Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

ViPSN-Gateway: Energy-aware Routing Gateway for Battery-free IoT Sensor and Actuator Terminals

Yilin Wang
ShanghaiTech University
Junrui Liang
liangjr@shanghaitech.edu.cn

ShanghaiTech University

Research Article

Keywords:

Posted Date: November 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11464244/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

ViPSN-Gateway: Energy-aware Routing Gateway for Battery-free IoT Sensor and Actuator Terminals

Yilin Wang[1] and Junrui Liang[*,1]

[1]School of Information Science and Technology, Shanghaitech University, 1st Zhongke Road, Shanghai, 201306, Shanghai, China.

Contributing authors: wangyl22022@shanghaitech.edu.cn; liangjr@shanghaitech.edu.cn;

Abstract

Battery-free Internet of Things (BF-IoT) terminals driven by energy harvesters (EHs) work intermittently and cannot stay online continuously, rendering conventional always-on IoT gateways incompatible. Existing BF-IoT gateways are usually of the "sensor and receiver" type. They rely on a single energy source and a single wireless protocol, and typically only support uplink communication. BF-IoT terminals can only serve as data-transmitting sensors, rather than command-receiving actuators. This work proposes ViPSN-Gateway, a pioneering energy-aware routing gateway solution which enables uplink, downlink, and inter-node communication for BF-IoT terminals. A set of mechanisms including data forwarding, temporary storage and active data-request are proposed to match random terminal wake-up behavior, which reduces receiver standby power by over 99.98%. Its modular design supports multiple low-power protocols such as Bluetooth Low-Energy (BLE) and Enhanced ShockBurst (ESB). ViPSN-Gateway also supports multiple energy sources. Field tests verify a reliable communication range of 50 m. The round-trip latency is less than 1 ms for ESB and 1–3 s for BLE. Integrated with Home Assistant (HA) via message queuing telemetry transport (MQTT), the gateway interconnects various BF-IoT terminals with mainstream commercial smart home ecosystems. These terminals can work autonomously under the control of HA and ViPSN-Gateway. Featuring ultra-low power consumption, multi-protocol and multi-energy compatibility, ViPSN-Gateway provides a routing solution tailored for BF-IoT terminals to enable large-scale, practical BF-IoT deployments.

Keywords: battery-free, smart home, low-power gateway, data exchange, multi-energy-source, multi-protocol, temporary storage, data-request mechanism

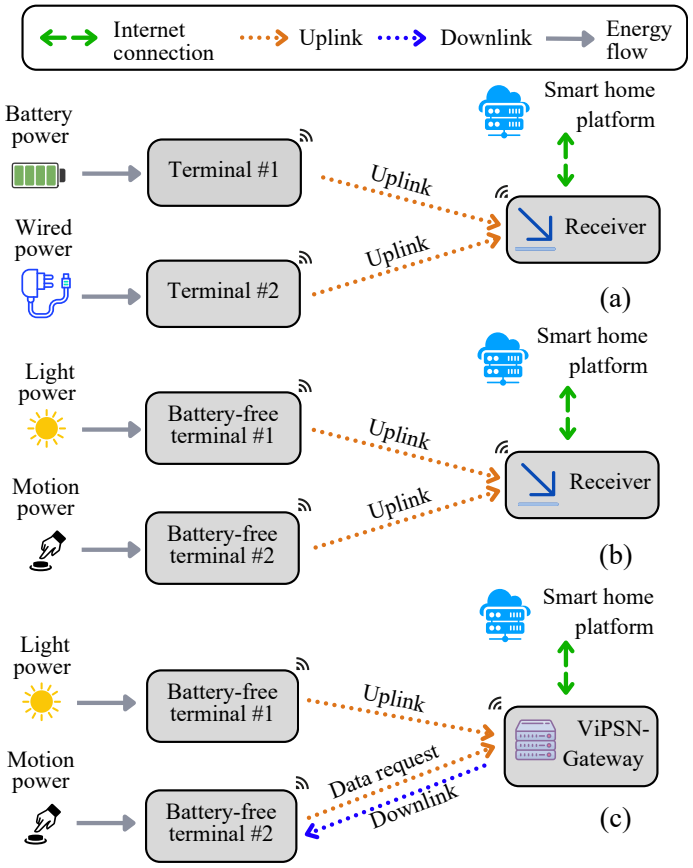


Fig. 1 Networks between gateway and terminals: (a) conventional external powered terminals; (b) battery-free terminals; (c) the proposed ViPSN-Gateway solution.

1 Introduction

Internet of Things (IoT) has revolutionized human interaction with surrounding environment by connecting various devices to the Internet [1]. This connectivity enables seamless and convenient interactions between users and devices, allowing for remote monitoring, controlling, and automation across various applications such as smart home [2–4], smart city [5], smart agriculture [6–9], safety guard [10–12], health care [13–15] and human motion detection [16, 17] etc. According to recent statistical data, global Internet of Things (IoT) market reached USD 805 billion in 2023. It is estimated to exceed trillion US dollars in 2026 [18].

The most important components of a large-scale IoT ecosystem are numerous IoT terminals [19–22]. These terminals can not only work as sensors to collect data from the external environment or users' input, but also as actuators to carry out commands from IoT platform. As shown in Fig. 1(a), conventional IoT devices rely on batteries or wired power; maintaining thousands of such terminals in a large-scale IoT system incurs heavy labor and deployment costs [23].

To solve this problem, as shown in Fig. 1 (b), BF-IoT terminals are introduced.

Despite the advantages of BF-IoT devices powered by EHs, their inherent intermittent operation caused by limited harvested energy creates three critical bottlenecks in practical deployment.

First, the energy collected by EHs is limited, which restricts the standby duration of the BF-IoT terminals. Consequently, most EH-based BF-IoT terminals cannot maintain continuous connectivity, making direct integration with energy-intensive wireless protocols (e.g., Wi-Fi) impractical. Most commercial smart home platforms require terminals to remain constantly online and send heartbeat packets periodically. Restricted by limited harvested energy, BF-IoT terminals cannot sustain continuous monitoring, and are therefore marked as offline by IoT platforms. Consequently, until now, most BF-IoT terminals have not been supported by commercial smart home ecosystems, such as Google Assistant, Apple HomeKit, and Xiaomi Mijia.

Second, existing BF-IoT solutions only support one-way uplink transmission, lacking reliable downlink and inter-node communication. Traditionally, this kind of BF-IoT terminal can only work as sensors sending data to the host unit, while the host unit cannot send data back to them. Different devices also can not exchange data. These limitations restrict the practical application of BF-IoT terminals. Such one-way communication makes it impossible for BF-IoT terminals to execute commands, display data, or support user interaction.

Third, traditional IoT gateways are not designed for BF-IoT terminals. They require terminals to remain constantly online and wait for data, yet BF-IoT terminals cannot meet this requirement. Most existing battery-free IoT gateways work as "sensor-receiver" type. The receiver delivers wireless power to sensors and collects their feedback data [24], [25], [26]. These gateways only support radio-frequency (RF)-powered devices. BF-IoT terminals powered by other environmental energy or human kinetic motion cannot be integrated.

To address these challenges, as shown in Fig. 1 (c), we propose ViPSN-Gateway, an energy-aware routing gateway dedicated to IoT devices.

A combined temporary storage and active data-request mechanism is adopted to eliminate standby energy consumption of receivers, while multi-protocol modular design ensures compatibility with diverse low-power wireless devices and mainstream smart home ecosystems.

There are three typical kinds of communication requirements, including uplink, downlink and inter-node communication. We designed three corresponding mechanisms to realize these communication requirements: forwarding, temporary storage and data-request.

For uplink communication, data packets are directly forwarded to the IoT platform. For downlink and inter-node communication, since receiver is BF-IoT terminal and cannot be constantly online, temporary storage and data-request mechanism will be activated. The gateway can temporarily store data packet if BF-IoT terminal is offline. When a BF-IoT terminal is online, it will send a data request to the ViPSN-Gateway and get the temporary stored data.

ViPSN-Gateway consists of two kinds of modules: communication module (CM) and Wi-Fi network module (NM). CM is designed to support different low-power communication protocols and realize bidirectional communication with BF-IoT terminals, each CM supports one protocol. NM is equipped with Wi-Fi connectivity, which allows it to communicate with the IoT platform via MQTT protocol.

ViPSN-Gateway can be employed in a variety of IoT scenarios, including smart home, smart agriculture, smart industry and smart healthcare. As an example, an IoT platform is built based on HA, and BF-IoT terminals are integrated into commercial smart home ecosystems.

The major contributions of this ViPSN-Gateway design:

- **Energy-aware routing for BF-IoT:** Aiming at the intermittent operating characteristic of EH-powered BF-IoT devices, ViPSN-Gateway proposes an energy-aware routing solution via forwarding, temporary storage and passive data-request mechanism. Different from conventional continuous channel listening schemes, this mechanism removes nearly all standby energy consumption on receivers.
- **Multi-energy-source compatibility:** ViPSN-Gateway provides a unified data exchange interface supporting multiple energy sources. Unlike conventional radio-frequency identification (RFID) gateways limited to RF power, ViPSN-Gateway works with photovoltaic, piezoelectric and motion powered BF-IoT terminals.
- **Multi-protocol compatibility:** ViPSN-Gateway supports multiple low-power wireless protocols and adopts a modular structure for easy expansion to accommodate more types of BF-IoT devices.
- **Smart home ecosystem compatibility:** ViPSN-Gateway bridges the connection gap between BF-IoT networks and commercial smart home ecosystems, enabling large-scale practical application of BF-IoT devices in smart home scenarios.

This work is organized as follows: Section 2 reviews the related works on routing gateway, energy harvesting, and battery-free terminals, it also provides a comprehensive comparison between this work and several previous works. Section 3 provides an overview of the ViPSN-Gateway system. Section 4 analyzes the communication strategies of ViPSN-Gateway. Section 5 analyzes the power consumption under different communication protocols and operating states. Section 6 introduces the hardware design of ViPSN-Gateway. Section 7 evaluates the performance of ViPSN-Gateway via latency measurements, field tests, and application experiments. Section 8 explores potential application scenarios of ViPSN-Gateway. Finally, Section 9 concludes this work.

2 Related Works

2.1 Routing Gateway

Many previous works already focus on designing a gateway platform for multiple IoT terminals. However, they are usually based on "sensor-receiver" paradigm. Different sensor terminals sense environment data and send data back to the corresponding gateway. In their working process, gateway cannot send data or commands back to

terminals, different terminals also cannot make data exchange. These disadvantages restrict the application of IoT terminals.

For example, in [25], the authors introduced a battery-free RFID sensor architecture for smart home IoT, eliminating distance-related phase ambiguity with a SAW filter and three-port structure. Powered by harvested RF energy, the sensor changes the phase of the reflected RFID signal based on the sensed parameter. Tests on flood and temperature sensors show it reaches an effective reading range of 7.9 m. Featuring low cost and no need for frequent calibration, the design offers a practical solution for passive wireless sensing in IoT scenarios. However, this system only supports sensor terminals powered by RF, terminals powered by other sources cannot be integrated. In addition, this communication is still "sensor-receiver" paradigm; it can only obtain information from sensors, and downlink communication is not realized.

2.2 IoT Communication Protocols

Many previous works already focused on improving communication procedure of smart home terminals. Through the optimization of communication protocol designs, the communication of such devices achieves higher reliability, extended transmission distance, and reduced energy consumption. Such communication protocols are typically developed as secondary protocols. They are designed based on fundamental protocols. These fundamental protocols include RFID [27], [28], LoRa [29], [30], [31], ZigBee [32], [33] etc. This development approach expands the application scenarios of the underlying protocols.

For example, in [31], the authors introduce a tree-structured LoRa network which is designed to enhance energy efficiency for IoT applications. Traditional LoRa networks often employ a star-structured network, which can lead to significant energy consumption in large-scale networks. The proposed tree-based architecture allows nodes to act as relays, propagating data from nodes further away from the base station. This approach not only reduces energy consumption but also extends network coverage and improves communication reliability.

2.3 Energy Harvesting and Battery-free IoT

Battery-free terminals are developed to relieve the trouble of arranging external wired power sources and replacing batteries in smart home scenarios. EH refers to technologies that harvest energy from ambient environment or user's motion. Ambient energy EHs are mostly based on wind [7, 34, 35], solar [36–39], temperature difference [40, 41], triboelectric nanogenerator (TENG) [42, 43], and RF [9, 36, 44, 45]. By adopting different kinds of EH, energy from the ambient environment and human motion can become the energy sources to power battery-free terminals.

In [22, 46], the authors introduced a basic component structure of battery-free terminals. This structure consists of four core units: energy generation unit (EGU) is EHs to generate energy. energy management unit (EMU) can collect and store the harvested energy, release this energy once sufficient energy is accumulated. energy user unit (EUU) consists of a low-power system-on-chip (SoC) and sensors to realize specific function. edge demonstration unit (EDU) is host unit which can make further execution.

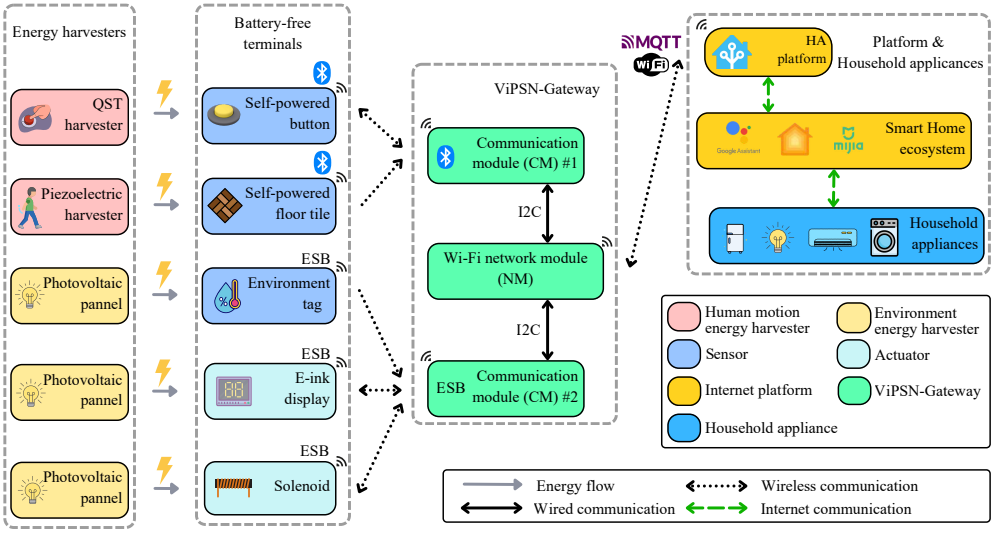


Fig. 2 ViPSN-Gateway system configuration.

2.4 Comprehensive Comparison

Table 1 compares this work with several previous works. Previous works on IoT protocols and gateways generally lack bidirectional communication, self-energy harvesting and multi-protocol compatibility.

3 System Overview

As shown in Fig. 2, to demonstrate the capability of the proposed ViPSN-Gateway, we connect five representative battery-free terminals to the system, including a self-powered pushbutton (ViPSN-Button), a self-powered floor tile (ViPSN-Floor), an environment tag (ViPSN-Tag), an E-ink display module (ViPSN-Eink), and a bistable solenoid (ViPSN-Solenoid). An IoT platform based on HA is built. We also integrate a Xiaomi Home desk lamp and a smart speaker which can be controlled by IoT platform to simulate household appliances being controlled in smart home scenarios.

The terminals selected not only include sensors to collect environment data and user's input, but also include actuators to display information and carry out commands from IoT platform. This design can demonstrate our wide compatibility.

ViPSN-Button is powered by a quasi-static toggling energy harvester (QST-EH) [50]. It can collect user's commands. When being pressed, QST-EH will also be pressed. An energy-buffer spring inside the QST-EH will be pressed when the force applied to it exceeds a threshold. The spring drives a magnet to reverse its polarity, which induces current in a coil and generates energy [51]. The ViPSN-Button communicates under the BLE protocol. Upon being pressed, it broadcasts BLE beacons. After capturing beacons, ViPSN-Gateway forwards data to the IoT platform, builds a connection, and transmits an acknowledgment (ACK). If ViPSN-Button receives the ACK, it will deliver a "Success" instant feedback to user.

Table 1 Comparison of State-of-the-Art IoT Communication Gateways

Ref.	Protocol	Latency	Distance	Bidirect. Comm.	Energy-aware	Multi-source
[47]	RIS	-	10 m	-	-	-
[28]	RFID	39 ms	-	✓	✓	-
[48]	Laser	-	2 m	-	-	-
[49]	RFID	35.8 ms	3 m	✓	✓	-
[25]	RFID	-	7.9 m	-	✓	-
This Work	BLE & ESB	BLE less than 3 s, ESB less than 1 ms	50 m	✓	✓	✓

ViPSN-Floor is a sensor, which is powered by a piezoelectric EH [11]. It can detect human passage and realize functions such as lighting linkage, security monitoring and fall detection. When a pedestrian steps on it, the embedded piezoelectric plate undergoes deformation and generates electrical energy. Similar to the ViPSN-Button, the ViPSN-Floor will broadcast BLE beacons after being activated. If the ViPSN-Gateway detects these beacons, it will forward the beacon data to the IoT platform. However, the ViPSN-Floor does not have an instant feedback display and does not receive ACK packets; it only requires single-direction communication with the ViPSN-Gateway. ViPSN-Floor can monitor pedestrian crossing events, which enables the realization of automatic light switching and security guard functions. ViPSN-Button and ViPSN-Floor can demonstrate the uplink communication ability of ViPSN-Gateway.

ViPSN-Tag is a sensor, which can sense the environment temperature and humidity. The collected data can be utilized by the IoT platform to control household appliances including air conditioners, dehumidifiers and humidifiers, delivering a comfortable living environment for users. It is powered by a photovoltaic (PV) panel, which can convert indoor light into electrical energy. Electrical energy is stored in an energy storage capacitor. An electrical energy buffer-release mechanism (EBRM) is adopted to regulate the energy storage and release processes. Once the capacitor voltage reaches the threshold, sufficient energy has been accumulated. The ViPSN-Tag is then activated. Once activated, it measures the ambient temperature and humidity, then transmits the sensed data to the ViPSN-Gateway via the 2.4 GHz RF channel using the ESB protocol. The environmental data sensed from the ViPSN-Tag can be displayed on ViPSN-Eink display module.

ViPSN-Eink is an actuator, it can display information. It is powered by a PV panel. Once sufficient energy is accumulated, the ViPSN-Eink module is activated and sends a data request to the ViPSN-Gateway. ViPSN-Eink can display temperature and humidity data sensed by the ViPSN-Tag. ViPSN-Tag and ViPSN-Eink can work together to demonstrate the inter-node communication ability of ViPSN-Gateway.

ViPSN-Solenoid is an actuator, which is powered by PV panel. It can carry out the actuation commands from the IoT platform. In smart home scenarios, such a solenoid can drive solenoid valves for water flow control and flue dampers for exhaust ventilation. When the solenoid coil is energized, it switches the indicator between two stable mechanical latch states. After the coil is de-energized, the indicator remains latched in its previously achieved state. ViPSN-Solenoid is capable of displaying binary on-off information and driving mechanical motions, thereby enabling applications such as valve actuation and mechanical switch toggling. ViPSN-Solenoid can be used to demonstrate the downlink communication capability of the ViPSN-Gateway.

4 Communication Strategies

The communication strategy of ViPSN-Gateway is designed to ensure efficient and reliable data exchange between battery-free terminals, the gateway, and the IoT platform.

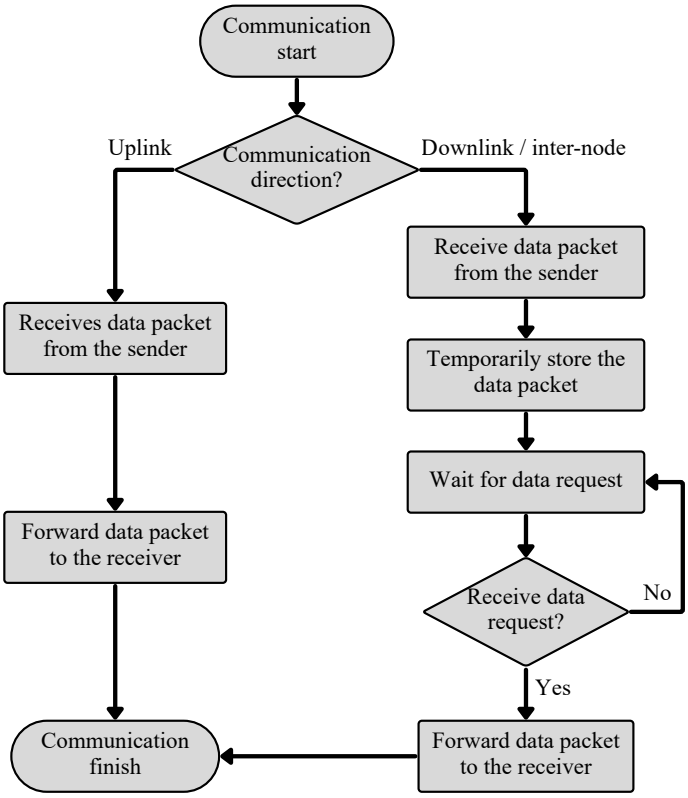


Fig. 3 Flowchart of the whole communication process.

4.1 Energy-aware Communication Framework

Based on the direction of information flow, communication procedures are categorized into three types: uplink, downlink, and inter-node communication. The complete communication flowchart is shown in Fig. 3.

4.1.1 Uplink Communication

Uplink communication means that a battery-free terminal uploads data packets to the IoT platform. The sender is a battery-free terminal and the receiver is the IoT platform. Since the IoT platform is constantly online, data packets will be directly forwarded to the IoT platform, no temporary storage is needed.

4.1.2 Downlink Communication

Downlink communication means that the IoT platform sends data packets to battery-free terminals, the sender is the IoT platform, and the receiver is battery-free terminal.

4.1.3 Inter-node Communication

Inter-node communication means that two battery-free terminals exchange data between each other, the sender and receiver are two different battery-free terminals.

Due to the limited energy supply, battery-free terminals are mostly offline. Therefore, downlink and inter-node communication rely on temporary storage and data-request mechanism.

4.2 Temporary Storage and Data-Request Mechanism

Traditional communication requires receivers to continuously monitor wireless channels for real-time packets, which is infeasible for energy-constrained battery-free terminals.

To solve this problem, we propose a temporary storage and data-request mechanism for downlink and inter-node communication. Since battery-free receivers stay offline most of the time, the gateway caches pending packets. When a battery-free terminal harvests enough energy, it wakes up and sends a data request. ViPSN-Gateway checks its buffer: matched cached data will be transmitted, otherwise the gateway responds with an empty ACK packet.

For battery-free terminals communicating under data-request mechanism, they can remain in sleep mode or even power-off mode during idle periods. In this way, receivers can achieve near-zero standby power consumption. For this reason, the proposed data-request mechanism can significantly reduce receivers' energy consumption compared with the traditional channel-monitoring mechanism.

Energy consumption experiments of traditional channel-monitoring and the proposed data-request mechanism are conducted in Section 5, which proves that the proposed scheme cuts receiver power consumption by over 99.98%.

4.3 Data Packet Structure

To make communication procedure more efficient, all battery-free terminals communicate under the same data packet structure, which includes three parts: device type, device address, and data packet content. The size of a typical data packet is 4 bytes, which is shown in Table 2.

4.4 Communication Protocols

ViPSN-Gateway has multi-protocol capability, which can support different kinds of battery-free terminals. In this work, we evaluated two protocols: BLE and ESB.

4.4.1 BLE

BLE is a low-power Bluetooth protocol developed by Bluetooth SIG [52]. In our system, ViPSN-Gateway works as the BLE host and battery-free terminals act as peripherals. Communication procedure is shown in Fig. 4(a), which includes the following six steps:

Table 2 battery-free Data Structure and Contents

Data byte 0 Device & operation	**Data byte 1** Device address	**Data byte 2** Data content byte 0	**Data byte 3** Data content byte 1
0x01: ViPSN-Button	Unique device address	Button number byte 0	Button number byte 1
0x02: ViPSN-Tag temperature		Temperature data byte 0	Temperature data byte 1
0x03: ViPSN-Tag humidity		Humidity data byte 0	Humidity data byte 1
0x04: ViPSN-Floor		Floor number byte 0	Floor number byte 1
0x05: ViPSN-Eink data request		0x00	0x00
0x06: ViPSN-Eink data forward		Forward data byte 0	Forward data byte 1
0x07: ViPSN-Solenoid data request		0x00	0x00
0x08: ViPSN-Solenoid data forward		0x00	0x00-keep, 0x01-up, 0x02-down
0x88: Empty packet		0x00	0x00

- **Terminal Broadcast and Gateway Scan:** battery-free terminals broadcast identity data (device names, addresses, and other customized data), and ViPSN-Gateway scans to launch connections.
- **Data Forwarding:** ViPSN-Gateway directly forwards beacons to the IoT platform for terminals without ACK demands. If ACK is required, ViPSN-Gateway will execute the following extra steps.
- **Connection Setup:** ViPSN-Gateway establishes a dedicated connection with the terminal for subsequent transmission.
- **Data Exchange:** ViPSN-Gateway sends ACK packet to the battery-free terminal. If battery-free terminal is requesting data, the ACK packet will include data it is looking for.
- **Communication Finish:** After receiving the ACK, the terminal powers off, and ViPSN-Gateway forwards the collected data to the IoT platform.

4.4.2 ESB

ESB is a fast and low-power protocol developed by Nordic Semiconductor [53]. In ViPSN-Gateway scenario, battery-free terminals act as primary transmitter (PTX), and gateway acts as primary receiver (PRX). Communication procedure is shown in Fig. 4(b), which includes the following four steps:

- **Terminal Send:** battery-free terminal sends data packets to ViPSN-Gateway.
- **Gateway Receive:** ViPSN-Gateway receives the data packet.
- **ACK Reply:** If there is a data request, ViPSN-Gateway will reply it with an ACK carrying the requested data. If not, an empty ACK will be replied.
- **Communication Finish:** The terminal powers off after ACK reception, and the gateway forwards data to the receiver.

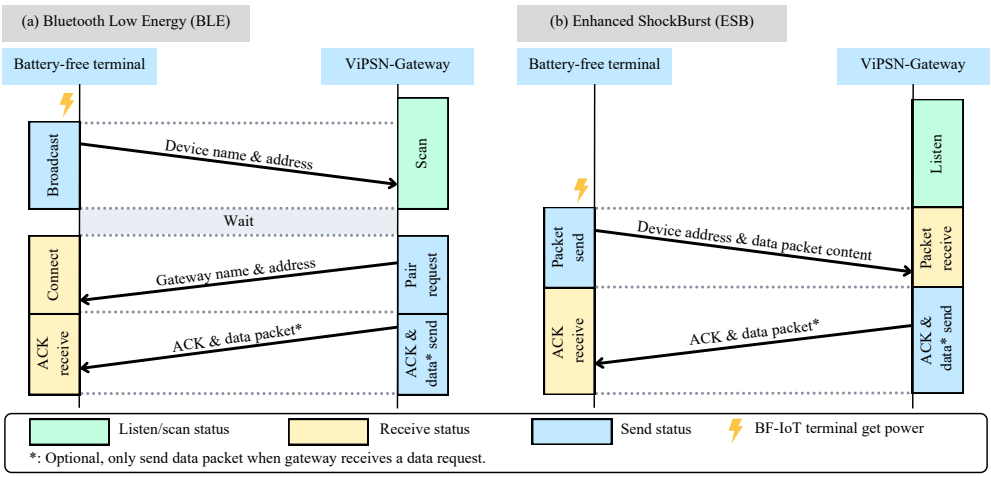


Fig. 4 Data exchange procedures. (a) BLE protocol. (b) ESB protocol.

5 Energy Consumption Analysis

We characterized the power consumption of BLE and ESB across multiple working states to compare their energy efficiency. To test the energy consumption on real battery-free terminals, we take PV-powered terminal as an example.

Before each test, the PV panel is disconnected from the EMU and energy storage capacitor voltage V_{sto} is zero. When test starts, the PV panel is connected to the EMU, making V_{sto} rise. Once the voltage reaches the preset threshold, the EBRM circuit turns on and discharges the stored energy. By tuning the voltage threshold and the capacitance value, the energy released in a single discharge cycle can be sufficient for the terminal to complete one full data exchange. By capturing the energy storage capacitor voltage V_{sto}, terminal input voltage V_{cc} and terminal load current i_{cc}, we quantified the energy expenditure of every communication stage.

5.1 BLE

When BLE communication starts, the terminal first sends BLE advertising packets and waits to be detected by the ViPSN-Gateway for connection establishment. The power consumption during this phase is 259.6 mW. After a link is set up between the ViPSN-Gateway and the terminal, data exchange is performed while maintaining the connection. The power draw for the connected idle state is 263.8 mW. BLE demands continuous connection retention, resulting in unnecessary substantial energy overhead. Total energy consumption of a whole communication process is 1.2 to 1.5 mJ.

5.2 ESB

ESB outperforms BLE in terms of simpler protocol stack and lower energy consumption. Energy is only drawn when transmitting packets (TX duration less than 2 ms), and the radio stays in deep low-power mode otherwise. Each packet transmission consumes 7-9 μJ, while the standby power is as low as 10.55 μW.

5.3 Data-request Mechanism

Temporary storage and data-request mechanism are proposed to solve the problem that battery-free terminal cannot maintain constantly online. To verify the energy-saving performance of the proposed mechanism, the ViPSN-Solenoid was selected as an example. In this example, the energy consumption of the traditional mechanism and the proposed mechanism are tested and compared.

As illustrated in Fig. 6(a) and 6(b), traditional mechanism requires terminal to sustain channel listening via high-speed clocks and 2.4 GHz peripherals during idle time, leading to high standby power of 45.91 mW.

As shown in Fig. 6(c) and 6(d), our data-request scheme lets the battery-free terminal stay asleep or fully powered off at idle. During this period, the standby power is only 8 μW, which can cut power consumption by 99.98% versus traditional channel-listening mechanism.

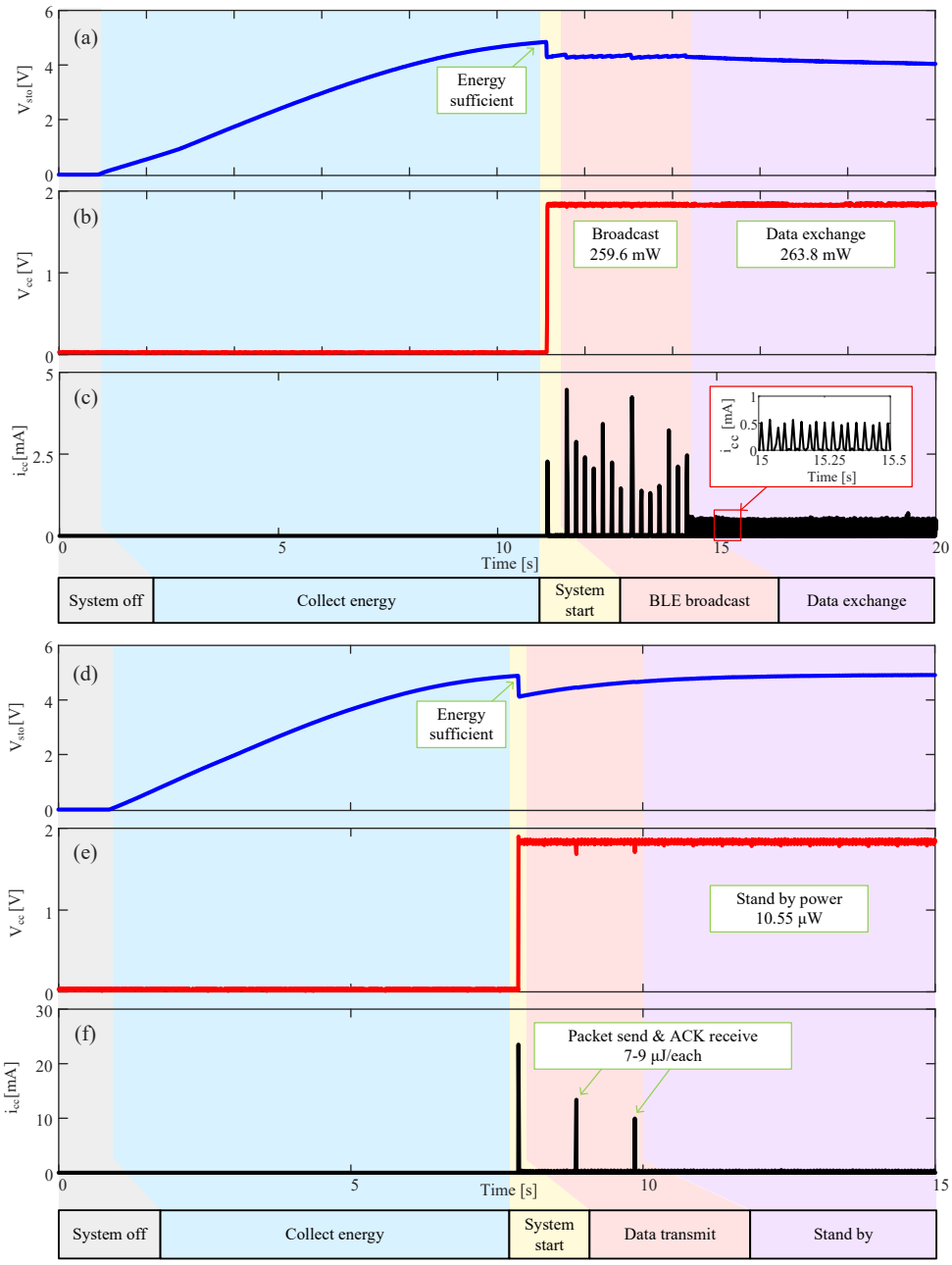


Fig. 5 Voltage and current curve. (a)-(c) BLE. (d)-(f) ESB protocol.

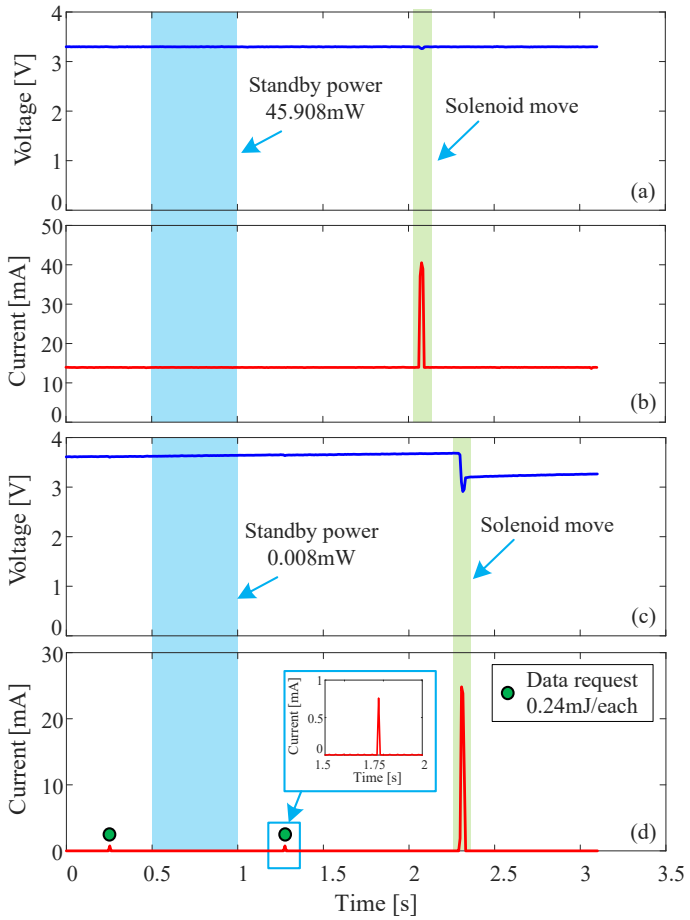


Fig. 6 Traditional mechanism: (a) voltage, (b) current. Proposed data-request mechanism: (c) voltage, (d) current.

6 Hardware Design

In this section, the hardware design of the ViPSN-Gateway is discussed in detail.

As illustrated in Fig. 2, the ViPSN-Gateway includes two kinds of modules: CM and NM. CM enables data communication with battery-free terminals through different wireless protocols.

NM is connected to the IoT platform via Wi-Fi, maintains an always-on status and forwards data packets between the CMs and the IoT platform using the MQTT protocol.

To ensure system expandability, the ViPSN-Gateway is designed with multiple CMs. Each CM supports a specific protocol, which allows for the addition of new

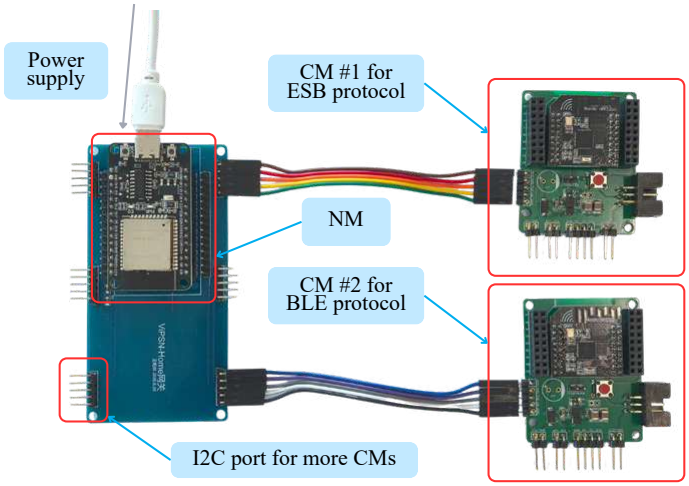


Fig. 7 Hardware of ViPSN-Gateway.

CMs to support new protocols. Two modules are connected to each other via inter-integrated circuit (I^2C) bus. Each CM is assigned a unique I^2C address, which enables NM to collect data from different CMs.

In our design, the CM utilizes nRF52832 low-power SoC from Nordic Semiconductor [54], which supports BLE and ESB protocols, enabling communication with a variety of battery-free terminals. For NM, we adopt ESP32-C3 SoC from Espressif Systems [55], which supports Wi-Fi, MQTT, and I^2C bus.

The proposed ViPSN-Gateway hardware is shown in Fig. 7. ViPSN-Gateway is powered by an external power source to ensure reliable connection to the IoT platform via MQTT protocol. Two CMs are connected to an NM via I^2C protocol. More I^2C ports are reserved for extension.

IoT platform is based on HA, which is executed on a PC virtual machine or Linux extension board. HA offers compatibility with a wide range of commercial smart home ecosystems and unifies the control of heterogeneous household appliances.

7 Experiments

7.1 Latency Test

To verify our proposed ViPSN-Gateway communication reliability, we conducted communication latency test. The test was carried out in an unoccupied and obstacle-free corridor. During the testing process, the ViPSN-Gateway and the battery-free terminal were placed at a fixed separation distance. When the experiment begins, the terminal transmits a data packet to the gateway and simultaneously sets a TX indicator pin from low to high level. Upon receiving the ACK returned by the gateway, the terminal will set an ACK indicator pin from low level to high level simultaneously. The

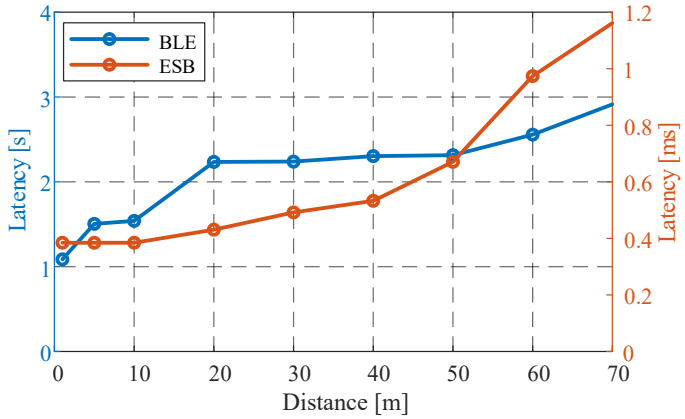


Fig. 8 Latency experiment result for BLE and ESB protocol. Note that the vertical axis for ESB is in milliseconds.

latency between two rising edges therefore represents the time required for one complete round-trip exchange; hence, communication latency is measured by capturing this high-level interval.

As shown in Fig. 8, round-trip latency rises with increasing transmission distance. For BLE protocol, the communication procedure requires a longer time to complete due to the need for broadcasting, scanning, and connecting. Typical latency time is 1-3 s.

In contrast, ESB does not require complex broadcasting, scanning, and connecting procedure, so its round-trip latency is controlled below 1 ms.

7.2 Field Test

To verify our proposed ViPSN-Gateway communication ability, we conducted field tests. The test environment is the same as that of the communication latency test. When test begins, battery-free terminal will firstly send a data packet to ViPSN-Gateway. Then the gateway receives the data packets and responds with an ACK packet. If a battery-free terminal successfully receives the ACK, communication is successfully finished. The communication procedure is regarded as failed if the gateway does not receive the data packet or battery-free terminal does not receive the ACK.

As Fig. 9 shows, communication success rates for both protocols decline with increasing distance. For BLE protocol, reliable communication distance is 50 m with 92% success rate. For ESB protocol, reliable communication distance can reach 50 m with 94% success rate.

7.3 Smart Home Application

To demonstrate the proposed ViPSN-Gateway solution for integrating battery-free terminals into the smart home ecosystem, we select Xiaomi Home smart home ecosystem introduced by Xiaomi as an example.

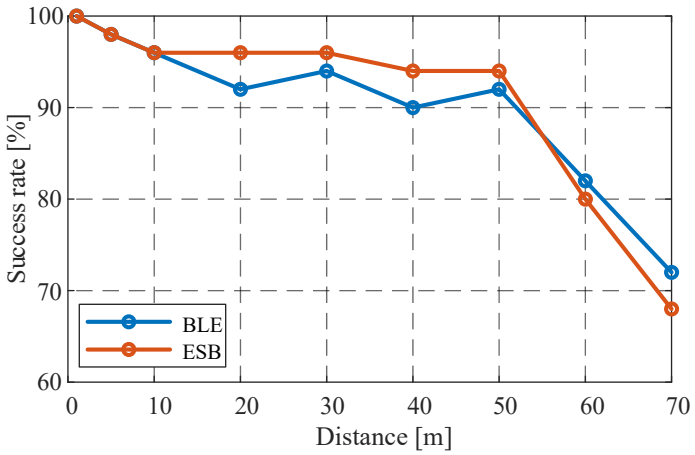


Fig. 9 Communication success rate of BLE and ESB protocol.

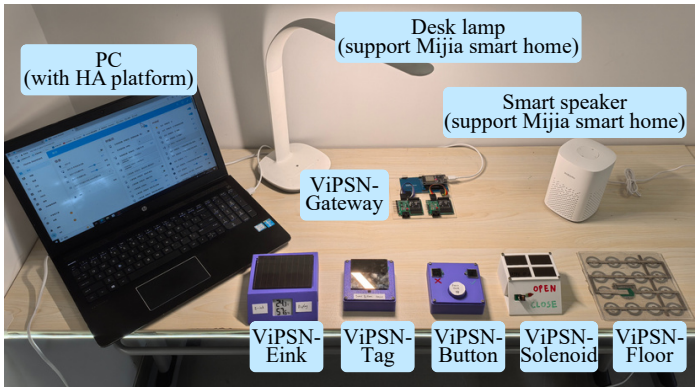


Fig. 10 Experimental setup.

The experimental setup is shown in Fig. 10. A demo video is available as a supplementary material.

8 Potential Application Scenarios

- **Smart Home:** With the help of ViPSN-Gateway, BF-IoT sensor and actuator terminals can be integrated into commercial smart home platforms. With the help of energy-aware routing, terminals can not only make terminals collect user's commands but also let terminals execute commands or display information. Battery-free design can significantly reduce wiring and battery replacement maintenance costs for smart homes, aligning with the low-carbon development trend of green IoT. Uploaded data from BF-IoT terminals (including pedestrian flow, temperature and humidity), combined with cloud-based AI algorithms, can be utilized for energy-consumption optimization and resident-behavior analysis.

- **Smart Supermarket:** E-ink electronic shelf labels are widely adopted in smart supermarkets to display commodity prices. Conventional electronic shelf labels rely on built-in batteries that require regular replacement, bringing heavy maintenance burdens. Leveraging ViPSN-Gateway, shelf labels can be driven by harvested light energy. Benefiting from the gateway's bidirectional communication capability, price information can be updated in real time, and update statuses are synchronously fed back to the management backend. This mechanism guarantees accurate price display and drastically cuts maintenance costs.
- **Smart Agriculture:** The bidirectional communication capability of ViPSN-Gateway empowers smart agriculture. Relying on the bidirectional communication ability of ViPSN-Gateway, BF-IoT terminals can not only serve as sensors to monitor environmental and soil conditions, but also act as actuators to control electromagnetic valves for automatic irrigation, thus cutting farm labor costs significantly.

9 Conclusion

This work introduced ViPSN-Gateway, a pioneering energy-aware routing gateway solution tailored for BF-IoT terminals. With the help of ViPSN-Gateway, flexible uplink, downlink and inter-node communication can be realized. BF-IoT terminals are no longer limited to "sensor and receiver" type. They can not only work as sensors to transmit data to IoT platform, but also can work as actuators to receive and execute commands. ViPSN-Gateway adopts a hybrid communication mechanisms including forwarding, temporary storage and active data request. These mechanisms match the random wake-up feature of energy-harvesting terminals. BF-IoT terminals can request data when they collect enough energy and online. It reduces the standby power of receivers by more than 99.98% compared with the traditional continuous channel-listening schemes. ViPSN-Gateway has a modular I2C-based architecture supports BLE and ESB protocols, and is compatible with BF-IoT terminals powered by all kinds of EHs including light, piezoelectric and human kinetic energy sources. Connected to the HA platform via MQTT, the gateway enables integration of BF-IoT terminals into commercial smart home ecosystems. Experimental results verify a 50 m reliable communication range, with round-trip latency of less than 1 ms for ESB and 1–3 s for BLE. ViPSN-Gateway provides a feasible communication framework and unified a data packet format for BF-IoT networks, broadening the practical deployment scope of battery-free IoT systems.

Acknowledgements. This work was supported by the National Natural Science Foundation of China under Grants 62271319 and U21B2002. Corresponding authors: Junrui Liang

References

[1] Laghari, A.A., Wu, K., Laghari, R.A., Ali, M., Khan, A.A.: A review and state of art of Internet of Things (IoT). Arch. Comput. Method Eng., 1–19 (2021)

[2] Arasi, M.A., AlEisa, H.N., Alneil, A.A., Marzouk, R.: Artificial intelligence-driven ensemble deep learning models for smart monitoring of indoor activities in iot environment for people with disabilities. Scientific Reports **15**(1), 4337 (2025)

[3] Tian, C., Chen, Z., Liang, J.: A battery-free and sensor-less photovoltaic tag for real-time indoor light illuminance evaluation. In: 2024 IEEE Int. Symp. Circuits Syst. (ISCAS), pp. 1–5 (2024). IEEE

[4] La Rosa, R., Livreri, P., Dehollain, C., Costanza, M., Trigona, C.: An energy autonomous and battery-free measurement system for ambient light power with time domain readout. Measurement **186**, 110158 (2021)

[5] Houssein, E.H., Othman, M.A., Mohamed, W.M., Younan, M.: Internet of Things in smart cities: Comprehensive review, open issues and challenges. IEEE Internet Things J. (2024)

[6] Mekki, K., Ghezaiel, N., Ben Slimene, M., Neffati, S., Rmili, H., Gharsallah, A.: Edge machine learning over iot for chipless rfid environmental sensing in smart agriculture. Scientific Reports **16**(1), 9512 (2026)

[7] Dang, T., Tran, T., Nguyen, K., Pham, T., Pham, N., Vu, T., Nguyen, P.: IoTree: a battery-free wearable system with biocompatible sensors for continuous tree health monitoring. In: Proc. ACM Int. Conf. Mobile Comput. Netw. (MobiCom), pp. 352–366 (2022)

[8] Ramson, S.J., León-Salas, W.D., Brecheisen, Z., Foster, E.J., Johnston, C.T., Schulze, D.G., Filley, T., Rahimi, R., Soto, M.J.C.V., Bolivar, J.A.L., *et al.*: A self-powered, real-time, LoRaWAN IoT-based soil health monitoring system. IEEE Internet Things J. **8**(11), 9278–9293 (2021)

[9] Le, G.T., Tran, T.V., Lee, H.-S., Chung, W.-Y.: Long-range batteryless RF sensor for monitoring the freshness of packaged vegetables. Sens. Actuators A Phys. **237**, 20–28 (2016)

[10] Lazaro, M., Lazaro, A., Villarino, R., Girbau, D.: Home surveillance system based on lora backscattering. Scientific Reports **15**(1), 12063 (2025)

[11] Wang, G., Hu, G., Liang, J.: Low-cost and compact piezoelectric energy harvesting floor tile for battery-free Bluetooth smart pavement. In: SPIE Sens. Smart Struct. Technol. Civ. Mech. Aerosp. Syst. 2024, vol. 12949, pp. 333–341 (2024). SPIE

[12] Li, X., Tang, H., Hu, G., Zhao, B., Liang, J.: ViPSN-pluck: A transient-motion-powered motion detector. IEEE Internet Things J. **9**(5), 3372–3382 (2021)

[13] Wuthibenjaphonchai, N., Haruta, M., Sasagawa, K., Tokuda, T., Carrara, S., Ohta, J.: Wearable and battery-free health-monitoring devices with optical power

transfer. IEEE Sens. J. **21**(7), 9402–9412 (2021)

[14] Kim, Y., Lee, J., Hong, H., Park, S., Ryu, W.: Self-powered wearable micropyramid piezoelectric film sensor for real-time monitoring of blood pressure. Adv. Eng. Mater. **25**(2), 2200873 (2023)

[15] Desnanjaya, I., Nugraha, I.M.A.: Real-time monitoring system for blood pressure monitoring based on Internet of Things. Indones. J. Electr. Eng. Comput. Sci. **35**(1), 62–69 (2024)

[16] Zhang, Z., He, T., Zhu, M., Sun, Z., Shi, Q., Zhu, J., Dong, B., Yuce, M.R., Lee, C.: Deep learning-enabled triboelectric smart socks for iot-based gait analysis and vr applications. npj Flexible Electronics **4**(1), 29 (2020)

[17] Cai, M., Liao, W.-H.: A coaxial wrist-worn energy harvester for self-powered Internet of Things sensors. IEEE Internet Things J. **10**(1), 133–143 (2022)

[18] International Data Corporation (IDC): Worldwide Spending on the Internet of Things Is Forecast to Surpass $1 Trillion in 2026, According to IDC. IDC. IoT World Magazine, accessed 2025-07-21

[19] Gulati, K., Boddu, R.S.K., Kapila, D., Bangare, S.L., Chandnani, N., Saravanan, G.: A review paper on wireless sensor network techniques in Internet of Things (IoT). Mater. Today Proc. **51**, 161–165 (2022)

[20] Jamshed, M.A., Ali, K., Abbasi, Q.H., Imran, M.A., Ur-Rehman, M.: Challenges, applications, and future of wireless sensors in Internet of Things: A review. IEEE Sens. J. **22**(6), 5482–5494 (2022)

[21] Čolaković, A., Hadžialić, M.: Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues. Comput. Netw. **144**, 17–39 (2018)

[22] Li, X., Xiao, M., Shen, X., Chu, J., Huang, W., Li, J., Li, Y., Cai, M., Chen, J., Zhang, X., *et al.*: ViPSN 2.0: A reconfigurable battery-free IoT platform for vibration energy harvesting. IEEE Internet Things J. **13**(11), 23043–23063 (2026)

[23] Cai, Z., Chen, Q., Shi, T., Zhu, T., Chen, K., Li, Y.: Battery-free wireless sensor networks: A comprehensive survey. IEEE Internet Things J. **10**(6), 5543–5570 (2022)

[24] Khalid, N., Iyer, A.K., Mirzavand, R.: A batteryless six-port RFID-based wireless sensor architecture for IoT applications. IEEE Internet Things J. **9**(19), 18550–18558 (2022)

[25] Khalid, N., Mirzavand, R., Saghlatoon, H., Honari, M.M., Iyer, A.K., Mousavi, P.: A batteryless RFID sensor architecture with distance ambiguity resolution for

smart home IoT applications. IEEE Internet Things J. **9**(4), 2960–2972 (2021)

[26] Tang, X., Zhang, Y., Shao, X., Yu, Y., Li, D.: Battery-free ultra-high-frequency wireless temperature sensing tag for IoT applications. IEEE Internet Things J. **12**(18), 37119–37131 (2025)

[27] Lee, S.-Y., Tsou, C., Huang, P.-W.: Ultra-high-frequency radio-frequency-identification baseband processor design for bio-signal acquisition and wireless transmission in healthcare system. IEEE Trans. Consum. Electron. **66**(1), 77–86 (2020)

[28] Piva, M., Coletta, A., Maselli, G., Stankovic, J.A.: Environment-driven communication in battery-free smart buildings. ACM Trans. Internet Things **2**(2), 1–30 (2021)

[29] Farhad, A., Ehsan, M.K., Sodhro, A.H., Huang, H.: Resource management in LoRaWAN with interpretability. IEEE Trans. Consum. Electron. **72**(1), 1634–1644 (2026)

[30] Pandey, S., Gupta, H.P., Mishra, R., Gautam, P., Rao, S.V.: Adaptive federated learning for health-centric hygiene monitoring using LoRa network. IEEE Trans. Consum. Electron., 1–1 (2026)

[31] Tehrani, Y.H., Amini, A., Atarodi, S.M.: A tree-structured LoRa network for energy efficiency. IEEE Internet Things J. **8**(7), 6002–6011 (2020)

[32] Das, R., Bera, J.N.: Multi-layer-partial-mesh-based fail proof HAN with decentralized multi gateway for smart home monitoring and control. IEEE Trans. Consum. Electron. **70**(1), 715–724 (2024)

[33] Romputtal, A., Phongcharoenpanich, C.: T-slot antennas-embedded zigbee wireless sensor network system for IoT-enabled monitoring and control systems. IEEE Internet Things J. **10**(23), 20834–20845 (2023)

[34] Wang, H., Xiong, B., Zhang, Z., Zhang, H., Azam, A.: Small wind turbines and their potential for Internet of Things applications. IScience **26**(9) (2023)

[35] Tian, S., Lai, L., Xin, J., Qu, Z., Li, B., Dai, Y.: Hybrid triboelectric-electromagnetic-piezoelectric wind energy harvester toward wide-scale IoT self-powered sensing. Small **20**(20), 2307282 (2024)

[36] Zhan, J.-L., Lu, W.-B., Ding, C., Sun, Z., Yu, B.-Y., Ju, L., Liang, X.-H., Chen, Z.-M., Chen, H., Jia, Y.-H., Liu, Z.-G., Cui, T.-J.: Flexible and wearable battery-free backscatter wireless communication system for colour imaging. npj Flexible Electronics **8**(1), 19 (2024)

[37] Bhusal, H., Khatiwada, P., Jha, A., Soumya, J., Koorapati, S., Cenkeramaddi,

L.R.: A self-powered long-range wireless IoT device based on LoRaWAN. In: 2020 IEEE Int. Symp. Smart Electron. Syst. (iSES)(Formerly iNiS), pp. 242–245 (2020). IEEE

[38] Wu, C., Che, L., Jin, S., Tian, C., Wang, G., Liu, S., Li, X., Hu, G., Tang, L., Liang, J.: Attendance tracking system using many battery-free photovoltaic Bluetooth beacon badges. In: Proceedings of the 12th International Workshop on Energy Harvesting and Energy-Neutral Sensing Systems, pp. 15–20 (2024)

[39] Chen, X., Hu, H., Zhou, J., Li, Y., Wan, L., Cheng, Z., Chen, J., Xu, J., Zhou, R.: Indoor photovoltaic materials and devices for self-powered Internet of Things applications. Mater. Today Energy **44**, 101621 (2024)

[40] Tuoi, T.T.K., Van Toan, N., Ono, T.: Self-powered wireless sensing system driven by daily ambient temperature energy harvesting. Appl. Energy **311**, 118679 (2022)

[41] Tuoi, T.T.K., Van Toan, N., Ono, T.: Thermal energy harvester using ambient temperature fluctuations for self-powered wireless IoT sensing systems: A review. Nano Energy **121**, 109186 (2024)

[42] Kam, D., Gwon, G., Ra, Y., Lee, D., Kim, Y.-s., Chae, J., Kim, J.W., Choi, D.: Mechanically guided 4d printing of a triboelectricity-driven acoustic transducer for self-powered and intelligent voice recognition. npj Flexible Electronics **9**(1), 73 (2025)

[43] Song, C.-H., Shin, J.B., Lee, R., Kim, Y., Lee, C.-J., Kim, J.-W.: Dual-scale polyimide dot clampers for durable fiber-based triboelectric nanogenerators. npj Flexible Electronics **10**(1), 107 (2026)

[44] Rigi, A., Mugisha, A.J., Arefian, A., Khan, S.R., Mitra, S.: Wireless battery-free body temperature sensing device for key workers. IEEE Sens. Lett. **6**(2), 1–4 (2021)

[45] Zhao, J., Song, J., Li, D.-a., Li, Y., Cheng, J.: Dual-band RF energy harvesting for low-power IoT devices. Wirel. Netw. **30**(4), 2511–2527 (2024)

[46] Li, X., Teng, L., Tang, H., Chen, J., Wang, H., Liu, Y., Fu, M., Liang, J.: ViPSN: A vibration-powered IoT platform. IEEE Internet Things J. **8**(3), 1728–1739 (2020)

[47] Liang, S., Ren, G.: Deployment and beamforming design for RIS-assisted indoor wireless communication in smart home. IEEE Trans. Consum. Electron., 1–1 (2026)

[48] Manie, Y.C., Yao, C.-K., Yeh, T.-Y., Teng, Y.-C., Peng, P.-C.: Laser-based optical wireless communications for Internet of Things (IoT) application. IEEE Internet Things J. **9**(23), 24466–24476 (2022)

[49] Maselli, G., Piva, M., Stankovic, J.A.: Adaptive communication for battery-free devices in smart homes. IEEE Internet Things J. **6**(4), 6977–6988 (2019)

[50] Wang, Y., Qiu, J., Fu, M., Wang, H., Liang, J.: ViPSN-button: A motion-powered wireless pushbutton with instant feedback. IEEE Internet Things J. **12**(24), 54791–54803 (2025)

[51] Liu, S., Li, X., Teng, L., Hu, G., Liang, J.: Energy and dynamic analysis of quasi-static toggling mechanical energy harvester. Nano Energy **104**, 107887 (2022)

[52] Bluetooth: Bluetooth Technology Website — The Official Website of Bluetooth Technology. Accessed: 20 Jun. 2026. https://www.bluetooth.com/

[53] Nordic: Enhanced Shockburst Technical Documentation. Accessed: 20 Jun. 2026. https://docs.nordicsemi.com/bundle/ncs-latest/page/nrf/protocols/esb/index.html

[54] Semiconductor, N.: nRF52832 Versatile Bluetooth SoC Supporting Bluetooth LE, Bluetooth Mesh and NFC. Accessed: 20 Jun. 2026. https://www.nordicsemi.com/Products/nRF52832

[55] Systems, E.: ESP32-C3 Wi-Fi and BLE 5 SoC. Accessed: 20 Jun. 2026. https://www.espressif.com.cn/en/products/socs/esp32-c3

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ViPSNGatewayDemoVideo.mp4