speed as possible because a large volume of data is cached in the terrestrial terminal. The 5-GHz Wi-Fi is used in the proposed drone-enabled IoRT to address the high-speed communication requirement between the drone relay and the terrestrial terminal. Additionally, given the 5-GHz

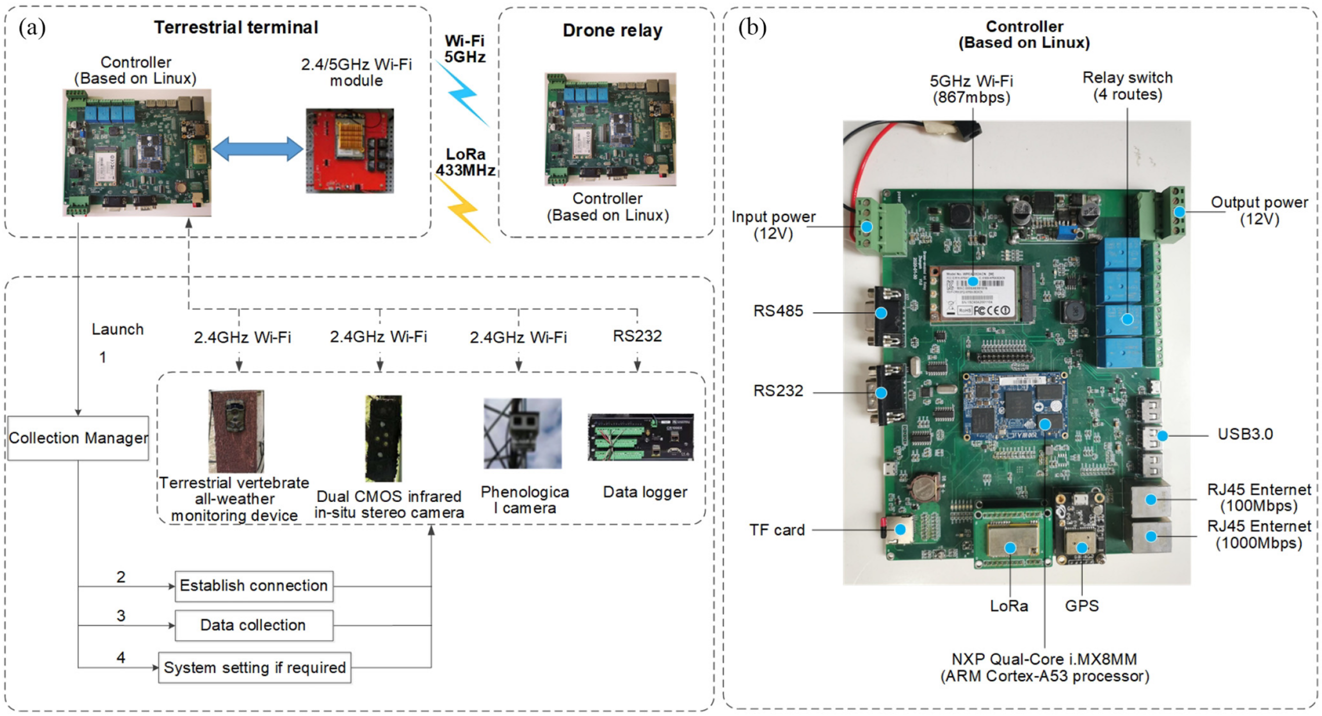

Fig. 5. Details of the communication links between the controller board and monitoring devices with a system flow chart and interface description of the controller: (a) 2.4-GHz wireless communication links employed between the controller and monitoring devices, including a terrestrial vertebrate all-weather monitoring device, dual CMOS infrared in situ stereo camera and phenological camera, and RS232 wire communication link established between the controller and data logger; the interfaces of the controller include power input and output interfaces, communication ports (RS232, RS485, and RJ45 Ethernet ports, all USB 3.0), communication modules (LoRa, 5-GHz Wi-Fi), a storage card (TF card), a relay switch, and a positioning module (GPS module) (b).

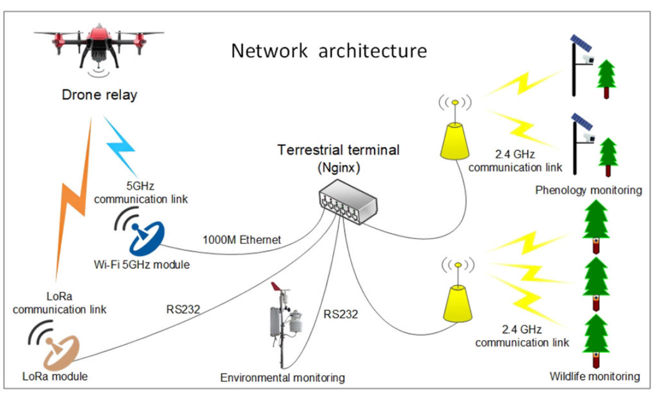

Fig. 6. Framework of the drone-enabled IoRT network.

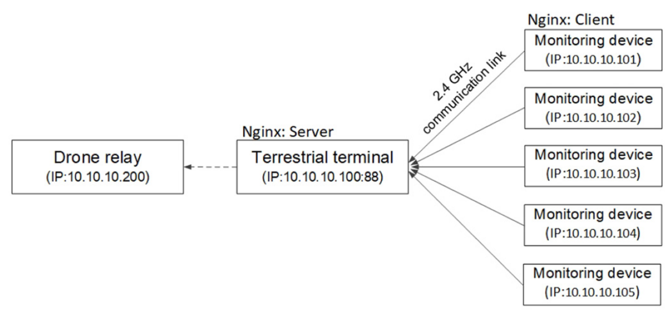

Fig. 7. Process of Nginx-based data transmission.

Wi-Fi high-power characteristics, we adopt the LoRa wireless technology as a wake-up method to remotely awaken the 5-GHz Wi-Fi module equipped on the terrestrial terminal through the wake-up signal transmitted by the drone relay.

2) Nginx-Based Data Transmission Strategy: Nginx is a cross-platform Web server, and compared to other Web servers, it has advantages, such as fast responses to requests, low memory consumption, and it supports the processing of large-scale concurrent connections. Therefore, Nginx is well-suited for the large-scale deployment of monitoring devices in the drone-enabled IoRT network. Considering the ecological monitoring in an extreme area, we adopt the Nginx-based data transmission method to enable monitoring devices to automatically upload monitored data to the terrestrial terminal. Additionally, due to the high-power operation of the Wi-Fi module, we design a data transmission time segment that can reduce the power consumption of the terrestrial terminal while prolonging its lifetime. Each monitoring device is designed to locally cache the monitored data and is triggered to upload cached data to the Nginx server based on different time segment. In the proposed design, we set the time segment for transferring data from 12 A.M. to 3 P.M., largely because the solar power supply is more sufficient during this time segment. Once the 2.4-GHz communication link is established between the terrestrial terminal and the monitoring devices, as specified by a designed time threshold, the devices command themselves to upload cached data to the Nginx server. The process of Nginx-based data transmission is presented in Fig. 7.

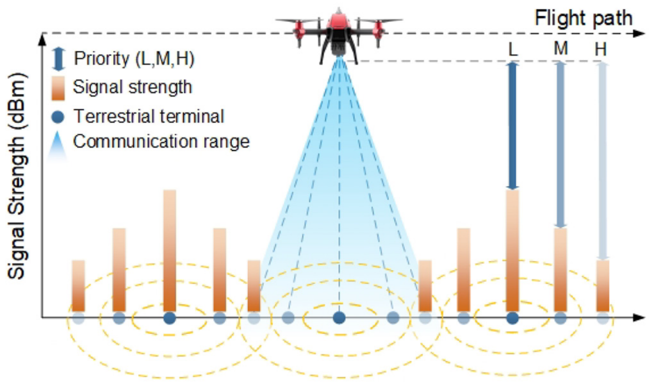

Fig. 8. Signal strength-based priority strategy for data transmission.

3) Signal Strength-Based Priority Strategy: To improve the efficiency of data fetching via the drone-enabled IoRT, we propose a signal strength-based priority strategy to transfer data transmission, enabling a reduced time consumption of data transmission between the drone relay and the terrestrial terminal. This drone relay configured with a wireless network adapter checks the 5-GHz wireless signal in real time when flights are directly over the terrestrial terminal, and it evaluates the strength of the received signal. The signal strength is used to determine which terrestrial terminal the drone fetches the data from. The less the signal strength, the more priority will be for the data transmission. As shown in Fig. 8, the drone flies to the location where the terrestrial terminal is deployed according to the planned flight path, and the priority of fetching data from the deployed terminal is ranked based on the received signal strength. Such a signal strength-based design provides an opportunity for each terminal to successfully transfer cached data to the drone relay within the range of a drone relay-terrestrial terminal 5-GHz signal. Moreover, this method also reduces the task of simultaneously transmitting data between the single drone relay and the multi terrestrial terminal.

IV. Experiments and Results

A. Experimental Area

Field experiments are conducted to assess the efficiency of the drone-enabled IoRT network in terms of the remote collection of monitoring data recorded by monitoring devices. Various environmental monitoring devices are deployed in extreme regions that are hardly accessible for humans or lack a ground public network. In the experimental area, the extreme environment could appropriately verify the proposed application of the drone-enabled IoRT network during the experiments.

The Qilian Mountains, located in the range from 97.25°–103.46°E and 36.43°–39.36°N, are marginal mountains in the northeastern Tibetan Plateau [39]. The altitude of the intermountain basin and wide valley generally varies between 3000 and 4000 m, the altitude of the wide valley basin varies between 4100 and 4200 m. The Qilian Mountains contain complex ecological environments, diverse vegetation distributions, and abundant wildlife, including snow leopard, musk deer, blue sheep, and other animals, most of which occur in extreme areas, such as mountaintops and overhanging rocks, that are difficult to access, where a public network is absent. In addition, the Qilian Mountains are rich in natural vegetation, including Picea crassifolia and Sabina przewalskii, of which *P. crassifolia* is a tree species unique to Northwest China, mostly distributed in valleys and shady slopes at altitudes ranging from 1600–3800 m.

The Heihe River Basin originating from the Qilian Mountains is the second largest inland basin in Northwest China, located between 97.1°–102°E and 37.7°–42.7°N. The Eco-Hydrology Observation Network in the Heihe River Basin [40], [41] is a multielement, multiprocess, multiscale, distributed, and 3-D comprehensive basin observation system that aims to provide a comprehensive simulation platform for Heihe River Basin remote sensing and synchronous ground observation tests. There are 11 observation stations, including three superstations and eight ordinary stations in the Heihe River Basin.

B. Experimental Setup

Multiscale monitoring of ecosystems encompassing wildlife, single plants, or biological communities with high biodiversity requires various monitoring devices. During the field experiments, the drone-enabled IoRT network integrated with a monitoring device, as a terrestrial terminal, allowed the monitoring device to be networked. The integrated devices include a terrestrial vertebrate all-weather monitoring device, dual CMOS infrared in situ stereo camera, phenological camera, and CR1000X datalogger, and these devices for wildlife and phenology monitoring were developed by [42]. Table I presents the installation locations of the deployed terrestrial terminals. In these experiments, the above integrated monitoring devices record data pertaining to the target of interest in real time while transmitting the monitored data to the wireless transceiver via a 2.4-GHz wireless link or RS232 wire link. Finally, the wireless transceiver transfers the cached data to the drone relay via the 5-GHz communication link when the drone performs the data collection task. Additionally, in the experiments of estimating the performance of the system, each test was conducted ten times with each scenario, and the results were averaged over ten experiments.

C. Demonstration Application of the System Applied in Ecosystem Monitorings

1) Wildlife Monitoring: We developed two terrestrial terminals utilized to monitor wildlife. Each terrestrial terminal comprised a transceiver and wildlife monitoring device and was deployed at one of two selected sites on the Qilian Mountains. The first terrestrial terminal was installed at a site without a ground public network, and the second terminal was deployed at a hard-to-reach site. Wild animals frequently occur at the selected installation location site. Fig. 9 shows the deployed terrestrial terminals linked with the drone-enabled IoRT network.

The developed terrestrial terminal is shown in Fig. 9(a), and the wireless transceiver and terrestrial vertebrate all-weather

TABLE I
LOCATIONS OF THE DEPLOYED TERRESTRIAL TERMINALS

Monitoring site	Monitoring variable	Monitoring device	Longitude	Latitude	Data type
	Wildlife	Terrestrial vertebrate all-weather monitoring device	38.50°	99.98°	Image
	Wildlife	Dual CMOS infrared in situ stereo camera	38.28°	99.53°	Image
	Phenology	Phenological camera	38.34°	100.17°	Image
	Phenology	Phenological camera	38.77°	100.32°	Image
	Environment	CR1000X	38.77°	100.32°	Text

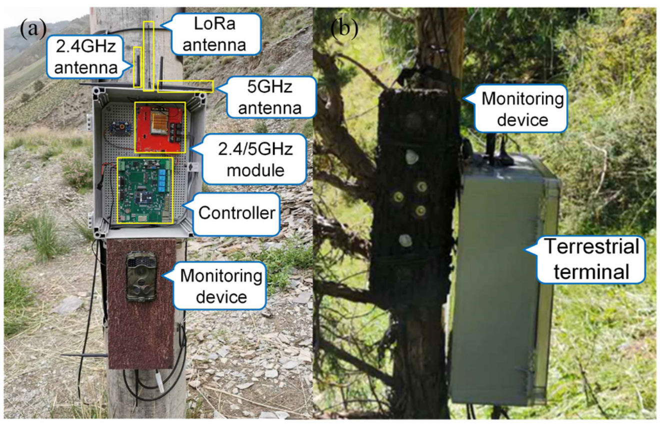

Fig. 9. Developed terrestrial terminals deployed for wildlife monitoring. (a) Terrestrial terminal integrated with a wireless transceiver and terrestrial vertebrate all-weather monitoring device deployed to monitor the blue sheep (*Pseudois nayaur*), Himalayan marmot (*Marmota himalayana*), woolly hare (*Lepus oiostolus*), and rusty-necklaced partridge (*Alectoris magna*) [N 38.50°, E 99.98°, 2330 m above sea level (a.s.l.)] and (b) terrestrial terminal integrated with a wireless transceiver and dual CMOS infrared in situ stereo camera deployed to monitor the snow leopard (*Panthera uncia*), musk deer (*Moschus chrysogaster*), blue sheep (*P. nayaur*), etc. (N 38.28°, E 99.53°, 3160 m a.s.l.).

monitoring device are integrated. We configured the wireless transceiver with an omnidirectional antenna, and it should be noted that this design extends the communication range between the drone relay and terrestrial terminal. Additionally, the terrestrial vertebrate all-weather monitoring device was integrated with an infrared camera, 2.4-GHz wireless transmission module, temperature and humidity sensor, solar panel, time control circuit, and software control display to support automatic data acquisition, time synchronization, and hierarchical storage. The aforementioned 2.4-GHz wireless technology was employed to realize communication between the transceiver and wildlife animal monitoring devices. This communication mode design yields certain advantages, including flexible deployment conditions (due to wireless communication technology) and a low cost (due to deployment without the need for additional wired networks). Thus, the images and videos recorded by the monitoring device were directly cached on the transceiver via the 2.4-GHz wireless communication link. The image resolution was 2560×1920 pixels, and the video duration was set to 30 s to save storage memory. The developed terrestrial terminal monitored the abundance, diversity, and range of activities of wildlife 24 h a day uninterrupted at the above hard-to-reach site.

Fig. 9(b) shows the other developed terrestrial terminal. This device was integrated with a wireless transceiver and dual CMOS infrared in situ stereo camera. The configuration of the wireless transceiver is the same as that of the monitoring device mentioned above, and this monitoring device integrated a 2.4-GHz wireless transmission module, sensor, synchronous control circuit, dual CMOS in situ stereo camera, power management system, and light source, of which the camera exhibited the functions of synchronous trigger control, laser night vision, and animal feature size measurement. Moreover, an intelligent algorithm to compute the size of the monitored animals was implemented in the monitoring device. Thus, the size of the target animals was calculated in three steps: 1) the difference between the left and right views of the target animals was determined through the obtained target images; 2) 3-D spatial information of the target animals was constructed; and 3) the size of the target animals was computed based on the constructed 3-D spatial information. In this terrestrial terminal, a 2.4-GHz wireless transmission link was also employed to transmit the monitored data between the wireless transceiver and monitoring device.

2) Phenology and Environmental Monitoring: Moreover, two other terrestrial terminals were developed for phenology and environmental monitoring. The terrestrial terminal for phenology monitoring was deployed at two selected sites, one of which occurred in the Qilian Mountains without a ground public network, and the other terminal was installed at the Huazhaizi station, which is located in the Heihe River Basin. In addition to phenology monitoring, we deployed a terrestrial terminal at the Huazhaizi station to monitor the environment. Fig. 10 shows the deployed terrestrial terminals linked with the drone-enabled IoRT network.

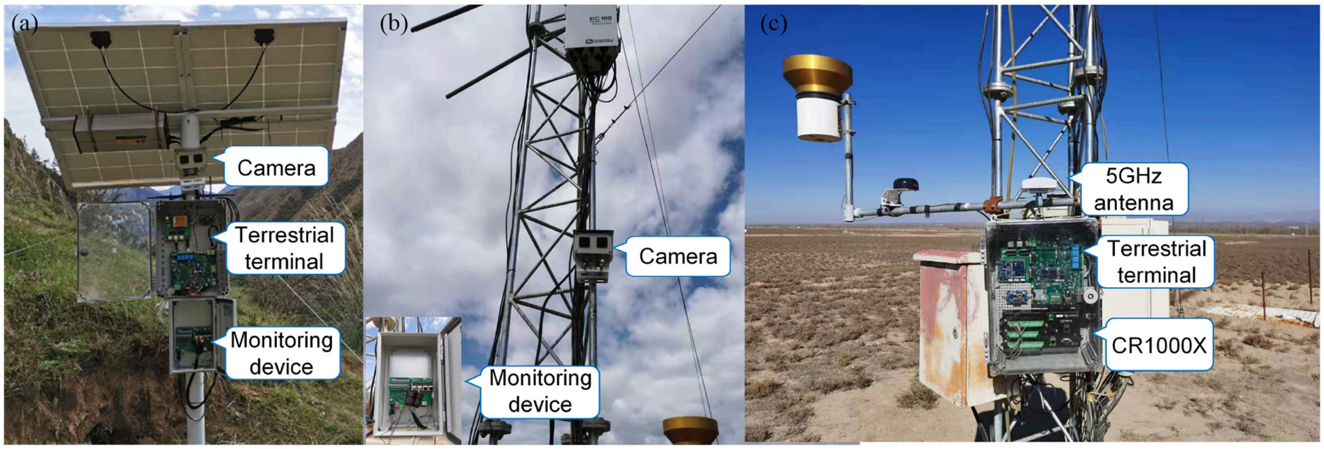

Fig. 10. Developed terrestrial terminals deployed for phenology and environmental monitoring. (a) Terrestrial terminal integrated with a wireless transceiver and phenology camera deployed to monitor Qinghai spruce (*P. crassifolia*) (N38.34°, E 100.17°, 2690 m a.s.l.) and arid desert meadow (N38.77°, E 100.32°, 1829 m a.s.l.). (b) Terrestrial terminal integrated with a wireless transceiver and CR1000X datalogger deployed to monitor the soil temperature (N 38.77°, E 100.32°, 1829 m a.s.l.).

Fig. 10(a) and (b) shows the terrestrial terminal developed for phenology monitoring, which comprised a phenology camera and wireless transceiver. The phenology monitoring device included a phenology observation instrument based on multispectral images, in which a 2.4-GHz wireless transmission module, solar photovoltaic module, and binocular camera were configured. The communication link between the phenology monitoring device and wireless transceiver was established through 2.4-GHz wireless technology. The image recording time interval was set to 30 min to limit the number of data cached in the terminal memory, aiming to not only save the transmission bandwidth between the drone relay and terrestrial terminal but also to enable efficient memory storage. The image resolution is 3840×2160 pixels. It should be noted that the phenology monitoring device was a binocular camera. Hence, two images were obtained simultaneously. During the all-weather operation of the phenology monitoring terminal, the two images were cached on the transceiver via the 2.4-GHz communication link in real time.

Additionally, in regard to environmental monitoring, the developed terrestrial terminal was integrated with a wireless transceiver and CR1000X datalogger, as shown in Fig. 10(c). An RS232 serial port was adopted to establish communication between the datalogger and transceiver. In addition, the available digital sensors, such as soil water sensors, were configured in the datalogger to monitor the surrounding environment in real time, and we set the sampling interval to 10 min. The height of the deployed sensors was set to 2 to 4 m to obtain environmental variables at different altitudes. It should be noted that the data format was time series data, and the file type was text. Thus, to achieve data transmission between the drone relay and terrestrial terminal, the corresponding process was quite straightforward and rapid. We argue that in the existing drone-enabled IoRT network, the above high-speed communication capability could satisfy the transmission requirements of the large amount of data recorded by the eddy covariance system expected to be deployed in the future.

D. Performance Analysis of the System Applied in Different Ecosystem Monitorings

1) Wildlife Monitoring: Fig. 11 shows the retrieved wildlife monitoring data recorded by the terrestrial terminal deployed on the Qilian Mountains via the drone relay during the drone-enabled IoRT network tests conducted in August 2020.

Fig. 11(a) shows the proposed application of the drone-enabled IoRT network, collecting cached images from the terrestrial terminal. Fig. 11(b)–(f) shows the monitored animals, including blue sheep (*Pseudois nayaur*), Himalayan marmot (*Marmota himalayana*), woolly hare (*Lepus oiostolus*), and rusty-necklaced partridge (*Alectoris magna*). These recordings are beneficial for animal behavior research, detection of rare species, elucidation of the effects of human disturbance and climate change, and research in other fields [43]. Through these images and videos, we could analyze the species distribution, population number, behavior, and habitat chosen in Qilian Mountain to provide a reference for wildlife protection, management, and resource utilization.

These images were recorded by the terrestrial terminal in real time when animals triggered the deployed infrared cameras. The recorded data were cached on the wireless transceiver and retrieved by the drone relay during drone flight over the terrestrial terminal. In the experiment, the size of cached images is 863 kB, and we determined that the time required for image transmission reached approximately 0.35 s. The experimental results demonstrate that the transmission rate between the drone relay and terrestrial terminal is very high.

2) Phenology Monitoring: Fig. 12 shows the phenology data pertaining to Qinghai spruce (*P. crassifolia*) and desert meadow remotely retrieved via the drone relay. The deployed binocular phenology camera could obtain two images at 30-min intervals. These long-term image data recorded by the phenology camera could be analyzed to automatically recognize key phenological phases of *P. crassifolia* and the desert meadow. We conducted this experiment by employing a drone

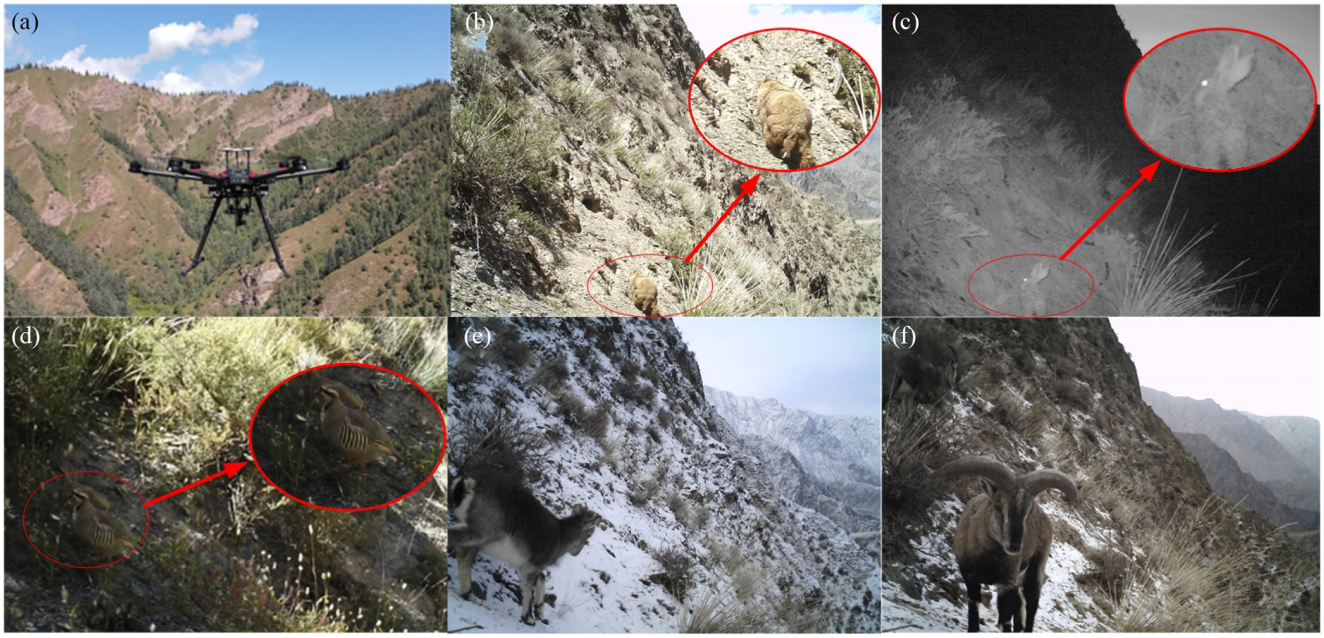

Fig. 11. Proposed application and retrieved wildlife images recorded by the terrestrial terminal deployed on the hillside (N 38.50°, E 99.98°, 2330 m a.s.l.) near the Liushuyuan protection station via the drone-enabled IoRT network, (a) demonstrated application, and monitored data retrieved by a drone in August 2020, including marmot (b), hare (c), Alectoris magna (d), and blue sheep (e) and (f).

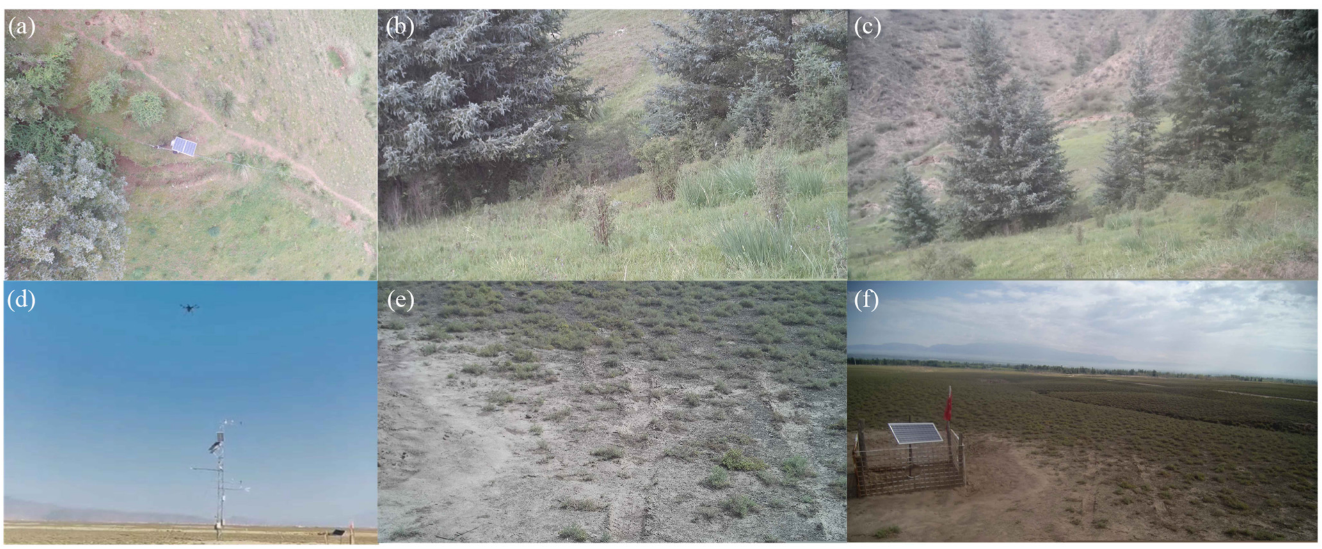

Fig. 12. Demonstrated application and retrieved phenology images recorded by the terrestrial terminals deployed in the Dayekou forest (N 38.34°, E 100.17°, 2690 m a.s.l.) and Huazhaizi station (N38.77°, E 100.32°, 1829 m a.s.l.) via the drone-enabled IoRT network, (a) and (d) show the proposed applications in the Dayekou forest and Huazhaizi station and the monitored data retrieved by the drone relay in August 2020, including *P. crassifolia* images recorded by the left and right lenses (b) and (c) and desert meadow images recorded by the left and right lenses (e) and (f).

to remotely collect monitoring data cached on the terrestrial terminal via the drone relay on 10 August 2020, as shown in Fig. 12(a) and (d). Fig. 12(b) and (c) shows the phenology data for *P. crassifolia* recorded by the phenology camera deployed in the Dayekou forest, and the phenology data of the desert meadow recorded by the phenology camera deployed at the Huazhaizi station are shown in Fig. 12(e) and (f).

We tested the time consumption to transfer a set of *P. crassifolia* phenology data that is 1 and 2.67 MB in size, and the time consumption reached 0.29 and 0.34 s. The experimental results were generally consistent with the above results (Section I). The communication capability between the drone relay and terrestrial terminal could be limited by the characteristics of the link technology, such as the antenna configuration and application scenarios, yielding different performance levels of data retrieval between the drone and terrestrial terminal.

3) Environmental Monitoring: Fig. 13 shows the demonstrated application of the collected environmental monitoring data retrieved by the drone-enabled IoRT network in August 2020. The terrestrial terminal deployed at the Huazhaizi station comprised a wireless transceiver and CR1000X datalogger, which contained three configured soil temperature sensors.

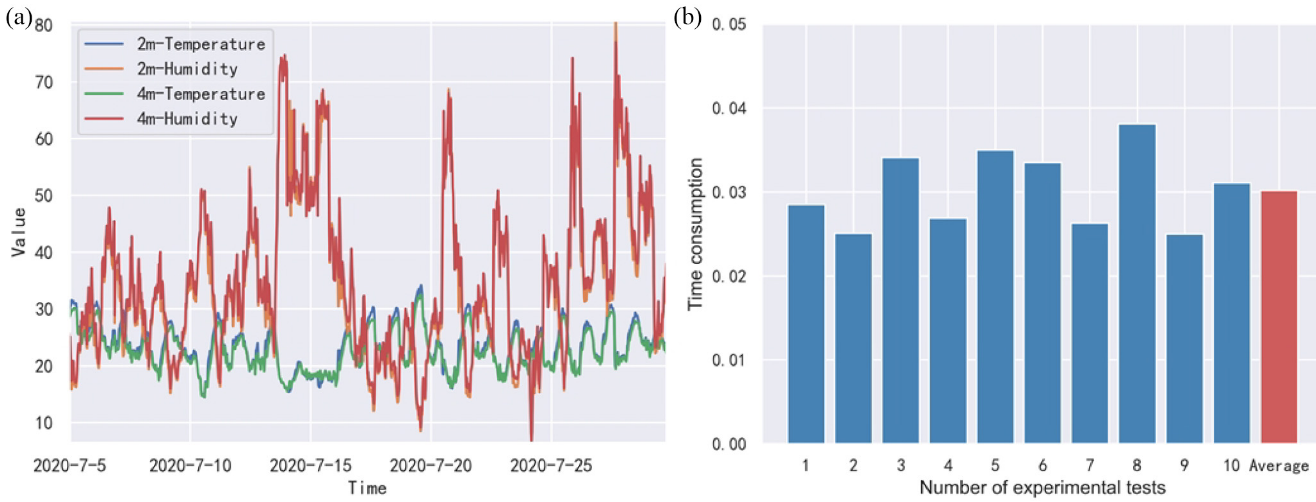

Fig. 13. Retrieved environmental data recorded by the terrestrial terminal deployed at the Huazhaizi station (N 38.77°, E 100.32°, 1829 m a.s.l.) via the drone-enabled IoRT network, the retrieved temperature and humidity data (a), the time consumption of the data transmission between the drone relay and the terrestrial terminal (b).

Fig. 13(a) shows the data collected by the drone, including temperature and humidity data recorded by the deployed terrestrial terminal at the different heights over a period of a month. In this experiment, the size of the cached data was approximately 571 kB, and we conducted ten times of experimental testing for evaluating the time consumption of fetching data via drone, as shown in Fig. 13(b). Fig. 13(b) shows the time consumption of the data transmission between the drone relay and the terrestrial terminal. The results indicate that the average consumption time reached approximately 0.0302 s. These results suggest that the environmental monitoring data cached on the terrestrial terminal could be remotely retrieved via the drone relay while maintaining an acceptable high transmission rate during drone flight at a 100-m altitude.

E. Performance Analysis of the System in Different Field Experimental Tests

1) Evaluating the Effect of the Improved System Compared to the Previous System: The processor performance of the system is one of the key enablers for enhancing the capability of wireless communication. Thus, we improved the hardware system in the drone-enabled IoRT network to increase the data transmission rate between the drone relay and the terrestrial terminal. Moreover, we conducted two experiments to verify the performance of the improved system by evaluating the time consumption of the data transmission between the terrestrial terminal and the drone relay. The previous and improved terrestrial terminals integrated with phenology monitoring devices were deployed in the Dayekou forest to test their performance of fetching 3 MB of image data from the terrestrial terminal by the drone relay. Fig. 14 shows the results of the time consumption for data transmission by using the original system and the improved system. The figure shows that the time consumption of the improved system and the original system is approximately 0.2 and 1 s, respectively. The experiment results show that the data transmission rate of the improved system is up to approximately 15 MB. Experimental

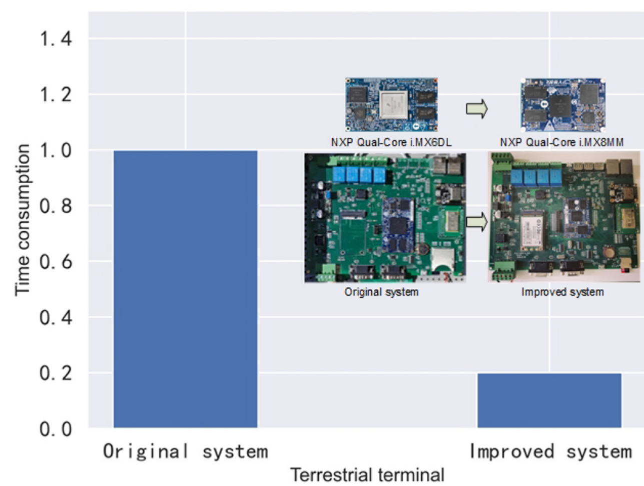

Fig. 14. Performance comparison of the drone-enabled IoRT system.

results suggest that the improvement can increase the average transmission rate between the drone relay and the terrestrial terminal, and as a whole can reduce the time consumption of the network system for data transmission.

2) Evaluating the Effect of the System With and Without Nginx Server: In this section, we conducted two experiments to evaluate the transmission time. One of the experiments was using a terrestrial terminal with the Nginx server to receive data from the cameras. In another experiment, a terrestrial terminal without the Nginx server was used to receive data from the cameras. The method used in second test was not optimized using the multiterminal parallel transmission. In previous work, only point-to-point data transmission was implemented when a drone came in the communication range of a terrestrial terminal. In this experiment, we conducted the tests by transferring images data cached in four cameras to a terrestrial terminal. In the tests, the image sizes were approximately 8–10 MB, and these images were cached in these

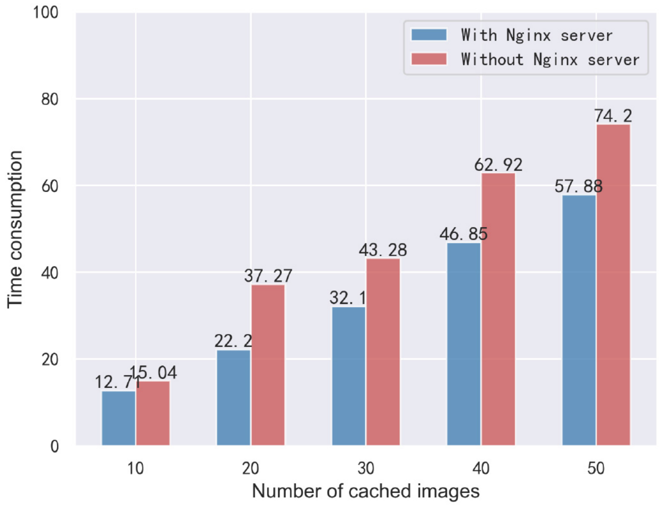

Fig. 15. Performance comparison of the system with and without Nginx server.

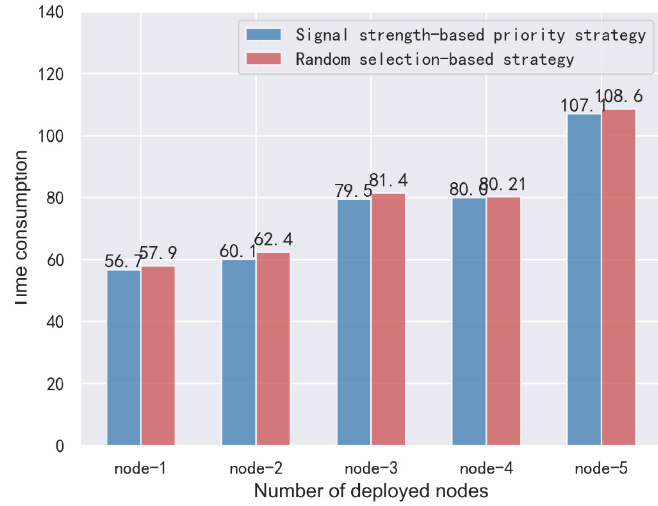

Fig. 16. Performance comparison of time consumption using the signal strength-based priority strategy and the random selection-based strategy.

cameras. The number of transferred images per time was set to 10, 20, 30, 40, and 50, and the flight altitude of the drone was set to approximately 50 m.

Fig. 15 shows the performance comparison for data transmission. The result indicates that when the number of transferred images is 10, the time consumed by the terrestrial terminal with the Nginx server is comparable to using the terrestrial terminal without Nginx server. As the number of transferred images increases, the transmission time increases. For example, when the number of transferred images reaches 50, the time consumed by the terrestrial terminal with the Nginx server and without the Nginx are 57.88 and 74.2 s, respectively. The differences in time consumption could be attributed to the query and transmission of images cached in these cameras. The experimental result suggests that the terrestrial terminal with Nginx server shows some advantages compared to the terrestrial terminal without Nginx server in terms of time consumption, and demonstrating the feasibility of the method in the drone-enabled IoRT.

3) Evaluating the Effect of the System With the Signal Strength-Based Priority Strategy: During the experimental tests, the signal strength-based priority strategy is used to fetch data from the terrestrial terminal through drone relay. We investigated the performance of the proposed method for data transmission between the drone relay and the terrestrial terminal by comparing it with the random selection-based strategy. In the experimental tests, the random selection-based strategy refers to randomly establishing a communication link between the drone relay and the terrestrial terminal to fetch data without performing any priority processing. While testing, 40 images were cached in five terrestrial terminals (named node-1, node-2, node-3, node-4, and node-5), which were deployed in different locations. The drone's flight paths were set from node-1 to node-5, and the flight height was 50 m.

Fig. 16 shows the total time consumption of data transmission using our introduced signal strength-based priority strategy and the random selection-based strategy. According to the results, the total time consumption of data transmission by using the signal strength-based priority strategy and the random selection-based strategy was 383.4 and 390.47 s, respectively. Experimental results show that the signal strength-based priority strategy employed in this work yields lower time consumption then a random selection-based strategy. This is because the drone swiftly began making a sweep of wireless signals and fetching data based on the signal strength-based priority strategy when the drone flight is over the terrestrial terminal. However, when a random selection-based strategy was employed, the drone needed to flight directly above the terrestrial terminal to fetch data. As a result, experimental tests demonstrate that the introduced scheme can yields higher performance than a random selection-based strategy in terms of time consumption of data transmission between the drone and the ground terminal.

4) Evaluating the Effect of the System With Different Underlying Surfaces: An important consideration in the drone-enabled IoRT network involves the different scenarios affecting the channel quality of the communication link between the drone relay and terrestrial terminal, thus compromising the final data transmission rate. The impact of the application scenario on the drone-enabled IoRT network is a key issue. Thus, in this experiment, we tested the drone-enabled IoRT network applied to different underlying surfaces, including the Huazhaizi station and the Dayekou forest. The Huazhaizi station, which is located in the Gobi Desert, can provide a line of sight of several kilometers between the drone relay and terrestrial terminal, and the Dayekou forest, which is referred to as a dense forest, affects the channel quality of the wireless communication link. In this experiment, the flight altitude was set to 100 m, and the size of the data cached on the terrestrial terminal was 10 MB, 100 MB, 1 GB, and 2 GB.

Fig. 17 shows the size of the cached data as a function of the time required to collect the cached data from the terrestrial terminal via the drone relay. In the demonstrated application at the Huazhaizi station, the results indicate that during the different application tests, the time consumption for remote data retrieval via the drone relay varied. Choosing the Dayekou

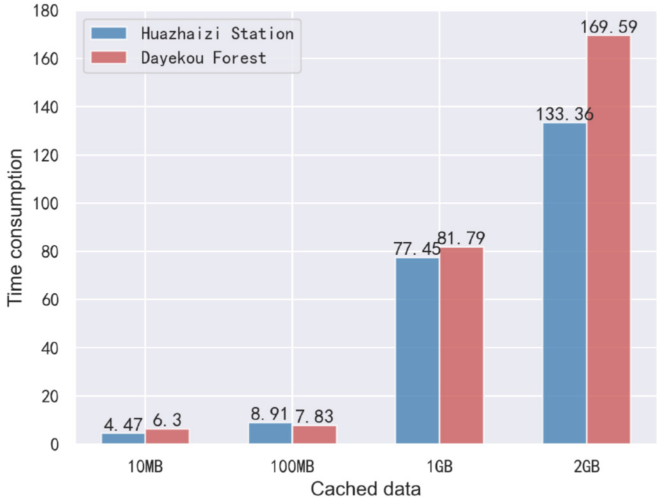

Fig. 17. Performance comparison of the drone-enabled IoRT network between the different underlying surfaces.

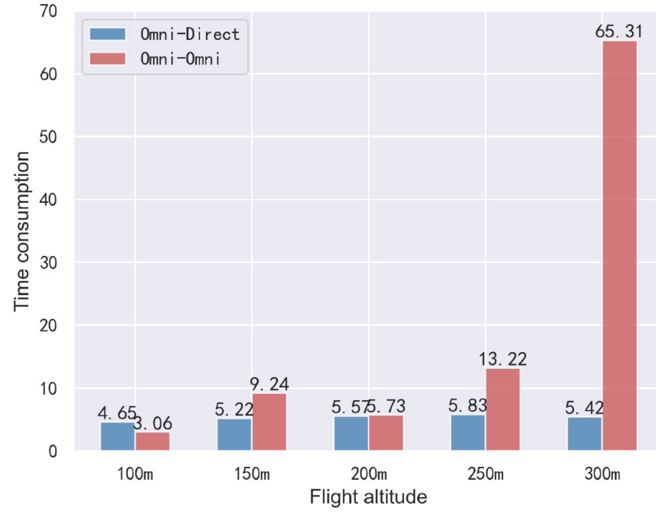

Fig. 18. Performance comparison of the drone-enabled IoRT system between the different configured antennas.

forest and Huazhaizi station as examples, we found that in the Dayekou forest and Huazhaizi station, the required transmission times to transfer 10 MB of data reached 6.3 and 4.47 s, respectively, and when the size of the cached data was 2 GB, the required times were 169.59 and 133.36 s, respectively. These experimental results suggest that the drone-enabled IoRT network applied to the different underlying surfaces, such as the Gobi Desert and dense forest, exerts a major impact on the data transmission capability.

5) Evaluating the Effect of the System With Different Antenna Selections: Additional testing was conducted to capture the performance of the drone-enabled IoRT network. The antenna, as the port to receive and transmit signals, is an indispensable part of the developed wireless transceiver, and its structure and performance play a key role in the communication quality. Thus, to analyze the impacts of antennas on the data transmission performance of the drone-enabled IoRT network, we conducted two experiments. In these experiments, we configured the drone relay with an omnidirectional antenna, while the antenna of the terrestrial terminal was an omnidirectional antenna or a directional antenna. Additionally, the size of the cached data on the terrestrial terminal was set to 10 MB, and the drone flew at different altitudes of 100, 150, 200, 250 and 300 m.

Fig. 18 shows the flight altitude of the drone as a function of the time required to collect cached data from the terrestrial terminal via the drone relay. The results of the first experiment demonstrate that for the terrestrial terminal configured with a directional antenna, the time consumption for data retrieval via the drone relay reached approximately 5 s at the different flight altitudes, which remained almost unchanged. In terms of the terrestrial terminal configured with an omnidirectional antenna, the time consumption for data transmission greatly increased with increasing flight altitude. For example, at a flight altitude of 100 m, the time consumption for cached data collection from the terrestrial terminal configured with omnidirectional and directional antennas reached 4.65 and 3.06 s, respectively. Moreover, at a flight altitude of 300 m, the time consumption for data collection reached 5.42 and 65.31 s, respectively. These experiments further suggest that configuring terrestrial terminals with different antennas could provide a powerful scheme to improve the data transmission capability of the drone-enabled IoRT network.

V. Discussion and Conclusion

Fetching data recorded by monitoring devices deployed in the field is usually not only time consuming but also laborious. Moreover, this task becomes infeasible due to harsh terrain conditions or snow cover and consequently leads to data recording issues attributed to device capacity overloading. Hence, retrieving recorded field data, especially in extreme remote and harsh environments, is urgent and essential. We conducted experiments to improve the capability of the drone-enabled IoRT system through hardware system design and tested the performance of various applications in extreme remote and harsh areas by comparing the time consumed. The integrated innovative design for this challenging problem, including the drone-enabled IoRT system, was integrated with a terrestrial vertebrate all-weather monitoring device, infrared camera, phenological camera, and CR1000X datalogger.

In summary, the data recorded by monitoring devices deployed in remote and hard-to-access regions are traditionally collected through human efforts. Fetching data recorded in extreme remote and farmost areas requires atleast 5 man-hours in the Qilian Mountains, and the process is dangerous, while the time required to perform the data collection task with a drone is only 30 min. Most importantly, the process is safe without risks to humans. The above flight experiments validated our analysis and evaluated the performance of the proposed scheme. The proposed applications of the drone-enabled IoRT network demonstrated that data recorded by monitoring devices deployed in extreme areas of interest could be highly efficiently retrieved.

The drone-enabled IoRT network benefits from high-speed relay and low-cost operation. However, in a previous drone-enabled IoRT network, the transmission rate between the drone relay and terrestrial terminal was approximately 3.5 MB/s, resulting in a low rate that could not meet the demand of transferring a large volume of data. In this article, considering the performance of fetching a large volume of data, we improved the hardware system of the drone-enabled IoRT network, and the experimental results indicated that the improved system increased the transmission rate up to 10–15 MB/s. Moreover, we optimized the software system, and introduced two schemes, i.e., the Nginx-based strategy for data transmission between the monitoring devices and the terrestrial terminal, as well as a signal strength-based priority strategy for data transmission between the terrestrial terminal and the drone relay. The introduced method improved the performance of data transmission in terms of time consumption. We also conducted data retrieval validation tests via the innovative drone-enabled IoRT network. The proposed ecosystem monitoring applications were implemented in the Qilian Mountains, including wildlife, plant phenology, and environmental monitoring. Monitoring data were retrieved from the deployed terrestrial terminals through drone relays. The retrieved wildlife images included *P. nayaur*, *M. himalayana*, *L. oiostolus*, and *A. magna*, the obtained phenology data included *P. crassifolia*, and the environmental variables included the soil temperature measured by sensors at different altitudes. The experimental results revealed that the time required to transfer wildlife images reached only 0.35 s. To transmit a set of phenology data, 0.29 and 0.34 s were required, and to collect environmental monitoring data, only 0.0302 s was needed.

The demonstrated application in the Qilian Mountains further revealed that the drone-enabled IoRT network could improve data retrieval in extreme areas lacking a ground public network or hardly accessible by humans. Specifically, the reduction in human efforts, resources, and cost could result in a considerably higher efficiency than that in conventional communication networks, such as the Internet and mobile phone networks, or that associated with the notable human efforts required to collect monitoring data in extreme areas. In this vein, the drone-enabled IoRT network could be employed to facilitate the remote retrieval of monitoring data in extreme areas of interest.

More improvement strategies of the drone-enabled IoRT network will be considered in the future, and the main perspectives for transmission data performance enhancement include adjusting the antenna configured on the terrestrial terminal. Improvements in the control systems of the drone relay and terrestrial terminal will also be considered and tested. More robust processing power of the control system is needed to achieve high-speed communication between the drone relay and terrestrial terminal. In addition to the above system improvement, additional application scenarios of the drone relay for remote data retrieval would be of practical interest. The obtained results indicated that application scenarios, such as the Gobi Desert and dense forest significantly impact data transmission in the drone-enabled IoRT network.

The drone-enabled IoRT network is confirmed to provide a highly valuable method for data retrieval in remote and hard-to-reach regions. This work offers broad application prospects, even though the considered approach represents a new ecosystem monitoring paradigm in extreme areas. The revolutionary improvement in data retrieval via the drone-enabled IoRT network could increase our knowledge of ecosystem processes in extreme areas.

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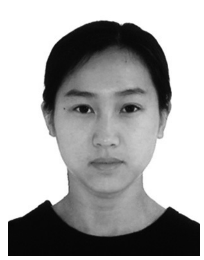

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