ViPSN-Button: A Motion-Powered Wireless Pushbutton With Instant Feedback

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***Abstract*—With the development of the Internet of Things (IoT), wireless pushbuttons are increasingly being used to control devices such as lights, fans, and air conditioners in smart homes and offices. In contrast to conventional systems, self-powered pushbuttons eliminate the inconvenience of cable arrangement and the cost of battery replacement. However, existing self-powered wireless pushbuttons can only send commands unidirectionally and lack an instant feedback mechanism. This limitation reduces system reliability and impairs the user experience. To tackle this issue, we propose ViPSN-button, a motion-powered wireless pushbutton that offers instant feedback. When the ViPSN-button is pressed, it can deliver instant feedback to the user. This feedback mechanism enables the user to confirm whether the host unit has successfully acknowledged their command. The ViPSN-button is powered by a quasistatic-toggling energy harvester (QST harvester). The entire communication process of the ViPSN-button includes three steps: sending commands, receiving acknowledgments (ACK), and displaying an indication. All of these actions are carried out solely by utilizing the energy generated from a single press action. Experiments demonstrate that the ViPSN-button can achieve low-power, fast, private, and reliable bidirectional communication under the enhanced ShockBurst (ESB) communication protocol. Field tests have been conducted, showing that the ViPSN-button can achieve reliable communication at a distance of 50 m. The ViPSN-button offers an innovative design concept for self-powered sensing nodes, facilitating bidirectional communication between host units and sensing nodes. This feature renders it highly suitable for a wide range of applications, including smart homes, smart offices, smart cities, and industrial IoT.**

***Index Terms*—Battery-free Internet of Things (IoT), energy harvesting (EH), instant feedback, quasistatic-toggling (QST) energy harvester (EH).**

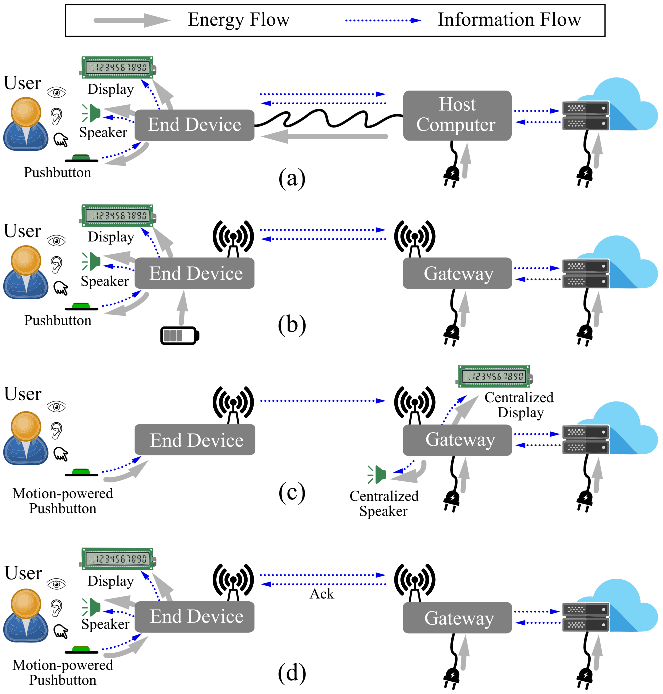

Fig. 1. Different pushbutton setups. (a) Conventional cable-connected system. (b) Conventional wireless system with battery-powered terminal. (c) State-of-the-art design using a motion-powered transmitter. (d) Proposed ViPSN-button, a motion-powered system with instant ACK feedback.

I. INTRODUCTION

With the rapid development of Internet of Things (IoT) technologies, seamless interaction with surrounding devices has become increasingly feasible. Sensing nodes represent the most fundamental components of the IoT. They are capable of sensing the environmental changes or capturing user input [1], [2]. IoT is widely used in various domains, including security guard [3], human action detection [4], [5], health monitor [6], [7], [8], smart city [9], [10], [11], smart building [12], and so on. Pushbuttons, as one of the most common types of sensing nodes, serve as critical interfaces for capturing user commands and transmitting them to the host unit.

As shown in Fig. 1(a), conventional pushbuttons are physically connected to the host unit via a cable. This cable can supply power and transfer data. Indicators can be integrated into the pushbutton unit to display feedback. However, cable arrangement is cumbersome and costly, especially when the distance between the pushbutton and the host unit is long. To address this problem, wireless pushbuttons have been developed, as illustrated in Fig. 1(b). These pushbuttons are battery-powered. They adopt communication protocols such as Bluetooth low energy (BLE), ZigBee, and sub-1-GHz protocols. Wireless communication makes the deployment of pushbuttons more flexible. However, these pushbuttons require

Received 19 May 2025; revised 16 September 2025; accepted 9 October 2025. Date of publication 17 October 2025; date of current version 8 December 2025. This work was supported by the National Natural Science Foundation of China under Grant 62271319 and Grant U21B2002. *(Corresponding authors: Haoyu Wang; Junrui Liang.)*

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Digital Object Identifier 10.1109/JIOT.2025.3622640

TABLE I
COMPARISON OF STATE-OF-THE-ART SELF-POWERED IoT SENSING NODES

Reference	Type	Generator	Manufacture & Type	Protocol	Frequency	Distance (indoor)	Feedback
[13]	Pushbutton	Electromagnetic	EnOcean PTM216Z	Zigbee	2.4 GHz	25 m	No
[14]	Pushbutton	Electromagnetic	Ebelong M1	RF 433	433 MHz	25 m	No
[15]	Pushbutton	Electromagnetic	Linptech K9Z	Zigbee	2.4 GHz	15 m	No
[16]	Light illuminance measure	Photovoltaic	Academic	BLE	2.4 GHz	Not provided	No
[4]	Motion sensor	Electromagnetic	Academic	BLE	2.4 GHz	15 m	No
[17]	Sensor platform	Radio-frequency	Academic	RFID	13.56 MHz	Several meters	No
This Work	Instant feedback pushbutton	Electromagnetic	Academic	ESB/BLE	2.4 GHz	50 m	**Yes**

periodic battery replacements, which can be expensive and labor-intensive in large-scale applications. Additionally, the frequent disposal of used batteries may give rise to environmental concerns.

To avoid the need for battery replacement, self-powered wireless pushbuttons have been developed. As shown in Fig. 1(c), this kind of pushbutton is powered by the kinetic energy from the user's motion. An energy harvester (EH) is employed to convert kinetic energy from the user's motion into electrical energy, powering this type of pushbutton [18], [19], [20]. Since energy generated by the EH is limited [20], the pushbutton should operate with maximum efficiency to minimize energy consumption. A long wait for feedback is not acceptable. For this reason, pushbuttons in previous studies can only realize unidirectional communication. They can only send data to the host unit. They cannot confirm whether the commands have been successfully acknowledged by the host unit.

Several manufacturers are active in the domain of self-powered pushbuttons. EnOcean [21] provides a complete self-powered button and receiver product series. EnOcean also developed its own wireless communication protocol. Alps Alpine [22] introduced a new EH mechanical design, which can realize quiet and gentle power generation. In addition to serving as the power source for self-powered buttons, this device can also supply power to other IoT sensing nodes. These IoT sensing nodes can be applied to scenarios such as door opening detection, smart locker systems, and public restroom occupancy detection. Table I presents a comparison of various self-powered IoT devices. Manufacturers and researchers adopt different kinds of communication protocols to send commands. However, these communications are all unidirectional.

This limitation leads to a significant uncertain risk, especially in applications where reliability is crucial, such as emergency call buttons or industrial control systems. For example, when a self-powered button is used as an emergency call button, it may fail to transmit emergency signals reliably. In extreme circumstances, such transmission failure may cause safety risks or even lead to severe accidents.

To overcome this limitation, we propose ViPSN-button, a self-powered wireless pushbutton that not only can send commands to the host unit but also receives instant feedback from it and displays this feedback to the user. This function allows the user to confirm that their command is successfully acknowledged by the host unit. The conceptual configuration of the ViPSN-button is shown in Fig. 1(d).

The ViPSN-button is powered by a quasistate-toggling energy harvester (QST harvester), which converts kinetic energy generated by a user's button press into electrical energy. This harvested energy is subsequently utilized to send commands to the host device, receive acknowledgment (ACK) signals, and display instant feedback indications to the user. Through optimized design of energy management and communication protocols, the ViPSN-button achieves reliable bidirectional communication by using the limited amount of harvested energy. The proposed ViPSN-button not only enhances the reliability of command transmission but also offers a novel direction for the development of self-powered IoT sensing nodes.

There are three major contributions of this ViPSN-button design.

1) *User Interaction:* The ViPSN-button is the first self-powered wireless pushbutton with instant feedback indication. It solves the critical issue of command ACK at the transmitter side, enhancing both user experience and system reliability.
2) *Energy-Neutral Design:* By balancing the energy supply and consumption in the communication and display process, the ViPSN-button is capable of executing the entire communication and display process with the tiny energy harvested from a finger press.
3) *Communication:* The ViPSN-button pioneers a new approach and presents more opportunities for bidirectional communication in energy-constrained IoT devices.

This article is organized as follows. Section II reviews the related work on energy harvesting, battery-free IoT, and energy management. Section III provides an overview of the ViPSN-button system, including all hardware components. Section IV introduces the methodology and challenges of developing the ViPSN-button. Section V presents the analysis of the energy harvesting model. Section VI introduces the low-power realization methods, including low-power software design. Section VII describes the experimental setup and results, including energy consumption, energy generation, and the communication field test. Section VIII explores potential application scenarios for the ViPSN-button in various IoT domains. Finally, Section IX concludes this article and outlines future research directions.

II. RELATED WORKS

A. Energy Harvesting

Energy harvesting serves as the foundational technology of self-powered IoT sensing nodes. EHs can convert energy from the environment or the user's motion into electrical energy. Existing technologies for EHs are mostly based on electromagnetic [3], [4], [23], [24], [25], [26], [27], piezoelectric [28], [29], [30], radio frequency (RF) [17], [31], [32], [33], photovoltaic (PV) [16], [31], and so on. Energy harvesting can be roughly classified into two research aspects based on the harvested energy scale. One is macroscale (> 1 W) energy harvesting, another one is microscale (< 1 W) energy harvesting [34]. Different types of EHs are introduced to harvest different kinds of energy. Energy sources can be divided into ambient sources and human sources [18].

Solar energy is a clean and easily available ambient energy source. Solar cells, which are semiconductor devices made of silicon, generate electricity when exposed to sunlight. Upon receiving sunlight, the PV effect causes electrons and holes to separate within the cell. The movement of these electrons can create an electric current. To optimize power output, regulators are employed to implement maximum power point tracking (MPPT). The efficiency of solar cells has reached 26% in recent years [35]. Typical solar cells can provide 500 W/m^2 in sunny outdoor environments and 10 W/m^2 in typical indoor illumination environments. IoT sensing nodes powered by solar energy should be placed in well-lit areas to ensure optimal performance.

Wind energy is another ambient energy source that can be converted into electricity through wind turbines. The efficiency of small-scale wind turbines ranges from 30% to 40%, depending on wind speed and turbine design [27]. In typical outdoor environments with wind speeds between 2 and 12 m/s, small-scale turbines can generate power outputs from a few watts to over 100 watts.

Energy derived from human activities is defined as human energy. Human movements, such as arm swinging, walking, and button pressing, can all generate energy. To harvest this kind of energy, various types of EHs have been developed. For instance, in the scenario of arm swinging, the EH is mounted on the user's wrist. The mechanical structure inside the harvester rotates to drive an electromagnetic generator. This process converts the kinetic energy of arm swinging into electrical energy [25].

Liu et al. [26] introduced the working principle of a QST harvester and analyzed its energy and dynamic characteristics. When the user presses the QST harvester, a magnet integrated within the device is toggled, causing the direction of the magnetic flux passing through the associated coil to reverse. According to Faraday–Lenz law, this action generates a voltage pulse. Upon releasing the QST harvester, the flux direction reverses once more, thereby generating another voltage pulse with opposite polarity. The energy harvested in this manner can be used to power the following electronics for sending wireless commands.

In pushbutton application scenarios, users are required to press a specific position. A QST harvester can function as a button, facilitating user pressing operations. When a user presses the button, the QST harvester is pressed simultaneously; this process enables the QST harvester to convert kinetic energy into electrical energy. The tactile feedback of pressing a QST harvester is similar to that of pressing a traditional button. For this reason, the QST harvester serves as the most suitable EH solution for the ViPSN-button.

B. Battery-Free IoT

Li et al. [23] introduced a vibration-powered IoT platform named ViPSN, which includes six parts: an energy generation unit (EGU), an energy transduction unit (ETU), an energy enhancement unit (EEU), an energy management unit (EMU), an energy user unit (EUU), and an edge demonstration unit (EDU). Some low-cost systems may omit or combine some of these units.

In [16], a battery-free PV tag is proposed for indoor light illuminance measurement. The tag employs a PV cell to harvest solar energy. It transmits a data packet to the host unit only when it has accumulated sufficient energy to support one transmission process. Specifically, the time required for the PV tag to collect adequate energy is inversely proportional to the ambient light intensity. This means that a brighter environment corresponds to a shorter energy harvesting duration. Subsequently, the host unit calculates the indoor light intensity. It performs this calculation by analyzing the time interval between the receptions of two consecutive data packets.

Lee and Choi [36] introduced a self-powered tire pressure sensor. They integrated a piezoelectric EH that can generate 380.2 μJ of energy per revolution under a 500-kgf load and at a speed of 60 km/h. The author also designed an energy management circuit, which can store harvested energy in a capacitor and provide a stable energy supply to the wireless pressure sensor. They also focused on the optimal design of the EH mechanical structure, enhancing the efficiency of energy harvesting even under low-speed conditions.

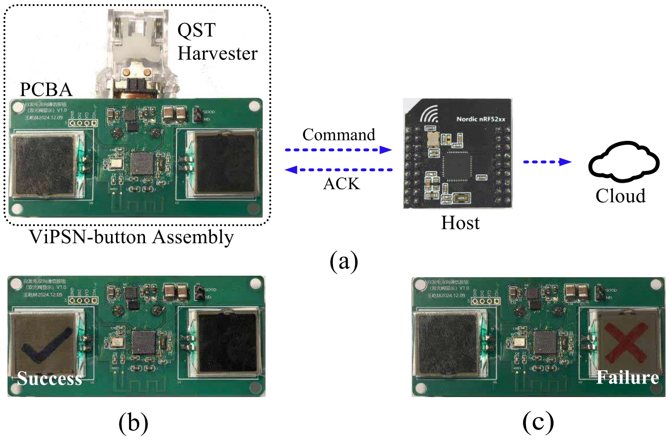
He et al. [33] introduced Hornbill, a battery-free electrochemical bio-tag powered by near-field communication (NFC). This device adopts a charge pump regulator and a dual-channel potentiostat to enable stable electrochemical detection without external batteries.

In [37], a vibration EH (VEH) equipped with a double-frequency upconversion (FUC) mechanism was introduced, which is capable of generating 75 μW at a 0.2-Hz vibration frequency. In smart city scenarios, cars or pedestrians can be the vibration sources for such harvesters.

In [31], a hybrid energy harvesting system that integrates solar and RF energy was introduced. This system enhances stability and efficiency, ensuring reliable operation of low-power IoT devices in varying conditions.

Human action, which is also known as motion power, can serve as an energy source for EH. In [4] and [25], EHs are placed on the user's wrist and collect energy generated by the arm shaking. This kind of EH can power sensors that can sense the user's step rate and the surrounding environment. Sensed data can be sent to the host unit to recognize the user's actions.

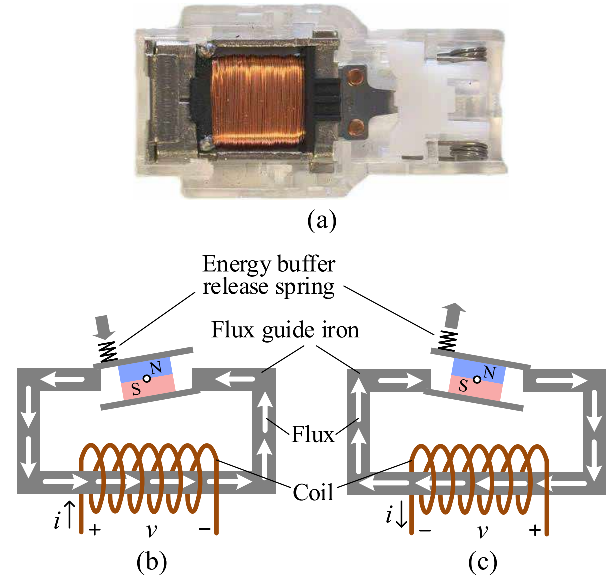
Wang et al. [38] introduced a piezoelectric energy harvesting floor tile. When excited by a footstep, the piezoelectric tile generates an impulsive voltage. An energy management circuit is designed to collect this energy to power a Bluetooth low energy (BLE) tag. This tile can be applied to measure pedestrian congestion, individual tracking, fall detection, and security surveillance.



(a)

(b) (c)

Fig. 2. (a) ViPSN-button system overview. (b) Successfully sent. (c) Failure.



(a)

(b) (c)

Fig. 3. QST harvester. (a) Real product. (b) and (c) Working principle.

C. Energy Management

The EMU serves as the intermediary between the EGU and the EUU, conditioning the harvested energy for optimal utilization. The EMU is in charge of rectification, energy buffering and release, voltage regulation, and so on. Teng et al. [39] introduced a concise discrete three-transistor energy management (3T-EM) circuit topology. The 3T-EM circuit can provide a regulated voltage to energy users. In addition, it can also track stored energy levels and only start energy supply when energy is sufficient for an EUU working process. The overall design of the 3T-EM circuit is optimized to minimize both the size of the printed-circuit board assembly (PCBA) and the number of its components.

A widely used EMU IC in energy harvesting applications is LTC3588-1 by Analog Devices, Inc. [40]. The LTC3588-1 features an energy-ready indicating mechanism. When the harvested energy is sufficient, the “PGOOD (power good)” signal maintains a high level. When the harvested energy is nearly exhausted, the “PGOOD (power good)” signal drops to a low level. This mechanism enables energy users to determine whether the energy supply is adequate. When energy is nearly exhausted, the system on chip (SoC) can be interrupted, allowing it to save critical data before energy failure occurs.

III. SYSTEM OVERVIEW

Fig. 2(a) shows the prototype of the ViPSN-button system. This experimental setup consists of two main components: a pushbutton unit and a host unit. When a user presses the button, the QST harvester converts the kinetic energy generated by the user’s motion into electrical energy. Subsequently, the pushbutton unit transmits a data packet to the host unit. Upon receiving this data packet, the host unit sends an ACK packet back to the pushbutton unit. If the pushbutton unit successfully receives the ACK packet, the entire communication process is completed. After this, an instant feedback indication is displayed to the user using a proper low-power display technology.

As analyzed in [23], the ViPSN-button is divided into four main components. The EGU, which is a QST harvester, converts the kinetic energy from a finger press into electrical energy. The EMU rectifies and manages impulsive energy, providing a reliable energy source to the EUU in a short period of time. The EUU collects information about the user’s operation, sends packets to the host unit, listens for feedback, and displays the communication results on a low-power display as visual feedback. The EDU is an optional unit if the system requires a visual demonstration of the switching command remotely through the Internet.

A. EGU

The EGU of the ViPSN-button is a QST harvester. When the user presses the button, the QST harvester is simultaneously pressed and actuated.

The QST harvester, which is shown in Fig. 3(a), serves as the primary energy source for the ViPSN-button. It converts the kinetic energy generated by a user’s button press into electrical energy. The principle of the QST harvester can be explained by clarifying three key features as follows.

1) *Potential Energy Precharging:* The spring within the QST harvester stores mechanical energy upon being pressed and releases it once the applied force exceeds a predefined threshold. This mechanism can ensure consistent energy output with each press.
2) *Instantaneous Magnetic Pole Swapping:* As shown in Fig. 3(b) and (c), when the spring releases its stored energy, it drives a magnetic core to move abruptly. This rapid movement changes the magnetic flux direction, inducing an electric current according to Faraday–Lenz Law.
3) *Easy-to-Process Output Voltage:* As Fig. 4 shows, the amplitude of voltage pulses generated by the QST harvester typically ranges from 10 to 30 V. This voltage range is easy for efficient management and storage by EMU.

As shown in Fig. 4, the QST harvester has two movement processes: pressing and releasing. Thus, it can generate a

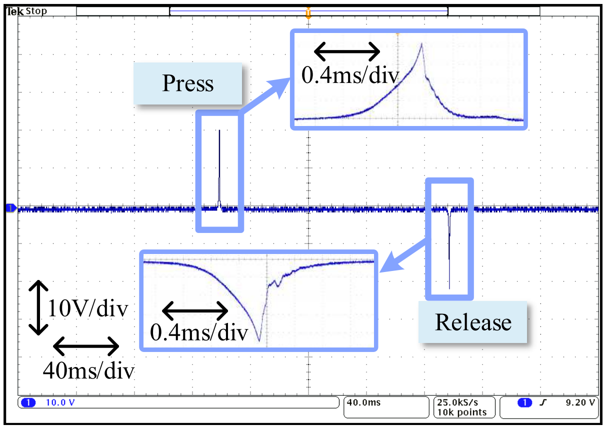


Fig. 4. QST harvester voltage waveform in a press-release cycle.

TABLE II
HARVESTED ENERGY OF SOME QST HARVESTERS

Manufacturer	Type	Peak force	Energy	Ref.
Alps Alpine	SPGA110100	6 N	170 μJ	[41]
Linptech	RPM5600	4 N	600 μJ	[42]
EnOcean	ECO260	2.7 N	210 μJ	[43]

bipolar voltage signal. A rectifier circuit is required within the EMU to manage this bipolar signal. Table II lists the amounts of harvested energy for various commercial QST harvesters.

The QST harvester also works as a button to trigger the command transmission. When the user presses the QST harvester, the pushbutton unit receives energy and sends the data packet immediately once the SoC finishes the cold start.

B. EMU

The EMU of the ViPSN-button adopts LTC3588-1, developed by Analog Devices, Inc. LTC-3588-1 is a nano-power EMU that integrates a low-loss full-wave bridge rectifier and a high-efficiency buck converter. This EMU provides a stable energy source with a constant digital voltage to the EUU. A built-in rectifier is suitable for processing the bipolar voltage signal generated by the QST harvester. The circuit topology of EMU can be found in the schematics of the ViPSN-button assembly in Fig. 5.

C. EUU

The EUU of the ViPSN-button employed a low-power SoC: nRF52832 by Nordic Semiconductor, Inc. This SOC integrates a 2.4-GHz wireless transceiver capable of transmitting data packets via Bluetooth low-energy (BLE) or enhanced Shock-Burst (ESB) communication protocol.

The ViPSN-button assembly includes two liquid crystal light valves (LCLVs) to display instant feedback indications. When the LCLV is energized, the opacity changes from a shielded state to a transparent state. Behind the two LCLVs, we install two small pieces of paper as the display background: one draws a green check mark and another a red cross mark. Therefore, the check mark is shown after each successful transmission, while the red cross mark is shown after each unsuccessful transmission, as shown in Fig. 2(b). The extremely low-power LCLV makes a good compromise between low-power consumption and demonstration of intuitive and colorful pictures.

IV. METHODOLOGY AND CHALLENGES

This section outlines the methodology employed to develop the ViPSN-button, focusing on the key components and mechanisms that enable its functionality. It also discusses the major challenges encountered in designing a self-powered wireless pushbutton with instant feedback and the methods adopted to overcome these challenges.

A. Methodology

The ViPSN-button adopts several innovative components and mechanisms to achieve its functions. The core methodology includes an energy buffer-release mechanism (EBRM) [44], a low-power communication protocol, an instant feedback display, and a multidevice identification mechanism.

1) Energy Buffer-Release Mechanism: Since the harvested energy is often intermittent and variable, the EBRM [44] is crucial for stabilizing the energy supply to the device. The EBRM collects and stores harvested energy, releasing it only when it reaches a threshold specifically designed to be sufficient for EUU to complete the entire communication and instant feedback display process. There are three main types of EBRM:

1) *No EBRM:* This type of EBRM directly converts and utilizes energy immediately, making it suitable for scenarios with a consistent power supply. Since the ViPSN-button communication process needs a period to complete, this method is not suitable.
2) *Mechanical EBRM:* This type of EBRM stores mechanical energy in a spring and releases it only when sufficient force is applied. The spring in the QST harvester, which releases energy only when the force exceeds a threshold, is an example of mechanical EBRM.
3) *Electrical EBRM:* This type of EBRM stores electrical energy in a capacitor within the EMU and releases it once the voltage threshold is met. Electrical EBRM is adopted in EMU to ensure a stable power supply for the entire communication process.

2) Low-Power Communication Protocol: To achieve instant feedback, a bidirectional wireless communication protocol is essential. We evaluated two protocols: BLE and ESB.

BLE is a low-energy communication protocol designed by the Bluetooth Special Interest Group (Bluetooth SIG) [45]. A pair of BLE devices can be divided into a host machine and a peripheral machine. The BLE communication process is as follows.

1) *Broadcast:* The BLE peripheral machine broadcasts its device name, address, and other customized data on advertising channels. This information is accessible to all host machines.
2) *Scan:* The BLE host machine scans advertising channels, identifies specific peripheral machines, and reads the data they are broadcasting.

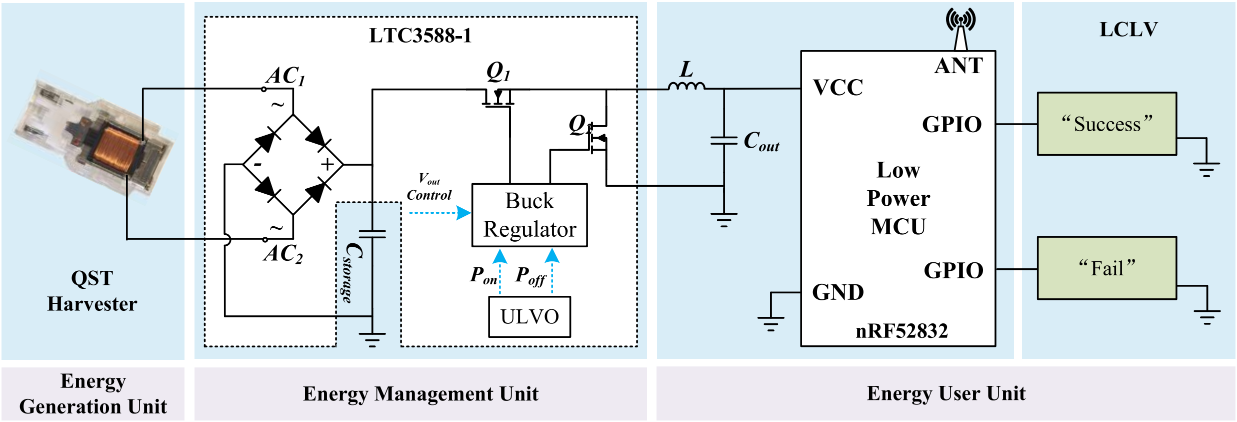


Fig. 5. Schematics of the ViPSN-button assembly.

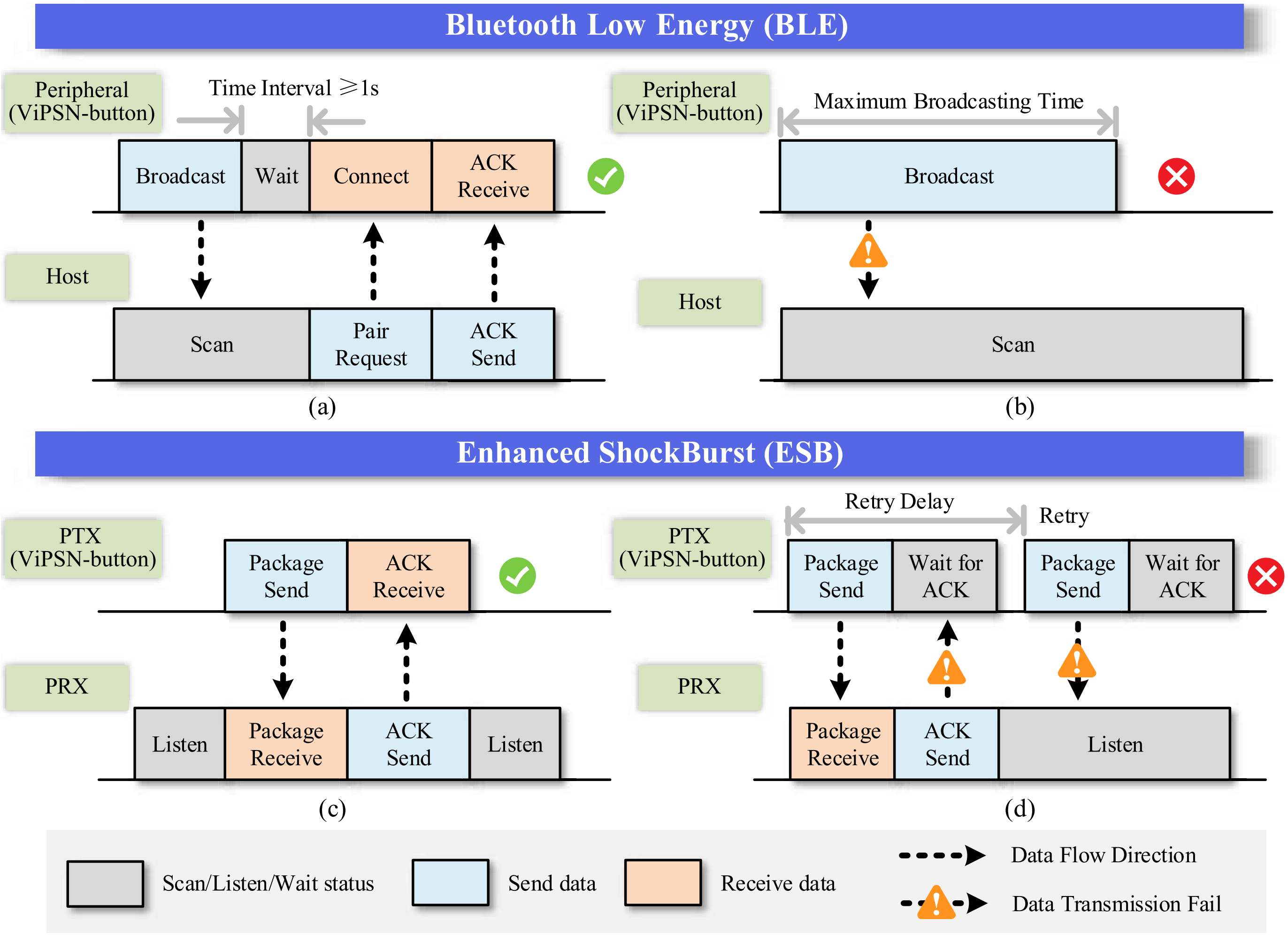


Fig. 6. BLE and ESB protocols. (a) BLE success. (b) BLE failure. (c) ESB success. (d) ESB fails.

3) *Connect:* The BLE host and peripheral machine establish a connection and subsequently communicate on other channels.

As Fig. 6(a) shows, when the ViPSN-button operates in the BLE mode, the host unit serves as the host machine, while the pushbutton acts as the peripheral machine. When the button is pressed, it first enters broadcast mode. The broadcast data includes the Bluetooth address, the button identification number, and the command signal.

When the host machine scans and identifies the peripheral machine, it establishes a connection and sends a feedback data packet. If all these procedures are completed, the communication is deemed successful, and a "success" feedback is displayed to the user. Conversely, if the host unit fails to

TABLE III
ENERGY CONSUMPTION OF SOME FEEDBACK DEVICES

Device	Voltage	Current	Power
LED (Red)	1.835 V	725.2 μA	1.331 mW
LED (Blue)	2.551 V	603.6 μA	1.540 mW
LED (Green)	2.285 V	276.8 μA	0.632 mW
Active buzzer	1.861 V	1073 μA	19.92 mW
LCLV	1.816 V	$<$ 0.3 μA	$<$ 0.5 mW

connect to the button within the waiting time, the communication procedure fails, and a "failure" feedback will be displayed.

ESB is another low-power communication protocol characterized by its fast and efficient communication. In the ESB communication protocol, there are two types of devices: one is the primary receiver (PRX), and the other is the primary transmitter (PTX). As Fig. 6(b) shows, a successful ESB communication with ACK has four steps.

1) *PTX Send:* PTX sends a packet to PRX.
2) *PRX Receive:* PRX receives the packet from PTX.
3) *ACK Packet Send:* After PRX successfully receives the packet, PRX sends an acknowledgment packet (ACK packet) to PTX.
4) *ACK Receive:* PTX receives the ACK packet after sending the data packet. If PTX can successfully receive an ACK packet from PRX, the entire communication process is completed.

If PTX does not receive an ACK packet from PRX, it will resend data several times. If all attempts fail, the communication procedure is deemed unsuccessful. The ESB protocol is characterized by two key features: ease of use and high speed. Without complex scanning and pairing steps, the entire communication process only takes a few milliseconds. Energy generated from a single press can easily cover the consumption.

When the ViPSN-button operates under this protocol, PTX is the pushbutton unit, while the host unit works as PRX. When a user presses the button, the pushbutton unit will send the data packet to the host unit. If the pushbutton unit successfully receives the ACK packet from the host unit, the entire communication process is deemed successful, then a "success" feedback will be displayed. Otherwise, a "failure" feedback will be displayed.

BLE requires a complex pairing and connecting process, which results in higher energy consumption and prolonged communication durations. In contrast, ESB is designed for fast and efficient communication, requiring only a few milliseconds for a complete transaction. Considering the limited energy harvested from a single button press, ESB is selected for its low-power characteristics and rapid communication capabilities.

3) Instant Feedback Display: Since the ViPSN-button needs to show whether communication is successful to the user, it is necessary to select a feedback mechanism. This mechanism should be visible or audible and as energy-saving as possible to extend the operation time for the device. Table III shows the power consumption of several devices used for providing feedback indications. Among these mechanisms for making local feedback, the LCLV has the lowest energy consumption. In addition, LCLV has a larger visible area and a longer display duration, making it easier for users to identify. These features make the LCLV an ideal candidate for providing visual feedback in energy-limited applications.

4) Multidevice Identification: In practical applications, multiple ViPSN-buttons and multiple host units often coexist in the same environment. Thus, distinguishing between different devices is necessary. For ViPSN-buttons that adopt the BLE protocol, each button and each host unit is assigned a unique Bluetooth address. These unique addresses serve as the basis for distinguishing different buttons from one another and different host units from one another. Each ViPSN-button stores the Bluetooth address of its corresponding host unit. It only permits this specific host unit to perform pairing operations with it and to send ACK data packets to it.

For buttons employing the ESB protocol, each button and each host unit is assigned a unique ESB address. This unique ESB address enables mutual distinction between individual buttons and host units. Each host unit shares an identical ESB address with its corresponding ViPSN-button. When an ESB data packet is transmitted by a button, the button also sends its own identification number. This identification number allows the host unit to identify which specific button has been pressed. Devices are required to have the same ESB address to establish communication with one another. Different host units are configured with distinct ESB addresses. Due to these distinct ESB addresses, host units with different addresses operate independently of each other. Each button can only receive ACK packets from its matched host unit.

B. Challenges

The development of the ViPSN-button encounters several challenges, including limited energy supply, the need for a reliable feedback mechanism, and the implementation of energy-saving strategies.

1) *Limited Energy Supply:* A single button press supplies limited energy for the entire communication process. This requires optimized energy management and communication protocols.
2) *Reliable Feedback Mechanism:* For feedback implementation, an LCLV is selected. This choice is based on two key advantages of the LCLV: low power consumption and clear visual indication.
3) *Energy Saving Strategy:* To save energy, the SoC software is optimized in three aspects: first, minimizing the number of operations; second, turning off peripherals immediately after use; third, reducing the execution time.

V. ENERGY MODELING

To analyze the energy generation process of the QST harvester, a theoretical model is established to describe the entire process, from the user's motion to energy collection, conversion, and consumption. The QST harvester involves several key physical mechanisms: mechanical energy input, energy buffering and storage, electromagnetic induction, and energy management.

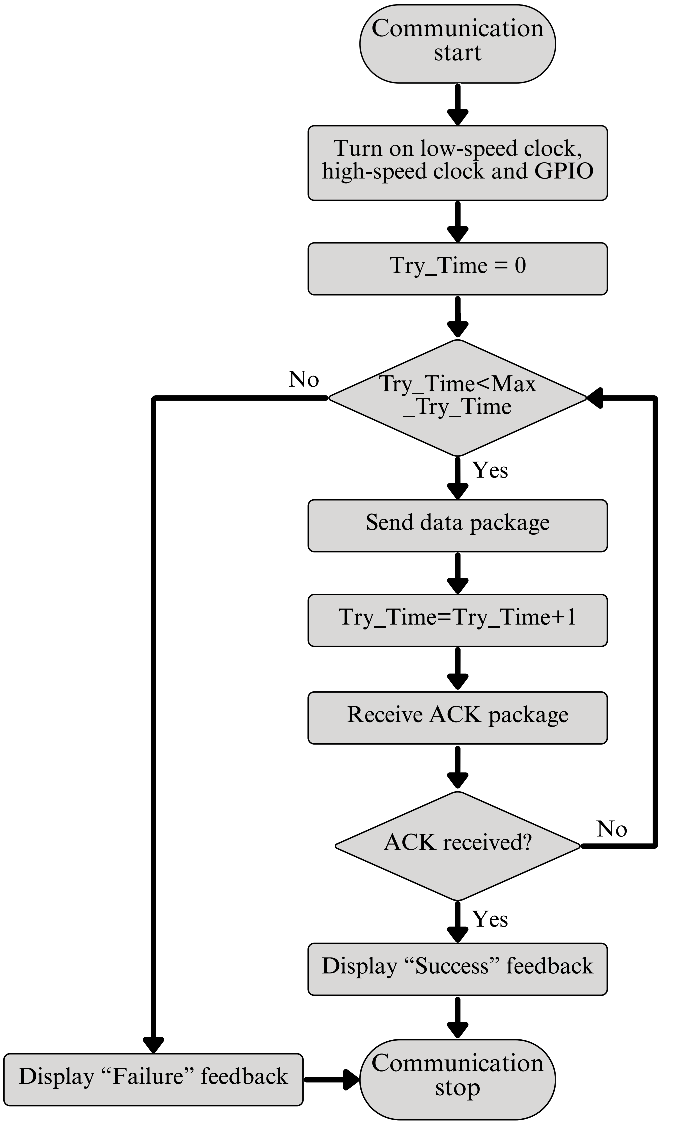


Fig. 7. Conventional flow.

When a user presses the button, mechanical energy is introduced into the system and accumulated by the energy-buffering spring in the QST harvester. According to Hooke's law, the elastic potential energy stored in the spring can be mathematically expressed as follows:

$$E_{\mathrm{mech}} = \frac{1}{2}kX^2 \tag{1}$$

where k is the spring constant and X is the critical displacement of the moving end of the button, which occurs under the user's press at the instant of toggling.

When the force applied to the QST harvester reaches the threshold, the spring releases, and the magnetic flux changes direction suddenly. It induces an impulsive electromotive force. According to Faraday–Lenz law, that is,

$$\mathcal{E} = -N\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{2}$$

where N is the number of turns in the coil and Φ is the magnetic flux through each turn.

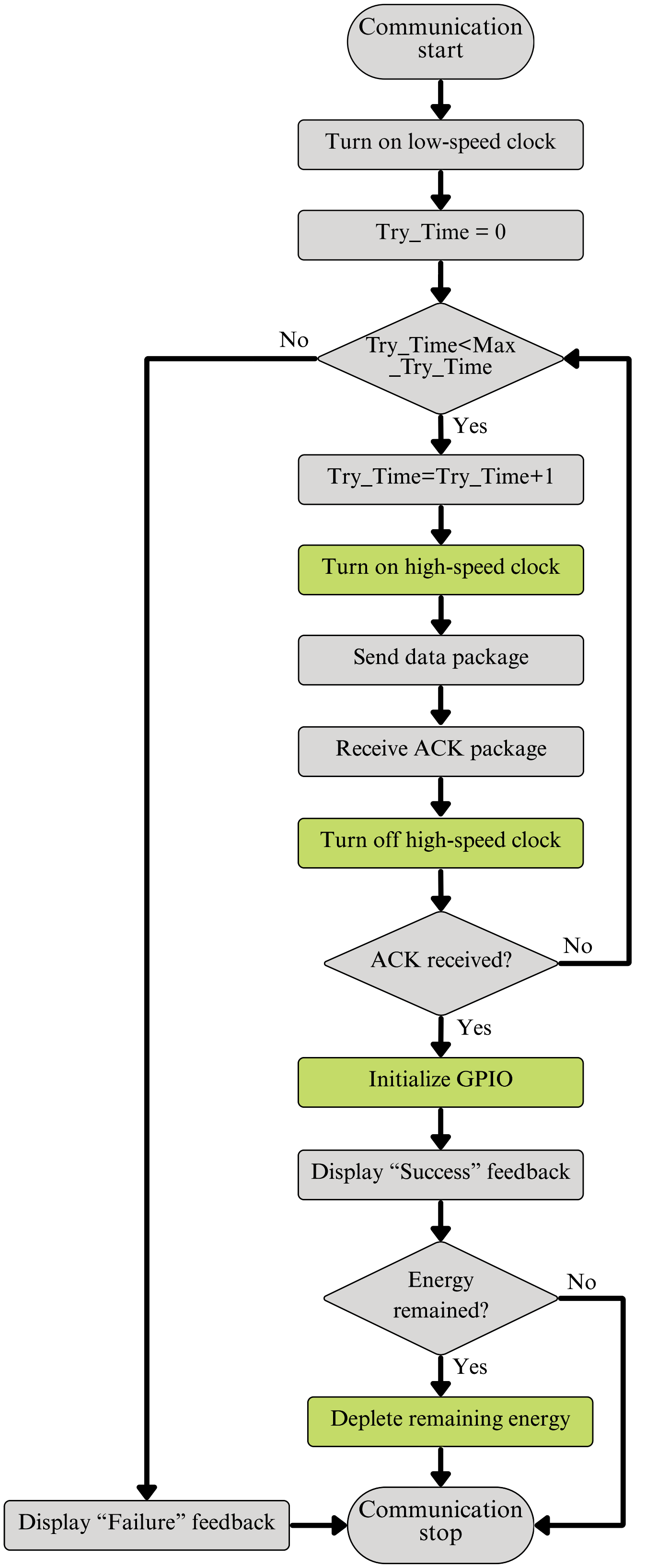


Fig. 8. Low-power optimized flow. Differences to the conventional flow are highlighted in green.

Since the electromagnetic induction process involves complex mechanic–magnetic–electric coupling dynamics, we simplify it by just assuming a constant energy conversion

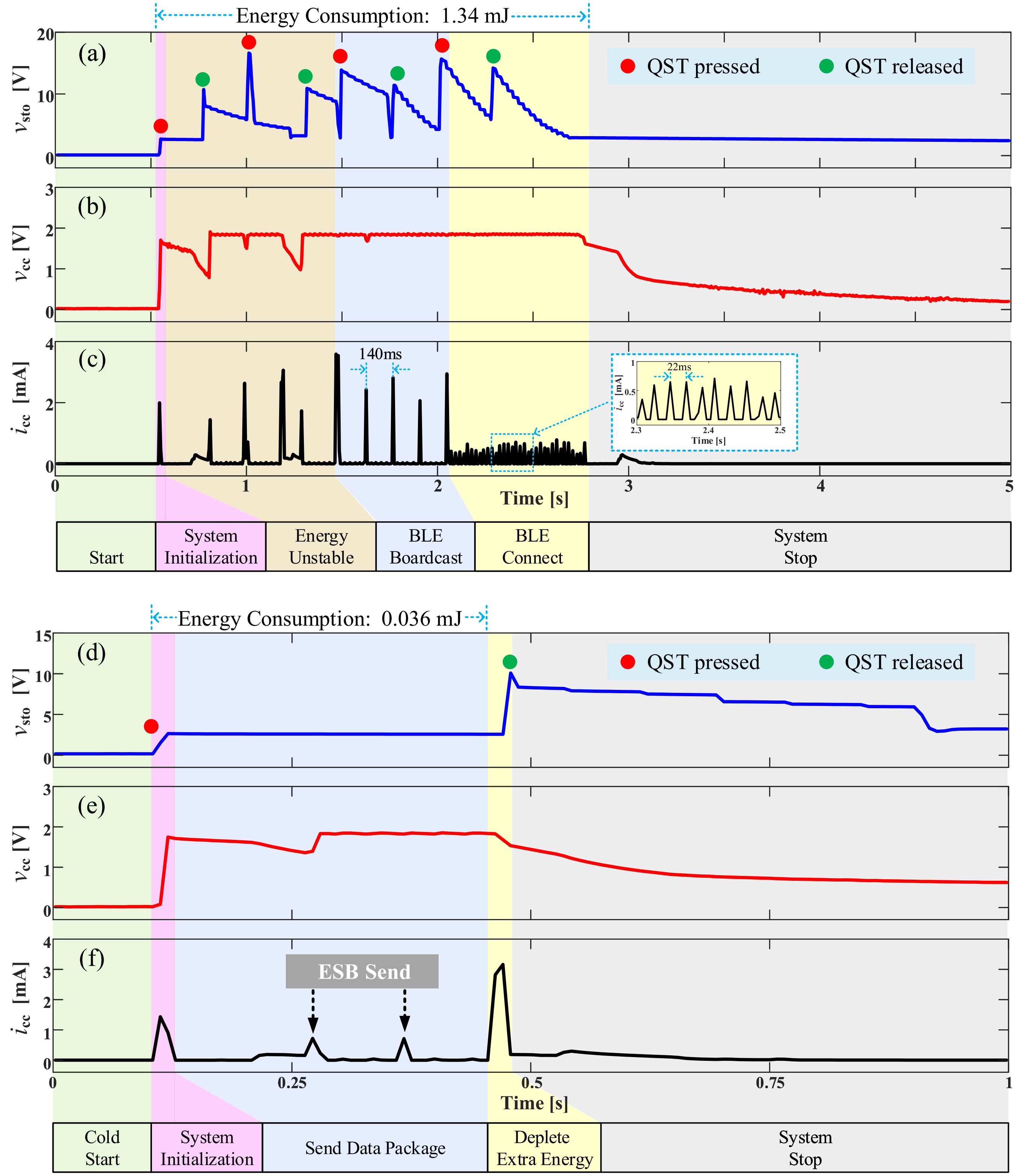


Fig. 9. Voltage and current curve in the experiment. (a)–(c) BLE protocol. (d)–(f) ESB protocol.

efficiency. Consequently, the electrical energy output in each toggling can be expressed as follows:

$$E_{\text{elec}} = \eta E_{\text{mech}}. \tag{3}$$

Energy collected by the QST harvester is stored in a capacitor C_{sto} in the EMU. The voltage across the capacitor after a toggling can be expressed as follows:

$$V_{\text{sto}} = \sqrt{\frac{2E_{\text{elec}}}{C_{\text{sto}}}}. \tag{4}$$

Denoting the instant load voltage as v_{cc} and instant load current as i_{cc}, the criteria of energy balancing between energy supply and load consumption is expressed as follows:

$$E_{\mathrm{elec}} \geq \int_{0}^{T_{\mathrm{end}}} v_{\mathrm{cc}}(t)\, i_{\mathrm{cc}}(t)\, \mathrm{d}t \tag{5}$$

where T_{end} is the finish time of all the scheduled tasks in each toggled instant.

VI. LOW-POWER REALIZATION

Since the QST harvester can only provide a limited amount of energy, a low-power design is necessary. This article adopts three key mechanisms to carry out low-power realization.

1) When using peripherals, only those that are necessary should be activated. After use, turn off these activated peripherals immediately.
2) Simplify the software program to shorten its execution time.
3) After all tasks are completed, deplete the excess energy to reset the entire system.

Conventional and optimized program flows are shown in flowchart Figs. 7 and 8, respectively. The high-speed clock only activates when the data packet is being sent and turns off immediately when transmission is finished. After all communication procedures are completed, additional energy is consumed to re-initialize the pushbutton unit. After the transmission process is completed, one of the two general-purpose input/output (GPIO) pins is activated. These two GPIO pins are, respectively, connected to the “success” LCLV and the “failure” LCLV. The activation of the corresponding GPIO pin provides instant feedback.

VII. EXPERIMENTS

A. Energy Consumption

1) BLE Protocol Energy Consumption: Fig. 9(a)–(c) shows the voltage and current waveforms under the BLE protocol. As analyzed in Section IV, the whole communication process of BLE includes broadcasting, scanning, and connecting. This procedure is more complex than the ESB protocol. The entire process takes at least 2 s to complete, and the energy consumption is measured as 1.34 mJ.

2) ESB Protocol Energy Consumption: Fig. 9(d)–(f) shows the voltage and current waveforms during one round of the send-and-ack process. As analyzed in the previous section, the ESB protocol is much faster than BLE. After the button is pressed, it takes less than 0.2 s to complete the whole communication process. Total energy consumption is 0.036 mJ, which is much less than that using the BLE protocol.

B. Energy Generation

The voltage waveform of the QST harvester is shown in Fig. 4. During a single press-release cycle, the magnetic flux passing through the coil of the QST EH undergoes two reversals. As a result, the QST EH can generate two voltage spikes with opposite polarities.

The circuit topology of EMU is shown in Fig. 5. An energy storage capacitor C_{sto} is adopted to store energy harvested by the QST harvester. The capacitance value affects both the maximum voltage and harvested energy. To evaluate the maximum voltage and harvested energy under different capacitor conditions, an oscilloscope is connected across C_{sto} without connecting any load. The maximum voltage can be measured according to the voltage waveform. Energy can be calculated according to the energy storage equation of a capacitor, that is,

$$E_{\mathrm{elec}} = \frac{1}{2} C_{\mathrm{sto}} V_{\mathrm{sto}}^{2}. \tag{6}$$

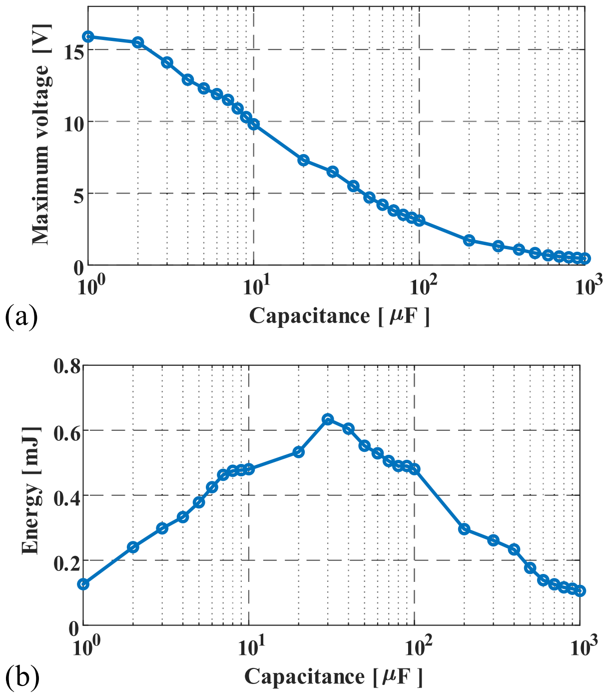


Fig. 10. (a) Maximum voltage versus capacitance. (b) Harvested energy versus capacitance in one press.

Fig. 10 shows the experimental voltage and energy results in one press.

According to the LTC3588-1 datasheet [40], LTC3588-1 is activated when the input (storage) voltage is higher than the output voltage. The output voltage is set to 1.8 V in this experiment. The maximum energy stored in the capacitor is 0.634 mJ. The corresponding voltage V_{sto} is 6.5 V. Since LTC3588-1 efficiency is higher than 50%, which means more than 0.317 mJ of energy is available to support the EUU in each operating cycle.

For the BLE protocol, this amount of energy is insufficient, which means that the QST harvester should be pressed several times to accumulate enough energy to power the communication process. In the experiment, it was found that the QST harvester should be pressed 4 times to accumulate sufficient energy, which is shown in Fig. 9(a).

For the ESB protocol, the energy generated by one single QST harvester press is sufficient to complete the entire communication process. In practical operation, after all communication processes are completed, a certain amount of residual energy remains. This remaining energy is intentionally dissipated by the SoC to reset the pushbutton unit, which is shown in Fig. 9(d). In practical application scenarios, requiring the user to press the button only once is more user-friendly and acceptable. For this reason, the ESB protocol is more suitable for practical implementation.

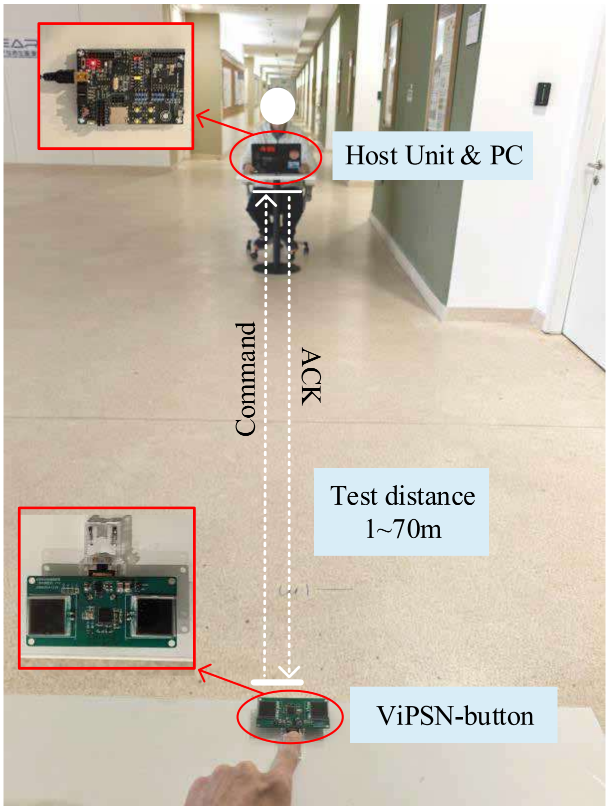


Fig. 11. Setup in the field test.

C. Field Test

To evaluate the reliability of bidirectional communication between the ViPSN-button and the host unit, we conducted field tests. As shown in Fig. 11, the field test is carried out in a long corridor. A host unit and a ViPSN-button were placed at the same height with no obstacle between them. The experimental processes are as follows.

1) *Setting Up Environment:* Place the ViPSN-button at a specific distance (1, 5, 10, 20, 30, 40, 50, 60, and 70 m) from the host unit. Ensure there is no obstacle between them. Power on the host unit. Make sure it is ready for communication.
2) *Transmitting Command:* Press the button. Read the instant feedback displayed on the ViPSN-button.
3) *Evaluating Result:* If ViPSN-button displays a “success” feedback, this attempt is successful. If a “failure” feedback is displayed, this attempt has failed.
4) *Repeating Experiment:* Do steps 2–3 for 50 rounds and calculate the success rate.

1) BLE Test Result: As discussed in the previous section, BLE consumes more energy than ESB. To realize a responsible command, it takes about four presses to accumulate sufficient energy. As shown in Fig. 12, the success rate of transmitting and receiving an ACK signal remains above 70% within a distance of 50 m.

As Fig. 12 shows, ESB can realize a reliable communication within a distance of 50 m, with a success rate of up to 98%. Beyond 50 m, the success rate drops significantly. Therefore, we recommend 50 m as a reliable communication range for the ESB version.

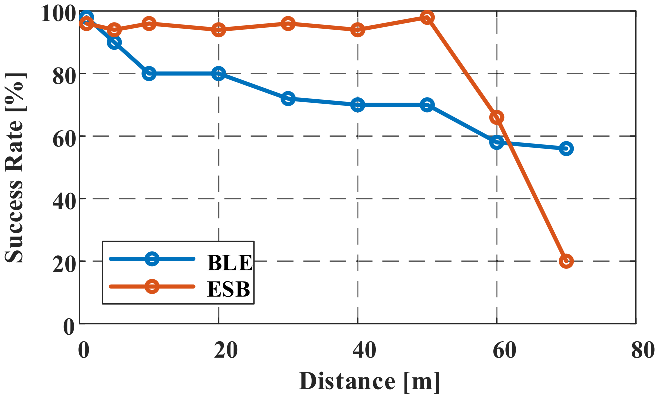


Fig. 12. Success rate in the field test.

Comparing the performances of BLE and ESB, ESB is more reliable, attributed to its higher success rate within a 50-m distance range. Moreover, the ESB version also enhances user experience by realizing “one-press, one-ACK.” Therefore, the ESB version firmware is more suitable for making a perfect ViPSN-button implementation.

VIII. POTENTIAL APPLICATION SCENARIOS

The ViPSN-button adopts motion-powered operation and provides instant feedback. It offers a reliable, private, user-friendly, and environmentally friendly remote control interface, making it suitable for various IoT applications. Potential application scenarios include the following.

1) *Smart Home:* ViPSN-button enables control of smart devices, including lights, curtains, and doorbells. It provides instant feedback to help users confirm whether their commands have been successfully received and executed. This function remains effective even when the target device is in another room. Besides, the self-powered design eliminates the trouble of frequent battery replacement for users, offering a user-friendly and environmentally sustainable smart home solution.
2) *Smart Office:* In the smart office scenario, the ViPSN-button can serve as a voting button in meeting rooms. Its instant feedback function allows users to confirm the successful submission of their votes. Additionally, this instant feedback is only accessible to the users themselves. There is no need to use loudspeakers to broadcast audible feedback. This design can effectively protect user privacy.
3) *Public Space:* In public spaces (e.g., restaurants, stations, and parks), the ViPSN-button can function as an interactive interface for service requests. In large restaurants specifically, the ViPSN-button can be used as a waiter-call device. This device enables customers to verify whether their requests have been received. Instant feedback is displayed directly on the ViPSN-button. This type of feedback supports quiet service responses to customers, which is particularly valuable in public environments requiring minimal noise disruption.

4) *Industrial IoT:* The ViPSN-button can be integrated into industrial control systems. It supports remote machine operation and status reporting. Instant feedback prevents miscommunication and enhances safety. This effect is more notable under energy and information dual uncertainties, which are caused by channel noise and energy limitation. For instance, the ViPSN-button can be used for remote calling of automated guided vehicles (AGVs). It visualizes and ensures the successful transmission of commands during this process.

IX. CONCLUSION

The ViPSN-button is the first self-powered wireless pushbutton with instant feedback indication. It is capable of not only sending commands to the host unit but also receiving feedback and displaying it to users. The instant visual feedback on the user side helps users confirm the successful reception of commands. This design enhances the reliability and improves the user-friendliness of the communication process. Additionally, this design contributes to the environmental sustainability of the system. To validate the proposed design, a prototype was developed. Experiments were conducted to measure the energy consumption of different feedback indication devices. Results showed that the LCLV is the most cost-effective device. In addition, the energy consumption of the prototype was measured and analyzed. The ESB version consumed less energy than the BLE version. This characteristic makes the ESB version more suitable for self-powered application scenarios. Field tests indicated that the ViPSN-button achieves reliable communication at a 50-m distance. This design enabled bidirectional communication for sensing nodes. Under strict energy budget constraints, the nodes can perform multiple functions. They can transmit commands or data to the host unit, receive signals from the host unit, and also visualize the received commands. It provides new insights for the development of self-powered ambient IoT terminals.

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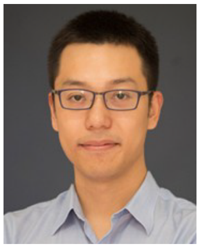

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