

Development and Analysis of Multi-WPAN Protocol-Based IoT Network Implementation

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Abstract— The integration of multiple communication protocols is becoming increasingly important to ensure seamless interoperability between devices in IoT networks. Recently, there has been a growing trend of combining Thread, Zigbee, and Bluetooth Low Energy network (BLE) to maximize the strengths of each protocol. However, this process can increase the complexity of device installation and operation, leading to additional cost burdens. Therefore, this paper proposes efficient communication strategies among multiple Wireless Personal Area Network (WPAN) protocols to enhance cost efficiency and address potential issues that may arise during the implementation of integrated networks.

Keywords— Multiprotocol, Internet of Things, Thread, Zigbee, Bluetooth Low Energy

I. INTRODUCTION

The unprecedented growth in the number of connected objects is realizing the concept of the Internet of Things (IoT). A prime example of such objects is the HVAC (Heating, Ventilation, and Air Conditioning) monitoring and control system, which leverages various sensors to create a smart home environment [1]. The development of the smart home IoT ecosystem primarily employs communication protocols under IEEE 802.15 Wireless Personal Area Network (WPAN) and IEEE 802.11 Wireless Local Area Network (WLAN). WPAN protocols, including Thread, Zigbee, and Bluetooth Low Energy (BLE), are widely used due to their low power consumption, low cost, and scalability. However, these protocols face limitations such as short communication range, low data rates, and interoperability issues.

One significant challenge shared by both manufacturers and consumers in building the smart home IoT ecosystem is the interoperability of communication protocols across devices. Consumers may encounter difficulties integrating new products with advanced features into their existing IoT ecosystems, as these new devices may not be compatible with older systems. This interoperability issue, if unresolved, could lead to long-term degradation in the home IoT market. To address this, the Matter protocol was recently proposed as a potential solution [2].

Matter is an open-source protocol developed to enhance interoperability among various smart home devices. It was first

announced in 2019 by the Connectivity Standards Alliance (CSA), with participation from major technology companies such as Apple, Google, and Amazon. The Matter stack architecture is composed of diverse network layers, including Wi-Fi for WLAN, Ethernet for Local Area Network (LAN), Thread for WPAN, Zigbee Direct, and BLE, enabling seamless communication among various devices. The primary goal of Matter is to improve user experience and facilitate device integration.

Thread, the main WPAN protocol used in Matter, provides low-power, low-data-rate communication, making it ideal for battery-dependent devices. It supports Internet Protocol version 6 (IPv6), ensuring easy integration with existing IP networks. Moreover, Thread offers high reliability and scalability through mesh networking and enables seamless connectivity with other networks via a border router.

In this paper, we propose and implement a method to integrate multiple WPAN protocols into a unified IoT network to resolve the interoperability issues of existing WPAN-based smart home IoT ecosystems. Specifically, the integration is based on Thread and the Co-Processor Communication Daemon (CPCd) algorithm, and its feasibility is validated through implementation. The structure of this paper is as follows: Section II introduces CPCd and the Radio Co-Processor (RCP), explains their roles in the proposed integration method, and describes their function in the experiments. Section III details the system implementation and experimental evaluation of the performance of Thread, Zigbee Direct, and BLE networks across various scenarios, leading to the optimal network configuration. Finally, conclusions are drawn in Section IV.

II. RELATED WORKS

A. Thread

Thread is a key low-power protocol adopted by Matter, making it suitable for smart home devices where battery life is critical. It enables IPv6 routing through border routers, which play an essential role in the network. Multiple border routers can be deployed to enhance network reliability, and they automatically take over each other's roles if one is removed. Off Mesh Routable (OMR) addresses allow seamless

connections to Wi-Fi/Ethernet networks or other Thread meshes.

Thread provides high reliability and scalability through mesh networking, allowing data to be transmitted via alternative paths even if certain devices fail. It is designed to enhance interoperability with other protocols like BLE and Zigbee, where BLE can handle initial setup and status monitoring, and Thread can manage continuous data communication. These features make Thread applicable not only in smart homes but also in industrial IoT and smart cities.

B. Zigbee Direct

Zigbee Direct connects Zigbee and BLE, enabling seamless communication between devices using these protocols. This allows BLE devices to securely access and control Zigbee devices within the network. Zigbee Direct consists of two primary device types:

- Zigbee Direct Device (ZDD): A device that simultaneously runs Zigbee and BLE stacks, supporting data exchange.
- Zigbee Virtual Device (ZVD): A BLE-based device that acts as a Zigbee device or performs specific roles within the Zigbee network, such as trust center or configuration tools.

Zigbee Direct offers two main services. The Zigbee Direct Commissioning Service enables ZVDs to configure and manage the network, while the Zigbee Direct Tunnel Service allows ZDDs to exchange data within the Zigbee network. These services ensure a reliable link between Zigbee and BLE devices.

C. Bluetooth Low Energy

BLE is a low-power, low-data-rate communication protocol suitable for smart home devices. It maintains low energy consumption and short latency, making it ideal for applications like fitness trackers and medical devices.

BLE uses standard profiles like GATT to ensure compatibility between devices from different manufacturers, enabling seamless data exchange. Its fast connection setup allows immediate communication between devices. Additionally, BLE strengthens security with encryption and authentication, ensuring data integrity and confidentiality, which are critical in smart home environments.

D. CPCd and RCP

CPCd is a software daemon that enables simultaneous communication across multiple protocols using a single device. It significantly enhances interoperability among various devices by supporting diverse wireless communication protocols, such as Thread, Zigbee, and BLE [3]. Through CPCd, users can construct networks that integrate Thread, Zigbee, and BLE protocols and exchange data between them in real time. This setup can be implemented by connecting multiple communication boards to a platform such as Raspberry Pi, creating a multi-protocol network environment.

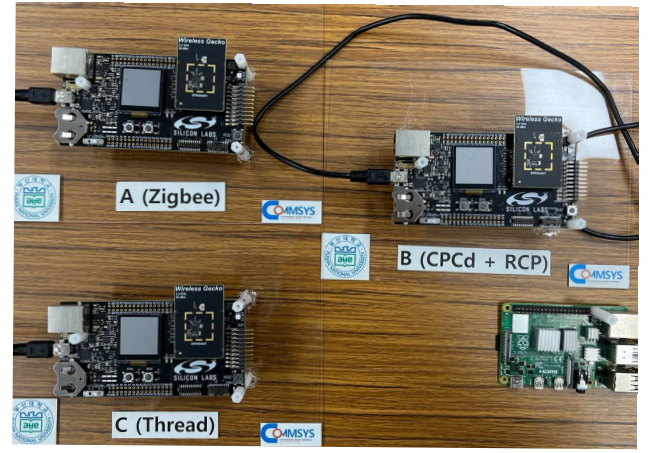


Figure 1. Experimental Device Configuration and Connection Structure

The RCP is a hardware device critical for efficiently monitoring and processing multiple wireless communication protocols simultaneously. It supports the concurrent reception and processing of protocols such as BLE, Zigbee, and Thread. For instance, when both Thread and Zigbee networks are active, the RCP monitors the data received from each network in real time and processes it according to the corresponding protocol.

One key feature of the RCP is its concurrent listening capability, which minimizes performance degradation while simultaneously processing multiple protocols. This functionality allows the RCP to efficiently receive and analyze multi-protocol signals and handle data packets for each protocol [4-5].

E. Integrated Network Management System

The proposed integrated network management system uses CPCd to create and manage Thread, Zigbee, and BLE networks. In the Thread network, CPCd acts as a border router to ensure smooth communication between devices and enables IPv6-based communication using OMR addresses. For Zigbee networks, CPCd serves as the coordinator, managing message transmissions between devices to ensure network stability and scalability [6-8]. In BLE networks, CPCd provides basic network configuration and data transmission capabilities.

To perform these functions effectively, CPCd utilizes the RCP to receive and process multiple protocols simultaneously. The RCP's concurrent listening capability ensures minimal performance degradation while processing multiple protocols. Furthermore, Zigbee Direct complements the limited functionality of CPCd's BLE network management by enabling BLE devices to monitor and control the state of Zigbee Direct devices.

III. SYSTEM IMPLEMENTATION AND EXPERIMENTATION

A. Experimental Setup

The experimental setup included a Raspberry Pi 4 as the Linux host, and SiliconLabs EFR32MG21 WSTK boards as

RCP and Zigbee/Thread devices, with a consistent device separation of approximately 2 meters. SiliconLabs Simplicity

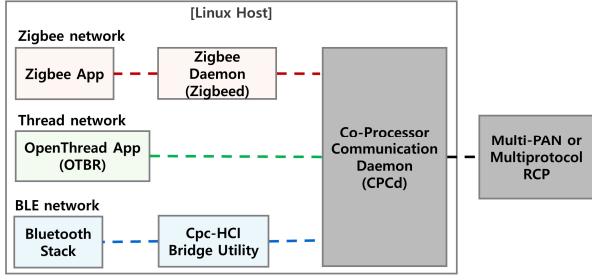


Figure 2. System architecture of CPCd with RCP

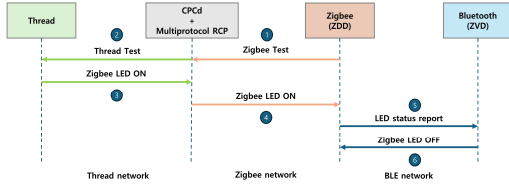


Figure 3. System architecture of CPCd with RCP

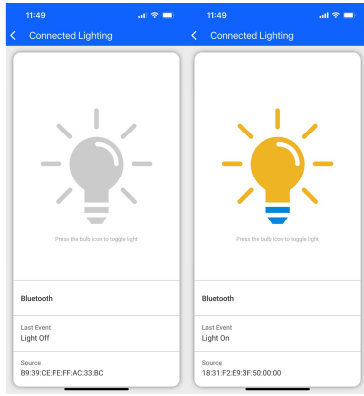


Figure 4. Status report received by BLE device from Zigbee Direct

Studio v5 was used to configure the communication boards, while smartphones and the Simplicity Connect application facilitated BLE communication.

The integrated network architecture, depicted in Figure 2, involved porting CPCd, applications, and stacks for Thread, Zigbee, and BLE communication onto the Linux host, which was then connected to the RCP board. Thread and Zigbee Direct communication boards were connected to the host for network initialization and protocol-specific configurations.

Table I. Round-Trip Time For Different Packet Lengths

Packet length (byte)	Round-trip time (min)(ms)	Round-trip time (avg)(ms)	Round-trip time (max)(ms)
64	48	55.234	84
128	97	108.943	147
256	165	179.840	539

Packet length (byte)	Round-trip time (min)(ms)	Round-trip time (avg)(ms)	Round-trip time (max)(ms)
64	48	55.234	84
512	337	363.501	715

Finally, smartphones were used to connect to Zigbee Direct devices via BLE, verifying successful BLE connections through logs.

The experimental sequence, shown in Figure 3, started by testing Thread and Zigbee connectivity using “Zigbee Test” and “Thread Test” messages. Subsequently, LED control commands were sent from Thread to Zigbee devices via CPCd, verifying the state changes of Zigbee LEDs. During this process, Thread and Zigbee networks operated on separate wireless channels, and the RCP’s concurrent listening feature prevented interference. Finally, LED state changes in Zigbee devices were reported to BLE devices and smartphones, which sent control commands back to Zigbee devices for state alterations.

B. Experimental Results

Received Signal Strength (RSS) values ranged between -50 and -60 dBm, indicating robust communication between devices, even in environments where the RCP formed networks with two protocols. As summarized in Table 1, no packet loss was observed during packet transmissions in the Thread-based network. The results showed smooth communication across typical packet lengths used in low-power, low-data-rate wireless communication protocols, without collisions with other protocols.

CPCd successfully exchanged messages and control commands with Thread and Zigbee devices. Zigbee Direct devices received control commands from CPCd, updated their LED states, and reported these changes to BLE devices and smartphones. BLE devices confirmed the updates and sent additional control commands, completing the bidirectional communication cycle. Videos documenting the experimental process can be found on GitHub at the following URL: <https://github.com/SeonghyeonPark24/Integration-and-Performance-Analysis-of-a-Multi-WPAN-Protocol-IoT-Network-Implementation>

IV. CONCLUSION

This paper proposed and implemented a method to enhance interoperability in IoT networks by integrating multiple wireless communication protocols. By combining Thread, Zigbee, and BLE networks, the advantages of each protocol were maximized, enabling seamless device interactions within a unified network. The results demonstrated the potential to optimize network capacity and improve operational efficiency.

Experiments verified that CPCd and RCP enable real-time monitoring and management of Thread, Zigbee, and BLE networks. CPCd leveraged the RCP’s concurrent listening capability to receive and process multi-protocol data without significant performance degradation. IPv6-based

communication via the Thread network's border router and direct communication between Zigbee and BLE devices through Zigbee Direct further validated the system's effectiveness.

This research highlights the feasibility of implementing an integrated network for seamless communication among diverse IoT devices in smart home environments. Future studies will focus on enhancing the structure and operational strategies of such networks to extend their applications to industrial IoT, smart buildings, and smart cities, thereby improving user convenience and network reliability. The findings contribute significantly to addressing interoperability issues in smart home IoT ecosystems and pave the way for more efficient multi-protocol IoT networks.

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