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Research Paper

Energy problem and key technologies in passive systems

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ABSTRACT

Energy limitation is the core problem of passive sensing and computing systems. The basic idea of solving energy limitation is “increasing sources and reducing expenditure”. With regard to the main research area and key technologies of “increasing sources and reducing expenditure”, this paper proposes a method to solve the energy problem of passive system and makes an analysis of some key technologies such as energy harvesting, energy management and energy use.

Key words: Internet of Things (IoT), passive system, energy harvesting, sensing.

INTRODUCTION

The existing battery technology still cannot meet the life expectancy of the equipment of Internet of Things (IoT). Replacing the battery will bring a high maintenance cost. Therefore, the technology of obtaining energy from the environment has attracted widespread attention. According to the latest report from International Data Company (IDC), the global IoT market value will reach 1.4 trillion US dollars in 2021 (IDC Worldwide, 2017). Machina Research, a market research firm, predicts that the number of IoT devices will increase to 27 billion by 2025 (Machina Research, 2016). How to provide energy for these devices is one of the key challenges facing IoT.

Combining energy harvesting technology from the environment and the existing IoT system, a passive sensing and computing system (hereinafter referred to as a passive system) is derived. A passive system is a special type of IoT embedded system, which has no power supply or battery power supply. Instead, they collect energy from their environment and perform tasks such as sensing, computing and communication. Common sources of energy for such systems include solar energy, environmental radio frequency and mechanical vibration. Existing passive systems include Everlast (Simjee et al., 2006) from University of California, Irvine, WISP (Sample et al., 2016) from University of Washington, MOO (Zhang et al., 2011) from University of Massachusetts and UFoP from Clemson University (Hester et al., 2015) etc.

At present, there are some typical applications of passive systems, such as the battlefield unmanned autonomous sensor network, passive structure health detection, sleep quality monitoring (Hoque et al., 2010), elderly fall detection (Shinmoto et al., 2013), food spoilage monitoring (Yeager et al., 2008) and other occasions. The equipment used in the application has the characteristics of small size and long life and can be deeply embedded into the physical environment in various forms. It is one of the important components of IoT and pervasive computing. Compared with battery-powered systems (such as wireless sensor networks), passive systems have the advantages of energy self-supply, long-term independent maintenance-free operation, and are expected to be widely used in IoT.

RESEARCH AREAS OF PASSIVE SYSTEMS

The composition of passive systems

Figure 1 shows a passive system that is mainly composed of three parts: energy harvesting, energy storage and load. (1) Energy harvesting module, which converts other forms of energy in the environment into stable electrical energy that the system can store and use. Different energy sources correspond to different energy harvesters and conversion circuits. For example, solar energy is collected by a solar panel and stored in a capacitor through a Buck converter. RF energy is received by an antenna and then stored in a capacitor through a multi-stage voltage doubling rectifier circuit. (2) Energy storage module, due to the limitation of

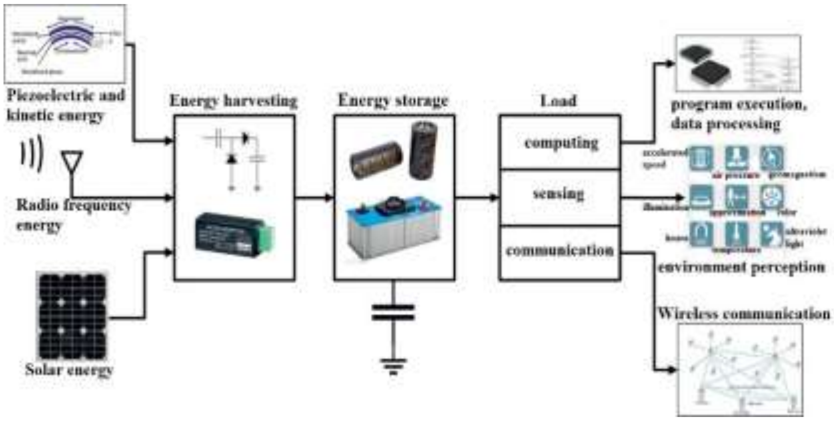

Figure 1: Typical structure of passive system.

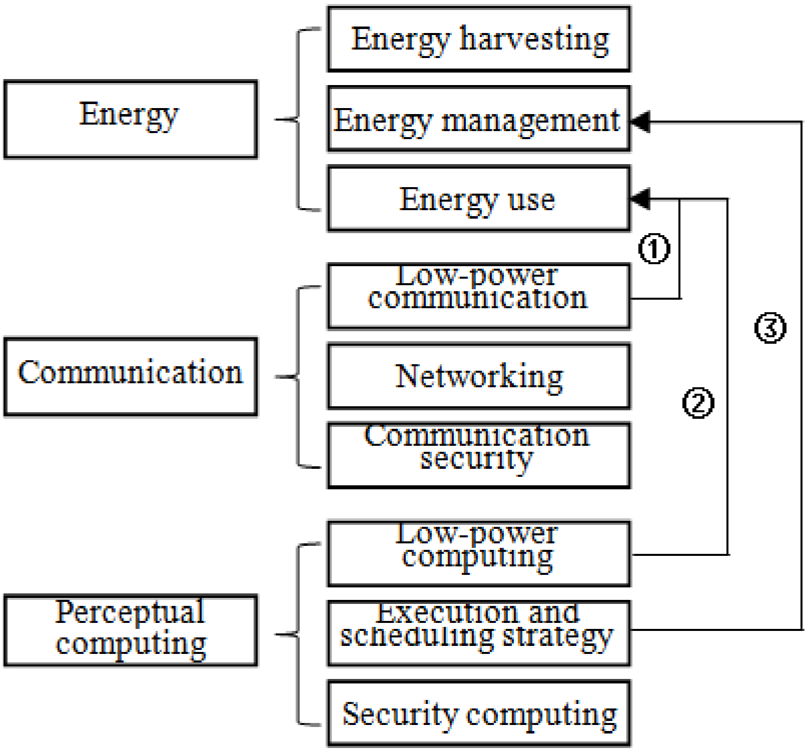

Figure 2: Current research areas of passive systems.

battery charge and discharge times; the passive energy storage module generally uses a super capacitor. In recent years, long-life and high-capacity solid-state batteries have also been gradually used in passive systems. (3) Load, stored energy can be supplied to the load to perform tasks and tasks in passive systems can be divided into sensing, computing and communication. Sensing refers to the system reading integrated sensor data. Computing can execute a program and can also process data read from sensors. Communication is to send the results of computing and sensing to remote receivers and it can also receive commands from the controller.

Research areas of passive systems

There are currently three main research areas of passive systems, namely energy research, communication research and perceptual computing. As shown in Figure 2, ① and ② represent energy use research, including low-power communication and computing and represents energy management research, including task execution and scheduling. (1) Energy research includes energy harvesting, energy management and energy use. Energy harvesting studies how to collect more energy from the environment, including optimizing energy harvesting efficiency and multi-source energy harvesting (collecting energy from multiple environmental energy sources). Energy management studies efficient task execution and scheduling strategies. Energy use studies low-power technology and minimizes power consumption while ensuring load performance, including low-power communication and computing. (2) Communication research includes low-power communication, networking and communication security. Low-power communication is a hot research area, studying how to use less energy to realize data communication (such as Wi-Fi and GPRS, etc), including backscatter communication and narrowband communication. The networking is based on low-power communication, such as low-power wide-area networks (WAN) based on narrow-band communication. Back-scattered communication cannot actively transmit wireless signals and therefore, its networking is not realized. The purpose of communication security research is to prevent malicious attacks or fraud information from affecting the correctness and reliability of communication during the communication process. (3) Perception computing research, which includes low-power computing, execution and scheduling strategies and security computing. Low-power computing uses some power management techniques to control the power consumption of passive systems to match the collected energy, such as Dynamic Voltage Scaling (DVS) and duty cycle.

The execution and scheduling strategy is to study the execution mode of a single task and the scheduling strategy between multiple tasks under the condition of limited energy so that the energy utilization rate is the highest. For example, when energy cannot complete a task at a time, breakpoint execution can be used to prevent task failure and energy wasting. Security computing refers to the successful completion of certain security algorithms such as AES encryption algorithm under limited computing condition.

According to the current research trend, we found that the energy problem is the core research area of passive systems. Common researches are about optimizing energy harvesting to increase the available energy, reducing energy waste caused by mission failure through the implementation of energy management planning tasks, and reducing communication and computing energy costs through low-power consumption communication and computing technology. However, algorithms such as security computing and networking rely on whether the system energy is sufficient.

THE ENERGY PROBLEM AND KEY TECHNOLOGY OF PASSIVE SYSTEMS

Energy limitation is the core problem that passive systems currently face. There are two main reasons: (1) Although existing passive systems can obtain energy from the environment, energy source is single and energy conversion efficiency is low, resulting in low capability of energy acquisition. (2) Since there are no low-power devices and architectures specifically designed for passive systems, the sensing, computing and communication loads of existing passive systems directly use those units used by the active system, resulting in large power consumption that exceeds the upper limit of energy supply of the energy harvesting module. In order to solve the contradiction between energy acquisition and load power consumption, existing passive systems often use compromise methods such as reducing the sensing precision and calculation and shortening the communication distance. For example, in the perception of passive systems, due to energy limitations, the system usually uses a low-power but low-precision analog-to-digital conversion ADC (usually 10 bit). To reduce the overhead, most of the computing tasks are transferred to the background server. The monitoring node only transmits the original data to the server. Because the collected energy is not enough to support high-power communication, backscatter communication is used, making the communication distance in passive systems above ten meters reduced to meters.

The basic idea to solve the problem of limited energy is to "increase sources and reduce expenditure." "Increase sources" is to increase the energy collected by the passive system from the environment. To achieve this goal, the existing work adopts two basic ideas: (1) Optimize energy harvesting and conversion efficiency, which is to increase the energy collected from the same kind of energy source. (2) Multi-source energy harvesting (also known as hybrid energy harvesting), that is, energy is collected from a variety of energy sources in the environment and is combined and converted to supply system loads. "Reduce expenditure" means reducing the waste of energy and reducing the energy needed for the load. For this reason, the current research focuses on improving energy efficiency and exploring low-power technologies.

The main research directions and key technologies for achieving “increase sources and reduce expenditure” can be divided into energy harvesting, energy management, and energy use based on different research goals, as shown in Figure 3.

Energy harvesting

Energy harvesting refers to capturing energy in the environment and converting it into energy that can be used by passive systems. As all energy sources for the system load, it mainly studies how to increase energy that can be used by the system. The main challenges for energy harvesting are as follows:

(1) Different energy sources have different characteristics: From the aspect of time, different environmental energy

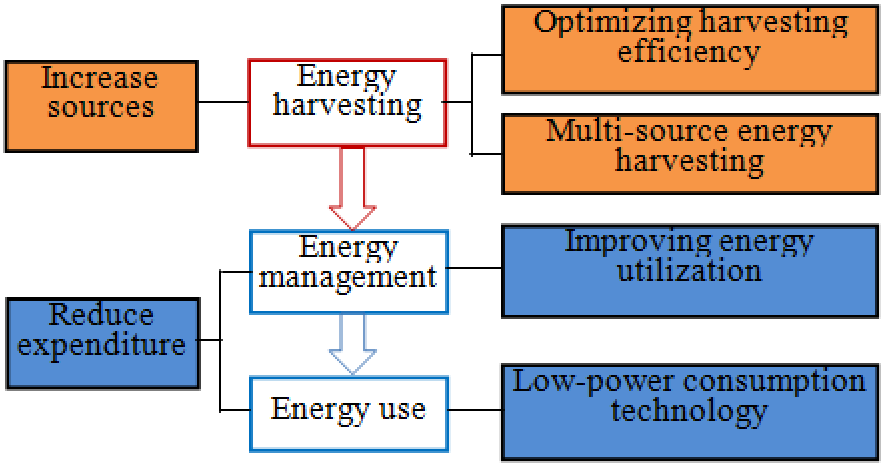

Figure 3: Main research areas of energy limitation problem.

has different time distribution characteristics. For example, solar energy is affected by sunlight intensity; mechanical vibration is difficult to predict (such as seismic energy), and the system does not know when it will be awakened in the future; RF energy is always available, but the energy density is low and the transmit power of the radio signal transmitter (For example, base station) is subject to Federal Communications Commission (FCC) regulations. Therefore, it is difficult to find a universal energy acquisition method in passive systems.

(2) Environmental energy is not controllable, that is, the time for energy generation cannot be controlled and the intensity of energy generation cannot be also controlled. For example, we cannot control the production of solar energy, and the light intensity is also affected by the weather; the generation and intensity of seismic energy cannot be controlled either. Other environmental energy (such as radio frequency) is partially controllable, that is, the generation of energy can be controlled, but the propagation process of energy in the environment is not controllable. For example, radio frequency propagation in the air may encounter problems such as multipath effect and obstruction of obstacles, which makes the energy intensity reaching the receiving antenna difficult to estimate. Therefore, it is difficult to increase energy of passive systems by controlling energy sources.

(3) Low collection and conversion efficiency: Collection and conversion efficiency refers to the efficiency of converting the collected energy into the available energy of the device. The collected energy is not stable, and it needs to be converted into stable DC by the process of rectification and voltage stabilization before it can be used by the system load. However, the existing energy collection and conversion efficiency is very low, resulting in limited energy available to the device. Take the WISP platform as an example, the efficiency of its collection and conversion is only 7.27% (Lui et al., 2011). These three challenges constitute an energy bottleneck in passive systems, resulting in many problems in system applications. For example, researchers at the University of Victoria in Wellington, New Zealand, designed a passive device that can extract energy from earthquakes to detect the movement of buildings in an earthquake. Since the system has no energy before the earthquake, after the earthquake, it must first collect enough energy to work. The system has a delay of 7.2 s from collecting energy to sending out the measurement results (Tomicek, 2013) and can only send 6 bytes of data, making it difficult to timely and accurately monitor and transmit dynamic data of buildings in earthquakes.

Based on the earlier mentioned three challenges, the current research mainly improves the performance of energy harvesting from the following two technical ways.

Optimizing energy harvesting and conversion efficiency

To optimize energy harvesting and conversion efficiency, we conducted research on RF energy collection and vibration energy collection, including dual-antenna structure for RF energy harvesting, seismic energy harvesting and track vibration energy harvesting.

(1) Dual antenna structure: Due to the low power consumption of backscattered communication, RF-powered passive systems commonly use backscatter as a means of communication. Considering design cost, when designing communication antennas, these systems use a single antenna to perform both communication and energy harvesting functions. However, the single-antenna structure causes the energy collection module to work insufficiently during backscatter communication, making the collected energy insufficient. To solve this problem, we proposed a dual antenna architecture in which one antenna

is allocated for communication and the other is for energy harvesting such that both modules are mutually independent. We also implemented two-antenna architecture on Computable Radio Frequency Identification (RFID) tags, optimized the performance of energy harvesting and conversion modules, and increased the tag's communication distance by nearly 60%.

(2) Seismic energy collection: Many applications need to obtain energy from seismic waves during the occurrence of an earthquake. The current method is to use piezoelectric ceramics. The principle is that when an object vibrates, a resonant piezoelectric ceramic can convert mechanical energy into electrical energy. However, the resonance frequency of existing piezoelectric ceramics on the market is fixed at 50 to 300 Hz, and the frequency of the earthquake is only 0.5 to 10 Hz, which leads to low efficiency in obtaining energy from earthquakes. We designed a mechanical structure that converts seismic vibration energy into mechanical energy using pendulum principle, and then used a gear set to buffer mechanical energy to drive the motor to generate electricity. We carried out a test on a seismic simulation platform. The results show that in the case of a seismic intensity of 7 levels, the module's power generation output can reach 1.1 W.

(3) Track vibration energy collection: Energy obtained from the tiny vibrations generated by the train passing over the rail track can be applied to the health detection of the rail traffic. Since the vibration frequency of the rail tracks is usually less than 5 Hz when the train passes by, piezoelectric ceramics are not suitable for collecting such vibration energy. We designed and implemented a rail vibration energy harvester that converts the millimeter-level vibration generated by the rail tracks during train running into electrical energy through mechanical transmission. The performance of the harvester is evaluated through a software simulation. For a high-speed train running at a speed of 350 km/h, the vibration amplitude generated by the rail track is 1.5 mm, and the power generated by the energy harvester can reach 39.28 W.

Multi-source energy harvesting

Passive systems can collect energy from multiple energy sources, convert and combine energy for system load to provide more energy for tasks in the load. For example, A. P. Sample added solar panels to RFID tags, enabling RFID tags to extract energy from RF signals and ambient lighting, thereby increasing the reading distance of the tags by a factor of 6 (Sample et al., 2011). Akan et al. (2017) proposed a IoT-oriented multi-source energy harvesting architecture. In addition, multi-source energy harvesting and optimized energy harvesting efficiency can be combined in many situations to bring more energy sources to passive systems.

Energy management

The purpose of energy management is to strategically control the use of energy, reduce energy waste and improve energy efficiency. In a passive system, failure to perform a task due to lack of energy results in energy waste. Therefore, the basic idea of energy management is to plan the task execution strategy according to the current energy state of the system (that is, the collected energy). According to different types of tasks, execution strategies can be roughly divided into two categories:

(1) One execution: It means passive systems perform one task at a time without any interruption after acquiring enough energy. For this purpose, the system assigns an energy threshold to each task to determine whether the task starts or not. This strategy defines the task as a small program that can be executed at one time, so it is suitable for short-term, light-weight tasks such as ambient temperature perception.

(2) Breakpoint execution: For tasks that cannot be completed in a short time, passive systems can use breakpoint execution strategies. Breakpoint execution means dividing a task into multiple short-term light-weight sub-tasks and performing as many sub-tasks as possible during each activation cycle of the system. When system energy is about to be exhausted, the system stores the breakpoints (that is, execution status and data) of the executing task in non-volatile memory, recovers the task after the system collects enough energy and continue from the previous breakpoint until the task is completed. Both of these strategies need to sense the current energy of the system. In order for the passive system to perceive energy, a common method is to use software to perform energy polling. Energy polling refers to sampling the current energy periodically through a digital-to-analog converter (ADC).

Due to the flexibility and ease of implementation of software, energy polling is used in passive systems widely (Buettner et al., 2011; Ransford et al., 2012). However, due to excessive power consumption, energy polling is not suitable for passive systems, especially RF-powered passive systems. Through experimental tests on the RF-powered WISP platform, we found that the average power consumption of energy polling accounted for 51.2% of the total power consumption of the system. As shown in Figure 4, the power consumption of energy polling increases with distance. The reason is that although the power consumption of the energy polling does not change due to the fixed sampling frequency, the total radio frequency

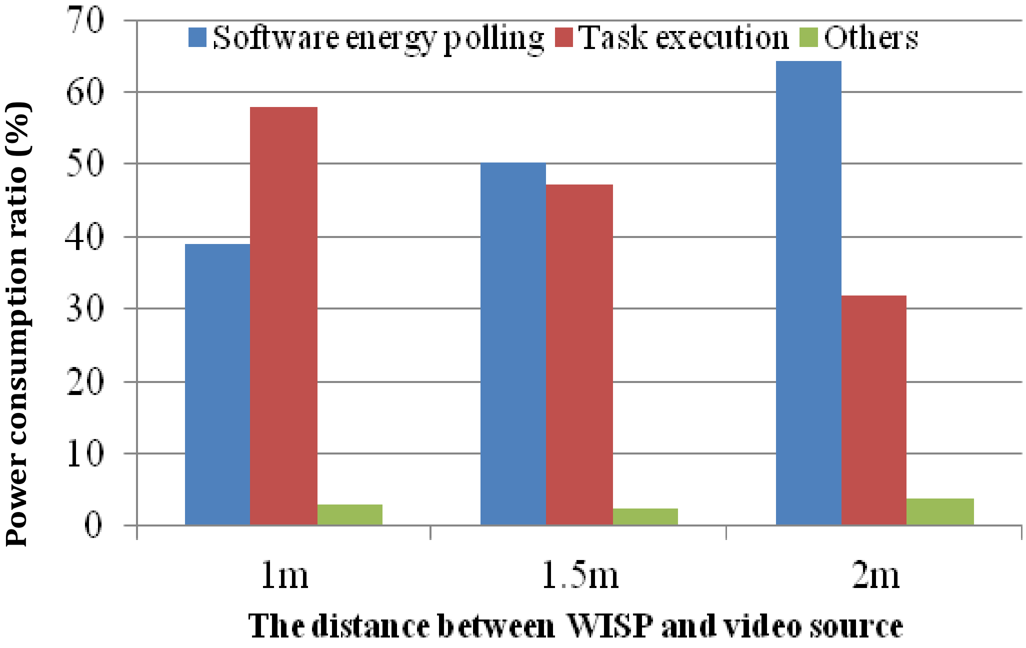

Figure 4: Power-consumption analysis of WISP platform.

energy collected decreases with increasing distance. Other energy is used for other parts of the system, such as system initialization.

In order to improve energy utilization, energy management needs to ensure that as much energy as possible is used for task execution. Existing studies have focused on improving energy efficiency by establishing task execution strategies and reducing energy waste in task execution. However, if the power consumption of the perceived energy cannot be reduced, the energy utilization rate will hardly increase. Therefore, we proposed a new energy detection method - hardware triggering and designed a low-power hardware energy monitoring module. When the collected energy reaches the expected energy threshold, the module outputs a trigger signal to wake up the system to perform the task, thus, avoiding energy polling, reducing the perceived energy overhead and making more energy used for task execution, thereby increasing energy efficiency from the current highest 64.7 to 94.9%, respectively.

Energy use

The energy collected by the passive system is ultimately used for task execution of the load, but the load of perception, computing and communication of the existing passive system directly adopts the architecture and method of the active system, resulting in excessive power consumption, and energy supply cannot satisfy demand. The research goal of low-power technology is how to use less energy to accomplish more tasks, thus, alleviating the energy shortage in passive systems.

According to the types of task, we divide the low-power consumption technology into three types, namely, communication, sensing and computing. Taking communication as an example, according to data transmission range, low-power communication technologies in passive systems can be classified into two types, “intra-board” and “outside board”.

“Intra-board” communication refers to data communication between the internal chips of a passive system. "Outside board" communication means that the system transmits data to external receivers through some form of wireless communication, including backscatter communication and narrowband communication.

(1) Low-power chip-to-chip communication: The current intra-board communication protocols commonly used in passive systems are I^{2}C and SPI. Compared to SPI, the number of buses required by I^{2}C is not affected by the number of chips, and it allows dynamic replacement of hosts on the bus, and is therefore more widely used in existing passive systems such as WISPs. However, the communication power of the I^{2}C bus is high, equivalent to the power consumption of a sensor or a Micro Controller (MCU). For example, on WISP, I^{2}C's power consumption reaches 324 μW, which is close to the power consumption of the onboard MCU (400 μW). Such high power consumption makes it difficult for WISP to perform long-term and large-scale chip-to-chip data communication. To reduce the power consumption of the I^{2}C bus communication, our latest research compromises the communication speed and power consumption, reducing its

power consumption to 2% to match energy requirements of passive systems without changing the I^{2}C protocol and existing chips.

(2) Backscatter communication: Wireless communication needs to modulate the baseband signal to a high-frequency carrier signal and send it to the air through an antenna. This kind of communication method that needs to generate a carrier wave has extremely high power consumption for a passive system. For example, the power consumption of Wi-Fi communication exceeds 100 mW, which is about 1000 times that of the RF-powered system. Therefore, backscatter communication is usually used in low-power passive systems. It is a kind of low-power communication technology based on radar principle. It does not actively emit electromagnetic waves (avoiding high power consumption of generating carrier). The baseband signal can be modulated into the reflected signal only by controlling the low-power electronic switch to switch in the antenna under different impedance circuits.
Researchers at the University of Washington have done a lot of work on backscatter communication. They used backscattering to implement three basic modulation methods: ASK, FSK and PSK. The combination of these three modulation methods can simulate the current Wi-Fi, ZigBee and other communication methods commonly used in IoT.

(3) Narrowband communication: The features of narrowband such as low power consumption, low data rate and long communication distance are considered to be the most suitable way for future IoT communications. A network based on narrowband communication is called a low power wide area network (WAN). Existing low-power WAN standards include NB-IoT, Lora, SigFox and eMTC. Low-power WANs can support battery-powered IoT devices to operate for more than 10 years. Although low-power WANs have not yet been applied to passive systems, we believe that the combination of low-power WANs with existing passive systems is feasible and has broad application prospects.

CONCLUSIONS

In the course of the aforementioned analysis of energy problems and key technologies in passive systems, although low-power WANs have not yet been applied to passive systems, we believe that the combination of low-power WANs and existing passive systems is feasible and its application prospects are extensive. However, the current power consumption of the low-power WANs is still too high for most passive systems. For example, the communication power consumption of the NB-IoT module XBee is about 840 mW (DIGI, 2017), which results in insufficient energy support for a long time communication of a large amount of data. Besides, before each communication a long time is needed to collect energy. Fortunately, in most IoT scenarios, the amount of data uploaded by nodes is small (usually only a few hundred to several kilobytes), does not need to be frequently uploaded and is not necessary real-time. Therefore, the passive system can use narrowband communication to send data to the receiving base station in batch after collecting enough energy. The maintenance-free advantages of passive systems combined with the long-distance communication distance of low-power WANs will become an important technology for IoT applications in the future.

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