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A Wireless Voting System Built with Many Battery-free Motion-powered Bluetooth Buttons

Cheng Tian, Zijie Chen, and Junrui Liang
School of Information Science and Technology
ShanghaiTech University, Shanghai 201210, China
Email: {tiancheng2022, chenzj1, liangjr}@shanghaitech.edu.cn

***Abstract*—The Internet of Things (IoT) has attracted increasing interest from academia and industry. It facilitates many applications, such as the wireless voting system. Yet, current wireless voting terminal devices are mostly powered by batteries. It requires a high maintenance cost for identifying and replacing low-energy batteries. This paper introduces a wireless voting system, which is implemented using many battery-free motion-powered Bluetooth buttons. The tiny power for Bluetooth wireless communication is generated by a local quasi-static electromagnetic mechanical energy harvester and regulated by an ultra-low-cost energy management circuit. The generated voting information is collected and sent to a cloud server for later data visualization. The system has been successfully implemented, tested, and applied in various real scenarios. The battery-free multi-terminal design provides a valuable reference and promising prospect for ubiquitous IoT and pervasive sensing systems.**

***Index Terms*—Battery-free IoT, quasi-static mechanical energy harvester, voting system, end-edge-cloud computing**

I. Introduction

The Internet of Things (IoT) is an emerging technology. It wirelessly connects smart devices and sensors to the existing Internet. It enables data exchange and interaction among different types of things. With the development of cloud computing and edge computing technologies, IoT has been further promoted as they provide various source data toward data mining, storage, and processing applications [1]. In this technological context, the smart voting system has become an attractive application. This system aims to provide users with a convenient voting experience through IoT-connected smart devices and sensors [2]. By simple gestures or clicks, users can express their approval and support for specific content, products, or activities. In addition, the data can be uploaded to the server for recording, analysis, and visualization [3]. Such systems can be applied in various fields, such as citizens supporting community activities and user feedback collecting.

However, most voting systems require battery-powered endpoint devices. With the rapid development of IoT, identifying low-energy batteries and replacing them must become prohibitively labor-intensive. Let alone the environmental-unfriendly disposal of waste batteries. Battery-free IoT technology has emerged in the last decade to help out these issues. Battery-free IoT devices do not require built-in batteries; instead, they harvest energy from the ambiance, such as radio-frequency (RF) microwave, solar, thermal, or kinetic energy. Kinetic energy harvesting (KEH) is an especially suitable technique for a robust voting system without considering volatile light and RF signal intensities [4]–[6]. It collects energy from various forms of motions, such as vibrations and human motions [7], [8]. Different electromechanical transduction mechanisms like piezoelectric [9], electromagnetic [10], and triboelectric effects are utilized for KEH exploration. This allows KEH to excel in specific scenarios, such as indoor environments or enclosed structures with weak solar irradiation or RF signals.

This study proposes a novel voting system built with many pervasive motion-powered and battery-free Bluetooth transmitting buttons. These buttons send voting signals to the edge computing node, which passes the information to a cloud server. The battery-free wireless button is powered by the motion energy captured by quasi-static electromagnetic energy harvesters [11]. The generated pulsed electricity is processed by an ultra-low-cost energy management circuit. This end-edge-cloud orchestrated IoT system sets a good engineering example for ubiquitous and energy-efficient sensing and computing.

II. System Architecture

The architecture of the proposed distributed system is shown in Fig. 1. The system comprises three parts: multiple motion-powered transmitting buttons, a receiver edge node, and a cloud server. Every end battery-free button is powered by a quasi-static electromagnetic energy harvester, which converts the energy associated with a human pressing motion into useful electricity. After rectification and regulation by a low-cost energy management circuit, the electrical energy is utilized to power a low-power system on chip (SoC) with Bluetooth Low Energy (BLE) function.

The second part is an edge computing node. It scans nearby Bluetooth signals and identifies the specific packets transmitted from the motion-powered buttons. The edge device then performs a local pre-processing of the received data and publishes the latest system status to the cloud server via WiFi.

The cloud server stores and analyzes application data and intercommunicates with edge nodes. Through the Internet, the data can be visited in real-time and comprehensively visualized on remote end terminals, such as PCs, laptops, or smartphones.

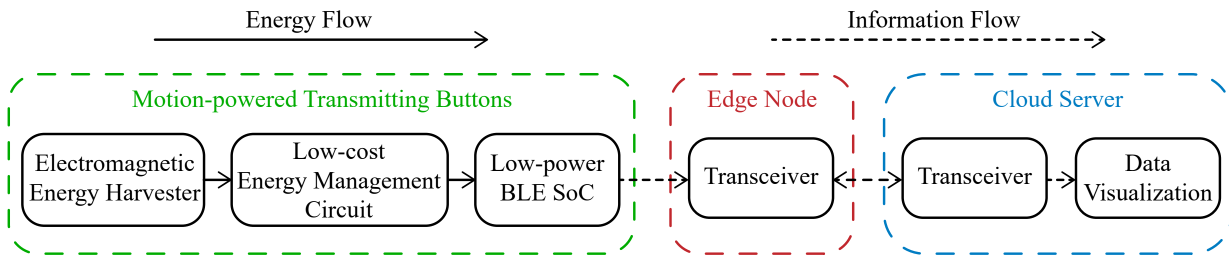

Fig. 1. System Architecture.

Fig. 2 illustrates the operational pipeline or time sequence in detail. Let's imagine an application scenario where a speaker delivers an engaging presentation, and the audience thoroughly enjoys the content. The audience can express their likes by pressing their end-side motion-powered voting buttons. The edge node instantly receives the BLE data, like voting counts and time stamps. The information is then transmitted to the cloud server in real-time for the dynamic voting count, performance analysis, data illustration, or even instantaneous feedback, all of which help better interaction between speaker and audiences. Once a speaker completes his/her presentation, the conference moderator can handily use their master button to lock and terminate the present voting session or reset the vote count for the next presentation. The edge computing node can identify audience and conference moderator signals. It then uploads the corresponding commands to the cloud server. The detailed operational process of the system is as follows:

- *Speaker's Presentation*: The speaker delivers an engaging presentation. The audience expresses their approval by pressing their voting buttons. The passive voting buttons collect kinetic energy and transmit the voting signals via Bluetooth to the edge computing node.
- *Edge Computing Node*: The edge computing node scans for Bluetooth signals and detects the voting signals from the passive voting buttons. It decodes the specific fields to obtain the voting command. The edge node processes and calculates the voting result locally and uploads the updated vote count to the cloud server through WiFi.
- *Real-time Display*: The cloud server receives the vote count uploaded by the edge computing node and displays real-time updates on the display platform. The audience can witness the dynamic changes in the vote count. The result reflects their likes for the presentation contents.
- *Next Presentation*: After the current speaker completes his/her presentation, the conference host uses the unique button to freeze the result. The edge computing node recognizes the signal from the host and uploads the command to the cloud. It immediately terminates the previous voting session and resets the vote count in preparation for the next presentation.

Through this process, the wireless voting IoT system achieves real-time voting from the audience and provides an instant update on the display platform. It enhances the effectiveness, interactivity, and performance assessment of presentations or lecture activities.

III. Motion-powered Battery-free Transmitter

Each voting terminal is a battery-free BLE button, including a quasi-static-toggling (QST) mechanical energy harvester and a low-cost energy management circuit. The QST energy harvester carries out the (mechanical) buffer and release mechanism, which was mostly implemented on the circuit side in many self-powered designs. Therefore, it eases the design of the energy management circuit to the most extreme.

A. QST Mechanical Energy Harvester

The motion-powered wireless switches are based on the instantaneous magnetic poles swapping principle [11]. Its configuration is shown in Fig. 3(a). These toggling switches have a significant common feature that they can work under extremely low-frequency or slow-motion excitations. To be more professional, such excitations can be called quasi-static motions. The triggering behavior of this quasi-static toggling (QST) energy harvester is very similar to those in the snap-through or bistable designs.

In each press-release motion, the QST harvester will generate two sharp voltage pulses, one positive and one negative, as shown in Fig. 3(b). The pulse height is usually more than ten volts. The duration is at the millisecond level. Each press-release motion can give about 0.7 mJ energy, which is sufficient for powering to send more than three BLE iBeacon signals with a cutting-edge low-power BLE SoC. The detailed working principle of the QST energy harvester can be referred to in our previous study [11].

B. Low-cost Power Supply for Embedded SoC

Low-dropout regulators (LDOs) and switched-mode dc/dc converters are popular choices for offering a stable supply voltage to the digital SoC. However, an extra quiescent current is consumed when using a regulator chip. To achieve ultra-low-power characteristics, in this study, we skillfully use a depletion-mode MOSFET as a low-cost regulator by referring to our previous paper [12].

The energy management circuit is shown in Fig. 4. As the energy from the QST mechanical energy harvester flows in the capacitor, the depletion NMOS starts working and regulates the voltage to a desired level. It powers the endpoint low-power IoT SoC while requiring no additional quiescent current. The

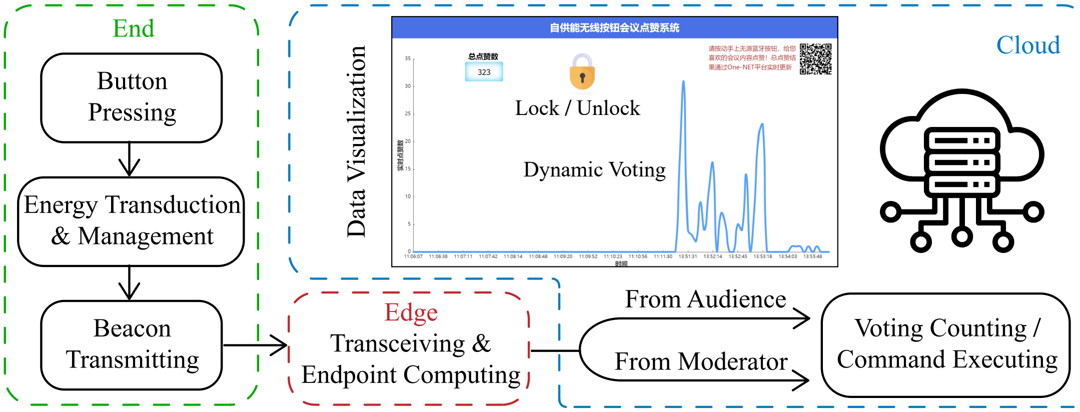

Fig. 2. Operation Pipeline.

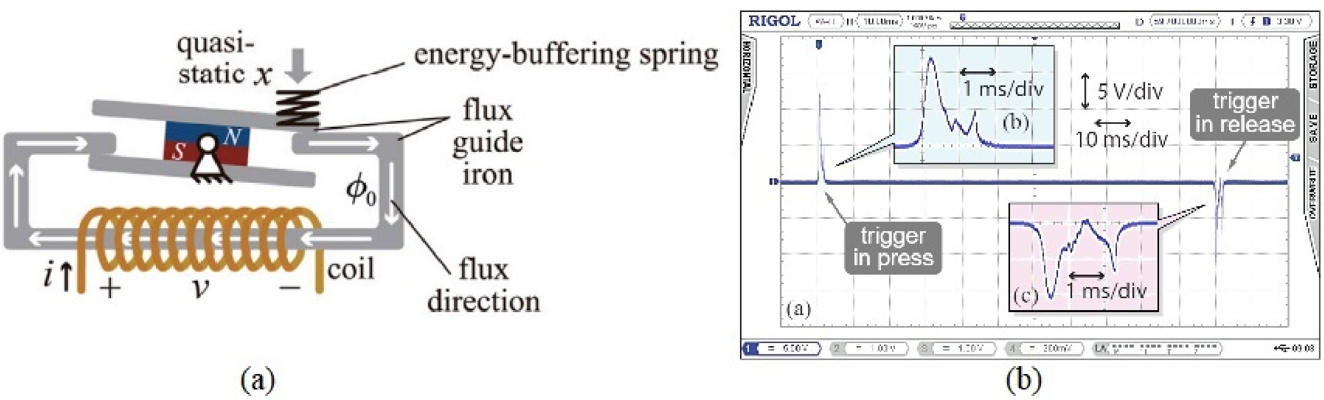

Fig. 3. (a) Configuration of a QST energy harvester [11]. (b) The generated voltage of a QST energy harvester in one round of press-release action.

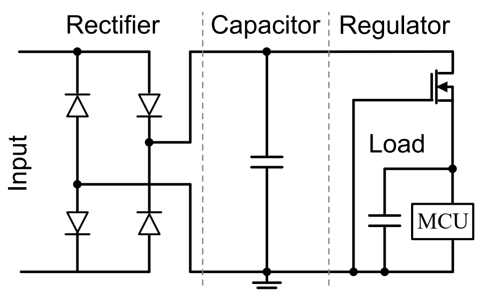

Fig. 4. Energy management circuit with an ultra-low-cost linear regulator.

drain current of the gate-grounded depletion MOSFET is calculated as follows

$$I_d = K_p \frac{W}{L} (-V_o - V_{th})^2, \tag{1}$$

where the K_p, W, L, V_o, V_{th} are the transconductance, width, length, output voltage, and threshold voltage of the depletion-mode N-type MOSFET. Therefore, after a simple transformation, we can obtain the output supply voltage as follows

$$V_o = -\sqrt{\frac{I_d L}{K_p W}} - V_{th}. \tag{2}$$

While using a BSS159N (Infineon Technologies Inc.) depletion-mode NMOS, the voltage can be regulated to 2 V to 2.8 V [12], which is acceptable for most low-power and wide-voltage IoT SoCs, such as nRF52832 (Nordic Inc.).

IV. Reinforcement of Voting Reliability

To best use the harvested energy, the BLE SoC continuously broadcasts pre-configured Bluetooth data packets through the device's chip after collecting sufficient energy from each human press action. This approach aims to reduce packet loss during Bluetooth transmission by broadcasting multiple Bluetooth data packets within an extremely short time frame. However, it introduces a new challenge of distinguishing between a single effective vote and multiple votes caused by an audience who rapidly and repeatedly presses a voting button.

To solve this issue, the edge computing node needs to implement an algorithm to process the Bluetooth data packets efficiently and tell the effective vote precisely. This algorithm must be able to differentiate repeated votes caused by an audience. By analyzing the timing and patterns of the received Bluetooth signals, the edge computing node can discern whether a series of identical packets corresponds to a single vote or multiple votes from one person.

The system can provide a reliable and fair voting result with a well-designed algorithm, as shown in Algorithm 1.

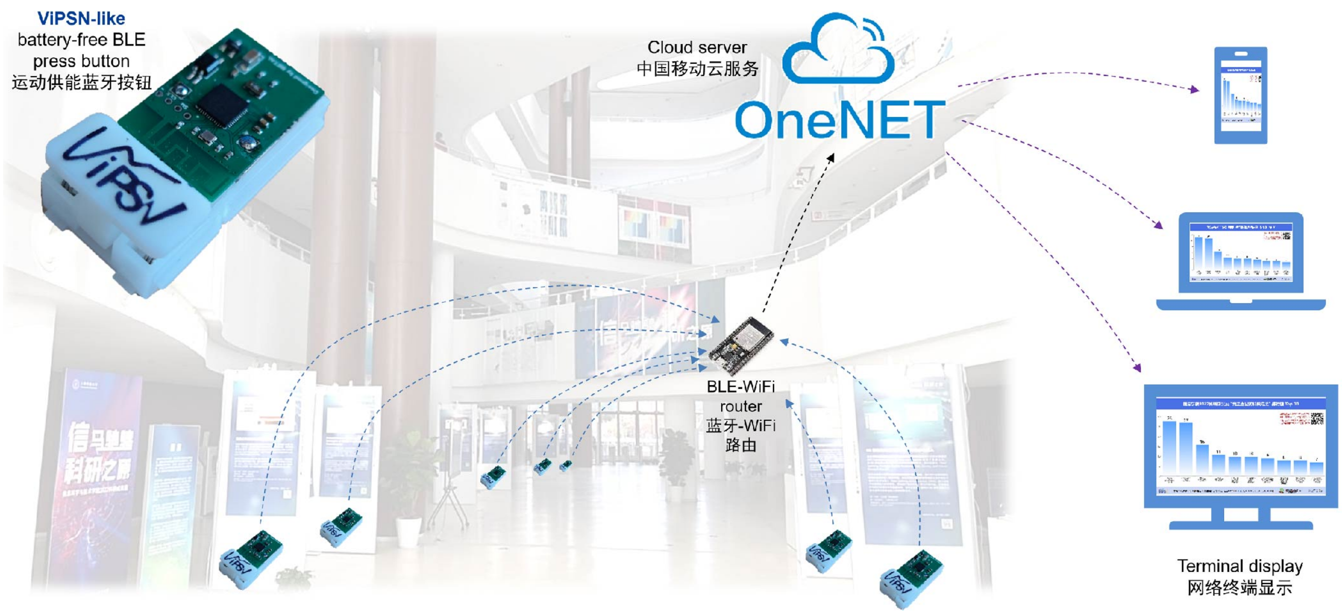

Fig. 5. System implementation and field test.

This algorithm, carefully designed and implemented, plays a pivotal role in ensuring the integrity and precision of the voting process. It exhibits its robustness by meticulously identifying and processing every Bluetooth data packet received from the various edge computing nodes within the network. Rather than treating each packet as a separate vote, the algorithm intelligently consolidates and validates them, ensuring that the final vote count remains accurate and unaffected by unintentional packet duplication. It enhances the overall performance and robustness of the wireless voting IoT system.

V. Experiment and Field Test

A wireless voting system using many battery-free motion-powered BLE buttons is implemented and deployed in an exhibition held at ShanghaiTech University in the summer of 2022. Fig. 5 illustrates the system configuration and site for deployment. The buttons and the edge node are developed based on the proposed motion-powered BLE transmitters and an ESP32 SoC (Espressif Systems Inc.). The data is collected, processed, and visualized on the OneNET cloud platform powered by China Mobile Inc. Users can access the recorded data from their smartphones, PCs, or any Internet-connected terminal.

This developed system has been successfully applied in various application scenarios. In the exhibition voting scenario, the battery-free voting buttons were distributed across an exhibition hall covering about a hundred square meters, and all reliably functioned. In addition, the system functions for real-time likes or votes in conference or lecture settings. It also performed well, bearing the many simultaneous clicks by dozens of people at a high frequency. During these stress tests, it remained stable and accurately recorded the majority of likes/votes.

Algorithm 1: Voting count algorithm by identifying BLE beacon signal.

```
Input: Bluetooth packets
Output: System commands
for each Bluetooth packet do
    if Bluetooth packet from Audience buttons then
        if Bluetooth packet is received repeatedly
          within one second then
            Do nothing
        else
            Increase the corresponding number of votes
        end
    else
        if The voting has not been terminated then
            Terminate the voting and record the final
              vote count
        else
            Refresh the vote number and start a new
              round of voting
        end
    end
end
```

Moreover, the versatility of this system extends well beyond the mere recording of likes or votes. It might also provide a dynamic interaction between the audience and the presented content in various exhibition and presentation settings, offering spectators an engaging and interactive platform. Diverse audience members can engage with distinct edge computing nodes, each of which might trim the presentation content to some extent according to the instantaneous feedback.

VI. Conclusion

This paper proposed a novel end-edge-cloud orchestrated voting system composed of many pervasive motion-powered Bluetooth buttons, an edge computing node, and a cloud server. The self-contained motion-powered IoT button is developed using a quasi-static electromagnetic energy harvester and an ultra-low-cost energy management circuit. The quasi-static design increases the energy harvesting efficiency and the interactive voting experience. After practical application in multiple scenarios, the system has demonstrated its effectiveness, robustness, and reliability.

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