

Research Article

Smart Grazing in Tibetan Plateau: Development of a Ground-Air-Space Integrated Low-Cost Internet of Things System for Yak Monitoring

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This paper analyzes the present situation and difficulties of yak breeding in the “Three Needy Autonomous Regions” of Sichuan Province, integrating the specific natural environments of Qinghai-Tibet Plateau. Research work focuses on the requirements of no network conditions, large-scale application, and ultralow use cost. We propose a smart grazing IoT system, in which collars and ear-tags are designed to collect the positions and physiological signs of yaks, BeiDou Satellite-Base Stations (BDS-BSs) are designed to build local area network and ultralong-distance communication, and what is more, UAV is designed to expand the communication range to hundreds of kilometers. According to the actual needs of grazing monitoring, we propose an effective data reduction method, so that BeiDou Satellite (BDS) short-message technology can be applied to the IoT communication with high efficiency and low cost. The author carried out a significant number of experiments and verification: (1) collar realized positioning and physiological signs collecting of yaks. (2) The local area network (LAN) scheme based on LoRa built a stable communication distance of more than 3 km. (3) Ultralong-distance communication scheme based on BDS short-message technology effectively solved the problem of no network and got excellent zero additional use cost. (4) A plateau mountainous grazing UAV is designed and developed to expand the communication range.

1. Introduction

In the vast northwest of China, especially in Tibet, Qinghai, Northwest Sichuan, Gansu, and Xinjiang provinces as we called “Qinghai-Tibet Plateau areas”, where the average altitude is 4000 meters, natural conditions are exceptionally arduous, and people’s production and life are challenging. From where the “Three Needy Autonomous Regions” of Ganzi, Aba, and Liangshan in Sichuan Province are the world-known poverty-stricken areas. With typical plateau mountain environments, the vegetation on the top of the mountains is mostly grass and low shrubs, which form nat-

ural ranches. Local people who live in the low altitude valleys have to graze on mountain tops, creating a unique habit of “living under the mountain, grazing and production on the mountain” in the Tibetan Plateau for thousands of years. It meanwhile indicates there would be dozens of kilometers’ travel distance from residential areas to grazing mountain tops. Generally, isolate mountain pastures may have a radius of more than ten kilometers, and contiguous pastures can reach a radius of hundreds of kilometers, as shown in Figure 1. With the Tibetan Plateau region’s unique terrain and climate conditions, only the warm climate from May to October is suitable for grass growth. Yaks mainly fatten

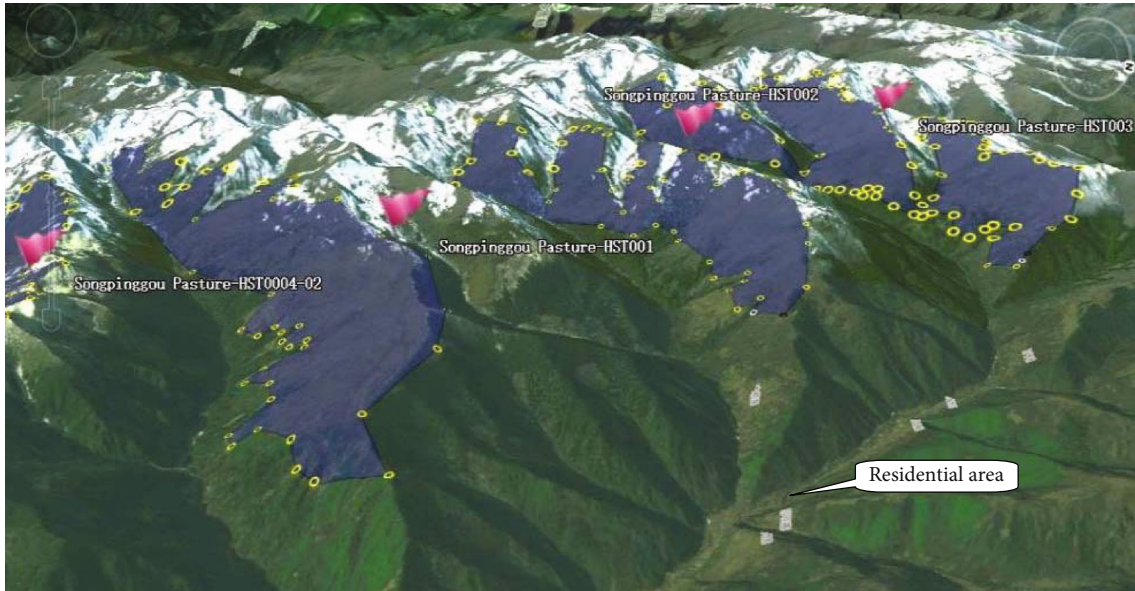


FIGURE 1: Geographical conditions of plateau mountainous pasture.

up in this period under natural grazing conditions. In other periods, the mountain pastures are capped with snow, which means the food is mainly withered grass. Although yaks can adapt to such climatic conditions, they have to thin down as the effect of limited food gradually. Under these natural conditions, the effective growth cycle of yaks merely maintains half a year. They usually need to grow 5-6 years before being put into the market, brings about the extremely low breeding efficiency.

As the mountain pastures are usually large and far away, the grass is difficult to transport. It is hard for herdsman to breed yaks. When it comes to snowy winter and spring, it is also challenging to find and cure the weak or sick yaks. What is more, March to April is the most challenging period, as the withered grass is exhausted out, and the green grass has not yet sprouted, and food is extremely scarce. Disease, loss, and unnatural death result in approximately 10% loss rate of yaks per year, which has become the primary risk of grazing and breeding.

Because of the above problems, how to monitor the locations and vital signs of yaks becomes very important. With accurate locations and vital signs, herdsman could effectively track and locate animals, and weak and sick yaks could be found and cured quickly. With the mountainous plateau's unique grazing conditions, it is urgent to develop long-endurance (more than half a year) and low-cost equipment for monitoring yaks. Under the background of China's Rural Revitalization Strategy, it is important to develop industries with local characteristics according to local conditions. Focusing on characteristic industries, injecting modern science and technology to promote industrial development is a practical solution.

Nowadays, IoT, big data technology, UAVs, and robotics are widely used in our life. These technologies are changing the society deeply, from service industry to manufacturing

industry and agriculture. A low-cost and large-scale IoT system is the obvious need of herdsman in Tibetan Plateau region. Barker and Hammoudeh presented a survey on low power consumption networking for IoT and WSN systems, focused on the power usage of various IoT network protocols, and highlighted the sensor nodes' battery life boosted from hours or days to months and years [1]. Shammar and Zahary studied different disciplines of IoT such as architecture, OS, network stack protocols, software, and application and introduced the IoT technology to be used in tracking and monitoring farm animals to allow real-time surveillance in crucial situations such as the outbreaks of infectious diseases [2]. Xu et al. presented a survey of existing IoT devices/products and classified the commonly used IoT devices into three categories: mobile/wearable devices, smart home/building devices, and network devices, which indicated the wide usage of smart IoT devices in our daily life [3]. Smart city is one of the main mature application fields of IoT technology, like simple daily life of shopping, living payment, transportation, and even in some crucial and complex situations. As COVID-19 is changing our courses of action toward ensuring health security, an IoT network was presented in an airport to monitor the soap levels, room capacity, distances, temperature, and humidity of toilets, basing on different sensors [4]. Cvar et al. extended the concept of Smart Villages (rural settlement) by the use of IoT technologies [5]. An energy harvesting LoRaWAN was deployed and operated in a sampled forest region of Eastern China for environment monitoring [6]. González et al. presented a low-cost, low-power, and real-time monitoring system basing on the development of a LoRa (short for long-range) sensor network for AQM and gas leakage event detection [7]. Davcev et al. presented an innovative, power efficient, highly scalable long-range, and low power consumption IoT agricultural system based on the LoRaWAN

network, which was used to collect air temperature and humidity, leaf wetness, and soil moisture readings in vineyard field [8]. UAVs are rapidly used in the field of agriculture such as weed mapping, soil and crop status monitoring, and pesticide spraying and even being used to monitor large-scale livestock in rural farms [9]. By collecting data from ground WSN, a UAV was utilized to adjust its trajectory for keeping droplet deposition in the target spraying area [10]. A long-term observation was conducted for the yield prediction of maize using an UAV [11]. Minhas et al. presented a reinforcement learning (RL) and UAV-aided multi-path routing scheme for public safety networks so as to increase network lifetime [12]. An IoT system can be established to monitor the grazing in mountain pastures of the Tibetan Plateau area.

With the rapid development of IoT technology, satellite positioning, sensor nodes, wearable devices, and communication networking technologies have been vigorously developed and widely used. Satellite navigation devices can be used to determine their positions using a satellite navigation system, such as GPS, Galileo, GLONASS, and BDS. GPS is a well-known and most widely used satellite positioning system, and BDS is the latest deployed navigation system. Li et al. presented an analysis of code bias based on multi-path combination observations, which improved the single-point positioning results, and the vertical component decreased by 0.42 m and by 0.28 and 0.1 m in north and east direction [13]. Wei et al. designed a remote monitoring system to track vehicles based on the combination of BDS and GSM, only spent little money on low price hardware and mobile network GSM fees [14]. Yang et al. introduced the basic performance of BDS-3 and presented that the post-processing orbit accuracy of the BDS-3 satellites had been increased to 0.059, 0.323, and 0.343 m, respectively, on radial, tangential, and normal directions [15]. Observation data in approximately 1 month were studied for determining the precise orbit for global positioning system models, and finally, researchers find out the GPS/BDS-3 combined solution got better accuracy performance compared to other solutions [16]. Jin and Su introduced that the BDS will provide highly reliable and precise PNT services as well as unique short-message communication under all-weather, all-time, and worldwide conditions [17]. Although satellite positioning technology has been well applied, researchers are still trying to develop more accurate, lower-cost, and more expandable applications. Especially the short-message technology, not just receiving signals but also sending signals, gives researchers a lot of imagination. Pereira et al. proposed an one M2M system for continuous patient monitoring in emergency wards, using low-cost and low-power WiFi-enabled wearable physiological sensors that connect directly to the internet infrastructure and run open communication protocols [18]. A boat tracking and monitoring system based on LoRa was presented and got the maximum coverage range of 4 km [19]. Sensors, LoRa, and circuits have been integrated into a WQMS system, which was low cost, small size, easy maintenance, continuous sampling, and long-term monitoring for many days [20]. Guidi et al. presented a wearable system comprised of a smart garment and portable electronics;

in fact, it was an elastic smart belt, which was fastened around the chest behind the shoulder area for heart rate variability monitoring in horses [21]. Accelerometer/gyroscope sensors were attached to the ears and collars of sheep, which could continuously survey the eating behavior sampled at 16 Hz and also be used to monitor health and welfare [22].

Advanced technologies should be used to monitor livestock and change the traditional arduous grazing production life of herdsmen in the Tibetan Plateau area. Navigation satellites are used for tracking the position of livestock. Smart sensors and wearable devices could be used to detect the sign information of yaks. Wireless sensor networks (WSNs) and the low-power wide-area network (LPWAN) are potential technologies for establishing the monitoring system and even IoT system.

To solve long-distance and wide-range communication between yaks and herdsmen, mobile communication and satellite communication are the most appropriate ways. However, pastures are usually vast uninhabited areas, and deploying a cellular network will be extremely expensive. The cost of commercial satellite communication services is even higher, which is difficult to adapt to the low-cost and large-scale use in the field of grazing. The BDS-3 short-message communication technology supports long-distance, low-cost, and two-way communication. As the high power consumption of BDS short-message communication technology, in order to meet the needs of long endurance, the device could be large and heavy, which will be difficult to design as a wearable collar. Therefore, it is essential to design independent collars and BDS-BSSs, so as to build a yak physiological sign data acquisition and transmission network system. Several BDS-BSSs could be enough to provide communication network services for isolated mountain pastures, and for contiguous pastures, UAV equipped with BDS-BSS to provide mobile communication network would be the most suitable solution. This paper focuses on using the BDS short-message communication technology to build the communication and data transmission platform, which achieves ultralow-cost communication, as the following points:

- (1) Design and develop the ear-tag to collect yaks' body temperature and heart rate data, using Bluetooth technology to send the data to the collar
- (2) Design and develop the collar to collect yaks' positioning data, using LoRa technology to send data of position, body temperature, and heart rate to the BeiDou Satellite-Base Station Sender (BDS-BSS) without internet in plateau and mountain areas
- (3) Design and develop the BDS-BSS, using LoRa technology to receive the collar's positioning data within a communication distance of more than 3 km, covering a range of 6 km on the mountain pasture
- (4) Design and develop the BeiDou Satellite-Base Station Receiver (BDS-BSR), aiming at building long-distance communication for the whole IoT system, which can communicate with the BDS-BSS. With

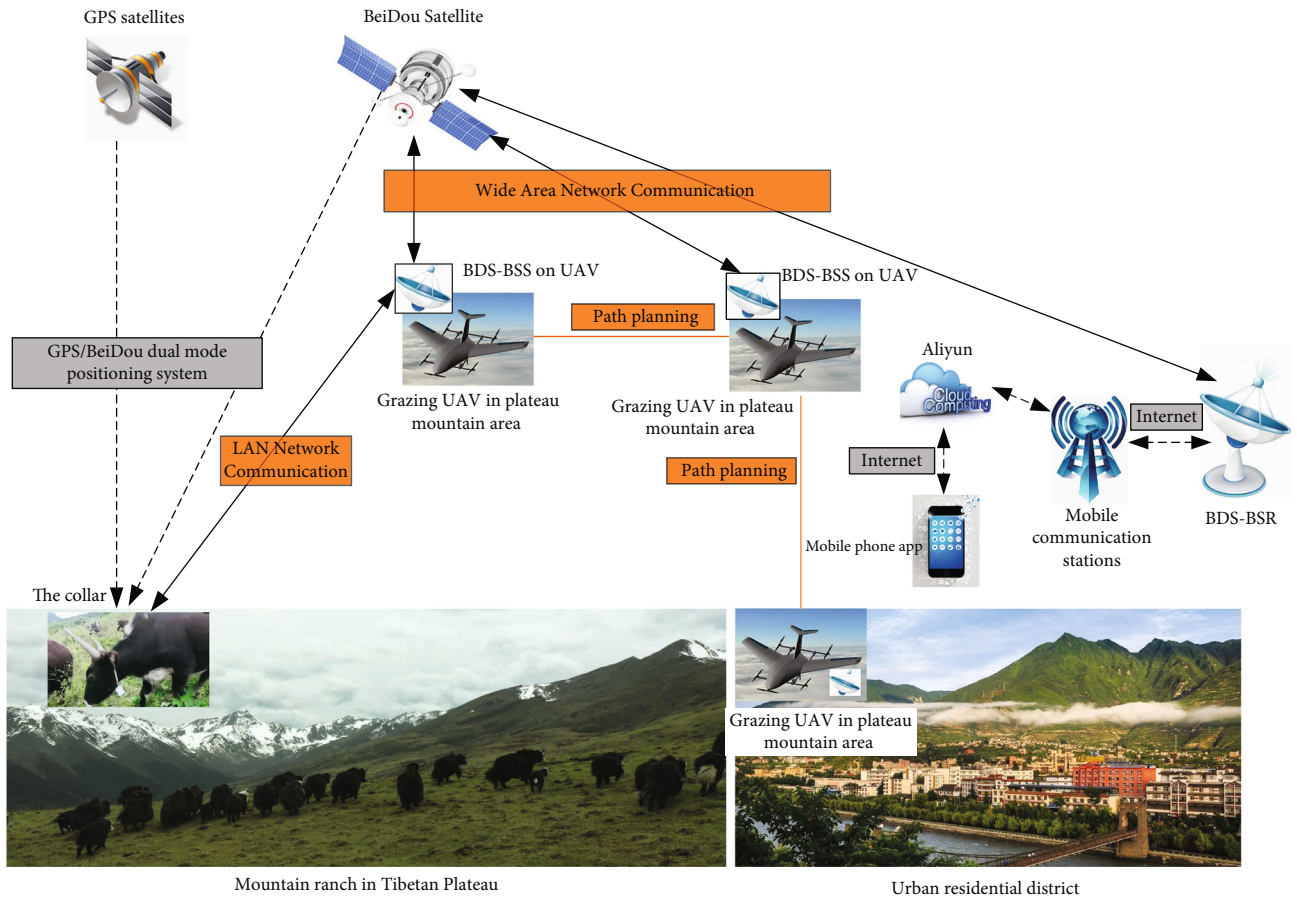


FIGURE 2: Architecture of air-space-ground integrated intelligent grazing system.

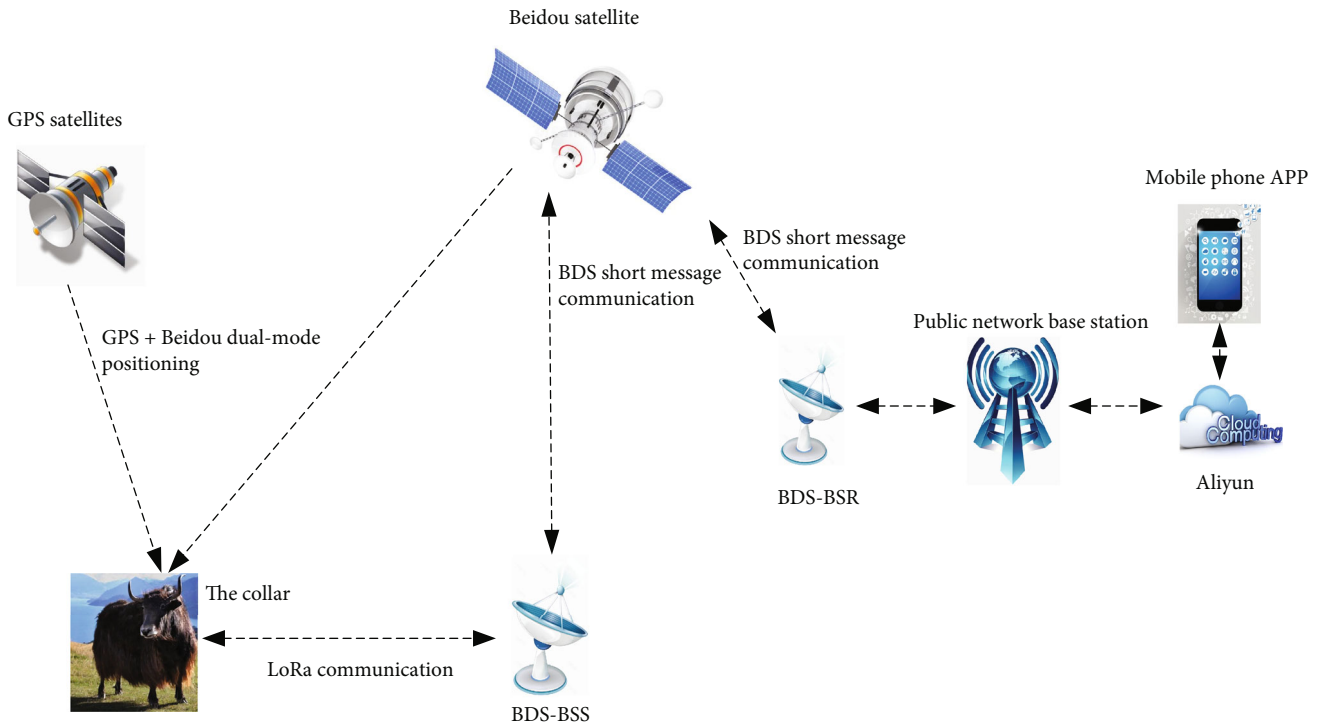


FIGURE 3: Subarchitecture of yak monitoring system based on fixed BDS-BSS.

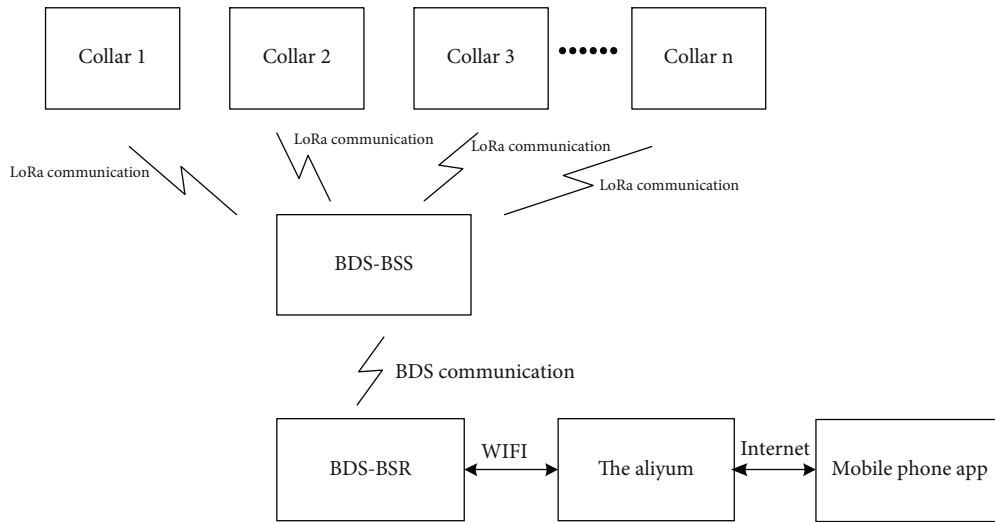


FIGURE 4: Subarchitecture of yak monitoring system diagram.

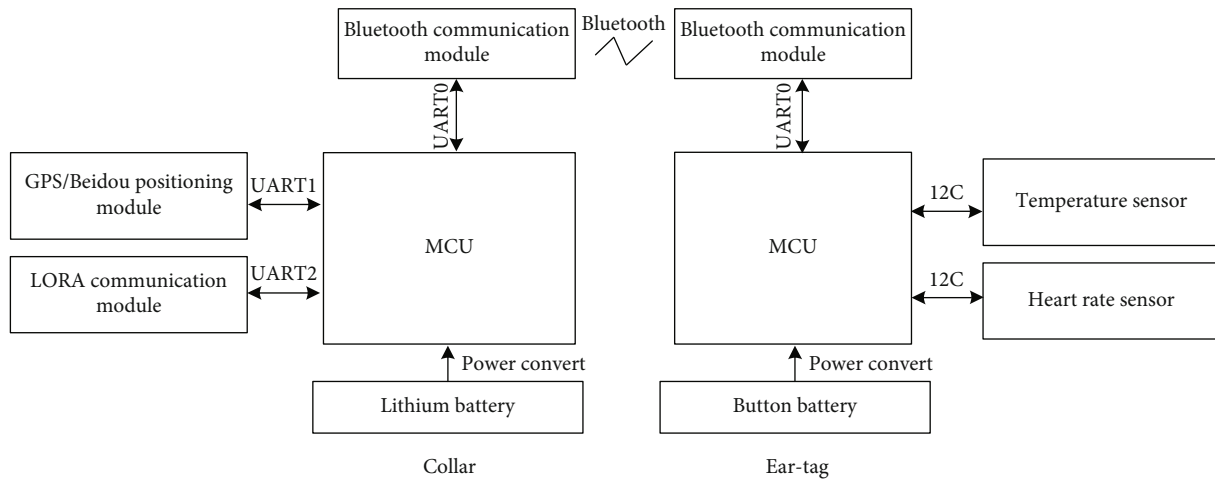


FIGURE 5: Block diagram of the monitoring equipment.

the BDS short-message technology (global communication technique), the BDS-BSR could receive the collar’s positioning data and upload it to Aliyun

2. Related Work

Smart grazing concept relates to location-aware devices to monitor the movement of yaks in pastures. Reference [23] used a differentially corrected global positioning system to distinguish grazing and resting activity patterns of cattle based on GPS recordings. Davis et al. developed a low-cost GPS Herd Activity and Well-being Kit (GPSHAWK) to monitor locomotion behavior of cattle, and location data was collected from its own GPS receiver, which was claimed as low-cost device of \$500 [24]. In fact, with the price of \$500, the GPS receiver would be too expensive to promote a universal application in grazing. By changing the collar/tag ratio, a low-cost IoT system was developed, based on which, some animals were fitted with GPS collars (100-150 € per device) and others were fitted with Bluetooth tags [25]. It is a good method to reduce per animal

cost, but the GPS collar is not cheap. Vázquez-Diosdado et al. proposed a monitoring system with an embedded edge device that includes a triaxial accelerometer and triaxial gyroscope sensors, which accurately classified walking, standing, and lying conditions and represented a potential approach of long-term automated monitoring [26]. Based on combined data of the 3D accelerometer and a GPS sensor fixed on a neck collar, Riabof et al. predicted the behavior of dairy cows on pasture, which is used to better understand the relationship between behaviors and pasture characteristics [27]. Xu et al. developed an efficient and accurate approach to study the social behavior of cattle groups, in which GPS location information was used to build a high-accuracy wireless tracking system [28]. Although a lot of researches on the application of positioning have been taken in the smart grazing field, lower cost and longer service time will be the most unremitting demands, especially for the huge number of yaks.

Positioning is the most important and basic demand in grazing monitoring, and physiological sign detection helps

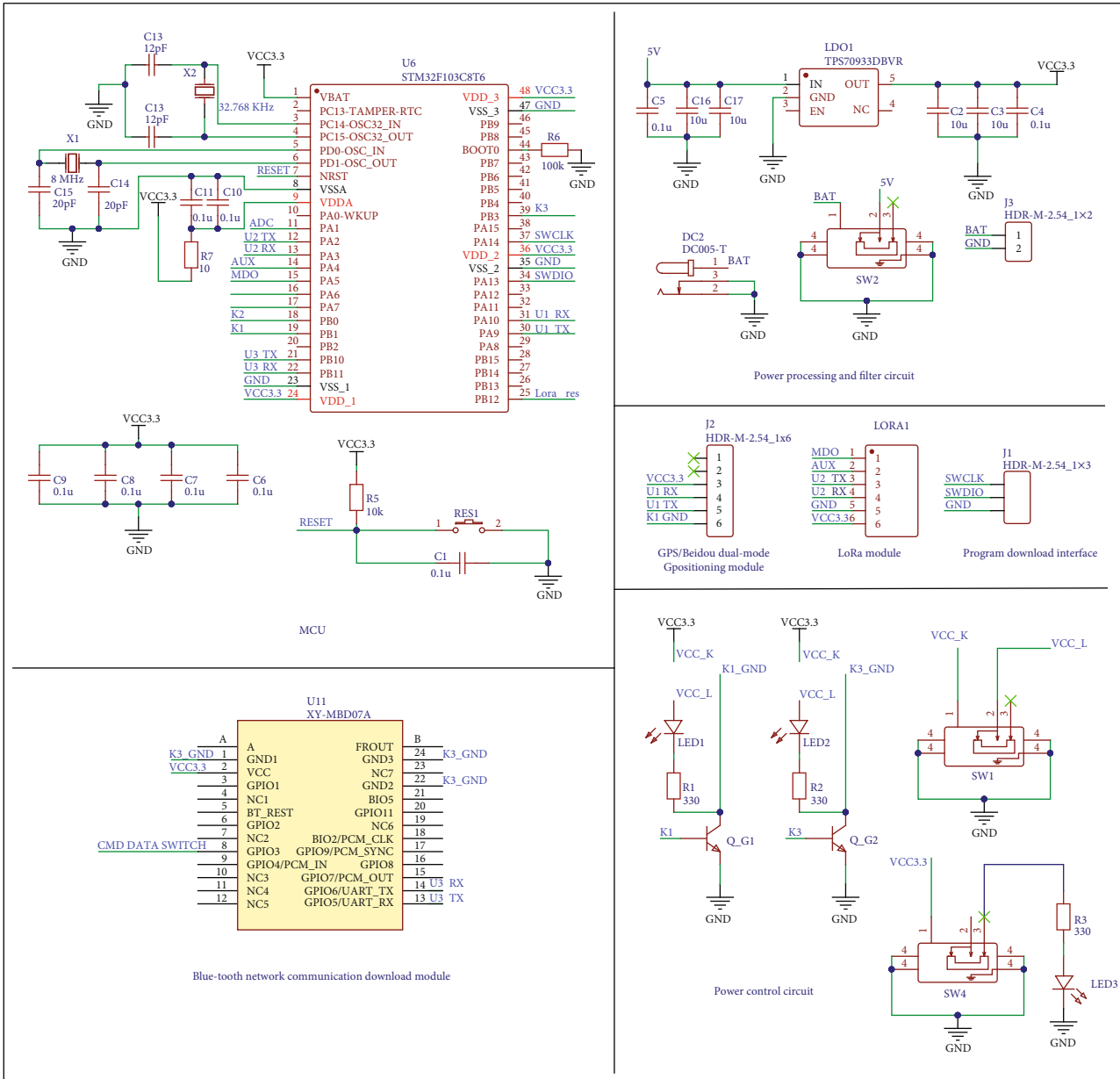


FIGURE 6: Schematic diagram of the collar.

herdsmen to intervene in the healthcare administration of yaks in time. Electrode pads were attached to the left side of the chest of each cow after removing the hair using clippers at three sites, and by this means, Aoki et al. recorded the cows' heart rate variability and applied power spectral analysis of HRV [29]. Various properties and capabilities of HR monitoring techniques were compared to check the potential to transfer the mostly adequate sensor technology of humans to livestock in terms of application. Nie et al. concluded the photoplethysmographic (PPG) technique as a feasible implementation in livestock, which could be integrated into an ear-tag [30]. Nie et al. also emphasized the challenges of transferring the PPG technique from human beings to livestock that whether the PPG theory based on skin blood perfusion is applicable for animals, and the similarities of skin between humans

and animals need to be checked first. Youssef et al. used PPG sensors on a pig's body to test whether it allows the retrieval of a reliable heart rate signal and concluded that the agreement between the PPG-based heart rate technique and the reference sensor was between 91% and 95% [31]. The reference also indicated that locations of the pig's body be chosen to place PPG sensor probe were important, because of their higher cutaneous perfusion and body fat. A number of cited works highlight that physiological sign detections are appealing and challenging for remote livestock monitoring, and there is no public literature on the detection of yak signs.

Smart grazing in Tibetan Plateau pastures is a typical application of long-range WSN and LPWAN systems. Raza et al. introduced and compared all kinds of LPWAN technologies such as SIGFOX, LoRa, INGENU RPMA,



FIGURE 7: Circuit board of the collar.



FIGURE 8: Physical collar and ear-tag.

TELENSA, QOWISIO [32], and NB-IoT [33], which provided the basis for scheme selection. LoRa is the most widely studied and applied technology in similar fields such as remote livestock tracking [34], piggery environment control [35], intelligent agriculture [36], and forestry monitoring [37], and these research works give us clear direction. Janssen et al. investigated a 2.4 GHz LoRa modulated and resulted in a maximum range of 333 km in free space, 107 m in an indoor office-like environment, and 867 m in an outdoor urban context [38], which indicated the great potential LoRa technologies for ultralong-distance grazing. By allocating the spreading factor and timeslot in the frame structure, DG-LoRa could support approximately five times more connections to the LoRa network satisfying a 5% data drop rate [39], which was just a simulation result. Berto et al. presented a peer-to-peer communication between nodes, without the use of gateways, and extend node reachability through multihop communication [40], which was claimed as a beneficial solution of “out-of-internet” communication. However, the so-called peer-to-peer communication only occurs between three nodes, and whether it can be applied on a large scale still needs further research and experiment. By using the LoRaWAN protocol stack, Guerrero et al. estimated the channel conditions and predicted the packet

delivery to ensure wireless networks’ dependability [41]. Despite a good number of cited LPWAN system research works, there is no public literature on the real application of out-of-internet conditions similar to Tibetan Plateau pastures. Long-distance, large area, mountainous, and out of mobile network conditions lead to the particularity of communication network construction.

Yak is a very special species, which grows in the form of natural grazing and leads to a super long travel distance, which brings great challenges to the design of the management system. Gaitan proposed and developed a long-distance communication architecture for medical devices based on the LoRaWAN protocol that allows data communications over a distance of more than 10 km [42], which is not long enough for grazing in the Tibetan Plateau. Gaggero et al. developed a prototype based on a quad-copter drone equipped with a LoRaWAN gateway, which verified that a UAV can be suitable for the envisioned purpose [43]. Behjati et al. developed a farm monitoring system that incorporates UAV, LPWAN, and IoT technologies to transform the current farm management approach, which presented the maximum achievable LoRa coverage of about 10 km [9]. The above-cited works cannot meet the actual needs of grazing in Plateau Tibetan areas, long-distance, large area, mountainous, out of mobile network conditions, and real-time monitoring. Satellite communication appears unique advantages under the above conditions, especially the free BDS Short-Message Satellite Communication System service.

3. System Architecture

We propose a ground-air-space integrated grazing system, as shown in Figure 2, which consists of the following two parts:

- (1) Subarchitecture of yak monitoring system based on fixed BDS-BSS, as shown in Figure 3. Collar was worn on the neck to collect position, body temperature, and heart rate signs of the yak. LoRa wireless communication technology is used to transmit signs and data between the collar and fixed BDS-BSS. BDS short-message technology is used to transmit signs and data between BDS-BSS and BDS-BSR. And then, the BDS-BSR uploads the relevant data to Aliyun. At last, herdsman can view the locations and signs of yaks from their mobile phones, which is convenient for monitoring yaks, as shown in Figure 4
- (2) *Large-Range Monitoring System Based on Plateau Mountainous Grazing UAV*. The UAV is used to carry a BDS-BSS, which is equipped as an integrated mobile BDS-BSS. With the flight of UVA, the monitoring area of pastures could be extended to more than 100 km², which is also used for yak search and rescue.

4. Design and Implementation

4.1. *Design and Implementation of Monitoring Equipment*. Figure 5 is a block diagram of collar subsystem, which

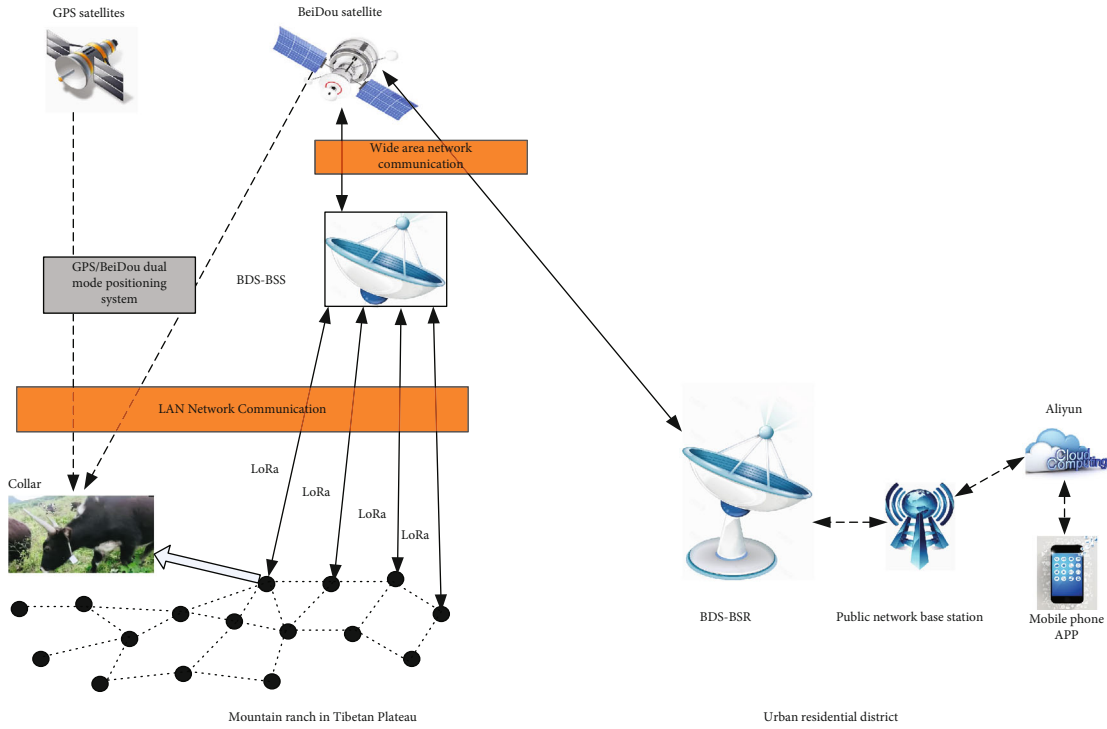


FIGURE 9: Communication network diagram.

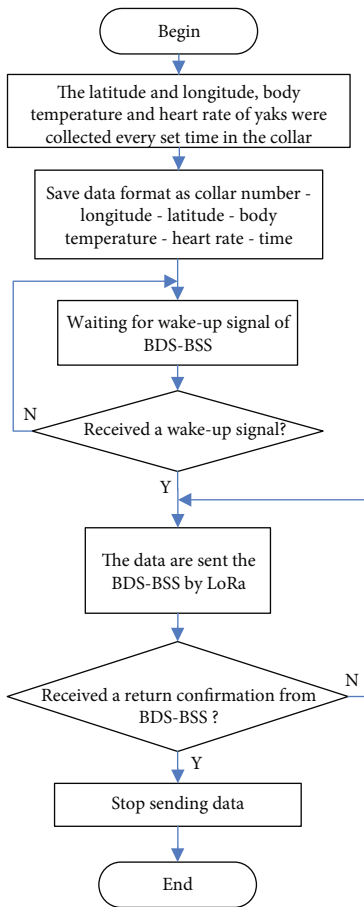


FIGURE 10: Collar communication diagram in LAN.

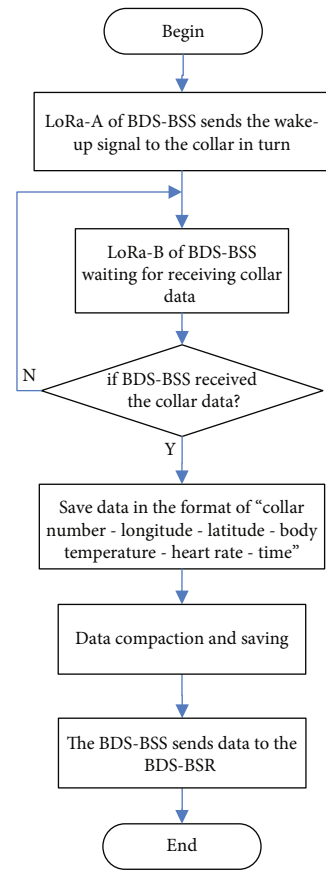


FIGURE 11: BDS-BSS communication diagram in LAN.

TABLE 1: Original data format description.

1-11	12-63	64-114	115-120	121-129	130-140
The collar number (1-2000)	Longitude	Latitude	Body temperature (30°~45°)	Heart rate (30~150/min)	Time (0-1440 minutes a day)

TABLE 2: Simplified data format description.

1-11	12-27	28-37	38-41	42-49	50-60
Collar number (1-2000)	D (0-50000)	Θ (0-628)	Body temperature—30 (0-15)	Heart rate—30 (0-120)	Time (0-1440)

includes a collar and an ear-tag, and the data communication is carried out by Bluetooth. The collar consists of microcontroller unit (MCU), BDS positioning module, LoRa communication module, Bluetooth communication module, and lithium battery. When it is in hibernation, no data is transmitted, which presents the lowest power consumption status. As it is awakened by BDS-BSS, the location and physiological signs will be transmitted to the BDS-BSS through the LoRa communication module. Moreover, the update frequency of location can also be set by the mobile phone APP. The ear-tag needs to be low power and miniaturization, so we selected low power MCU and used RTC settings to change the state of sleep and awakening circularly. The circuit schematic is designed as shown in Figure 6, and the PCB is designed and soldered as shown in Figure 7. Finally, the shell modeling design of the collar and ear-tag is carried out. The physical collar and ear-tag are shown in Figure 8.

4.2. Design and Implementation of Network Communication.

As shown in Figure 9, this communication system includes two parts, LAN and WAN networking. The LAN communication system includes collars and BDS-BSS, and the WAN communication system is composed of numbers of BDS-BSSs and BDS-BSRs.

4.2.1. LAN Communication. The collar collects and saves positioning, temperature, and heart rate data according to the set time of APP. When collar receives the wake-up signal of BDS-BSS, the saved data are sent to the BDS-BSS through LoRa wireless communication. The BDS-BSS configures two LoRa modules A and B to collaborate with collars. LoRa A sends a wake-up signal to the collar, and LoRa B receives the returned data of collar. The data is consisting of “collar number - longitude -latitude- body temperature - heart rate - time.” After receiving the data, the BDS-BSS saves the data and sends a confirmation message to the collar. The data transmitting in LAN communication network is chronologically ordered as shown in Figures 10 and 11.

4.2.2. WAN Communication and Data Compression. The WAN communication network is based on BDS short-message technology, and data transmits between BDS-BSSs and BDS-BSR. BDS supplies a bidirectional short-message communication service, which is a unique function and the first navigation satellite with message communication in the world. However, the BDS short-message communication service can send only 78 bytes

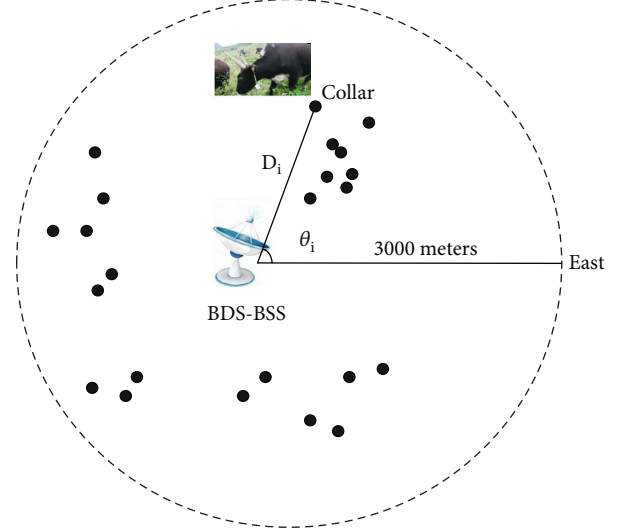


FIGURE 12: Collar azimuth relative to the BDS-BSS.

with maximum transmission frequency of twice a minute, which seriously restricts the application of mass data communication. Therefore, data compression and multicard multiplexing are essential means to improve communication capability.

(1) The Definition of Original Data Format. The data saving format in BDS-BSS is shown in Table 1. A complete piece of collar data is divided into 6 portions that 11 bits are reserved of collar number, 52 bits for longitude, 51 bits for latitude, 6 bits for body temperature, 9 bits for heart rate, and 11 bits for collecting time, in total of 140 bits. BDS short-message information can only send 4 collars' data at one time. The BDS-BSR will take 250 minutes to collect 2000 yaks' data of a common pasture, which seriously affects the real-time monitoring.

(2) Data Simplification. Therefore, it is necessary to simplify and reorganize the data, and we invested considerable energy in data compression in this research project. Firstly, we calculate the distance D between collar and BDS-BSS as Formula (1) described. And then, calculate the azimuth (θ) of the collar relative to the BDS-BSS as Formula (2). With this processing, the decimal point of longitude and latitude is removed and two positive integers are obtained, which compressed D and θ into 16 bits and 10 bits. The yak's body temperature value subtracts 30 (body temperature ranges from 30° to 45°), and the remaining integers occupy 4 bits. The remaining integers

TABLE 3: Data difference format.

11 bits	6~22 bits	5~15 bits	4-8 bits	5-13 bits	3 bits
11	6 0~16	5 0~10	4 0~4	5 0~8	3
Collar number (1-2000)	$D_i - D_{i-1}$ (0-50000)	$\Theta_i - \Theta_{i-1}$ (0-628)	The difference of body temperature (0-15)	The difference of heart rate (0-120)	time

occupy 8 bits after heart rate value subtracts 30 (heart rate ranges from 30 to 150 per minute), as shown in Table 2. BDS-BSS can send out 10 collars' data at one time, which takes 100 minutes to transmit 2000 yaks' data.

As shown in Figure 12, the distance between the collar and BDS-BSS is D_i , and the accuracy is 1 meter. The calculation formula is as follows:

$$D_i = \sqrt{(E_i - E_0)^2 + (N_i - N_0)^2} \bullet 100000. \quad (1)$$

The angle between the collar and BDS-BSS is θ_i , and the accuracy is 0.01 radian. The calculation formula is as follows:

$$\theta \begin{cases} \theta_i = \arccos \left(\frac{E_i - E_0}{D_i} \right) \bullet 100, (N_i - N_0) > 0, \\ \theta_i = \arccos \left(\frac{E_i - E_0}{D_i} \right) \bullet 100 + \pi, (N_i - N_0) < 0. \end{cases} \quad (2)$$

E represents longitude, N represents latitude, E_0 represents the longitude of BDS-BSS, N_0 represents the latitude of BDS-BSS, E_i represents the longitude of collar, and N_i represents the latitude of collar, $i = 1-2000$.

(3) Data Compression. Through the following data compression method, the transmitted capacity could be increased to 36 yaks per minute, which means 2000 yaks in one pasture could be monitored every hour:

- (1) BDS-BSS receives the data of collar $C_{i,0}$ and saves it to array $A_{i,0}$, which is stored in an external memory chip as format of Table 2
- (2) BDS-BSS reads out the data of $A_{i,0}$ and sends it to BDS-BSR. BDS-BSR receives the data of $A_{i,0}$ and saves it to array $S_{i,0}$, which is stored in an external memory chip as format of Table 2
- (3) BDS-BSS receives the data of collar $C_{i,i+1}$ and saves it to array $A_{i,i+1}$, which is stored in an external memory chip as format of Table 2. Calculate that $A_{i,i+1}$ subtracts $A_{i,i}$ in portions except collar N_0 and time, and the result is saved to array $B_{i,i+1}$ as shown in Table 3. The time is selected as interval time according to the settings of the mobile phone APP, which occupies fixed 3 bits as shown in Table 4. The data in $B_{i,i+1}$ is expressed as fixed digits and variations, and the length of the data is changeable. Under normal conditions, the variations of

TABLE 4: Interval coding.

Interval time (minutes)	Coded signal
1	001
15	010
30	011
60	100
360	101
1440	111

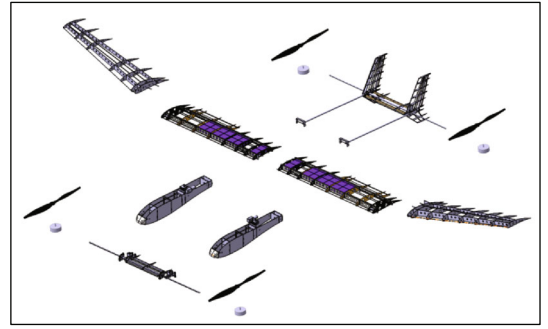


FIGURE 13: Grazing UAV in digital model.



FIGURE 14: Physical prototype of grazing UAV.

movement, temperature, and heart rate could be small. With this method, the transmission data is reduced to 34 bits in minimum and 72 bits in maximum, which promotes transmission efficiency greatly

- (4) BDS-BSS reads out the data of $B_{i,i+1}$ and sends it to BDS-BSR. BDS-BSR receives the data of $B_{i,i+1}$ and saves it to array $R_{i,i+1}$, which is stored in an external memory chip as format of Table 3

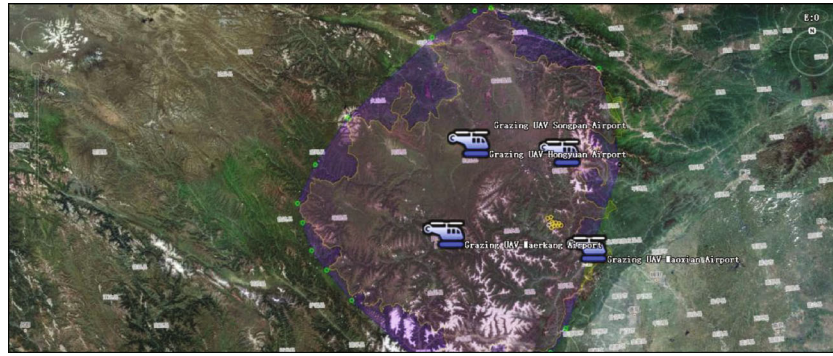


FIGURE 15: Flying area planning and station setting of mountaintop pasture in Aba Prefecture.

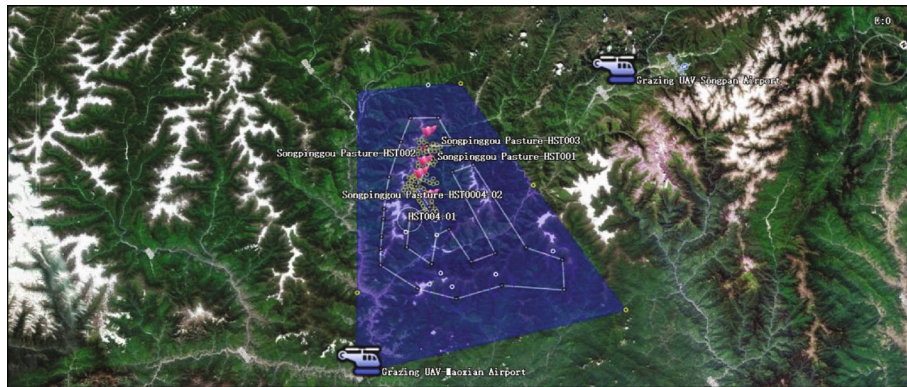


FIGURE 16: Precise planning of flight route of mountain pasture in the region.



FIGURE 17: Pasture scene of Songpinggou.



FIGURE 18: Wear a collar for the yak.

- (5) BDS-BSR recovers the data into original format as Table 1 basing on $S_{i,i}$ and $R_{i,i+1}$, and upload it to Aliyun

4.3. Design of UAV for Plateau and Mountainous Grazing

4.3.1. Design of Plateau Mountainous Grazing UAV. Facing the needs of natural grazing application in the geographical environment of Plateau Tibetan areas, we define “plateau mountainous grazing UAV”(PMG-UAV) as a new type of special-purpose UAV, which holds functions of flexible take-off and landing, long-distance flight, and ultralong

hang time. At the same time, as the communication network carrier, PMG-UAV is a basic platform, which needs long-term and high-frequency use, and should also have the requirements of high reliability and low cost. To this end, we designed a fixed-wing and multiaxis electric UAV, which could vertically take off and land, and tilt four-rotor for long-distance flight.

With a general design of double fuselage and three-wing layout, the PMG-UAV gets a maximum weight of 37 kg, load



FIGURE 19: Yak with collar.



FIGURE 20: BDS-BSS position on satellite map.



FIGURE 21: BDS-BSS position real scene.

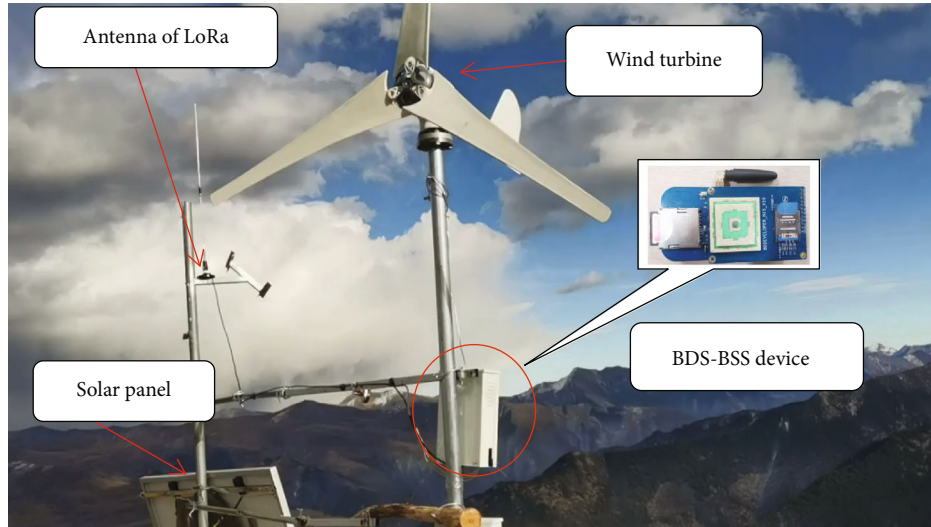


FIGURE 22: BDS-BSS and power generation facilities.

of 5 kg, wing area of 3 m², and a flight distance of more than 200 km. We arranged a 20.5 kg lithium battery in the main wing box to achieve a flight time of more than 6 hours (the currently completed prototype scheme). To further improve the flight time, 12 kg lithium battery and 8.5 kg solar thin-film scheme are designed to achieve a hang time of more than 10 hours (prototype scheme for further promotion). Considering the requirements of low use cost, we designed the aircraft into a detachable fuselage and a four-section detachable wing structure, so that the length of a single component does not exceed 2.5 m, which is convenient for storage and transportation. The digital model and physical prototype of the PMG-UAV design are shown below in Figures 13 and 14.

4.3.2. PMG-UAV Regional Flight Planning. By carrying BDS-BSSs, PMG-UAVs will build a convenient and flexible communication network with collars, so as to realize the data collection of yaks' physiological signs. At present, we have conducted a detailed investigation on the geographical characteristics of Aba Prefecture. There are about 1430 pastures, with a single pasture area of about 6-38 square kilometers, which is a flat, long, and banded. Due to the huge pastoral area in Aba Prefecture, we divide it into four parts and set up a PMG-UAV station in each area, as shown in Figure 15.

As shown in Figure 16, we have made a preliminary plan for the flight route in one of the four areas. Multiple PMG-UAVs are designed to fly in relay mode, so as to meet the needs of timely monitoring and data collection in whole area.

5. Test and Experiment

5.1. Experiment Deployment

5.1.1. Wearing the Collar. Yaks are wearing collars in one of our contracted Aviation Ecological Pasture, in Songpinggou



FIGURE 23: BDS-BSR real scene.

TABLE 5: Test results of different communication distance data.

The distance (m)	LoRa transmission rate (Kbps)	Number of data sent	Number of data received	The packet loss rate
500	0.3	100	100	0%
1000	0.3	100	99	1%
1500	0.3	100	98	2%
2000	0.3	100	96	4%
3000	0.3	100	89	11%

Township, Aba Prefecture of Sichuan Province, as shown in Figures 17–19.

5.1.2. Implementation of BDS-BSS. The BDS-BSS is installed at the top of the pasture, including power supply devices. With abundant solar and wind energy resources in the plateau mountain pasture, the wind and solar power supply

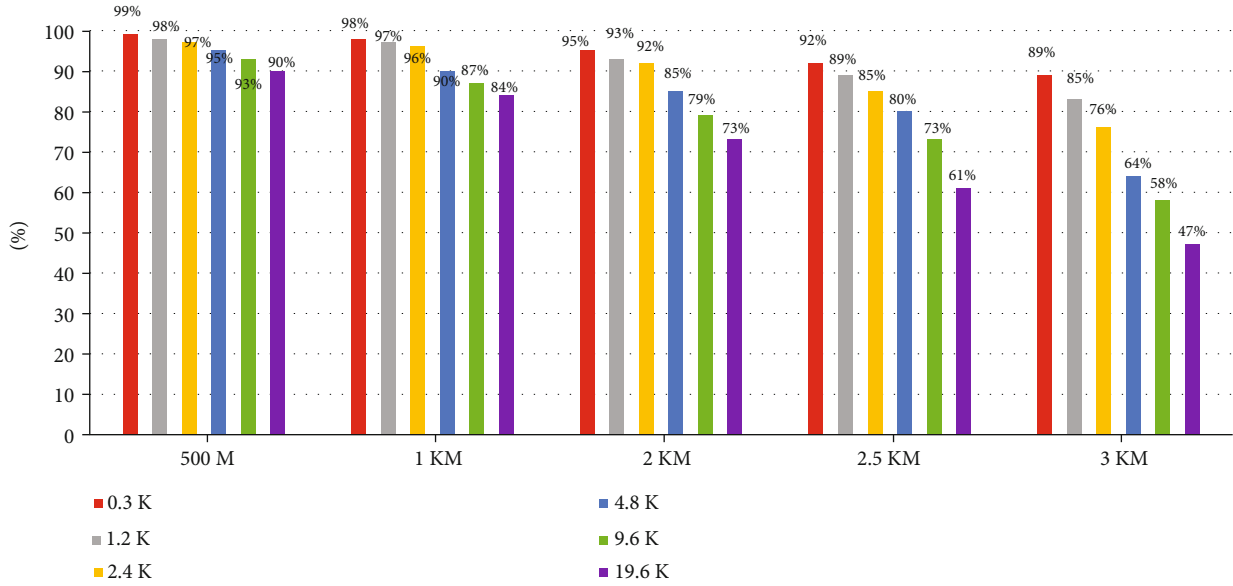


FIGURE 24: The test results of packet loss rate in different transmission rate and distance.

TABLE 6: Test results of maximum stable communication distance.

LoRa data transmission rate (Kbps)	Furthest communication distance (km)
0.3	4.3
1.2	3.2
2.4	2.5
4.8	2.0
9.6	1.4
19.2	0.9

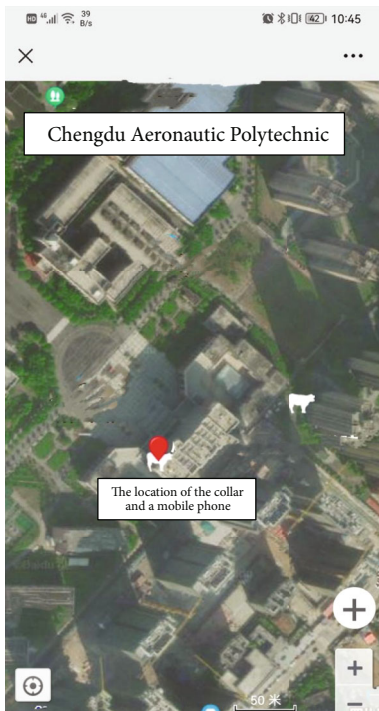


FIGURE 25: Collar position on mobile APP.

```

{
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  "location": {
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    "coordinates": [
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      32.12452266947445
    ]
  },
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}

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      31.75286313999558
    ]
  },
  "created_by": "system",
  "created_date": "ISODate("2020-12-10T23:03:20.866-0000")",
  "last_modified_by": "system",
  "last_modified_date": "ISODate("2020-12-10T23:03:20.866-0000")",
  "_class": "com.wingedcare.farm.domain.DeviceTelemetry"
}
    
```

FIGURE 26: Data received from BDS-BSS..

system is selected to power the BDS-BSS, as shown in Figures 20–22.

5.1.3. *Implementation of BDS-BSS.* BDS-BSR is placed at a higher place, such as the roof, with WiFi signal coverage, as shown is Figure 23. After BDS-BSR receives the data, it uses WiFi communication to upload all the received data to Aliyun every minute. The location information can be displayed intuitively on the mobile APP which is designed by ourselves independently. Other functions of APP will be enriched and updated gradually in later works.

5.2. Test Result

5.2.1. *Communication Distance Test.* The communication distance between the collar and BDS-BSS in 0.5 km,

Message ID	Tag	Key		
08C1F3DC78285ACF9800335B844F300 11.193.243.220:55752 543 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793552	2020-12-10 23:12:04	2020-12-10 23:12:04
08C1F3DC78285ACF9800335B73163030 11.193.243.220:55752 543 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793557	2020-12-10 23:17:14	2020-12-10 23:17:14
08C1F3DC78285ACF9800335E1FA19439 11.193.243.220:38045 543 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793563	2020-12-10 23:23:26	2020-12-10 23:23:26
08C1F3DC78285ACF9800336F636BF70 11.193.243.220:55831 543 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793566	2020-12-10 23:26:32	2020-12-10 23:26:32
08C1F3DC78285ACF98003366A35A154E 11.193.243.220:38011 543 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793572	2020-12-10 23:32:44	2020-12-10 23:32:44
08C1F3DC78285ACF9800336795852370 11.193.243.220:55146 543 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793573	2020-12-10 23:33:46	2020-12-10 23:33:46
08C1F3DC78285ACF9800336C51AE6854 11.193.243.220:55880 542 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793578	2020-12-10 23:38:56	2020-12-10 23:38:56
08C1F3DC78285ACF9800338305888FF0 11.193.243.220:55880 542 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793603	00:03:44	00:03:44
08C1F3DC78285ACF98003383F798CF10 11.193.243.220:55594 543 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793604	00:04:46	00:04:46
08C1F3DC78285ACF9800338072915D0D 11.193.243.220:55146 543 Bytes	HQTT_COMMON	bedou"GID_firm@@@bedou _id_1"26793615	00:15:07	00:15:07

FIGURE 27: Format of data uploaded to Aliyun.

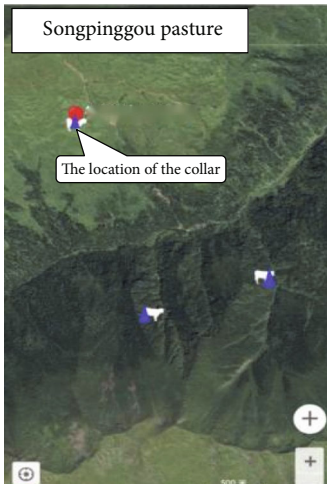


FIGURE 28: Yaks' positions in APP.

1 km, 2 km, and 3 km is tested and resulted as shown in Table 5.

A packet loss rate of less than 12% is regarded as allowed communication. We can see that the BDS-BSS fixed at the top of the experimental pasture can serve a good LAN communication within the range of 3 km. And the packet loss rate of the LoRa module gets a linear relationship with distance. With further distance, the packet loss rate promotes, and the communication is still successfully established sometimes.

5.2.2. Relationship between LoRa Transmission Rate and Distance. To verify the relevance of packet loss rates in different transmission rates and distances, we took several collars to test the receiving data within the same transmitting power, antenna gain, and frequency and within the same BDS-BSS LoRa module. The test is conducted under different transmission rates, as shown in Figure 24. And the farthest transmission distance under different transmission

TABLE 7: Communication tests at different heights.

Height (m)	Percentage of communication success rate (%)
30	100
40	100
50	100
60	100
70	100
80	100
90	100
100	100

TABLE 8: Communication tests at different speeds.

Different speeds (km/hour)	Percentage of communication success rate (%)
4	100
6	100
8	100

rates is shown in Table 6, with the condition of less than 12% packet loss rate.

Within the 3 km range, the packet loss rate of data transmission is less than 12%, which is considered effective communication. When the LoRa module's transmission rate is 0.3 Kbps, the reliable communication distance can reach 4.3 km. We selected the LoRa data transmission rate of 0.3 Kbps and built a feasible LAN communication network that ensured effective communication of 3 km.

5.2.3. Data Reception and Presentation. The first step is to test in school, we put the collar and a mobile phone in the same outside place, and a cow pattern and a red dot were displayed on the mobile APP and mobile satellite map

TABLE 9: Equipment cost and usage limitations.

Equipment name	Equipment components	Usage limitations	Price
Collar	A collar and an ear-tag	Temperature is -10~50°C Altitude is below 3500 m	\$62.0
BDS-BS	BDS-BSS, BDS-BSR, and power generation facilities	Temperature is -30~60°C Altitude is below 3500 m	\$2326.4
PMG-UAV	Aircraft structure, navigation system, and flight control system	Flight speed is 75 km/h Flight altitude is 6000 m	\$7528.1

separately. As the collar positioning data is uploaded to Aliyun via the BDS-BSR, it could be displayed correctly on the mobile APP. As shown in Figure 25, the cow pattern represents the measured collar position, the red dot is the calibration point, and the two icons overlap well.

The second step is field test in Songpinggou pasture. The test was implemented in December 10th, 2020. We installed collars on three yaks and obtained the data sent by BDS-BSS, as shown in Figure 26. Then data was uploaded to Aliyun, as shown in Figure 27. The yaks' positioning data was displayed correctly in APP, as shown in Figure 28. The blue triangles were the actual collar position of yaks reflected on the APP, and the red mark was the location of the BDS-BSS.

5.2.4. UAV Extended Communication Experiment. Because of the size and weight limitation of UAVs' low-altitude flight, we only use the four-rotor flight mode for communication verification in low-altitude and low-speed flight states, and the high-altitude and long-distance flight verification needs to be further carried out in pasture. The communication experiment results under low-altitude and low-speed flight are shown in Tables 7 and 8.

The experiment results indicate that the UAV-based LAN communication network can serve excellently under low-altitude and low-speed flight state, which provides potential capabilities of IoT accessing in ultralarge area according to the flight distance of UAVs.

The above test results show that it is feasible to use PMG-UAV to realize BDS data transmission and communication.

5.2.5. Equipment Cost and Usage Limitations. As shown in Table 9, all the equipment cost and the corresponding usage limitations were presented. All the devices meet the low-cost requirements, which can work stably and continuously in Aba Prefecture.

6. Conclusion

We proposed a low-cost grazing IoT system framework for the actual needs of yak breeding in Plateau Tibetan areas and carry out targeted design and experimental verification on terminal equipment (collar and ear-tag), communication base station (BDS-BSS and BDS-BSR), and PMG-UAV. The experimental results show that the scheme can achieve real-time yak sign data collection within 3 km of a single base

station, and ultralong-distance data transmission gets zero additional use cost. The smart grazing system framework proved to be effective, feasible, low-cost, and extendable and fully met the needs of yak grazing in the Tibetan Plateau.

BDS short-message technology is applied to the field of IoT for the first time, and a yak sign data compression method based on BDS and the actual situation of grazing is proposed, which improved the short-message communication capacity of four times and makes real-time communication possible.

The specific requirements for plateau mountainous grazing UAV are further clarified, and a feasible low-cost PMG-UAV scheme is presented, which provides a preliminary scheme for the IoT access of large-area pastures over 100 km².

In further research, we will promote the following aspects: (1) the flight test of the PMG-UAV in the pasture of Aba Prefecture, (2) flight verification along regional route planning, (3) the study of building communication network with multiple PMG-UAVs, and (4) upgrade the APP and combine it with the whole system so as to realize good application experience.

Abbreviations

BDS:	BeiDou Satellite
BDS-BS:	BeiDou Satellite-Base Stations
BDS-BSS:	BeiDou Satellite-Base Station Sender
BDS-BSR:	BeiDou Satellite-Base Station Receiver
PMG-UAV:	Plateau mountainous grazing UAV
IoT:	Internet of Things
UAV:	Unmanned aerial vehicle
MCU:	Microcontroller unit
WSNs:	Wireless sensor networks
LPWAN:	Low-power wide-area network.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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