Applications and Challenges of Acoustic Wake-Up Technology

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Microsystems with capabilities of acoustic signal perception and recognition are widely used in unattended monitoring applications. In order to realize long-term and large-scale monitoring, microsystems with ultra-low power consumption are always required. Acoustic wake-up is one of the solutions to effectively reduce the power consumption of microsystems, especially for monitoring sparse events.

acoustic wake-up microsystem system long life

1. Introduction

With the development of the Internet of Things (IoT) and its related technologies, such as the machine learning (ML) algorithm, MEMS transducer, 5G cellular network, etc., a large number of IoT terminals are urgently needed [1][2]. Microsystems, with the ability of sensing, data processing, transmitting, and executing, are one of the most important terminals of the IoT. In many unattended scenarios, microsystems are used for long-term, large-scale surveillance. However, due to the limited power of the microsystem, the use of low-power electronic components still cannot meet the needs of ultra-long-term surveillance. Energy harvesting can be applied to extend battery life [3]. However, the efficiency of energy harvesting is susceptible to the external environment. Also, the energy harvesting module increases the complexity and size of the microsystem. For many applications in unattended scenarios, events of concern rarely occur. Continuous detection of such sparse events wastes most power of the microsystem [4]. Thus, a wake-up strategy for microsystems is studied. The wake-up strategy refers to the microsystem continuously detecting the events of concern while keeping other modules off, which is also known as low-power sleep mode, and when the events of concern occur, the microsystem turns on all the modules and switches to a high-power active mode. By adopting the wake-up strategy, most of the wasted power is conserved, and the power efficiency is significantly improved, which greatly extends the battery life of the microsystem [5]. Different types of signals are used for event detection in wake-up microsystems, such as acoustic, mechanical, magnetic, optical, infrared, RF, et al. [6][7][8][9][10][11]. Among them, the acoustic signal has the advantages of strong universality, long monitoring distance, rich data information, and abundant acoustic sensors. Therefore, the study of acoustic wake-up microsystems has aroused great interest among researchers.

2. System Wake-Up Architecture

Two fundamental modules are required for acoustic wake-up microsystems, which are the wake-up module and the back-end function module. The wake-up module is responsible for acoustic sensing and recognition, and waking up the back-end function module when a specific target appears or a specific event occurs. The back-end function module remains in a low-power or even zero-power sleep mode before waking up, and it performs the main functions of the microsystem after waking up, such as data processing, actuator controlling, and data transceiving. Acoustic wake-up microsystems require ultra-low sleep power consumption and a small size, which results in limited sensing and data processing performance. Although there are many high-performance MEMS acoustic transducers and high-precision classification algorithms applied to the target and event sensing and recognition, not many are able to be implemented in acoustic wake-up microsystems. The system wake-up architectures are divided into 4 categories according to whether the wake-up module or the back-end function module consumes power in sleep mode. The power consumption caused by the current leakage of electronic devices, batteries, etc., is treated as zero power consumption.

2.1. Architecture 1: Low-Power Recognition and Low-Power Sleep

In the low-power recognition and low-power sleep architecture, aka Architecture 1, when the microsystem is in sleep mode, the wake-up module consumes power for acoustic sensing and recognition, while the back-end function module also consumes power waiting for the wake-up signal, usually a voltage signal of high or low, from the wake-up module, as shown in **Figure 1**. In the back-end function module, there must be a chip capable of switching between high-power active mode and low-power sleep mode. This architecture is the most used and most mature wake-up architecture in various electronic devices, and also in microsystems.

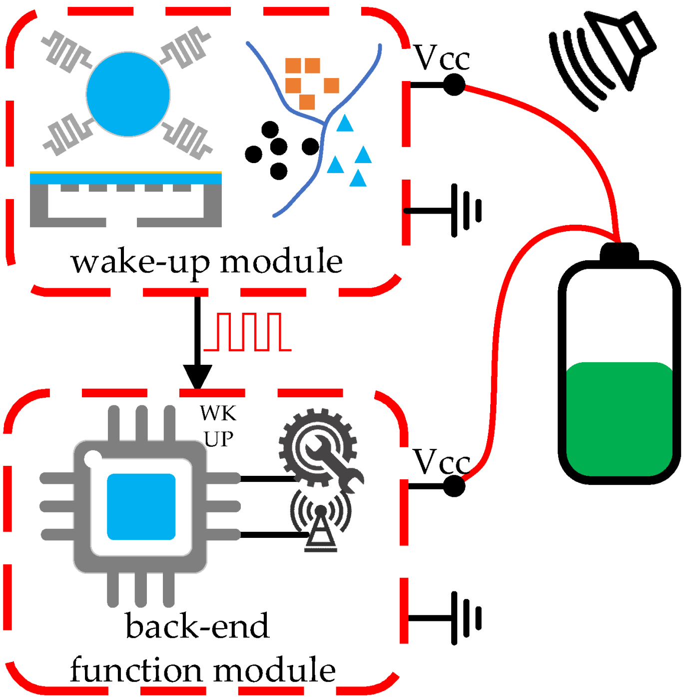

Figure 1. Architecture 1: low-power recognition and low-power sleep.

2.2. Architecture 2: Zero-Power Recognition and Low-Power Sleep

In the zero-power recognition and low-power sleep architecture, aka Architecture 2, the wake-up module performs acoustic sensing and recognition with zero power consumption, while the back-end function module remains the same as in Architecture 1, as shown in **Figure 2**. Zero-power sensing and data processing technologies, such as high-sensitivity piezoelectric transducers, passive amplifiers, passive filters, and passive classifiers, are required. When the target acoustic signal appears, the wake-up module recognizes it and then generates a wake-up signal for the back-end function module.

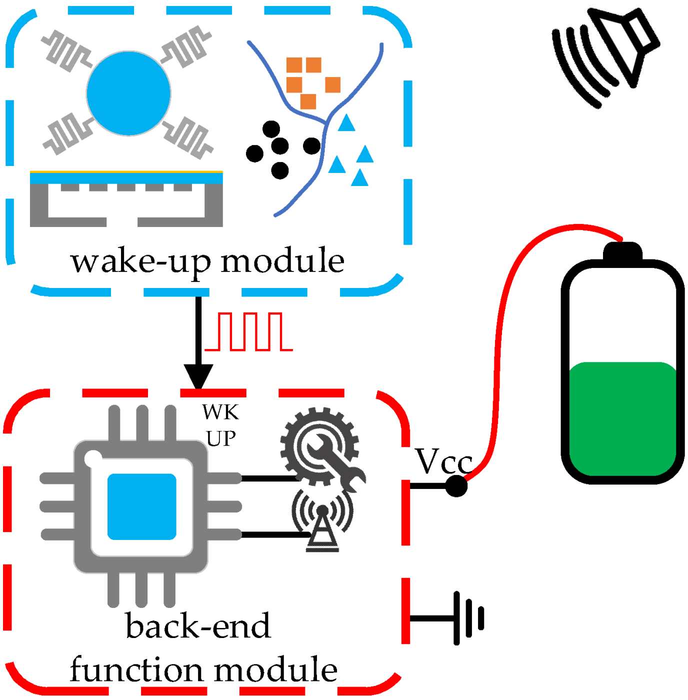

Figure 2. Architecture 2: zero-power recognition and low-power sleep.

2.3. Architecture 3: Low-Power Recognition and Zero-Power Sleep

In the low-power recognition and zero-power sleep architecture, aka Architecture 3, the wake-up module performs acoustic sensing and recognition with power consumption, which is similar to the wake-up module in Architecture 1. However, there is a switch in the module, which is used for controlling the current flowing through the back-end functional module, as shown in **Figure 3**. In addition, a chip with the function of switching working modes in the back-end function module is no longer needed. In sleep mode, the back-end function module is powered off instead of in a low-power sleep state. This switch-included wake-up module is much more universal and can easily be used to reform the wake-up function of various electronic systems. Nonetheless, the switch increases the size and power consumption of the wake-up module.

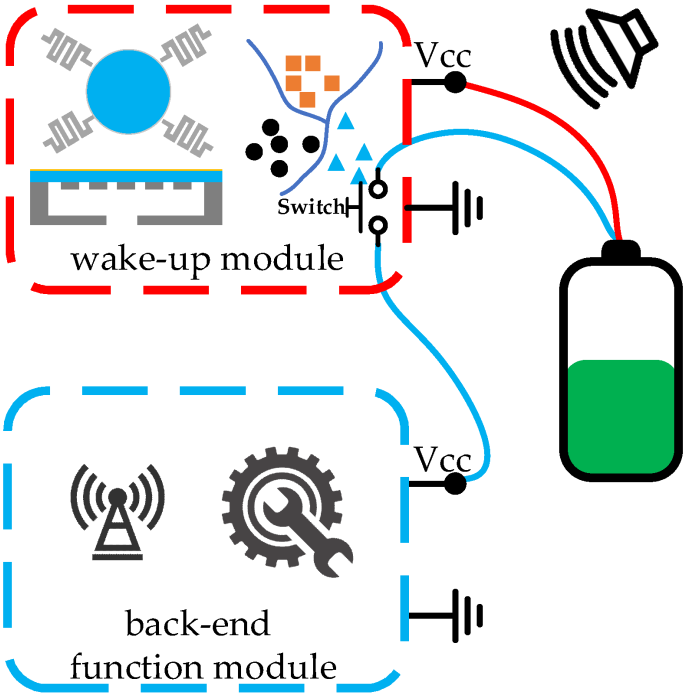

Figure 3. Architecture 3: low-power recognition and zero-power sleep.

2.4. Architecture 4: Zero-Power Recognition and Zero-Power Sleep

In the zero-power recognition and zero-power sleep architecture, aka Architecture 4, the microsystem consumes absolutely zero power in sleep mode. A wake-up module with zero-power sensing, recognition, and circuit switching is the key to this architecture, as shown in **Figure 4**. Acoustic sensing, signal processing, and switch actuation are all powered by the energy in the acoustic signal.

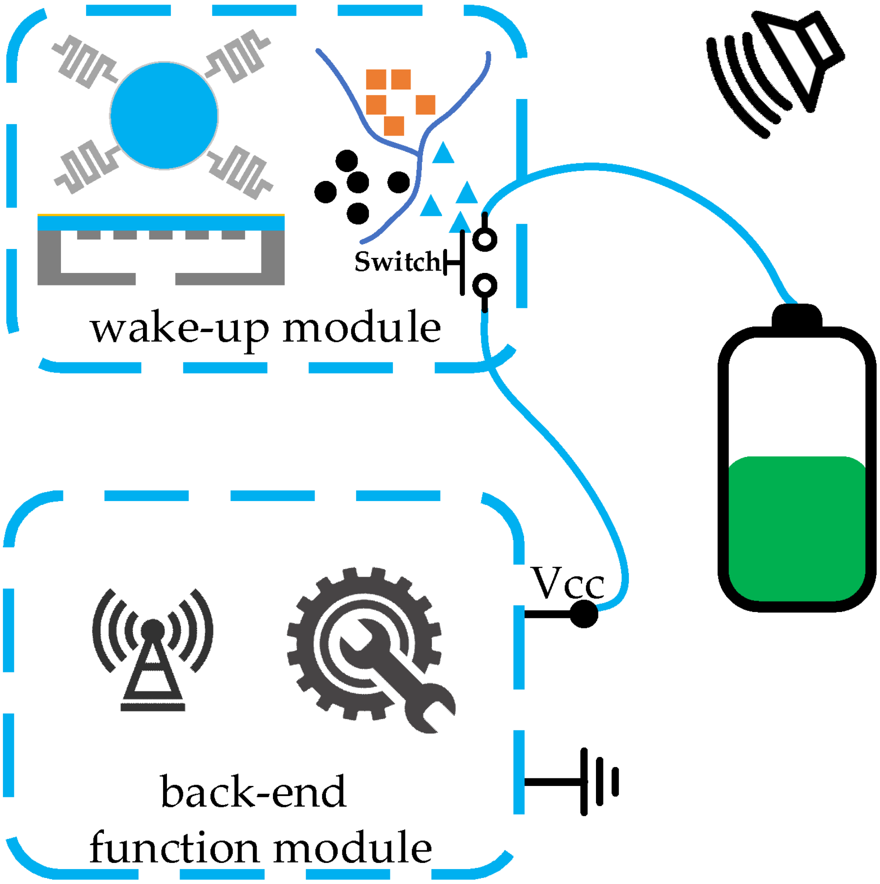

Figure 4. Architecture 4: zero-power recognition and zero-power sleep.

3. Applications

3.1. Perimeter Surveillance

For vast border areas, wilderness areas, scattered warehouses, etc., detecting intrusions, although rarely happening, is very important for security reasons. Targets such as human beings, vehicles, and wildlife, are of constant concern for both civilian and military use [12][13][14][15][16][17]. Traditional high-power monitoring methods, such as live cameras, require a power grid for power supply which is impractical for many applications. The presence and movement of specific targets are always accompanied by sounds with specific acoustic features. Thus, targets can be detected and recognized by applying an acoustic wake-up microsystem. When multiple microsystems are applied to form a sensing network, moving target localization and tracking can also be achieved by analyzing the amplitude differences, time of arrival (TOA), and time difference of arrival (TDOA) of the acoustic signals [18][19][20].

3.2. Structure Health Monitoring

Structural health monitoring of important infrastructures, such as bridges, dams, tunnels, and transmission towers, is related to our safety. Timely detection of abnormalities and failures of their structure is urgently desired to avoid heavy losses. When cracks appear in a structure, its acoustic signature changes. Thus, structure health monitoring can be done by acoustic recognition [21]. Most structure health monitoring requires active acoustic emission with high power consumption [22], which is not suitable for the acoustic wake-up microsystem. Fortunately, passive acoustic emissions may be utilized for structure health monitoring without power consumption, such as the sounds produced by the cars on the bridges, and by the running water through the dams and tunnels. By deploying acoustic wake-up microsystems on these infrastructures, low-power-consumption, long-term, and real-time monitoring of structural abnormalities can be achieved, which will guarantee the safety of people and property.

3.3. Human Health Monitoring

Human health has always been the most important issue in our daily lives. Medical diagnoses by wearable acoustic monitoring devices have been investigated, including heart and lung sound recognition, and wheeze detection [23][24][25]. In the foreseeable future, more acoustic microsystems will be applied to the continuous monitoring of abnormal health signals to ensure early detection and treatment. With the acoustic wake-up technology, ultra-long-term monitoring without charging or battery replacement can be realized, which greatly improves the convenience of the use of wearable health monitoring devices.

3.4. Agriculture Application

Agriculture is the practice of plant and livestock cultivation. It has been the foundation of our lives since ancient times. The application of modern technologies in agriculture can effectively increase the production of crops and livestock, releasing farmers and herdsmen from heavy work. Weather conditions [26][27], insects [28][29], birds [30], and livestock behaviors [31], which are closely related to agricultural production, can be detected by acoustic signals. Acoustic wake-up microsystems are worthy of application in these instances, especially for rare exceptions, such as severe weather conditions, invasive alien species, and unknown avian influenza infections, which occur rarely but impact significantly.

3.5. Biodiversity Research

Biodiversity research is important for ecological stability and life science research. Finding different creatures, especially rare ones, in the vast wilderness or the deep sea is sometimes difficult. Bioacoustics signals can be used for biodiversity studies both on land and underwater [32][33][34][35][36][37]. A vast, low-power, long-life monitoring network can be built by the acoustic wake-up microsystem to achieve biodiversity research. Only useful acoustic signals are detected and processed, which greatly reduces the amount of useless information.

3.6. Smart City

Urban life is full of various acoustic signals, which makes the ears so important to us. Acoustic wake-up microsystems are like the ears of a smart city that are used for monitoring various events and targets. Acoustic signals are already investigated for indoor moving target detection [38][39], traffic control [40], speaker recognition [41], and providing human interfaces to IoT ends [42]. With the increasing number of acoustic microsystems, a wider and more powerful IoT will greatly facilitate our daily lives.

4. Challenges and Future Research Directions

The core purpose of the acoustic wake-up microsystem is to significantly extend the battery life for sparse acoustic event detection, by means of saving wasted power, improving power efficiency, and reducing power consumption. But it also brings some disadvantages. Under the condition of strictly limiting the sleep power consumption of the microsystem, its acoustic recognition ability is reduced, including limited identifiable sound categories, limited recognition sensitivity, and limited recognition accuracy. Until now, the number of acoustic wake-up microsystems is still small, especially systems with Architecture 2, Architecture 3, or Architecture 4. Microsystem technology is a system technology including hardware and software. To better promote the development of the acoustic wake-up microsystem, it is necessary to conduct research on both software and hardware, which is aimed at lower sleep power consumption and higher recognition capabilities.

4.1. Software

Software in a microsystem must be efficient and designed for specific applications. Due to the limited power supply and long life requirement of the acoustic wake-up microsystem, the software is always optimized to reduce computation and improve efficiency, including data input, output, and calculation processes. For the acoustic wake-up microsystem, the acoustic classification algorithm is the core of the software. Algorithms with higher classification accuracy and lower computation amount are desired. Thus, research on acoustic feature selection and extraction, and feature-based classification algorithm needs to be further studied according to the microsystem's application scenarios and requirements.

4.2. Hardware

For the hardware, nanowatt and zero-power components are required for the acoustic wake-up microsystem. For acoustic sensing, the technology of MEMS acoustic transducers needs to be studied to improve their uses, including the MEMS microphone, MEMS hydrophone, and MEMS acoustic switch, and to improve their performance, including higher sensitivity, lower power or even zero power consumption, lower noise and smaller size. A high sensitivity piezoelectric microphone can lower the power consumption, and the voltage output from the microphone may directly drive a MEMS switch or a CMOS switch without using an active amplifier. For acoustic signal processing, nanowatt processors are needed to implement machine learning algorithms and other classification algorithms. Other low-power or even zero-power signal processing components in the system circuit are also required, such as the amplifier, analog-to-digital (ADC) converter, solid-state relay, clock, etc. The current leakage in the circuit components is non-negligible in ultra-long-life wake-up microsystem applications. To implement acoustic wake-up microsystems of Architecture 3 and Architecture 4, a switch with little current leakage is essential. The CMOS switch with ultra-low current leakage, MEMS electrostatic switch with low trigger threshold, and zero-power acoustic switch with wider bandwidth can be tested as solutions. Especially for Architecture 4, there is an urgent need for a zero-power acoustic switch that can respond to multiple frequency bands and remain on without consuming power.

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