# ViPSN-home: Integrating Battery-free IoT End Devices Into Smart Home Ecosystems

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***Abstract*—Battery-free Internet of Things (BF-IoT) devices independently harvest energy from ambient energy sources, including light, motion, radio-frequency, temperature difference, etc. However, the trickling nature of this energy imposes limitations on the standby duration and results in intermittent connectivity. As a consequence, achieving seamless integration between battery-free end-devices and smart home ecosystems has been challenging. This paper introduces ViPSN-home, which aims to integrate BF-IoT devices into the mainstream smart home ecosystems through Home Assistant (HA). ViPSN-home utilizes a continuously powered gateway to gather data packets from adjacent IoT end devices. Subsequently, it forwards these packets to executing devices through the message queuing telemetry transport (MQTT) protocol. It ensures dependable data transmission even in the presence of intermittent connectivity. Moreover, a home automation solution based on HA has been developed to incorporate BF-IoT end devices into smart home ecosystems. ViPSN-home enables straightforward bidirectional communication between BF-IoT end devices and other devices in the mainstream smart-home ecosystems, such as Amazon Alexa and Xiaomi Mijia. It exhibits compatibility with multiple prevalent low-power communication protocols. Consequently, it is capable of accommodating a wide variety of IoT end-devices in different smart-home applications.**

***Index Terms*—Energy harvesting (EH), battery-free Internet of Things (BF-IoT), message queuing telemetry transport (MQTT), Home Assistant (HA), smart home.**

## I. Introduction

The Internet of Things (IoT) has revolutionized the way people interact with their surroundings by connecting various types of devices to the Internet [1]. This connectivity allows for seamless and convenient interaction between users and devices, enabling remote monitoring, control, and automation in various applications such as smart home [2], smart agriculture [3], safety guard [4], [5], health care [6] and human motion detection [7] etc. The key components of a large-scale IoT ecosystem are numerous IoT end devices [8]. They play a crucial role in collecting data from the external environment and carrying out user interactions. These IoT end devices act as the eyes and ears of the IoT ecosystem. They provide valuable information to enable intelligent decision-making and automation.

Battery-free IoT (BF-IoT) end devices [9] can escape the trouble of arranging wires and replacing batteries. These IoT end devices adopt energy harvesting (EH) devices to collect ambient energy from light, wind, radio-frequency (RF) signal or human motions and convert the energy into electricity. They can eliminate the need for cables or batteries for a power supply. However, the energy generated by energy harvesters is limited. It restricts the effective standby duration of the BF-IoT end devices. Consequently, most EH-based BF-IoT end devices cannot maintain continuous connectivity, making direct integration with energy-intensive wireless protocols (e.g. Wi-Fi) impractical. This intermittent connectivity also means that traditional bidirectional communication between BF-IoT end devices and the host device, or among different BF-IoT end devices, is not feasible. For this reason, until now, most BF-IoT devices are not supported by commercial smart home ecosystems, such as Google Assistant, Apple HomeKit, and Xiaomi Mijia.

To make a breakthrough, we propose ViPSN-home, a holistic solution connecting BF-IoT end devices to the Internet and most existing smart home ecosystems. ViPSN-home consists of a customized gateway connecting to a commercial Home Assistant (HA) platform. The gateway can receive data packages from the ViPSN series BF-IoT end devices [10], [11]. The HA platform can receive these data packages and control household appliances from different smart home ecosystems.

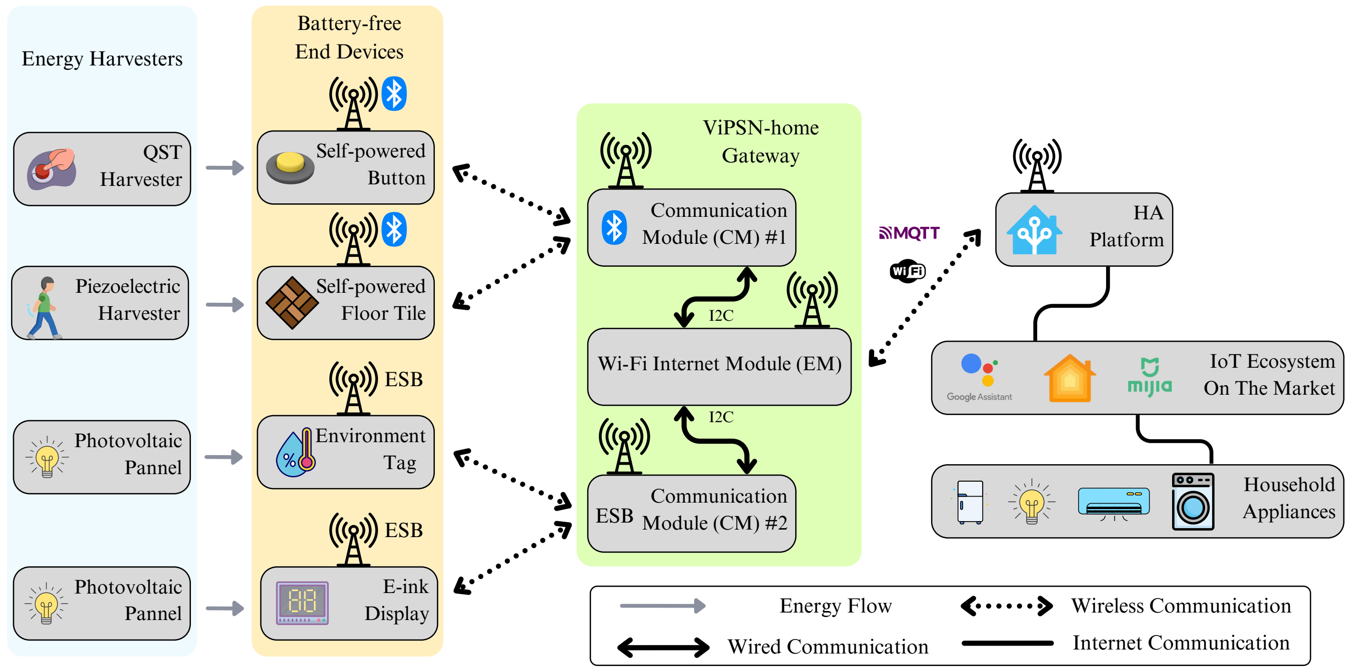


Fig. 1. ViPSN-home system configuration.

ViPSN-home gateway supports two low-power communication protocols: Bluetooth Low-Energy (BLE) and Enhanced ShockBurst (ESB), which can support different kinds of BF-IoT end devices. The ViPSN-home gateway is also equipped with WiFi connectivity, allowing it to seamlessly connect to the Internet and transmit data to the HA platform via the message queuing telemetry transport (MQTT) protocol.

When the ViPSN-home gateway receives data packages from the IoT end devices, it forwards them to the HA platform via the MQTT protocol. Conversely, when the HA platform needs to send data packages to an end device, it sends the data packages to the gateway via MQTT. If the end device is online, the gateway will forward these packages. If the end device is offline, the gateway will temporarily store these data packages and forward them to the end devices when it returns to the online state.

In addition to facilitating communication between end devices and the HA platform, the ViPSN-home gateway also enables communication between different IoT end devices. Communication procedure also supports forwarding and temporary storage, which is similar to communication within the HA platform.

Fig. 1 shows an example configuration of the proposed ViPSN-home system. There are four different BF-IoT end devices. They are, from top to bottom rows, a quasi-static-toggling (QST) harvester-powered pushbutton, a piezoelectric harvester-powered smart floor tile, a photovoltaic cell (PV) powered sensing tag and a PV-powered E-ink display. These BF-IoT end devices can sense environment parameters or the user's motions. They communicate with the gateway through either Bluetooth Low Energy (BLE) or Enhanced ShockBurst (ESB) protocol. Furthermore, the E-ink display module needs to download the display information from the HA platform to display. Therefore, bidirectional communication capability is necessary for the ViPSN-home system.

Home Assistant (HA) is a free and open-source software used for home automation. It serves as an integration platform connecting different on the market smart home ecosystems. Therefore, all the sensed environmental information and commands sent by user through BF-IoT end devices are forwarded to the HA platform for generating control commands to household appliances from different smart home ecosystems.

This paper makes three significant contributions:

- **Smart home ecosystems integration:** ViPSN-home, for the first time, connects different types of BF-IoT end devices to on the market smart home ecosystems.

- **Bidirectional communication for BF-IoT:** By adopting forwarding and temporary storage mechanisms, ViPSN-home offers a bidirectional communication solution for BF-IoT end devices, which are unable to constantly stay online.
- **Multi-protocol support:** The ViPSN-home gateway supports different low-power wireless protocols, enabling the connection with more BF-IoT devices.

## II. Related Works

BF-IoT is developed to relieve the trouble of arranging external wired power sources and replacing batteries. These two ways of power supply are still widely adopted in smart home [2], smart agriculture [3], safety guard [4], [5], health care [6], and human motion detection [7], etc. By adopting different kinds of EH, energy from the ambient environment and human motion can become the energy sources to power BF-IoT end devices. They also adopt different kinds of wireless communication protocols to communicate with host units.

Ambient energy EH mostly based on wind [3], [12], light [2], [13], temperature difference [14], motions [4], [11], and RF waves [15], [16], [17] etc.

In [2], the authors introduce a battery-free photovoltaic tag, which can measure indoor light illuminance. The tag uses a photovoltaic cell to collect solar energy and sends data packages to the host unit when sufficient energy is collected. The brighter the environment is, the less time it will take for photovoltaic cells to collect a sufficient amount of energy. The host unit can calculate light intensity by measuring the time interval between each data package.

In [14], the authors introduce a battery-free wireless IoT sensing system driven by daily ambient temperature changes. The system uses a thermoelectric generator (TEG) and phase change material (PCM) to convert thermal energy from environmental temperature changes into electricity. Experimental results show that the TEG can achieve an average maximum output power of 340 mW, with a DC-DC electronic conversion efficiency of 28.3%, and a total storable energy of about 1.46 joules per day. The system can sense ambient temperature and humidity and transmit the information to a computer via RF communication. Outdoor experiments have verified the system's feasibility. It shows potential for practical applications such as smart homes, precision agriculture, and environmental monitoring.

Human motion EH is mostly based on piezoelectric [4], triboelectric [18], or electromagnetic effect [10], [11].

In [10], the authors introduce a vibration-powered IoT platform, named ViPSN. ViPSN consists of six parts: energy generation unit (EGU), energy transduction unit (ETU), energy enhancement unit (EEU), energy management unit (EMU), energy user unit (EUU), and edge demonstration unit (EDU). Some low-cost systems may omit or combine some of these units. The ViPSN-home system introduced in this paper is derived from the original design of the ViPSN platform.

In [4], the authors introduce a battery-free wireless floor tile based on piezoelectric energy harvesting (PEH), which converts the mechanical energy from footsteps into electrical energy to power a Bluetooth node. Each floor tile consists of 15 piezoelectric harvesters, which can generate power when stepped on. When the BLE node gets power, it broadcasts a BLE beacon packet. The host unit can collect this broadcast package to realize functions such as crowdedness calculation, individual tracking, fall detection, security guard, etc.

## III. System Overview

ViPSN-home consists of two main components: a gateway and an HA platform. The gateway works as an intermediate device that can exchange data packets between BF-IoT end devices and the HA platform. The HA platform can receive sensed data, control BF-IoT end devices, and integrate these end devices into various smart home ecosystems.

As shown in Fig. 1, since the ViPSN-home gateway should keep a WiFi connection to ensure reliable operation, it has been divided into two parts: communication module (CM) and WiFi Internet module (EM).

The function of CM is to exchange data packets between IoT end devices and the EM. In this first design, the primary chip of the CM is an nRF-52832 low-power system-on-chip (SoC) produced by Nordic Semiconductor Ltd. It supports both Bluetooth Low Energy (BLE) and Enhanced Shock Burst (ESB) communication protocols; therefore, it is ready to communicate with different kinds of BF-IoT end devices. The CM connects to EM via a Inter-Integrated Circuit (I2C) bus.

The primary chip of the EM is the ESP32 (SoC) produced by Espressif Systems Ltd. It establishes a connection to the HA platform through the WiFi and MQTT protocol. Separating CM and EM into two distinct parts can enhance the expandability of the ViPSN-home gateway. By adding different types of CM, it can support various communication protocols.

The HA platform is adopted to connect all individual IoT end devices by integrating different smart home IoT ecosystems. It supports many prevailing commercial IoT platforms such as Google Assistant, Apple HomeKit, Amazon Alexa, Xiaomi Mijia, etc. It generates home automation commands for controlling household appliances according to the audio instructions or other sensed environmental data. HA provides the best solution to integrate all kinds of BF-IoT end devices into most existing smart home ecosystems.

To demonstrate the proposed ViPSN-home solution, we designed an IoT system that consists of three battery-free sensing node modules and a battery-free display module. These modules are connected to the ViPSN-home gateway by different protocols.

The environment tag (ViPSN-tag) is powered by a PV cell. Once a sufficient amount of energy is accumulated, it measures ambient temperature, humidity, and light intensity, then transmits the sensed data to the ViPSN-home gateway via 2.4 GHz RF channel using the ESB protocol. The ViPSN-home gateway subsequently forwards these data packets to the HA platform through WiFi and using the MQTT protocol.

The self-powered pushbutton (ViPSN-button) is powered by a quasi-static toggling energy harvester (QST-EH). When a user presses the button, QST-EH will be pressed together. The energy-buffer spring retains the motion energy and releases it at some points. It drives a magnet to flip its polarity, energizes an adjacent coil, and therefore generates electricity [11]. Upon activation, the button broadcasts BLE beacons, which are received by the ViPSN-home gateway. By forwarding the beacon commands to the HA platform, the system is able to control household appliances in accordance with the customized home automation program.

The smart floor tile (ViPSN-floor) is powered by a piezoelectric EH [4]. When a pedestrian steps on a tile, the step motion excites the piezoelectric EH to generate electricity. Similar to the battery-free button, the floor tile broadcasts a BLE beacon signal upon activation. The gateway forwards these beacon signals to the HA platform. The ViPSN-floor may be employed to monitor unauthorized intrusion in order to safeguard security personnel.

The three aforementioned battery-free IoT sensing nodes, namely the ViPSN-tag, ViPSN-button, and ViPSN-floor, transmit data packets solely to the HA platform. These nodes showcase the uplink communication capacity from the BF-IoT nodes to the ViPSN-home gateway.

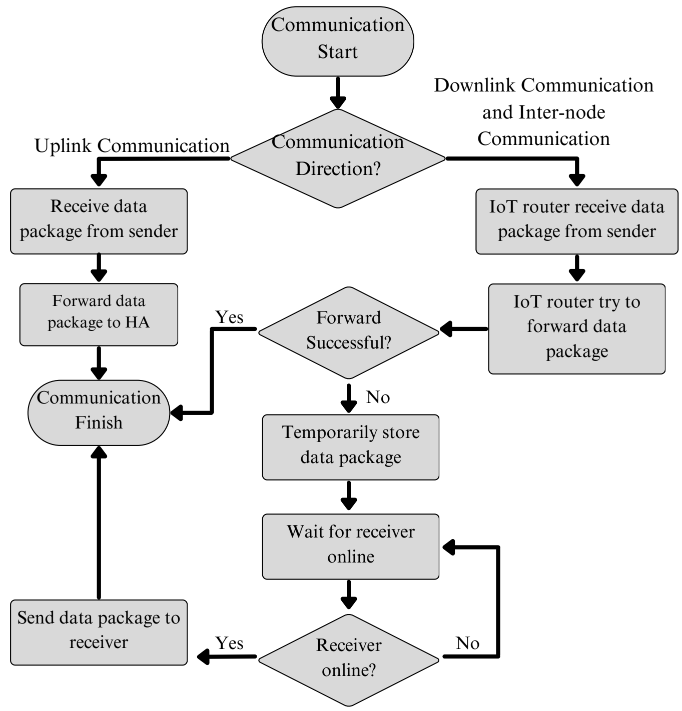


Fig. 2. Communication flowchart.

The fourth BF-IoT device is ViPSN-Eink, an E-ink display module powered by indoor lighting. Once a sufficient amount of energy is accumulated, the module is activated and requires data from the ViPSN-home gateway. It can display the sensed environmental information or whatever received information to users. These nodes showcase the downlink communication capacity from the ViPSN-home gateway to the BF-IoT nodes.

## IV. Communication Strategy

The communication strategy of ViPSN-home is designed to ensure efficient and reliable data exchange between BF-IoT end devices, the gateway, and the HA platform. The strategy is implemented through five key processes: device registration, request handling, downlink communication, uplink communication, and inter-node communication. The communication flowchart is drawn in Fig. 2.

### A. Device Registration

During system initialization, each end device is assigned a unique address code. All the addresses are registered in a ViPSN-home gateway address code table.

Additionally, each end device keeps a local address code table containing the identifiers of other end devices it can communicate with. This registration mechanism guarantees that all end devices are recognized efficiently and all data routing is managed appropriately within the network.

### B. Request Handling

When a BF-IoT end device accumulates sufficient energy to activate, it sends a data request command to the ViPSN-home gateway. Upon receipt of this request, the gateway conducts a check for any previously stacked data packets associated with the end device. If stacked packets exist, these packets will be forwarded to the end node; otherwise, the gateway will acknowledges the request with a "no data" response. This process ensures that end devices are promptly updated with pending information upon each round of activation.

### C. Uplink Communication

In uplink communication, when a BF-IoT end device needs to transmit measured values or user commands to the HA platform, it first sends the data packet to the ViPSN-home gateway. Then, the gateway forwards this data packet to the HA platform using the MQTT protocol. This guarantees that real-time data originating from BF-IoT end devices is effectively transmitted to the HA platform for prompt processing and visualization.

### D. Downlink Communication

For downlink communication, when the HA platform needs to send instructions or data to a BF-IoT end device, the HA platform firstly sends this data packet to the ViPSN-home gateway. The gateway attempts to forward the data packet and waits for an acknowledgment (ACK) from the end device. If an ACK is received, the specific round of communication is confirmed as a successful trial. If no ACK is received, the data packet is temporarily stored in the gateway. A retry occurs when the end device is activated and the data request command is received once more. This mechanism ensures reliable delivery of instructions and data to the battery-free devices, even under circumstances of intermittent connectivity.

### E. Inter-Node Communication

When communication between IoT end devices is required, the sender transmits data packet along with the receiver's address to the ViPSN-home gateway. Then, the gateway do the same communication procedure like downlink communication. This mechanism ensures seamless inter-device communication, even in dynamic network environments where end devices are frequently and intermittently connected or disconnected.

## V. Experiment & Demonstration

To demonstrate the proposed ViPSN-home solution for integrating BF-IoT end devices into the smart home ecosystem, we set up the four types of self-powered devices, i.e., ViPSN-button, ViPSN-floor, ViPSN-tag, and ViPSN-Eink, to control a smart desk lamp from the Xiaomi Mijia ecosystem and display the information from a Xiaomi Bluetooth temperature and humidity sensor. Taking the ViPSN-button connection for example, the experimental steps are listed as follows:

- **Step 1:** Utilize the Mijia smart home APP to bind the smart desk lamp to your account.
- **Step 2:** Bind a user's Xiaomi account ID and password to the HA software platform.
- **Step 3:** Conduct a test on the control of the Mijia lamp through the HA platform. If all functions operate correctly, the Mijia lamp can be toggled on and off via the HA platform.
- **Step 4:** Configure the MQTT protocol on the HA platform. Establish a rule to turn the lamp on/off upon receiving a specific MQTT data packet.
- **Step 5:** Configure the ViPSN-home gateway and register the self-powered devices on the gateway. Proceed with the specific MQTT data packet once a ViPSN-button BLE command is received.
- **Step 6:** Double-check the data chain and function from the self-powered ViPSN-button to the Mijia lamp.

The experimental setup is summarized in Fig. 3.

## VI. Conclusion

This paper introduced ViPSN-home, a holistic solution integrating battery-free IoT (BF-IoT) devices into the prevailing smart home ecosystems through Home Assistant (HA). To overcome the intermittent connectivity of BF-IoT, we designed an optimized communication strategy to ensure a reliable and efficient data exchange. The key device in ViPSN-home is a customized gateway. It takes care of the upstream communication with all BF-IoT end devices and the downstream HA platform. It also supports multiple low-power protocols. Experiments validated and demonstrated the proposed system. The ViPSN-home design opens up a new era of massive BF-IoT devices facilitating the ubiquitous sensing and control in a smart home scenario.

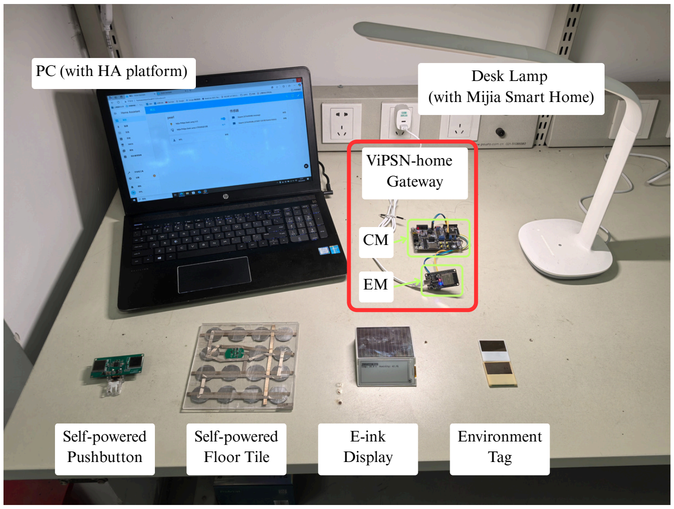


Fig. 3. Experimental setup.

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