

IEET: Improving Emergent Events Transmission for Home Elderly Care With Multi-Layer BLE Topology Control

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Abstract—As the elderly population continues to grow, timely health monitoring and emergency response for the elderly become particularly crucial. However, traditional wireless sensor networks face challenges such as transmission delays, high energy consumption, network congestion, and packet collisions during emergencies, which impact the health and safety of the elderly. To address these issues, this paper proposes a novel multi-layer topology control mechanism, called Improving Emergent Events Transmission (IEET), which integrates tree and mesh topologies while applying channel selection and subrated connection strategies. The tree topology effectively constructs a distinct path for emergent transmission, filtering out channels susceptible to contentions and collisions. It employs a subrated connection scheme to adjust the connection interval for transmitting emergency messages, thus reducing transmission delay and energy consumption. Additionally, the mesh topology addresses traffic congestion near the gateway, reducing packet collisions and improving the reliability of packet transmission. As a result, emergent information can be swiftly transmitted to the gateway, mitigating the impact of emergencies on the elderly. Simulation results demonstrate that the proposed IEET outperforms existing mechanisms in terms of average packet latency, network lifetime, and energy consumption for sensors in Bluetooth Low Energy (BLE) networks.

Index Terms—BLE, mesh, multi-layer topology control, energy conservation, emergency.

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I. INTRODUCTION

WITH advancements in medicine, the issue of aging is becoming increasingly serious. The proportion of the lifespans and a global decline in birth rates [1], [2]. This demographic shift contributes to a growing number of elderly individuals living alone. It is urgent to provide a safe and healthy home environment for the elderly to accommodate this aging population. Many elderly individuals suffer from chronic diseases, such as diabetes, heart disease, and hypertension. These conditions require long-term continuous monitoring of healthy parameters, such as blood sugar, heart rate, and blood pressure [3]. With financial constraints faced by younger generations, the need to work often leaves many elderly individuals living alone. Moreover, elderly individuals are susceptible to unforeseen incidents, such as falls, fluctuations in blood pressure, abnormal sugar levels, gas leaks, and other emergencies. Once these emergent events are detected [4], it is urgent to construct a reliable network using Internet of Things (IoT) technology, which can rapidly and effectively transmit emergent events to the gateway in case of an emergency. Upon receiving the emergent message, family members or caregivers can promptly assist the elderly individuals in dealing with these incidents. This research is dedicated to mitigating the adverse effects of emergencies on elderly individuals, significantly enhancing their quality of life through advancements in smart home technology. Moreover, this research holds significant implications for promoting the overall health and well-being of society.

In the field of consumer electronics, data transmission can be categorized into non-Bluetooth and Bluetooth-related communication. The following reviews the studies falling in the non-Bluetooth category. Yang et al. [5], Tebe et al. [6], and Poongodi et al. [7] utilized fifth generation (5G) communication to transmit medical data and enhance communication performance. However, many elderly individuals living in remote rural areas lack access to 5G networks, and it is currently impractical to replace sensors embedded with 5G in their homes. Additionally, Misra et al. [8] and Niaz et al. [9] employed the IEEE 802.15.6 standard for event communication involving in-body sensors. However, this protocol was primarily designed for applications within wireless body area networks and might not be suitable for sensors located in other areas of an elderly home.

In recent years, there has been growing interest in BLE networks within the field of consumer electronics [10], [11]. Most research on BLE technology has focused on improving transmission delays [12], [13], [14], [15], [16], [17] and conserving energy [18], [19], [20], [21], [22]. For example, Ng and She [14] utilized Q-learning to minimize end-to-end packet delivery latency and conserve energy. However, the complexity of the neural network posed challenges in training at the gateway due to computing limitations in elderly home environments. In the context of emergencies, previous research conducted by Álvarez et al. [15] established a Bluetooth mesh network using mobile phones or relays for communication in disaster relief scenarios. However, this solution might not be suitable for elderly individuals living alone, as it is impractical to expect them to possess multiple phones. Li et al. [18] combined energy conservation and collision avoidance in path construction, aiming to reduce energy consumption and prolong the lifetime of the network. However, sensors closer to the gateway forwarded a large number of packets, leading to traffic congestion. To address this issue, Zhang et al. [23] proposed a suitable scheduler and congestion controller for multipath transmission control protocol to improve transmission throughput and robustness in healthcare applications. However, their solutions were specifically tailored for Android consumer electronics and did not apply to sensors in home environments for the elderly.

This paper presents an IEET mechanism that exploits BLE-standard-compliant topologies to create an efficient network. The proposed IEET develops BLE-network-based technology utilizing topologies like piconets, scatternets, and mesh, all conforming to BLE protocol standards [24]. The feasibility and operational capabilities of these topologies have been validated in prior research and industry applications [25], [26]. The introduced technology, which encompasses channel selection and subrated connection techniques, adheres to the BLE protocol, ensuring that the proposed IEET is supported by the BLE standards. Such adherence guarantees that the development of subsequent elderly care-related application systems based on this research will be straightforward to implement.

In addition, the proposed IEET crafts a novel multi-layer topology by integrating tree and mesh topologies to optimize packet transmission for various data types. The tree topology enables swift data delivery in emergencies by providing direct paths, thus reducing delays. Moreover, the mesh topology enhances network resilience and data reliability by addressing congestion issues near the network gateway. Furthermore, the implementation of a subrated connection strategy in the proposed IEET adjusts data transmission intervals based on emergencies, striking a balance between rapid response for emergency data and energy efficiency for sensor communication. This innovative approach ensures efficient and reliable network performance tailored to the specific demands of BLE-based applications. The main contributions of the paper are summarized as follows:

1) *Construction of Tree and Mesh Topologies*: The proposed IEET constructs a tree topology to minimize transmission delay and a mesh topology for sensors near the

gateway, aiming to alleviate the collision and contention phenomena.

2) *Minimization of Transmission Delay for Emergent Events*: The proposed IEET constructs an emergency path for each emergent sensor to reduce packet collisions and achieve minimal transmission delays.

3) *Conservation of Energy for General Events*: The proposed IEET adopts a subrated connection scheme to conserve energy. Specifically, emergent sensors use a long connection interval for sending general event data to save energy and switch to a short connection interval immediately for sending emergency packets when emergencies occur.

The remainder of the paper is organized as follows. Section II provides a comprehensive review and comparison of relevant previous studies. Section III presents the network environment and problem formulation in detail. Section IV presents the proposed IEET mechanism in detail. Section V discusses the simulation and performance evaluation of the proposed IEET. The summary and future work are discussed in Section VI.

II. RELATED WORK

This section categorizes data transmission and energy conservation into non-Bluetooth and Bluetooth-related communication protocols, focusing on their application in elderly care and emergency response.

A. Non-Bluetooth Communication Protocol

Recently, 5G technology [5], [6], [7] has emerged as a crucial enhancement in communication performance. For example, Yang et al. [5] highlighted a 5G-enabled prototype for multiple-dimension biochemical data collection in tele-healthcare, showcasing rapid data transmission to the cloud and medical facilities with minimal delay. Similarly, Tebe et al. [6] and Poongodi et al. [7] utilized 5G to transmit medical data and enhance hospital operations, respectively, ensuring high transmission reliability and low latency. However, the accessibility of 5G in remote rural regions remains a challenge, especially for elderly residents. The feasibility of replacing the sensors embedded with 5G-enabled sensors in their homes is not currently practical.

To overcome this, Jesús-Azabal et al. [27] employed an interest-based routing algorithm with opportunistic networks to improve remote monitoring and emergency detection in aging individuals living alone, facilitating asynchronous communication. However, this network also heavily relied on a specific platform. In a different approach, Zhang et al. [28] introduced a multi-objective optimization evolutionary algorithm with a penalty mechanism (MOEA-PM), aiming to improve the flexibility and timeliness of smart healthcare data. However, MOEA-PM often requires substantial computational resources, which might lead to longer processing durations. Lu et al. [29] developed a digital twin-based scheduling model, designed to forecast forwarding delays in a smart healthcare system. This model aimed to establish an optimal routing strategy, subsequently integrated into the physical networks to minimize transmission delays. However, their effectiveness

heavily relies on the accuracy of predicting forwarding delays, making them particularly sensitive to changes in network environments.

B. Bluetooth-Related Communication Protocol

Recently, most physiological monitoring devices in elderly homes have utilized BLE. Several Bluetooth-related communication protocols have been proposed to improve transmission delay [12], [13], [14], [15], [16], [17] and conserve energy [18], [19], [20], [21], [22]. For example, Etxaniz and Aranguren [12] provided an empirical model for latency in multi-hop BLE networks with asynchronous links, providing precise latency estimations for each communication hop. To balance energy conservation and communication latency, Chen et al. [13] proposed a power management mechanism to meet the latency constraints of broadcasting applications by adapting the advertising interval to minimize the resubmission overhead caused by runtime collision. Similarly, Fatihah et al. [16] presented a mathematical model to reduce data collection latency in dense BLE networks, developing a low-complexity algorithm for rapid and adaptive BLE network optimization in dynamic wireless environments. However, these models primarily focus on the latency of the advertising state, neglecting other BLE states. The proposed IEET constructs an emergent path for each emergent sensor and selects optimal channels to ensure that BLE sensors can avoid conflicts across all BLE states. It also constructs a mesh topology for sensors near the gateway to reduce collisions and transmission delays.

For energy conservation, Hong and Shin [19] proposed virtual connections that decoupled applications from network-specific operations for selective connections, aiming to reduce the energy consumption of wearable consumer electronics. However, virtual connections require specific support from devices and applications, which could render some older devices incompatible. Yu et al. [20] and Ng et al. [21] explored enhancements in BLE network topologies using mesh topology. Yu et al. [20] developed a balanced mesh-ring topology with a hybrid routing strategy for improved energy efficiency. Ng et al. [21] introduced an overlay protocol to extend the beacon lifetime and enhance packet forwarding within the mesh topology. However, their approaches treated all nodes equally, failing to differentiate between emergency and general nodes. This lack of differentiation meant that general nodes competed for network resources with emergency nodes, thereby increasing the transmission latency for emergency nodes. To address this issue, the proposed IEET categorizes sensors in the home environment for elderly care into emergency and general sensors. It constructs emergent transmission paths for emergency sensors, aiming to avoid conflicts with general transmission. It also adopts a subrated connection scheme for emergency sensors to conserve energy.

To further enhance energy efficiency, Chakraborty et al. [30] proposed a fog computing-based scheme for secure and energy-efficient data aggregation in healthcare, designed to reduce communication overhead and energy consumption. Similarly, Singh et al. [31] also proposed two data forwarding

strategies to construct energy-optimal and delay-optimal paths in wireless sensor networks, aiming to ensure delay guarantees with minimum transmission costs. However, their analyses focused on network node aspects without considering protocol. The proposed IEET adopts a subrated BLE connection scheme to adjust the connection intervals for forwarding the emergent messages, aiming to decrease transmission delay and conserve energy.

Some other researchers [8], [9], [32], [33], [34] have focused on Wireless Body Area Networks (WBANs) in emergency scenarios. Misra et al. [8] proposed an energy-efficient medium access control protocol of the IEEE 802.15.6 standard, designed for regular and emergency event communication in WBANs. Similarly, Niaz et al. [9] devised a traffic load-aware channel bonding algorithm to enhance off-body communication performance between sink nodes and gateway, using the same standard. Taleb et al. [32] proposed a healthcare WBAN platform by applying LoRa technology, incorporating a fuzzy logic controller to optimize system sleep mode durations and data transmission rates. Additionally, Chowdhury [33] developed a comprehensive strategy for WBANs, including fast data transfer, emergency time slot allocation, processing node allocation, and energy-saving task execution. Moreover, Nasreen and Ravindran [34] proposed a dual-stage capacity allocation method to reduce interference and maximize the capacity in WBANs with suboptimal channel quality, particularly those carrying high-priority data. Despite these advancements, current WBANs are prone to sensitivity regarding network topology and environmental changes, lacking sufficient adaptability to address the dynamic variations in real-world home elderly environments. To address this, the proposed IEET considers the signal strength, traffic flow, and connection quality of sensors in home elderly environments to construct a multi-layer BLE topology, which facilitates the transmission of emergent events when changing network topology and environmental conditions.

Table I provides a comparative summary of the proposed IEET and related work. The ‘protocol’ column indicates the mechanism employed, while ‘emergency’, ‘collision’, ‘energy conservation’, and ‘traffic congestion’ denote whether the mechanisms consider these aspects. Compared with the related work, the proposed IEET utilizes BLE and establishes a multi-layer topology for the transmission of both emergent and general events, to reduce collisions and conserve energy.

III. NETWORK ENVIRONMENT AND PROBLEM FORMULATION

This section provides the network environment and assumptions, models of communication and energy, problem description, and objectives.

A. Network Environment and Assumptions

Assume there are m rooms $R = \{r_1, r_2, \dots, r_m\}$ in the home environment of an elderly person living alone. There are $n + 1$ Bluetooth sensors $S = \{s_1, s_2, \dots, s_n\} \cup G$ randomly deployed in the considered space R , where G denotes the gateway. These sensors can be further divided into two types: general

TABLE I
THE COMPARISONS OF THE PROPOSED IEET AND RELATED WORK

Mechanism	Protocol	Emergency	Collision	Energy conservation	Traffic congestion
[5]~[7]	5G	Yes	No	No	No
[8]	IEEE 802.15.6	Yes	No	No	No
[9]	IEEE 802.15.6	No	No	No	No
[14]	BLE	No	No	Yes	No
[15] [17]	BLE	No	Yes	Yes	No
[16]	BLE	Yes	No	No	No
[18] [34]	BLE	Yes	Yes	Yes	No
[19]~[20]	BLE	No	Yes	Yes	No
[21]	BLE Mesh	No	No	Yes	No
[22]	BlueSync	No	No	Yes	No
[23]	Not specified	No	Yes	Yes	Yes
[27]	Opportunistic	Yes	No	Yes	Yes
[28][29]	Not specified	Yes	Yes	No	Yes
[30] [31]	Not specified	No	Yes	Yes	No
[32]	LoRa	Yes	No	Yes	No
[33]	Not specified	Yes	No	Yes	No
Proposed IEET	BLE	Yes	Yes	Yes	Yes

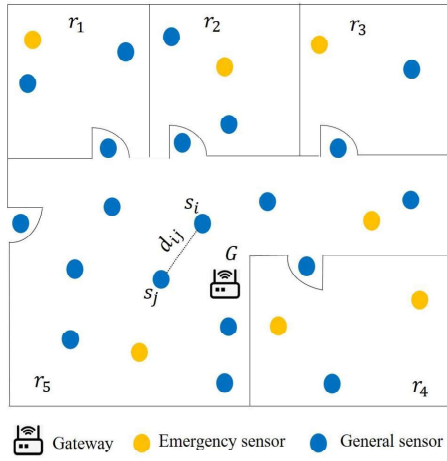


Fig. 1. The network environment of the proposed IEET.

sensors and emergent sensors. The gateway plays the role of forwarding the received data to the Internet, utilizing either Wi-Fi or 5G technology. The other sensors communicate with each other through Bluetooth technology. Let S^{gel} and S^{emt} denote the sets of general and emergent sensors, respectively. Specifically, $S^{gel} = \{s_1^{gel}, \dots, s_a^{gel}\}$ includes a sensors and $S^{emt} = \{s_1^{emt}, \dots, s_b^{emt}\}$ consists of b sensors. The sensors in S^{gel} are mainly responsible for regularly collecting home environmental information or general events related to the elderly. Each sensor in S^{emt} is used to detect some emergency events such as gas leaks and sudden falls.

Fig. 1 illustrates a representative example of the considered home environment R . The Bluetooth sensors are randomly deployed in five rooms, denoted as $R = \{r_1, r_2, \dots, r_5\}$. There is one gateway G . The general sensors S^{gel} and emergent sensors S^{emt} are marked with blue and yellow colors, respectively.

The following presents the applied communication and energy models.

B. Communication Model

Let ω denote the transmission rate. Let $T_{i,j}$ represent the transmission time of one packet from the sensor s_i to s_j . Let

$d_{i,j}$ denote the distance between s_i and s_j . Let $\delta_{i,j}$ denote the transmission success rate from the sensor s_i to s_j . Assume that each packet has κ bits. The value of $T_{i,j}$ can be calculated by Eq. (1).

$$T_{i,j} = \frac{d_{i,j}}{\omega} * \kappa * \left\lceil \frac{1}{\delta_{i,j}} \right\rceil. \quad (1)$$

Let $P_i = \{p_{i,l} | p_{i,l} = (s_i, \hat{s}_1, \dots, \hat{s}_n, G = \hat{s}_{n+1})\}$ represent all possible paths from $s_i \in S$ to the gateway G , where $p_{i,l}$ denotes l -th path from the sensor s_i to gateway G . Let T_i^l represent the total time required for transmitting one packet from each sensor $s_i \in S$ to gateway G along the path $p_{i,l}$. The value of T_i^l can be computed by Eq. (2).

$$T_i^l = \sum_{j=1}^{n_l+1} T_{i,j}. \quad (2)$$

C. Energy Model

In addition to the communication model, the energy model [35] is introduced here. Let $E_i^{sensing}$ denote the energy consumption for performing the sensing task. The value of $E_i^{sensing}$ can be calculated according to Eq. (3).

$$E_i^{sensing} = e_s \lambda_i, \quad (3)$$

where e_s denotes the energy consumed by perceiving for each time, λ_i denotes the data perception rate of the sensor s_i .

Assume that s_i and s_j are sender and receiver, respectively. Let $E_{i,j}^{T,k}$ and $E_{i,j}^{R,k}$ denote the energy consumption for transmitting and receiving one packet from the sensor s_i to s_j , respectively. The value of $E_{i,j}^{T,k}$ and $E_{i,j}^{R,k}$ can be calculated as shown in Eqs. (4) and (5), respectively.

$$E_{i,j}^{T,k} = \kappa \varepsilon_1 + \kappa d_{i,j}^\gamma \varepsilon_2, \quad (4)$$

$$E_{i,j}^{R,k} = \kappa \varepsilon_1, \quad (5)$$

where ε_1 denotes the energy consumption per bit for transmitting or receiving electronic, ε_2 denotes the energy consumption per bit/m² of the transmit amplifier, and γ denotes the path loss exponent.

Let $E_{i,j}$ represent the total transmission energy consumption for transmitting one packet from the sensor s_i to s_j . The value of $E_{i,j}$ is calculated according to Eq. (6).

$$E_{i,j} = \left\lceil \frac{1}{\delta_{i,j}} \right\rceil (E_{i,j}^{T,k} + E_{i,j}^{R,k}). \quad (6)$$

Let E_i^l denote the total energy consumption of $p_{i,l}$ from the general sensor $s_i \in S^{gel}$ transmitting κ bits to gateway G . The value of E_i^l can be calculated by Eq. (7).

$$E_i^l = \kappa E_i^{sensing} + \sum_{j=1}^{n_l+1} E_{i,j}. \quad (7)$$

Based on the abovementioned communication and energy models, the next subsection gives the problem description of this work.

D. Problem Description

Let ε_j be a Boolean variable that denotes whether s_j is an emergency sensor. The value of ε_j can be defined by Eq. (8).

$$\varepsilon_j = \begin{cases} 1, & \text{if } s_j \in S^{emt}, \\ 0, & \text{if } s_j \in S^{gel}. \end{cases} \quad (8)$$

To monitor the home environment R , communication can be divided into two types: emergent and general communication. For emergent communication, the source sensor $s_i^{emt} \in S^{emt}$ should transmit data to gateway G via multi-hop communication as quickly as possible when an emergent event occurs. The transmission delay from the emergent sensors to gateway G must be minimal to guarantee high healthcare quality. For emergent communication, this paper aims to construct an emergent path for forwarding data from the emergent sensor s_i^{emt} . On the contrary, the general sensors $s_k^{gel} \in S^{gel}$ are responsible for collecting environmental information such as temperature, humidity, or the events involving the elderly, including getting up, sleeping, going to the toilet, and taking a bath. Since these data are not emergent, this paper aims to construct an energy-efficient path for forwarding them, aiming to maximize energy conservation. Therefore, the goals of this paper are presented as follows.

1) *Goal of Minimal Transmission Delay for Emergent Sensors:* The major goal of this paper is to minimize the transmission delay for emergent events. That is, paths constructed from each source emergent sensor $s_i^{emt} \in S^{emt}$ to gateway G , should forward the emergent data as quickly as possible when emergent sensors detect occurrences of emergent events.

2) *Goal of Minimal Energy Consumption for General Sensors:* Assuming the first goal has been achieved, the second goal of this paper is to further minimize the energy consumption for general events. That is, paths constructed from each general sensors $s_k^{gel} \in S^{gel}$ to gateway G , should save energy as much as possible.

E. Problem Objectives

The paper aims to construct a Bluetooth topology, which can transmit emergent data with minimal transmission delay from each source emergent sensor $s_i^{emt} \in S^{emt}$ to gateway G .

Assuming the first goal has been achieved, the second goal is to further minimize energy consumption from each general sensor $s_k^{gel} \in S^{gel}$ to gateway G . This section proposes the objective functions of this paper, followed by the presentation of two constraints that must be satisfied.

Let $P_i^{(best,emt)}$ denote the best path for emergent sensor s_i^{emt} such that emergent data of s_i^{emt} can be forwarded to gateway G along the path $P_i^{(best,emt)}$ requiring minimal delay. The major objective function is presented below.

Major Objective function:

$$P_i^{(best,emt)} = \arg \min_{s_i \in S^{emt}} T_i^l. \quad (9)$$

Under the condition that the major goal has been achieved, there are still many solutions for constructing a path from each general sensor to the gateway. The second goal is to reduce the total energy consumption for transmitting the general data to the gateway. Let $P_k^{(best,gel)}$ denote the best path for general sensor s_k^{gel} forwarded to gateway G . Equation (10) gives the second objective function of this paper.

Objective function 2:

$$P_k^{(best,gel)} = \arg \min_{s_k \in S^{gel}} E_k^l. \quad (10)$$

There are some constraints, which must be satisfied to achieve the objectives. Assume that t_j denotes the j -th time slot in a period T . Let $\alpha_{i,j}^{sensing}$, $\alpha_{i,j}^{comm}$, and $\alpha_{i,j}^{sleep}$ be three Boolean variables, representing whether or not the sensor s_i stay in sensing, communication, or sleeping state at the time slot t_j , respectively. Equations. (11), (12), and (13) define the values of $\alpha_{i,j}^{sensing}$, $\alpha_{i,j}^{comm}$, and $\alpha_{i,j}^{sleep}$, respectively.

$$\alpha_{i,j}^{sensing} = \begin{cases} 1, & s_i \text{ stays in a sensing state in } t_j, \\ 0, & \text{otherwise,} \end{cases} \quad (11)$$

$$\alpha_{i,j}^{comm} = \begin{cases} 1, & s_i \text{ stays in a communication state in } t_j, \\ 0, & \text{otherwise,} \end{cases} \quad (12)$$

$$\alpha_{i,j}^{sleep} = \begin{cases} 1, & s_i \text{ stays sleeping in } t_j, \\ 0, & \text{otherwise.} \end{cases} \quad (13)$$

The following *state constraint*, which is shown in Eq. (14), makes sure that the sensor s_i must stay in either sensing, communication, or sleeping state at any time slot $t_j \in T$.

1) State Constraint:

$$\alpha_{i,j}^{sensing} + \alpha_{i,j}^{comm} + \alpha_{i,j}^{sleep} = 1. \quad (14)$$

The second constraint called the *Connectivity Constraint*, which is shown in Eq. (15), ensures that there exists at least one path $p_{i,l} \in P_i$ from each sensor $s_i \in S$ to gateway G at any given time slot $t_j \in T$. Let N_i denote a set of neighboring sensors of the sensor $s_i \in S$. Let $h(s_i, G)$ denote the number of hops from s_i to G . The *Connectivity Constraint* guarantees that each sensor $s_i \in S$ can find a neighbor $s_j \in N_i$ closer to G . In case the sensor s_j is a neighbor to G , it can directly forward the received data to G .

2) *Connectivity Constraint:* For each sensor $s_i \in S$, one of the following two conditions should be satisfied.

$$\begin{aligned} (a) & \exists s_j \in N_i, \text{ such that } h(s_i, G) > h(s_j, G), \\ (b) & G \in N_i. \end{aligned} \quad (15)$$

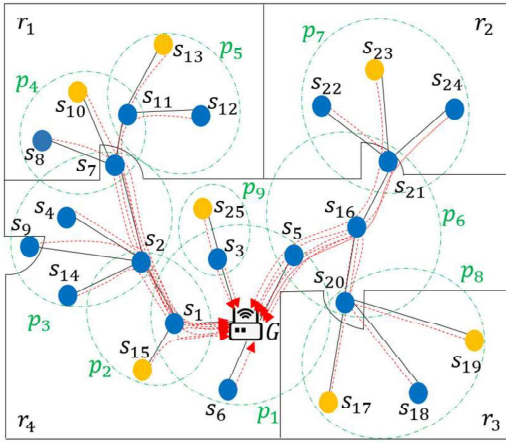


Fig. 2. The constructed tree topology of the proposed IEET.

The third constraint is the *Flow Constraint*, which guarantees that data can be successfully forwarded to gateway G . Let F_k^{in} , F_k^{out} , and F_k^{gen} denote the number of packets received, transmitted, and generated by the forwarder s_k in path $P_i^l = (s_i, \dots, s_k, \dots, G)$, respectively. Each forwarder s_k should satisfy the following *Flow Constraint*.

3) *Flow Constraint*:

$$F_k^{in} + F_k^{gen} = F_k^{out}. \quad (16)$$

The next section will present the proposed IEET mechanism, which aims to achieve the two goals given in Eqs. (9) and (10) while satisfying the Eqs. (14), (15), and (16) constraints.

IV. THE PROPOSED IMPROVING EMERGENT EVENTS TRANSMISSION MECHANISM

This paper aims to construct a Bluetooth topology, called IEET, which is designed to embed multi-layered structures combining both tree and mesh topologies. The proposed IEET facilitates the creation of an emergent path from each emergent sensor, $s_i^{emt} \in S^{emt}$, to gateway G . This path is designed to ensure the transmission of emergent packets with minimal delay. Additionally, the proposed IEET also constructs a path from each general sensor, $s_k^{gel} \in S^{gel}$, to gateway G , aiming to conserve energy during the transmission of non-emergent packets.

In the BLE network, a piconet comprises two or more Bluetooth sensors that share the same hopping sequence. These piconets can interconnect to form a larger network, known as a scatternet. Fig. 2 illustrates a typically scatternet structured as a tree topology. For instance, piconet p_4 in Fig. 2 is organized in a tree topology where the master s_7 plays the root and the slave sensors s_8 , s_{10} , s_{11} act as terminal nodes. In this topology, all slave sensors transmit data to the master sensor. Then the master s_7 then forwards the packets from its slaves to gateway G through other piconets using a multi-hop forwarding mechanism.

The tree-based topology is simple. However, the sensors, such as s_1 , s_2 , and s_5 , which are closer to gateway G , are responsible for forwarding a large volume of packets.

This often results in traffic congestion that can obstruct the transmission of emergent events, leading to significant delays. To address this issue, the proposed IEET introduces a mesh topology as an additional layer, especially for sensors proximate to gateway G . This mesh topology aims to disperse the traffic flow, balance energy consumption, as well as reduce contention and collisions. Consequently, the proposed IEET aims to construct a dual-layer BLE topology. The first layer adopts a mesh topology to alleviate contentions and collisions, while the second layer utilizes a tree topology to ensure a dedicated path for emergent sensors. This section initially presents the development of the tree topology as part of the proposed IEET. Subsequently, the construction of the mesh topology is discussed.

A. 2nd Layer of IEET: Constructing a Tree Topology

The piconet constructed in BLE networks is like a tree topology. The BLE protocol is designed for managing tree topology. In this topology, the master schedules the transmissions of its slaves, which act as leaves in the tree. However, since the packets generated by these sensors need to be forwarded to the gateway, the simplest packet routing from each slave to the gateway is described as follows. As shown in Fig. 2, slave s_{10} transmits its packets to the master s_7 in piconet p_4 . Upon receiving packets from the slaves, the master s_7 forwards them to the gateway through another piconet p_3 , which is closer to the gateway. To achieve this, master s_7 can play the role of a slave in the piconet p_3 . When master s_7 intends to forward its received packets to gateway G , it simply needs to park all its slaves, switch to another piconet p_3 and act as a slave to forward its packets to its master s_2 . This completes the packet forwarding from the piconet p_4 to piconet p_3 , which is closer to gateway G . In this way, since the master s_7 alternates between the master and slave roles in different piconets (p_4 and p_3), it serves as a relay. All slaves, playing the leaves of the tree, can forward their packets to the gateway by applying this packet forwarding mechanism. Consequently, the constructed topology becomes a multi-layer tree structure. In the multi-layer tree topology, each terminal node may be either an emergent sensor or a general sensor. The major goal of this paper is to reduce the transmission delay for emergent events detected by emergent sensors. To achieve this, the topology construction protocol should guarantee several important properties for emergent sensors, including playing the role of a leaf node, constructing a dependent path, allocating suitable channels, and adopting a short polling period, aiming to mitigate collision and contention phenomena.

To guarantee these properties, the proposed construction of the tree topology must consider several factors: constructing an independent emergent transmission path, filtering out bad channels, which are prone to contentions and collisions, and using an adaptive connection interval. The following presents the proposed tree topology, which consists of the *Emergent Path Construction Phase*, *Channel Resignment Phase*, and *Connection Interval Reduction Phase*.

1) *Emergent Path Construction Phase*: The objective of this phase is to construct an emergent path for each emergent

sensor in the tree topology. The primary task is to select the optimal forwarder, which provides the highest connection quality, for the emergent sensor $s_i^{emt} \in S^{emt}$ to play the master role. Emergent sensors connected in the same piconet are prone to being triggered simultaneously. This might cause contentions. Therefore, it is necessary to distribute these sensors across different piconets.

Let N_i denote a set of neighboring sensors for the emergent sensor $s_i^{emt} \in S^{emt}$. Let $\rho_{i,j}$ denote the signal strength received by the emergent sensor s_i^{emt} from neighboring sensor $s_j \in N_i$. Let $\rho_{i,max}$ and $\rho_{i,min}$ denote the maximum and minimum signal strengths received by s_i^{emt} , respectively. Let η_{ij} be the normalized value of $\rho_{i,j}$. The value of η_{ij} can be derived by Eq. (17).

$$\eta_{ij} = \frac{\rho_{i,j} - \rho_{i,min}}{\rho_{i,max} - \rho_{i,min}}. \quad (17)$$

Let f_j denote the traffic flow of the sensor s_j . Let f_{max} and f_{min} denote the maximum and minimum traffic flows of sensors in N_i , respectively. That is,

$$f_{max} = \max_{s_j \in N_i} f_j \text{ and } f_{min} = \min_{s_j \in N_i} f_j.$$

Let θ_j denote the normalized value of f_j , which can be derived using Eq. (18).

$$\theta_j = \frac{f_j - f_{min}}{f_{max} - f_{min}}. \quad (18)$$

Let d_j denote the number of hops from the sensor $s_j \in N_i$ to gateway G . Let d_{max} and d_{min} denote the maximum and minimum numbers of hops from any s_j to gateway G among all $s_j \in N_i$, respectively. Let ϑ_j denote the normalized value of d_j . The value of ϑ_j can be derived using Eq. (19).

$$\vartheta_j = \frac{d_j - d_{min}}{d_{max} - d_{min}}. \quad (19)$$

Let Q_j denote the connection quality of the link connecting the neighboring pair s_i^{emt} and s_j . The value of Q_j is calculated using Eq. (20).

$$Q_j = \alpha * \eta_{ij} + \beta * \theta_j + (1 - \alpha - \beta) * (1 - \vartheta_j), \quad (20)$$

where α and β are the weights. Let s_i^{best} denote the best forwarder for emergent sensor s_i^{emt} . It can be derived using Eq. (21).

$$s_i^{best} = \arg \max_{s_j \in N_i} Q_j. \quad (21)$$

Recall that $P_i = \{p_{i,l} | p_{i,l} = (s_i^{emt}, \hat{s}_1, \dots, G)\}$ denotes the path from the emergent sensor s_i^{emt} to gateway G . The first sensor $\hat{s}_1$, which is responsible for forwarding packets from s_i^{emt} to gateway G , can be derived using Eq. (22).

$$\hat{s}_1 = s_i^{best}. \quad (22)$$

The emergent path P_i can be constructed step by step repeatedly applying the operations given in Eqs. (17) ~ (22) to find the next best forwarder. Once a good path has been constructed in this phase, the next phase aims to allocate the best channels to the links belonging to the emergent path P_i .

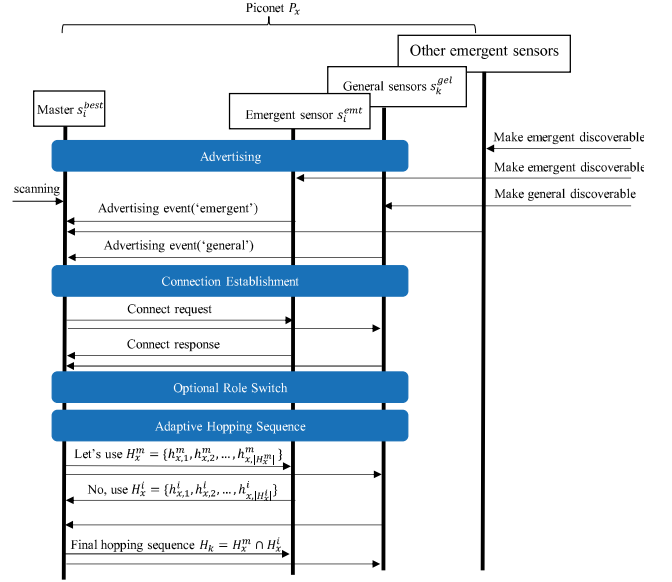


Fig. 3. The process of constructing a tree topology.

2) *Channel Reassignment Phase*: The purpose of this phase is to reserve the best channels for connecting s_i^{emt} and s_i^{best} , aiming to improve the reliability and throughput of the BLE network. The quality of each channel may change over time. To guarantee the optimal channels of the emergent sensor, an adaptive hopping sequence mechanism can be applied. Generally, the master s_i^{best} determines the hopping sequence during the construction of the piconet P_x . Let $H_x^m = \{h_{x,1}^m, h_{x,2}^m, \dots, h_{x,|H_x^m|}^m\}$ be the hopping sequence determined by the master s_i^{best} during piconet construction. Once the piconet has been constructed, the emergent sensor may change the hopping sequence by applying adaptive hopping. Let $H_x^i = \{h_{x,1}^i, h_{x,2}^i, \dots, h_{x,|H_x^i|}^i\}$ denote the new hopping sequence determined by the emergent sensor s_i^{emt} , where $H_x^i \subseteq H_x^m$. The emergent sensor s_i^{emt} removes the channels that are either poor in quality or occupied by other emergent sensors. Let H_x denote the final hopping sequence of the piconet P_x . The value of H_x can be derived using Eq. (23).

$$H_x = H_x^m \cap H_x^i. \quad (23)$$

According to the *Emergent Path Construction Phase* and *Channel Reassignment Phase*, the process of constructing a tree topology is illustrated in Fig. 3. The roles participating in these two phases are the master s_i^{best} , emergent sensor s_i^{emt} , general sensor s_k^{gel} and other emergent sensors. Initially, the master s_i^{best} executes the advertising procedure, aiming to find opportunities to connect with the slaves. Then, the connection establishment procedure aims to construct a link between the master and each slave. Should the master or slave wish to switch roles, they can initiate the optional role-switch procedure. Finally, the emergent sensor s_i^{emt} can adopt an adaptive hopping sequence procedure to modify its hopping sequence for improved communication quality.

3) *Connection Interval Reduction Phase*: In this phase, the emergent sensor aims to reduce the connection interval to

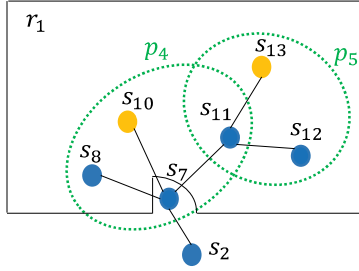
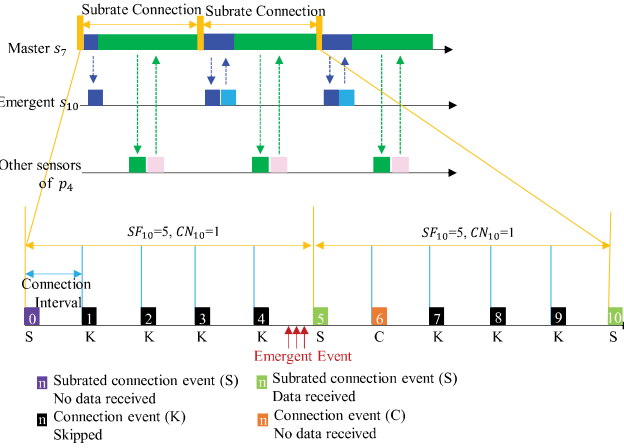
Fig. 4. The example of a tree topology in a room r_1 .

Fig. 5. An example of a subrated connection.

improve packet transmission latency for the link connecting s_i^{emt} and s_i^{best} . In case of an emergent event, the emergent sensor $s_i^{emt} \in S^{emt}$ must immediately forward the emergent packets to gateway G . On the contrary, if no emergent event occurs, the emergent sensor should also function as a general sensor. That is, it remains in a normal state, regularly forwarding sensing packets to gateway G , aiming to conserve energy. Therefore, emergent sensors should use a long connection interval for sending general sensing packets to conserve energy and switch to a short connection interval immediately when transmitting emergent packets during emergent events. However, changing the connection interval parameters of an existing connection is a time-consuming process. To accelerate this process, this paper adopts a subrated connection scheme, aiming to conserve energy and quickly switch to a short connection interval.

Let CI_i^o and CI_i^s denote the original and subrated connection intervals of the emergent sensor s_i^{emt} , respectively. Let SF_i and CN_i denote the subrated factor and continuation number, respectively. The value of CI_i^s can be calculated using Eq. (24).

$$CI_i^s = CI_i^o / SF_i. \quad (24)$$

The connection interval will be significantly shortened using a subrated connection. As a result, using a subrated connection can reduce the waiting time required to change from a long connection interval to a short connection interval.

As shown in Fig. 4, there is a tree topology in the room r_1 . The scatternet consists of two piconets, p_4 and p_5 . Sensors s_7 and s_{11} play the master roles in piconets p_4 and p_5 , respectively. Consider the emergent sensor $s_i^{emt} = s_{10}$. Fig. 5

illustrates an example of a subrated connection for piconet p_4 . Assume that the original interval $CI_{10}^o = 5$ slots. Assume that the subrated factor SF_{10} is 5, and the continuation number CN_{10} is 1. This implies that the subrated connection interval CI_{10}^s for the emergent sensor s_{10} is

$$CI_{10}^s = 5/5 = 1 \text{ slot.}$$

When no emergent event occurs, the emergent sensor s_{10} usually transmits a packet to the master s_7 every five slots, skipping the other four connections. However, if an emergent event occurs before the 5th slot, the emergent packet is transmitted by the emergent sensor s_{10} in the 5th slot. Since the continuation number CN_{10} is 1, sensor s_{10} can continuously transmit an emergent packet in the 6th slot. As shown in Fig. 5, since the sensor s_{10} has transmitted the emergent packet in the slot 5th, it has no packet left in the buffer. Therefore, the sequence of continuation ends at the 6th slot. The 7th, 8th, and 9th connections are skipped. These connection events will be repeatedly executed.

B. 1st Layer of IEET: Constructing a Mesh Topology

The purpose of this section is to construct a mesh topology, aiming to avoid traffic congestion for sensors closer to the gateway. In the mesh topology, there are multiple connections from the sensors to the gateway, aiming to reduce contentions and improve the reliability of packet transmission.

Let C_i denote the count of descendants for the sensor s_i . Let λ_c denote the upper bound of descendant counts. This means that, at most λ_c nodes are allowed to share the common link to the gateway. In the mesh topology, each sensor compares C_i and λ_c . If $C_i > \lambda_c$, sensor s_i notifies its slave s_j with the maximum C_j to establish additional links to avoid contention. Let ψ_j denote the number of new links that need to be established. The value of ψ_j can be calculated by Eq. (25).

$$\psi_j = \left\lceil \frac{C_i}{\lambda_c} \right\rceil - 1 \quad (25)$$

The new links can be constructed by applying the operations given in Eqs. (17) to (22). The best forwarder can be chosen from the neighboring sensors $N_j \setminus \{s_i\}$. Finally, the selected forwarders should update their counts of descendants.

As shown in Fig. 6 (a), sensor s_2 has 9 descendants. That is, C_2 is 9. Assume that the value of λ_c is 6, sensor s_2 will notify s_7 , which has the maximum number of descendants, to establish a new link as derived from Eq. (25). The forwarder selection can apply the operations given in Eqs. (17) to (22) and select s_{25} as the best forwarder. Then, the new link can be established between s_7 and s_{25} as shown as Fig. 6(b). Finally, the forwarders s_1 , s_2 , s_3 , s_7 and s_{25} update their descendants' counts.

Following these processes of constructing tree and mesh topologies, the constructed topologies of the proposed IEET are shown in Fig. 7. The proposed IEET constructs two-layer topologies, where the first layer is a mesh within the area surrounded by the red dotted circle to alleviate the phenomena of contentions and collisions. The second layer is a tree within the area surrounded by the blue dotted circle to allocate a dedicated path for each emergent sensor.

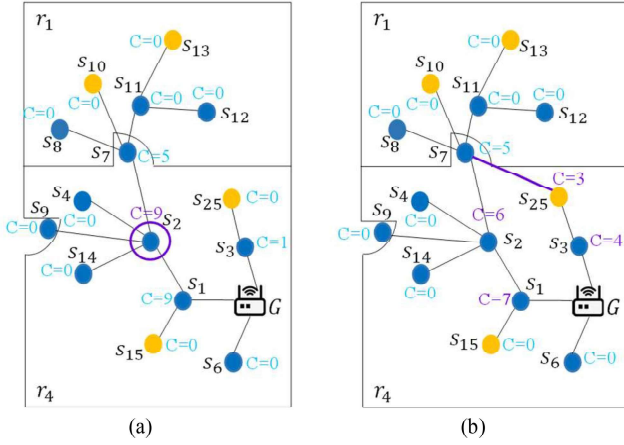


Fig. 6. The process of constructing mesh topology with $\lambda_c = 6$.

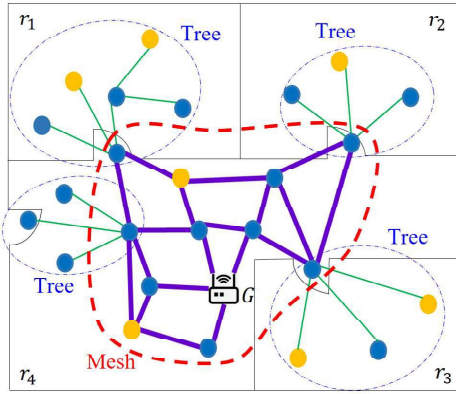


Fig. 7. The constructed topology of the proposed IEET.

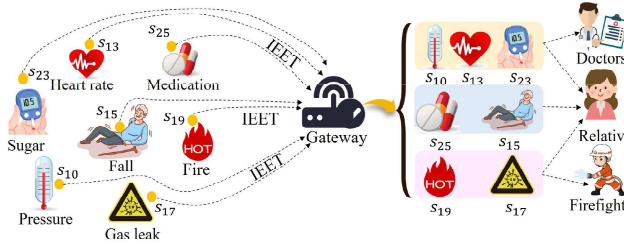


Fig. 8. Integrated emergency response system in elderly homes using IEET mechanism.

As shown in Fig. 8, various emergency sensors are located at different positions in the home environment of the elderly. For instance, emergency sensors s_{10} , s_{13} , s_{15} , s_{17} , s_{19} , s_{23} and s_{25} are utilized for monitoring the sugar, blood pressure, heart rhythm, falls, gas, fire, and medication intake of the elderly, respectively. Whenever any of these sensors detect abnormal data, the gateway receives the sensor data through the proposed IEET mechanism and identifies the specific type of emergency event based on the sensor ID, such as falls, fire alarms, or other medical emergencies. These messages automatically initiate specific responsive measures, including triggering alarm bells, shutting off the gas, or notifying relevant doctors, family members, or firefighters. This ensures the safety of elderly individuals at home.

C. Complexity Analysis

The proposed IEET mainly consists of constructing tree and mesh topologies. The following provides analyses of the time and space complexities.

1) *Time Complexity Analysis*: The tree topology consists of three phases, including emergent path construction, channel reassignment, and connection interval reduction. The emergent path constructing phase aims to select the optimal forwarder. For each emergency sensor $s_i^{emt} \in S^{emt}$, the proposed IEET needs to traverse all neighboring sensors and calculate the connection quality. In the worst case, the time complexity of this phase is $O(b \times (n - 1))$, where b denotes the number of emergency sensors, and n denotes the number of sensors in the network. The time complexity of the channel reassignment phase depends on the number of emergent paths and channels. The number of channels is a constant. The time complexity of this phase is $O(b)$. Additionally, the connection interval reduction phase requires adjusting the connection interval for each emergency sensor. The time complexity of this phase is $O(b)$. Synthesizing the analysis above, during the process of establishing a tree topology, the total time complexity for each emergency sensor node is

$$O(b \times (n - 1)) + O(b) + O(b) = O(b \times n).$$

For a tree topology averaging k branches, there are a total of n levels. Therefore, in the path from an emergency sensor node to the gateway, the above procedure will execute $\log_k n$ times. Consequently, the round-trip time complexity from an emergency sensor node to the gateway and back is $O(b \times n \times \log_k n)$.

The mesh topology requires dispersing the traffic from sensors to the gateway. The time complexity of this phase is $O(n^2)$ in the worst case. In summary, the overall time complexity of the proposed IEET is $(O(b \times n) + O(b \times n \times \log_k n))$. Since the value of b is always less than n , the total time complexity for tree and mesh topologies is $O(n^2)$. Herein, it is emphasized that such time is only spent during the network construction process. Once the network is established, in the process of serving the elderly, each emergency sensor only needs to transmit from itself to the gateway. Therefore, during the service period, its time complexity is $O(\log_k n)$.

2) *Space Complexity Analysis*: The space complexity is primarily influenced by the number of sensors in the network and the number of neighbors for each sensor. The worst space complexity is $O(n \times (n - 1))$.

V. PERFORMANCE EVALUATION

This section focuses on evaluating the performance improvement of the proposed IEET approach in comparison to the Tree-based topology, existing LBMMRE-AOMDV (Load Balancing Maximal Minimal nodal Residual Energy Ad hoc On-demand Multipath Distance Vector) [36], and JECF (Joint Energy Conservation and collision avoidance for Path construction) [18]. The Tree-based topology is responsible for constructing the scatternet. However, it did not differentiate between emergency and general sensors, overlooking critical aspects such as selecting optimal forwarders and channels

TABLE II
SIMULATION PARAMETERS

Parameters	Values
Simulator	MATLAB Bluetooth Toolbox
Initial battery	120mAh
Voltage	1.5V
Packet size	20bytes
Transmit Power	0dBm
Communication radius	10m

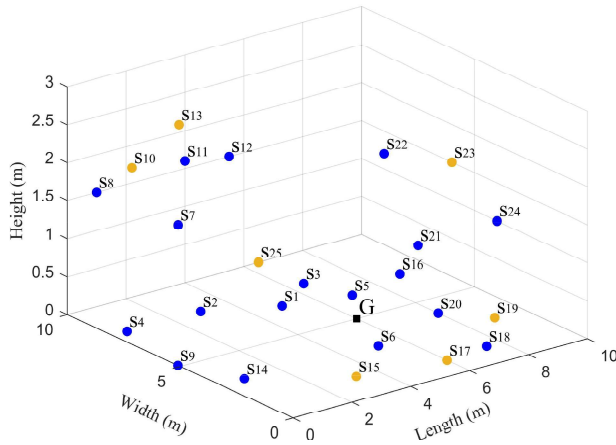


Fig. 9. The simulated network environment.

to prevent collisions. The LBMMRE-AOMDV constructed a mesh network using hop count and residual energy as the routing criteria. However, deploying all sensors in the mesh topology could lead to packet flooding problems, resulting in increased energy consumption for packet forwarding and collisions. The JECPC constructed disjoint paths to avoid collisions for emergency sensors deployed in the same room. It established emergency paths, optimizing the sharing of general sensors to conserve energy for emergency sensors deployed in different rooms. However, it did not address the issue of traffic congestion, which commonly occurred at sensors near the gateway. The proposed IEET combines both tree and mesh topologies, leveraging the strengths of both approaches. The following section presents the simulation environment and the corresponding results.

A. Simulation Environment

Table II provides an overview of the simulation parameters used in this paper. The simulator uses MATLAB Bluetooth Toolbox. Each sensor has an initial battery of 120 mAh, a voltage of 1.5V, and sends a packet of 20 bytes. The transmission power is set at 0dBm, and the communication radius is set at 10 meters. Additionally, Figure 9 shows the simulated network environment. There are 25 sensors and a gateway G deployed in an elderly home environment. Both the gateway and all sensors are equipped with BLE components. Emergency and general sensors are marked in yellow and blue, respectively.

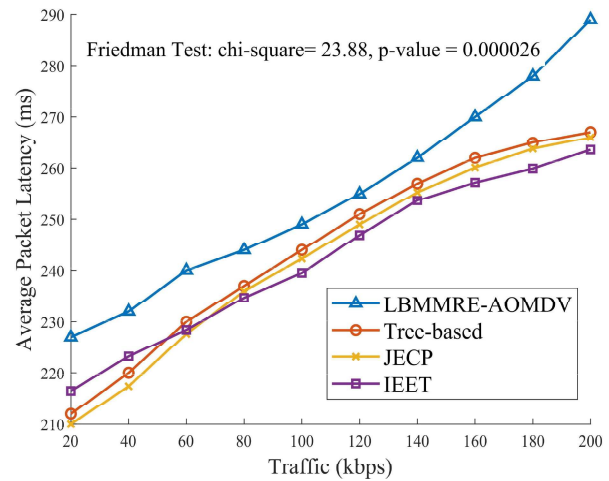


Fig. 10. Comparison of LBMMRE-AOMDV, Tree-based, JECPC, and IEET in terms of the average packet latency.

TABLE III
THE AVERAGE TIME OF STATES FOR EMERGENCY SENSOR s_{10}

Method	Transmission(s)	Idle(s)	Listening(s)	Sleeping(s)
Tree	0.2503	0.3129	0.5238	3.913
Mesh	0.2047	4.7653	0.03	0
IEET	0.1862	0.2328	0.0636	4.5174

B. Simulation Results

Figure 10 aims to compare LBMMRE-AOMDV, Tree-based, JECPC, and the proposed IEET in terms of the average packet latency from the emergency sensor s_{10} to the gateway G by varying traffic levels ranging from 20 to 200 kbps. In general, all curves show a trend where the average packet latency increases with traffic. This occurs because collisions and contentions increase with traffic, consequently extending the transmission time. In particular, the average packet latency of JECPC is lower than that of Tree-based, LBMMRE-AOMDV, and IEET at low traffic levels. However, as traffic increases, packet collisions also increase, resulting in higher average packet latencies for the Tree-based topology at high traffic levels. The proposed IEET outperforms LBMMRE-AOMDV, Tree-based, and JECPC mechanisms in most cases. The main reason is that the proposed IEET constructs a mesh topology, allowing sensors closer to the gateway to disperse traffic flow and reduce collisions. As a result, the average packet latency can be shortened.

As shown in Fig. 10, to further highlight the differences between the proposed IEET mechanism and other mechanisms, statistical analysis using the Friedman test is incorporated into the simulation analysis. To ensure the reliability and significance of the statistical results, our experiment was conducted 100 times. The simulation results show a p-value of 0.000026, which is significantly below the threshold of 0.05, indicating that the proposed IEET mechanism significantly outperforms the other mechanisms in terms of average packet latency.

Table III compares the proposed IEET with the Tree and Mesh topologies in terms of the average time spent in

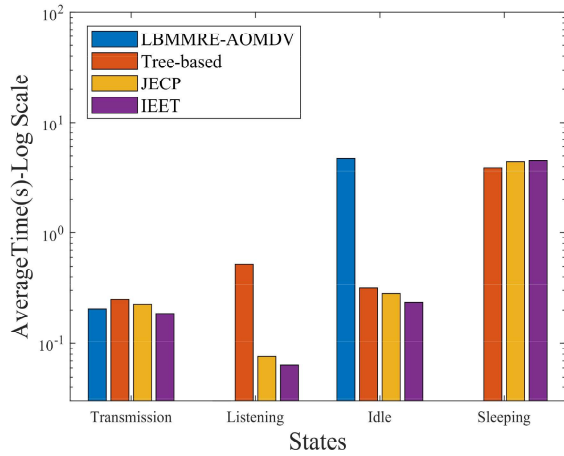


Fig. 11. Comparison of LBMRE-AOMDV, Tree-based, JEC, and IEET in terms of average time spent in four states for emergency sensor s_{10} .

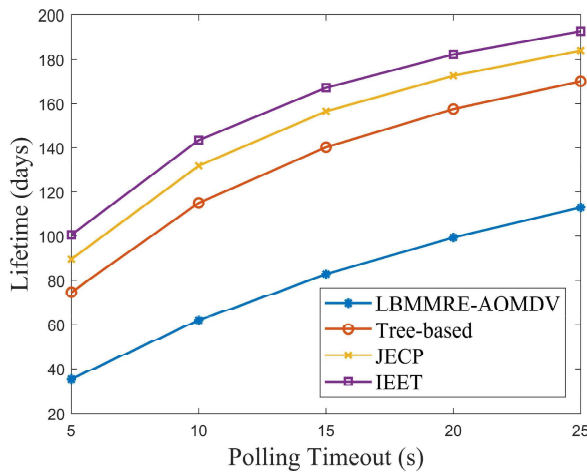


Fig. 12. Comparison of LBMRE-AOMDV, Tree-based, JEC, and IEET in terms of the lifetime of emergency sensor s_{10} by varying polling timeout.

transmission, listening, idle, and sleeping states for the emergency sensor s_{10} . The simulation duration is 5 seconds, and the throughput is maintained at 25 kbps. It is observed that the proposed IEET effectively reduces the transmission, idle, listening, and sleeping times compared to the tree and mesh topologies. The reason is that the proposed IEET integrates both tree and mesh topologies and adopts a subrated connection, aiming to reduce transmission waiting time.

Figure 11 compares LBMRE-AOMDV, Tree-based, JEC, and the proposed IEET in terms of the average time spent in transmission, listening, idle, and sleeping states for the emergency sensor s_{10} . The proposed IEET outperforms the LBMRE-AOMDV, Tree-based, and JEC mechanisms in all states. LBMRE-AOMDV spends much time in idle states. The proposed IEET adopts a subrated connection scheme, which quickly switches to a short connection interval, aiming to reduce transmission time compared with the Tree-based and JEC. The proposed IEET integrates both tree and mesh topologies, thereby effectively reducing the time spent listening and idle, which can increase sleeping time and save energy consumption.

Figure 12 compares the LBMRE-AOMDV, Tree-based, JEC, and the proposed IEET in terms of the lifetime of

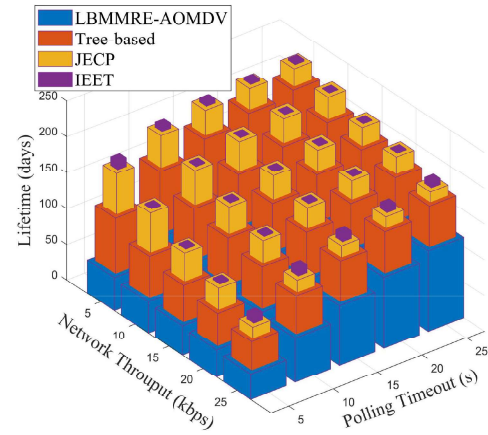


Fig. 13. Comparison of LBMRE-AOMDV, Tree-based, JEC, and IEET in terms of the lifetime by varying polling timeout and network throughput.

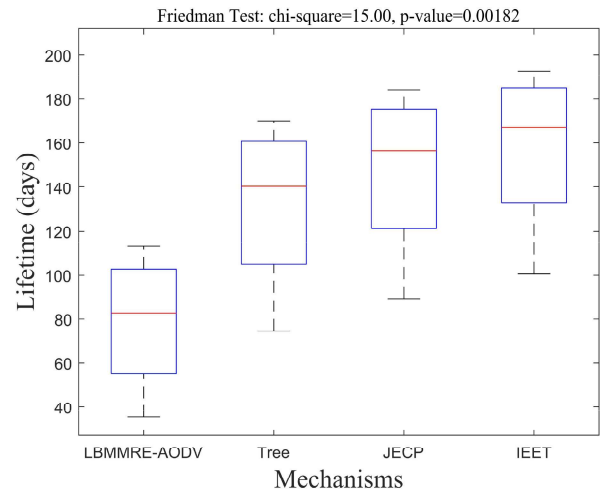


Fig. 14. Comparative analysis of the lifetimes of various mechanisms using the Friedman test.

emergency sensor s_{10} by varying polling timeouts ranging from 5s to 25s. The lifetime increases with the polling timeout. Figure 13 further compares LBMRE-AOMDV, Tree-based, JEC, and the proposed IEET in terms of lifetime by varying polling timeout and network throughput. The poll timeout varies from 5s to 25s and the network throughput is varied ranging from 5 kbps to 25 kbps. In general, the lifetimes of all curves decrease with increased network throughput. However, the proposed IEET outperforms the LBMRE-AOMDV, Tree-based, and JEC mechanisms in all cases. The main reason is that the proposed IEET constructs tree and mesh topologies. In the tree topology, the proposed IEET uses a long connection interval for sending general sensing packets to save energy. Moreover, the proposed IEET constructs a mesh topology for sensors closer to the gateway, aiming to disperse the traffic flow, balance energy consumption, and reduce collisions. As a result, energy consumption can be saved, and the lifetime of each sensor is extended.

Figure 14 shows the results of the Friedman test, which compares the lifetimes of different mechanisms, specifically LBMRE-AODV, Tree, JEC, and the proposed IEET. The box plots indicate significant differences in the lifetime

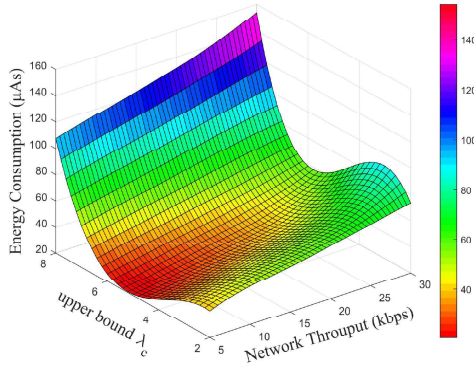


Fig. 15. The Energy consumption by varying upper bound λ_c and network throughput.

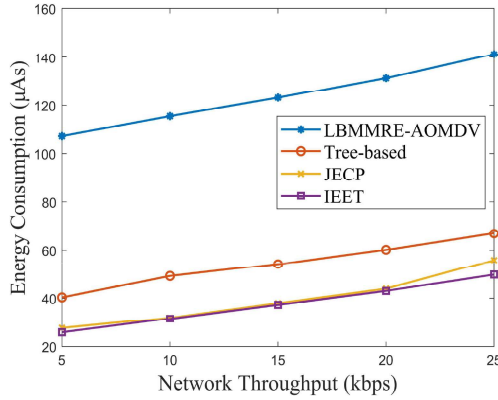


Fig. 16. Comparison of LBMRE-AOMDV, Tree-based, JEC, and IEET in terms of Energy consumption by varying network throughput.

distributions among the mechanisms. The proposed IEET demonstrates a higher median and a more stable lifetime distribution, while the lifetime of the LBMRE-AODV mechanism is relatively lower. The results of the Friedman test (chi-square value of 15.00, p-value of 0.00182) confirm that these differences are statistically significant, further validating the superior performance of the proposed IEET in enhancing network lifetime compared to other mechanisms.

Figure 15 further compares the energy consumption by varying the upper bound λ_c of descendants' counts. The value of λ_c ranges from 2 to 8. Network throughput varies from 5 kbps to 30 kbps. A common trend observed is that the value of λ_c affects energy consumption. Determining the value of λ_c is very important. A small value of λ_c tends to construct a mesh topology, while a large value of λ_c tends to construct a tree topology.

Figure 16 compares LBMRE-AOMDV, Tree-based, JEC, and the proposed IEET in terms of the energy consumption of the emergency sensor s_{10} by varying the network throughput. The network throughput varies from 5 kbps to 25 kbps. Energy consumption refers to the average energy required to send a single packet from s_{10} over a duration t_d , which can be calculated using Eq. (26).

$$E = \frac{(I_{TX} * t_{TX} + I_L * t_L + I_{Idle} * t_{Idle} + I_s * t_s)}{t_d * n_{packets}}. \quad (26)$$

where E denotes the energy consumption, and $n_{packets}$ denotes the number of packets by s_{10} in duration t_d . The notations I_{TX} , I_L , I_{Idle} and I_s denote the currents of transmission, listening, idle, and sleeping, respectively. The notations t_{TX} , t_L , t_{Idle} and t_s denote the times of transmission, listening, idle, and sleeping, respectively, within the duration t_d . That is

$$t_d = t_{TX} + t_L + t_{Idle} + t_s. \quad (27)$$

As shown in Fig. 16, energy consumption increases with network throughput. The energy consumption of the proposed IEET is less than that of LBMRE-AOMDV, Tree-based, and JEC mechanisms in all cases. The reason is that the proposed IEET adopts a subrated connection in the tree topology. It utilizes long intervals for general sensing packets, leading to energy savings. On the contrary, it dynamically switches to shorter intervals swiftly for emergency sensing packets, aiming to reduce switching time. On the other hand, the proposed IEET can choose an appropriate upper-bound λ_c to construct a mesh topology for those sensors closer to the gateway, thereby minimizing collisions and retransmissions. As a result, energy consumption can be saved.

VI. CONCLUSION

This paper proposes a topology control mechanism, called IEET, for BLE networks. The proposed IEET mechanism aims to minimize transmission delays when forwarding emergency events and to conserve energy consumption during the forwarding of general information. Initially, it constructs a tree topology to reduce transmission delays. Additionally, it adopts a subrated connection scheme to adjust the connection intervals for emergency sensors within the tree topology, aiming to further decrease transmission delays. Then, the proposed IEET constructs a mesh topology for sensors near the gateway if these sensors reach the upper bound of descendants' counts. This mesh topology helps alleviate collision and contention phenomena. Simulation results demonstrate that the proposed IEET outperforms existing mechanisms in terms of average packet latency, network lifetime, and energy consumption.

For future research, as the sensors and Bluetooth devices considered in this study are fixed, future studies will explore wearable devices for the elderly, such as smartwatches, bracelets, wristbands, shoes, etc. These devices also have Bluetooth communication capabilities and can monitor the elderly's activities, postures, and physiological states in real time. This includes tracking blood oxygen levels, heart rates, behavioral trajectories, and activities such as step count, falls, and sleep patterns. These data are crucial for ensuring the safety and health of the elderly. However, due to the mobility of the elderly, their Bluetooth devices may dynamically leave or join the network, posing challenges to maintaining the tree and mesh topologies and constructing paths as discussed in this paper.

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