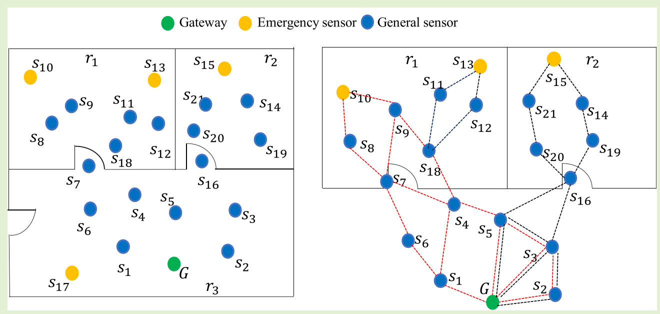
JECP: Joint Energy Conservation and Collision Avoidance for Path Construction in Bluetooth Networks

Xuan Li, Qiaoyun Zhang, Chih-Yung Chang, *Member, IEEE*, Shin-Jer Yang, and Diptendu Sinha Roy

***Abstract*—With the growing elderly population of the world, the number of elderly people who live alone is continuously growing. Providing them with high-quality healthcare has become a major concern nowadays. In order to detect the elderly people's sudden danger of living alone, this article proposes a path construction mechanism, called JECP, which aims to conserve energy and avoid collision for the emergent sensors in Bluetooth mesh networks. In case that the emergent sensors are deployed in the same room, the proposed JECP constructs disjoint paths to avoid collisions, which are triggered by the same emergent event at the same time. The other case is that the emergent sensors are deployed in different rooms. The probability that these emergent sensors are triggered by the same event is very small. Hence, the proposed JECP constructs the best emergent path that shares the general sensors as much as possible to save energy consumption. The experimental results show that the proposed JECP outperforms the existing mechanisms in terms of transmission delay and energy consumption for the emergent sensors in Bluetooth low-energy (BLE) networks.**



***Index Terms*— Bluetooth, collision avoidance, emergency, energy conservation.**

I. Introduction

WITH the development of science and technology, especially the advancement of medicine, the rate of population death is decreasing year by year. The elderly population comprises the fastest growing in the world population. In addition, the young population has declined gradually with delayed and non-marriage. Nowadays, "aging" is often regarded as an important and one of the most difficult problems in modern society, which must be solved immediately, and has caused social and economic problems with insufficient medical resources.

The number of elderly people who live alone is continuously growing. Providing them with quality healthcare has become a major concern nowadays. The elderly people are susceptible to sudden emergent events, such as sudden falling that may lead to death, gas leakage in the kitchen, wire fire in the living room, and incomplete combustion of the water heater in the bathroom. To provide special care for elderly people living alone, the smart monitoring system should collect important information through various sensors with wireless communication [1]. Therefore, it is urgent to establish a wireless network that can help the emergent sensors transmit the information to the gateway in case of emergency.

Several wireless communication technologies can be applied in the home environment, such as Bluetooth, ZigBee, and WiFi [2], [3]. In particular, Bluetooth is famous for its low power consumption [4]. In the past, Bluetooth could only support one-to-many or one-to-one transmissions. Recently, the Bluetooth Special Interest Group presented Bluetooth Mesh [5], which allowed devices to communicate in a mesh network. In addition, the established Bluetooth networks were more power-saving than the other transmission technologies.

Manuscript received 11 December 2022; revised 14 March 2023; accepted 14 March 2023. Date of publication 28 March 2023; date of current version 1 May 2023. This work was supported in part by the Research Project of Chuzhou University under Grant 2022XJYB05, in part by the Natural Science Foundation of Anhui Province under Grant 2108085QF266, and in part by the Anhui Outstanding Youth Fund Project under Grant 2022AH030109. The associate editor coordinating the review of this article and approving it for publication was Prof. Jari Nurmi. *(Corresponding author: Chih-Yung Chang.)*

Xuan Li is with the Purple Mountain Laboratories, Nanjing 210000, China (e-mail: lixuan1986@vip.qq.com).

Qiaoyun Zhang is with the Department of Computer Science and Information Engineering, Tamkang University, New Taipei 25137, Taiwan, and also with the School of Computer and Information Engineering, Chuzhou University, Chuzhou 239000, China (e-mail: zqyun1986@126.com).

Chih-Yung Chang is with the Department of Computer Science and Information Engineering, Tamkang University, New Taipei 25137, Taiwan (e-mail: cychang@mail.tku.edu.tw).

Shin-Jer Yang is with the Department of Computer Science and Information Management, Soochow University, Taipei 11102, Taiwan (e-mail: cssjyang@scu.edu.tw).

Diptendu Sinha Roy is with the Department of Computer Science and Engineering, National Institute of Technology, Shillong 793003, India (e-mail: diptendu.sr@nitm.ac.in).

Digital Object Identifier 10.1109/JSEN.2023.3258416

In literature, most studies [6], [7], [8], [9], [10], [11], [12] concerned on energy conservation and collision avoidance for Bluetooth mesh networks. Study [7] used the flooding method for transmitting packets in Bluetooth mesh networks, which might cause problems such as excessive burden on other nodes in the network and increased energy consumption. However, constructing the emergent paths was attracted little attention. In past research on emergencies, the studies [13], [14] established a Bluetooth network through mobile phones or relays for disaster relief communication. However, they were not suitable for the elderly living environment.

This article proposes a JECP mechanism for Bluetooth path construction. The proposed JECP can achieve energy conservation and collision avoidance for emergency transmission. For those messages which are not emergent, they can be delivered to the gateway in a manner of energy conservation. On the other hand, the emergent messages can be successfully transmitted to the gateway, without collision occurrence. This guarantees that the emergent events of the elderly people can be handled immediately. The main contributions of this article are summarized as follows.

A. Establishing a Bluetooth Mesh Network

The proposed JECP constructs emergency networks based on Bluetooth sensors to support end-to-end communication in case of emergency.

B. Avoiding Packet Collision

The proposed JECP constructs the disjoint paths to avoid collision for the emergent sensors deployed in the same room, aiming to reduce the number of retransmissions and improve the success rate of packet transmission.

C. Conserving Energy for General Sensors

The proposed JECP arranges more sensors to stay in sleep mode when the emergent sensors are deployed in different rooms. The paths constructed from all source emergent sensors to the gateway should be shared as many as possible, aiming to minimize the number of working sensors and further improve the lifetime of the Bluetooth network.

The rest of this article is organized as follows. Section II reviews the related work. Section III presents the network environment and problem formulation. Section IV gives detailed descriptions of the proposed JECP algorithm. Section V investigates the performance evaluation. Finally, Section VI gives the conclusion.

II. Related Work

In the literature, many studies have been proposed for Bluetooth networks. They can be divided into two categories: energy conservation and collision avoidance.

Study [7] proposed a balanced flooding protocol for mesh networks over Bluetooth low energy (BLE), aiming to save battery lifetime and to increase the lifetime of the network. However, the mechanism might increase the total energy consumption of the BLE networks.

In addition to the issue of energy consumption, the real-time packet transmission is the other important issue which might impact the delivery ratio of the emergent events. Study [8] proposed a multi-hop real-time BLE (MRT-BLE) protocol, developed on top of BLE, that allowed for bounded packet delays over mesh networks. This protocol adopted time-division multiple-access approaches that exploited a transmission allocation scheme able to support the timely exchange of multi-hop real-time data packets. Patti et al. [9] proposed a BLE-based real-time multi-hop protocol, with bounded message delays to overcome this limitation. They tried to address the problem of transmission overlaps to support real-time communication. The proposed protocol was capable of bounded latencies but lacked coordinated transmission scheduling to avoid collisions.

Guo et al. [10] proposed an on-demand scatternet formation and multi-hop routing protocol for BLE-based wireless sensor networks. The source node sent a route request message to the master. The master found the destination based on the breadth-first search. Upon receiving all possible routing paths, an originator selected the shortest path. However, the proposed protocol always took a long time to search for the shortest path, and it might lead to collision occurrence, since all packets passed through the shortest path. For emergent events, the delay of message delivery is much more important than the path length.

Study [11] proposed a technique of spreading Status over time to reduce the delay time of message delivery due to collisions and to improve the reliability of receiving confirmation messages in a Bluetooth mesh network. Study [12] proposed a scheme called anti-collision voting based on BLE. It alleviated the exponential growth of advertising collisions and achieved efficient consensus between the devices and humans by localized message advertising. However, these studies did not put forward any suggestions for emergencies.

Study [13] proposed an emergency detection system with security-enhanced support. The BLE communication technology was used to connect sensor nodes and mobile relays. After sending medical data to the cloud server, the relay node was responsible for emergency detection and alert generation. However, it did not take into consideration the energy conservation issue. In case the emergent sensors were deployed in different rooms, the paths of these sensors might be shared to reduce energy consumption, since these sensors would not be triggered at the same time. Study [14] proposed the Bluetooth Mesh emergency network, which could quickly establish a Bluetooth mesh network by mobile phones for emergency disaster communication. However, this research only relied on mobile devices to establish a mesh network, which was not suitable for the elderly in their living environment.

III. Network Environment and Problem Formulation

This section introduces the network environment, problem description, and objectives.

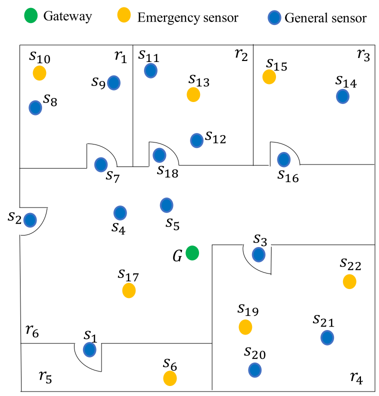


Fig. 1. Scenario of the considered network.

A. Network Environment

This article considers the home environment where an elder lives alone. Many sensors have been deployed for collecting the action data of the elder and detecting emergent events such as the elder falling, a gas leak, or fire accidents. Let $R = \{r_1, r_2, \ldots, r_m\}$ denote the considered space, which consists of m rooms r_i $(1 \le i \le m)$. Let $S = \{s_1, \ldots, s_n\} \cup \{\mathrm{G}\}$ be the $n + 1$ Bluetooth sensors randomly deployed in R. Depending on the hardware functions and capabilities, the Bluetooth sensors are further divided into three roles: gateway sensor, emergency sensors, and general sensors. The gateway sensor, denoted by G, mainly plays the role of an access point to the Internet, which connects to the Internet via Wi-Fi or 5G technology. It is responsible for forwarding the received data to the Internet. Without the loss of generality, assume that there is one gateway denoted by G in each home environment. The n sensors are further divided into two sets, $S = S^{\text{emt}} \cup S^{\text{gel}}$. The emergent sensor set $S^{\text{emt}} = \{s_1^{\text{emt}}, \ldots, s_a^{\text{emt}}\}$ consists of a sensors. Each sensor in S^{emt} is embedded with some sensing components and can detect the emergent event and then create an emergency message in a very short time. It is usually deployed in the kitchen, toilet, or other places where emergent accidents are likely easy to happen. The general sensor set $S^{\text{gel}} = \{s_1^{\text{gel}}, \ldots, s_b^{\text{gel}}\}$ consists of b general sensors each of which can communicate with the other sensors via Bluetooth. The general sensors are mainly responsible for collecting environmental information or elder's action regularly.

Fig. 1 gives an example of the considered Bluetooth network. There are six rooms $R = \{r_1, r_2, \ldots, r_6\}$. The Bluetooth sensors are randomly deployed in R. The gateway sensor, emergency sensors, and general sensors are marked with green, yellow, and blue colors, respectively.

Due to the energy limit of sensor nodes, the sensor needs to stay sleeping to save energy. In a nonintrusive elderly homecare monitoring system, if all the sensors stay sleeping, they cannot deliver the emergency message immediately to the gateway once an emergency service occurs. The corresponding emergency service will be delayed causing danger to the elderly.

B. Problem Description

Let δ_{ij} be a Boolean variable that represents whether or not the Bluetooth sensor s_i is deployed in the room r_j. That is

$$\delta_{ij} = \begin{cases} 1, & \text{if } s_i \in r_j \\ 0, & \text{if } s_i \notin r_j. \end{cases} \tag{1}$$

Let ε_i be a Boolean variable that denotes whether or not s_i is an emergency sensor. Equation (2) defines the value of ε_i

$$\varepsilon_i = \begin{cases} 1, & \text{if } s_i \in S^{\text{emt}} \\ 0, & \text{if } s_i \in S^{\text{gel}}. \end{cases} \tag{2}$$

To support homecare services, the communication services of Bluetooth sensor networks are further divided into emergent communication type and data collection type. In case the source sensor is $s_i^{\text{emt}} \in S^{\text{emt}}$, the emergent message should be transmitted to G in a multi-hop manner. Then, an emergent routing path should be constructed which aims to forward the emergent message of s_i^{emt} to gateway G. On the contrary, if the source sensor is $s_i^{\text{gel}} \in S^{\text{gel}}$, the purpose of s_i^{gel} is to collect environmental information. Therefore, an energy-efficient path for forwarding the message of s_i^{gel} should be constructed.

Let p_i denote the emergency path from the emergency sensors s_i^{emt} to the gateway G. Let O_{ij} denote the common sensor set of paths p_i and p_j. The O_{ij} can be derived by the following:

$$O_{ij} = \left\{ s_x | s_x \in \left(p_i \cap p_j \right) \right\}. \tag{3}$$

It is noticed that the source emergent sensors, say s_x^{emt} and s_y^{emt}, might be deployed in the same or different rooms. In case that s_x^{emt} and s_y^{emt} are deployed in the same room, they are easy to be triggered at the same time if an emergent event occurs. For example, when there is a fire event occurred in the kitchen, several emergent sensors such as carbon dioxide sensors and temperature sensors in the kitchen will be triggered. The triggered sensors will transmit emergency messages to the gateway at the same time. If the emergent paths have common sensors, a collision is easy to occur. Therefore, the corresponding emergent paths p_k^x and p_k^y (with source nodes s_x^{emt} and s_y^{emt}) in the same room should be disjoint. The following condition can be used to verify whether or not two emergent sensors s_x^{emt} and s_y^{emt} are deployed in the same room r_i.

$$\delta_{x,i} * \delta_{y,i} = 1. \tag{4}$$

1) Collision Avoidances Policy: In the same room, the paths constructed for all source emergent sensors $s_x^{\text{emt}} \in S^{\text{emt}}$ should not have common sensors. This policy aims to avoid collision.

On the other hand, assume that two emergent sensors s_x^{emt} and s_y^{emt} are deployed in different rooms. The probability that two emergent events occurred at the same time in different rooms is very small. The two sensors would not be triggered at the same time. As a result, the corresponding two paths p_k^x and p_k^y where the source nodes are s_x^{emt} and s_y^{emt}, respectively, are not easy to occur collisions even if they share some common sensors. This indicates that the two paths p_k^x and p_k^y can share some common sensor nodes. In addition, minimizing the number of working sensors can maximize the number of sensors staying in the power-saving mode, achieving the purpose of energy consumption. Therefore, when constructing the routing paths p_k^x and p_k^y for emergent sensors s_x^{emt} and s_y^{emt}, respectively, the policy includes as many as possible common sensors. The following condition can be applied to check whether or not the two emergent sensors s_x^{emt} and s_y^{emt} are deployed in different rooms r_i and r_j, respectively:

$$\delta_{x,i} * \delta_{y,i} = 0. \quad (5)$$

2) Energy Conservation Policy: In different rooms, the paths constructed for all source emergent sensors $s_x^{\text{emt}} \in S^{\text{emt}}$ should share as many as possible common sensors to be the working sensors. This policy helps save energy consumption by arranging more sensors to stay in sleep mode.

C. Problem Objectives

The article aims to propose a topology construction protocol for a Bluetooth home network that supports an emergency path for each emergency sensor to deliver its emergent message to the home gateway. This section initially presents the objective function of this article. Then, it proposes several constraints that should be satisfied when developing the topology construction protocol.

Recall that m denotes the number of rooms in considered space R. Let n_{xy} denote the number of common sensors in O_{xy}. Equation (6) gives the objective function for constructing the network topology for all emergency sensors $s_x^{\text{emt}} \in S^{\text{emt}}$ according to *Collision Avoidances Policy*.

Objective function 1:

$$\min \left(\sum_{i=1}^{m} \sum_{\substack{s_x^{\text{emt}}, s_y^{\text{emt}} \in S^{\text{emt}} \\ x \neq y}} n_{xy} \right) \text{ where } \delta_{x,i} * \delta_{y,i} = 1. \quad (6)$$

Herein, it is noticed that $\delta_{x,i} * \delta_{y,i} = 1$ indicates that the Bluetooth sensors s_x and s_y are deployed in the same room r_i. This article aims to minimize the number of common sensors for all source emergency sensors in the same room. Equation (6) reflects this goal.

Equation (7) gives the second objective function for all emergency sensors $s_x^{\text{emt}} \in S^{\text{emt}}$ in different rooms according to *Energy Conservation Policy*.

Objective function 2:

$$\max \left(\sum_{i=1}^{m} \sum_{\substack{s_x^{\text{emt}}, s_y^{\text{emt}} \in S^{\text{emt}} \\ x \neq y}} n_{xy} \right) \text{ where } \delta_{x,i} * \delta_{y,i} = 0. \quad (7)$$

The condition $\delta_{x,i} * \delta_{y,i} = 0$ implies that Bluetooth sensors s_x and s_y are deployed in different rooms. This article aims to maximize the number of common sensors for all source emergency sensors in different rooms.

When obtaining the best solution, some constraints given in the following must be satisfied. Let t_x represent the xth time slot in cycle T. Let Boolean variables $\beta_{s_i,x}^{\text{sen}}$, $\beta_{s_i,x}^{\text{slp}}$, and $\beta_{s_i,x}^{\text{com}}$ represent whether the sensor s_i stays in sensing, sleeping, or communication states in t_x, respectively. That is

$$\beta_{s_i,x}^{\text{sen}} = \begin{cases} 1, & s_i \text{ stays in a sensing state in } t_x \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

$$\beta_{s_i,x}^{\text{slp}} = \begin{cases} 1, & s_i \text{ stays in sleeping state in } t_x \\ 0, & \text{otherwise} \end{cases} \quad (9)$$

$$\beta_{s_i,x}^{\text{com}} = \begin{cases} 1, & s_i \text{ stays in communication state in } t_x \\ 0, & \text{otherwise.} \end{cases} \quad (10)$$

The following *state constraint* ensures that the sensor can stay in one of sensing, sleeping, and communication states at any given time slot.

1) State Constraint:

$$\beta_{s_i,x}^{\text{sen}} + \beta_{s_i,x}^{\text{slp}} + \beta_{s_i,x}^{\text{com}} = 1. \quad (11)$$

In addition to the state constraint, another constraint, called the *energy constraint*, makes sure that the energy of each sensor should be less than or equal to its total energy in any time slot t_x. Let ρ_i^{dischg} denote the energy discharging rate of each sensor $s_i \in S$. Let E_i denote the total energy of the sensor s_i.

2) Energy Constraint:

$$\sum_{t_x \in T} \rho_i^{\text{dischg}} * \beta_{s_i,x}^{\text{sen}} \leq E_i - \varepsilon, \quad \forall s_i S \quad (12)$$

where ε denotes the reserved energy for basic operation including state switch and status control.

The third constraint, called *Connectivity Constraint*, makes sure that the path should be connected from each sensor to the gateway. Let $P_i = \{p_{i,j} | p_{i,j} = (s_i, \hat{s}_1, \ldots, G)\}$ denote all possible paths from $s_i \in S$ to the gateway G, where $p_{i,j}$ denotes jth path from s_i to G. The connectivity constraint further makes sure that there is at least one path for all sensors.

3) Connectivity Constraint:

$$\prod_{t_x \in T} \prod_{\hat{s}_i \in p_{i,j}} \beta_{\hat{s}_i,x}^{\text{sen}} = 1, \exists p_{i,j} \in P_i. \quad (13)$$

To provide safe care in a nonintrusive elderly homecare monitoring system, every room should have at least one emergency sensor. The following *safe constraint* makes sure that the number of emergency sensors n_i in each room r_i must be more than or equal to 1.

4) Safe Constraint:

$$n_i \geq 1, \quad \forall r_i \in R. \quad (14)$$

IV. Joint Energy Conservation and Collision Avoidance for Path Construction

This article aims to propose a topology construction protocol for a Bluetooth home network that supports an emergency path for each emergency sensor to deliver its emergent message to the gateway. The proposed JECP considers two policies: *collision avoidances policy* and *energy* *conservation policy*. The *collision avoidances policy* is mainly applied when constructing the path for those emergent sensors deployed in the same room. It indicates that the paths constructed for all source emergent sensors in the same room should be disjoint to avoid the collision. On the other hand, the *energy conservation policy* is mainly adopted in a situation where the emergent sensors are deployed in different rooms. In this case, the paths constructed for all source emergent sensors should share as many as possible common sensors to save energy consumption. Through the proposed JECP, the whole Bluetooth network can quickly transmit emergent information without collision and achieve effective energy savings.

The proposed JECP contains three phases. The first phase is the *broadcasting phase*. In this phase, the gateway and all sensors broadcast their information to the surrounding and establish a temporary path to transmit the information required for the next phase. The second phase is the *role identification phase* which aims to identify the roles of emergent sensors. The final phase is the *topology construction phase*. This phase aims to establish a dedicated emergency path for each emergency sensor. The following presents the details of each phase.

A. Broadcasting Phase

Assume that each node knows its role, which may be a gateway, emergent, or general sensor. In this phase, the gateway will start broadcasting its information to the surrounding sensors. The received sensors will establish a temporary path connected to the sender (gateway), and continue to broadcast their information, including their IDs and roles accordingly. Upon receiving the broadcast message, each receiver will maintain a neighboring table that records the neighbor information including the signal strength of each sender and the sender ID. Then, the receiver will connect to the sender according to the received signal strength indicator (RSSI) value.

Fig. 2 gives an example of an elder's home that consists of three rooms. There are 21 sensors and a gateway randomly deployed in rooms r_1, r_2, and r_3. The node marked with green color denotes the gateway. The gateway initially broadcasts its role ID to sensors s_1, s_2, s_3, s_4, and s_5. Upon receiving the gateway message, the sensor s_1 creates a connection to G, and then broadcasts both its ID and role to sensors s_4, s_6, and s_{17}. On receiving the message from s_1, sensor s_6 connects to s_1 and then broadcasts both its ID and role to sensors s_7. All sensors will repeatedly execute the above-mentioned operations until they have connected to the neighbors who are closer to the gateway. As shown in Fig. 2, the sensor s_{10} establishes a temporary path that is marked with a red dotted arrow to gateway G.

B. Role Identification Phase

In this phase, the gateway identifies whether the role of each sensor is an emergent or general sensor. To achieve this, each sensor transmits its information to the gateway along the temporary paths established in *broadcasting phase*. The information contains the role of the sensor that is emergent or general, room information, forwarding probability, and traffic. This helps the gateway identify the role of each sensor. The room information of the emergency sensor aims to help the gateway know the room that the emergency message comes from. The forwarding probability represents the proportion of the sensor to the overall emergency paths, and the total forwarding probability of an emergency node is 1. The successful transmission opportunity of an emergent message from an emergency sensor to the gateway increases with the number of paths it connects to the gateway. Therefore, the forwarding probability of an emergency sensor can help the gateway construct the topology in the later phase. The traffic is the data amount passing through the sensor. The sensor with low traffic would be a better candidate to be selected as the node of the emergency path. These four parameters are mainly used for the third phase to construct the topology.

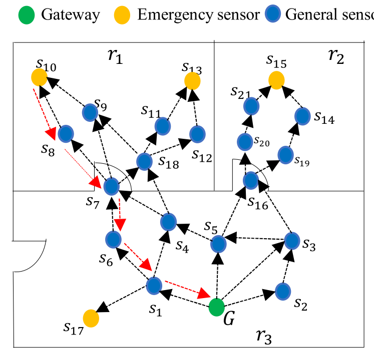


Fig. 2. Process of the broadcasting phase.

C. Topology Construction Phase

This phase aims to construct a Bluetooth topology for emergent sensors. The gateway will construct the emergency path for each emergency sensor when it receives the emergency information from that sensor. Two policies, including the *collision avoidances policy for emergency sensors* and the *energy conservation policy for general sensors*, are proposed in this phase. The details of the two policies are presented in the following.

Let $C^i_{n_i * n_i}$ denote a 2-D *forwarding matrix* of the sensor s_i, where n_i denotes the number of nodes passed from the sensor s_i to the gateway G. Let c_{xy} denote the forwarding condition (FC) in short, which represents whether or not the Bluetooth sensors s_x and s_y are neighboring and sensor s_x might forward its packet to s_y. That is

$$c_{xy} = \begin{cases} 1, & \text{FC is satisfied} \\ 0, & \text{othewise} \end{cases} \quad (x \neq y). \tag{15}$$

Fig. 2 gives an example of the forwarding matrix of sensor s_{10}. There are ten nodes, including $s_8, s_9, s_{18}, s_7, s_6, s_4, s_1, s_5, s_3$, and s_2, which might be the internal nodes of paths starting from the sensor s_{10} to the gateway G. The forwarding matrix C^{10}_{12*12} of sensor s_{10} can be shown in the

TABLE I
FORWARDING PROBABILITY OF THE SENSORS

G	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{18}
1	$\frac{11}{16}$	$\frac{5}{64}$	$\frac{5}{32}$	$\frac{5}{8}$	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$

following:

$$C^{10}_{12*12} = \begin{pmatrix} & S_{10} & S_8 & S_9 & S_{18} & S_7 & S_6 & S_4 & S_1 & S_5 & S_3 & S_2 & G \\ S_{10} & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S_8 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S_9 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{18} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ S_7 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ S_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ S_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ S_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ S_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ S_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ S_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ G & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}. \quad (16)$$

Let $W^i_{n_i*n_i}$ denote a 2-D forwarding probability matrix from the sensor s_i to the gateway G. Assume that the total forwarding probability from each emergent sensor is 1. Let ω_{xy} denote the element in xth row and yth column of $W^i_{n_i*n_i}$. It represents the forwarding probability from the sensor s_x to the sensor s_y. The value of ω_{xy} can be calculated by the sum of forwarding probabilities from all other sensors within one step to s_x dividing the number of sensors from s_x to the other sensors. It can be derived as follows:

$$\omega_{xy} = \begin{cases} \dfrac{\sum_{z=0}^{n_i} c_{zx}}{\sum_{y=0}^{n_i} c_{xy}}, & x = i \\ \dfrac{\sum_{z=0}^{n_i} (c_{zx} * \omega_{zx})}{\sum_{y=0}^{n_i} c_{xy}}, & \text{othewise} \end{cases} \quad (x \neq y). \quad (17)$$

Let ω^i_j denote the probability of sending data from s_i to the gateway G and passing through s_j. The value of ω^i_j can be calculated by the sum of forwarding probabilities from all other sensors within one step to s_j. It can be derived as follows:

$$\omega^i_j = \sum_{k=0}^{n} {}_i\, \omega_{kj} \; (i \neq j). \quad (18)$$

According to (17), W^{10}_{12*12} can be derived as follows (19), shown at the bottom of the next page.

According to (18), the probability of sending data from s_{10} to the gateway G passing through each sensor can be calculated as shown in Table I.

The gateway will start to plan the emergency path for each emergency sensor when it receives the emergency information from all emergency sensors.

Case 1: Collision Avoidances Policy for Emergency Sensors

This policy aims to avoid packet collision when there is more than one emergency sensors deployed in the same room. The paths constructed from all source emergent sensors to the gateway should be disjoint. To prevent the emergent paths in the same room from collision, the gateway will compare the four parameters, including the emergent sensor name, room information, forwarding probability, and traffic.

First, the policy chooses the shortest paths from the emergency sensor to the gateway G. Then, gateway G calculates the quality of all the shortest paths.

Recall that $P_i = \{p_{i,j} | p_{i,j} = (s_i, \hat{s}_1, \ldots, G)\}$ denotes all possible paths from $s_i \in S$ to the gateway G. Let ρ_j denote the number of sensors passed by the shortest path $p_{i,j}$. Let η_k denote the number of emergency paths passing through s_k. Let $\eta_{\min}$ and $\eta_{\max}$ denote the minimum and maximum numbers of emergency paths passing through s_k, respectively. Let e_k denote the emergency path ratio of the sensor s_k. The value of e_k can be derived as follows:

$$e_k = \frac{\eta_k - \eta_{\min}}{\eta_{\max} - \eta_{\min}}. \quad (20)$$

Let f_k denote the traffic flow of the sensor s_k. Let $f_{\max}$ and $f_{\min}$ denote the maximum and minimum flows in S. Let ξ_k denote the flow ratio contributed by the sensor s_k. The value of ξ_k can be derived as follows:

$$\xi_k = \frac{f_k - f_{\min}}{f_{\max} - f_{\min}}. \quad (21)$$

Let ϑ_k be the signal strength of the sensor s_k. Let $\vartheta_{\min}$ and $\vartheta_{\max}$ denote the minimal and maximal signal strengths, respectively. Let ϵ_k denote the signal strength ratio of the sensor s_k. The value of ϵ_k can be calculated as follows:

$$\epsilon_k = \frac{\vartheta_k - \vartheta_{\min}}{\vartheta_{\max} - \vartheta_{\min}}. \quad (22)$$

Let $Q_{i,j}$ denote the quality of the jth path for the emergency node $s^{emt}_i \in S^{emt}$ to the gateway G. The value of $Q_{i,j}$ will be the bottleneck of the sensor node passed in the path. Equation (23) depicts the calculation of $Q_{i,j}$

$$Q_{i,j} = \min_{1 \leq j \leq P_J} \frac{\omega^i_j \epsilon_j}{\xi_j e_j} \left(\rho_j > 0\right). \quad (23)$$

Finally, gateway G chooses the best emergency path that has the maximum quality to cope with the packet collision problem. Let p^{best}_i denote the best emergency path from $s_i \in S$ to the gateway G. It can be derived as follows:

$$p^{\text{best}}_i = \arg\max_{\forall\, j} Q_{i,j}. \quad (24)$$

As shown in Fig. 3, there are two emergent sensors s_{10} and s_{13} in the same room r_1. The red dotted lines represent all possible paths from the emergency sensors s_{10} to the gateway G, while the black dotted lines represent all possible paths from the emergency sensors s_{13} to the gateway G. It is obvious that the red and black paths are partially overlapped. Since sensors s_{10} and s_{13} are deployed in the same room, they might be triggered by the same event and hence need to transmit the emergent information to the gateway simultaneously. If the emergent paths have common sensors, a collision will have occurred. Therefore, the emergent paths of different sensors in the same room should be disjoint.

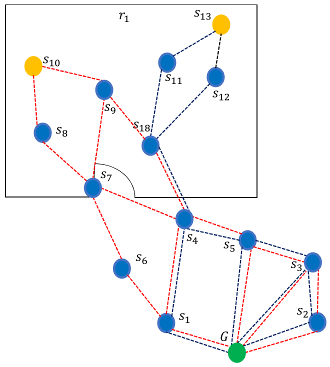


Fig. 3. Emergency sensors are deployed in the same room.

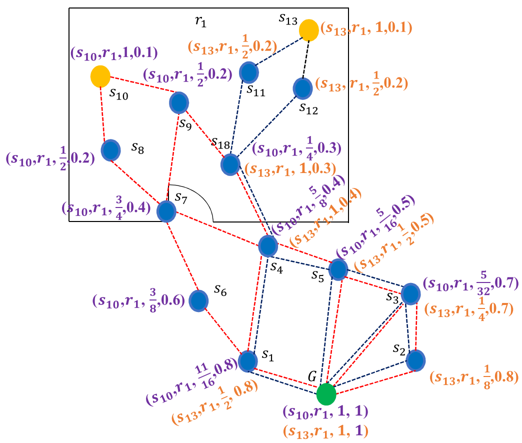


Fig. 4. Execution of the proposed *collision avoidances policy*.

Fig. 4 gives an example of the execution of the proposed *collision avoidances policy*. As mentioned in the *role identification phase*, the values of four important parameters have been already collected by the gateway. The purple and orange parameter values are sent from the emergency sensors s_{10} and s_{13} to the gateway G, respectively. The gateway G will choose the best emergency path from all possible paths for the emergency sensors s_{10} and s_{13} according to (23) and (24). For instance, there are eight paths from the emergency sensor s_{10} to the gateway G. Since P_{10} denotes the set of all possible paths from the sensor s_{10} to the gateway, which is sorted in the order of path length. That is

$$P_{10} = \left\{ \begin{array}{c} (s_{10}, s_8, s_7, s_6, s_1, G), \\ (s_{10}, s_9, s_7, s_6, s_1, G), \\ (s_{10}, s_9, s_{18}, s_4, s_1, G), \\ (s_{10}, s_9, s_{18}, s_4, s_5, G), \\ (s_{10}, s_8, s_7, s_4, s_5, G), \\ (s_{10}, s_9, s_7, s_4, s_5, G), \\ (s_{10}, s_9, s_{18}, s_4, s_5, s_3, G), \\ (s_{10}, s_9, s_{18}, s_4, s_5, s_3, s_2, G) \end{array} \right\}.$$

First, the gateway G chooses the first six paths from the six possible paths in P_{10} because they are the shortest paths. Then, $Q_{10,j}$ can be calculated as shown in Table II, according to (23).

Finally, the gateway G chooses the best emergency path p_{10}^{best} that has the maximum quality

$$p_{10}^{\text{best}} = \arg \max_{\forall j} Q_{10,j} = \arg Q_{10,1} = \{s_{10}, s_8, s_7, s_6, s_1, G.\}$$

Case 2: Energy Conservation Policy for General Sensors

This case is different from case 1, since it considers the situation that emergency sensors are deployed in different rooms. In this situation, the probability that two emergency sensors are triggered at the same time is small. Therefore, the

$$W_{12*12}^{10} = \left(\begin{array}{ccccccccccccc} & S_{10} & S_8 & S_9 & S_{18} & S_7 & S_6 & S_4 & S_1 & S_5 & S_3 & S_2 & G \\ S_{10} & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S_8 & 0 & 0 & 0 & 0 & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S_9 & 0 & 0 & 0 & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{18} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{4} & 0 & 0 & 0 & 0 & 0 \\ S_7 & 0 & 0 & 0 & 0 & 0 & \frac{3}{8} & \frac{3}{8} & 0 & 0 & 0 & 0 & 0 \\ S_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{3}{8} & 0 & 0 & 0 & 0 \\ S_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{5}{16} & \frac{5}{16} & 0 & 0 & 0 \\ S_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{11}{16} \\ S_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{5}{32} & 0 & \frac{5}{32} \\ S_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{5}{64} & \frac{5}{64} \\ S_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{5}{64} \\ G & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right). \quad (19)$$

TABLE II
VALUES OF $Q_{10,j}$ WITH COLLISION AVOIDANCES POLICY

$Q_{10,1}$	$Q_{10,2}$	$Q_{10,3}$	$Q_{10,4}$	$Q_{10,5}$	$Q_{10,6}$
5.12	4.18	3.91	3.64	4.92	3.98

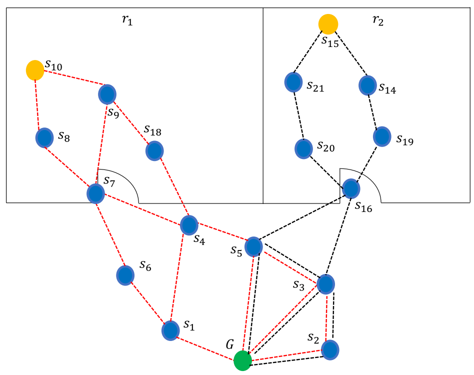


Fig. 5. Emergency sensors are deployed in the different rooms.

major goal for constructing the paths is energy conservation, which aims to arrange more sensors to stay in sleep mode. To achieve this goal, the paths constructed from all source emergent sensors (from different rooms) to the gateway should be shared as many as possible common sensors. This can minimize the number of working sensors.

First, the shortest paths will be considered from the emergency sensor to the gateway G. This policy reduces the number of working sensors in the paths. Then, gateway G calculates the quality of all the shortest paths. The value of $Q_{i,j}$ can be derived as follows:

$$Q_{i,j} = \min_{1\leq j\leq P_J} \frac{\omega_j^i \epsilon_j e_j}{\xi_j} \left(\rho_j > 0\right). \tag{25}$$

The best path p_i^{best} can be derived as follows:

$$p_i^{\text{best}} = \arg\max_{\forall\ j} Q_{i,j}. \tag{26}$$

As shown in Fig. 5, there are two emergent sensors s_{10} and s_{15} in rooms r_1 and r_2, respectively. The red and black dotted lines represent all possible paths from the emergency sensors s_{10} and s_{15} to the gateway G, respectively. The red and black paths are partially overlapped. Since sensors s_{10} and s_{15} are deployed in different rooms, the probability that they are triggered by the same event is very small. If the emergent paths have common sensors, the energy consumption of the awake sensors will be saved. Therefore, the emergent paths of sensors in the different rooms should be shared as many as possible.

Fig. 6 gives an example of the execution of the proposed *energy conservation policy*. The purple and orange parameter values were sent from the emergency sensors s_{10} and s_{15} to the gateway G, respectively. Then, the gateway G chooses the best emergency path from all possible paths in P_{10} for the emergency sensor s_{10} according to (25) and (26). The values of $Q_{10,j}$ can be calculated as shown in Table III, according to (25).

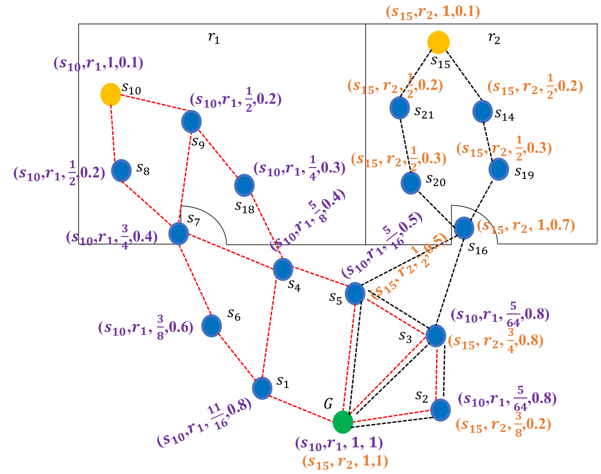


Fig. 6. Execution of the proposed *energy conservation policy*.

TABLE III
VALUES OF $Q_{10,j}$ WITH ENERGY CONSERVATION POLICY

$Q_{10,1}$	$Q_{10,2}$	$Q_{10,3}$	$Q_{10,4}$	$Q_{10,5}$	$Q_{10,6}$
5.55	4.61	5.33	5.1	5.78	4.84

Finally, the gateway G chooses and constructs the best emergency path p_{10}^{best} that has the maximum quality

$$p_{10}^{\text{best}} = \arg\max_{\forall\ j} Q_{10,j} = \arg Q_{10,5} = \{s_{10}, s_8, s_7, s_4, s_5, G\}.$$

V. PERFORMANCE EVALUATION

This section evaluates the performance improvement of the proposed JECP against the existing and MRT-BLE [8] and Load balancing maximal–minimal nodal residual energy *ad hoc* on-demand multipath distance vector (LBMMRE-AOMDV) [15]. The existing MRT-BLE adopted the time-division multiple-access approaches to support the timely exchange of multi-hop real-time data packets for improving the throughput and collision. The LBMMRE-AODMV constructs a mesh network using hop count and residual energy as the routing criterion, without considering other factors such as nodes roles. The following gives the simulation of the environment and results.

A. Simulation Environment

The monitoring region of the experiment is shown in Fig. 7. There are 21 sensors deployed in three rooms. The gateway sensor, emergency sensors, and general sensors are marked with green, yellow, and blue colors, respectively. Table IV lists the simulation parameters of this experiment. The simulator uses MATLAB. The packet size is set at 20 bytes. The initial battery of the sensors is 1000 units. The energy consumption of packet transmission and reception are 1.5 units and 1.0 unit, respectively. The maximum network throughput is 0.3 Mb/s. The communication radius is 10 m.

B. Simulation Results

Fig. 8 aims to compare the quality of all different paths $\{p_1, p_2, \ldots, p_8\}$ from the emergent sensor s_{10} to the gateway G.

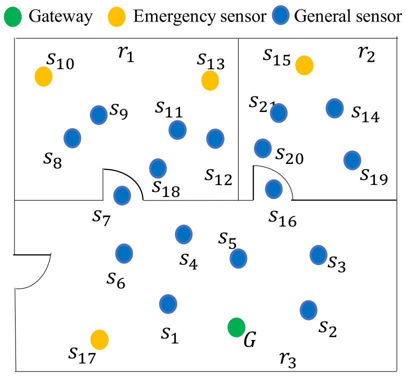


Fig. 7. Monitoring region of the experiment.

TABLE IV
SIMULATION PARAMETERS

Parameters	Values
Simulator	MATLAB
Packet size	20bytes
Initial battery	500mAh
Energy consumption of packet transmission	2.5 mW
Energy consumption of packet reception	1 mW
Maximum network throughput	0.3Mbps
Communication radius	10m

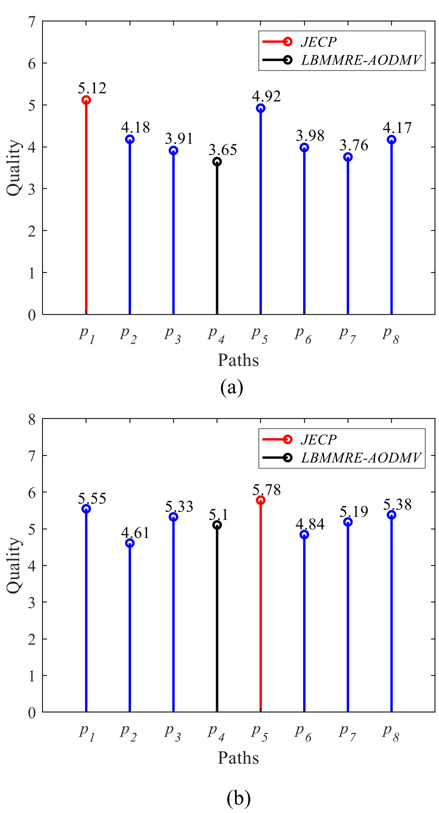


Fig. 8. Quality of all different paths from the emergent sensor s_{10} to the gateway *G*. (a) Same room. (b) Different rooms.

Fig. 8(a) and (b) considers the sensors deployed in the same room and different room, respectively. As shown in Fig. 8, the LBMMRE-AODMV mechanism always chooses the path p_4

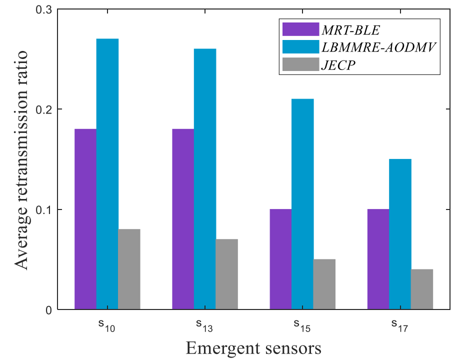


Fig. 9. Comparison of MRT-BLE, LBMMRE-AODMV, and JECP in terms of the average retransmission ratio from the emergent sensors to the gateway.

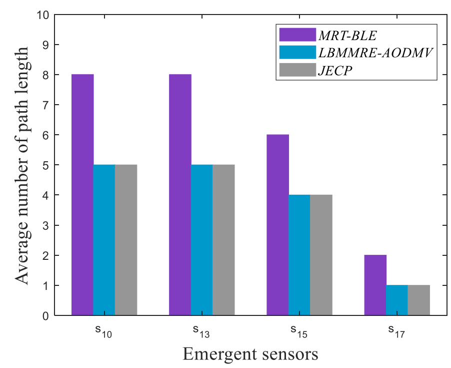


Fig. 10. Comparison of MRT-BLE, LBMMRE-AODMV, and JECP in terms of path length from the emergent sensors to the gateway.

which is the shortest path and achieves larger residual energy. However, it might not achieve the best quality, as compared with the proposed JECP.

As shown in Fig. 8(a), the different paths are constructed, and their qualities are calculated by applying (23) when the emergent sensors s_{10} and s_{13} are deployed in the same room. Path p_1 that has the maximum quality is chosen as the best emergency path. This occurs because the sensors contained in the path p_1 have a higher forwarding probability, lower traffic flow, and fewer common sensors. As a result, it can avoid the emergent sensors triggered by the same event at the same time. As shown in Fig. 8(b), the different paths are constructed, and their qualities are calculated by applying (25) when the emergent sensors s_{10} and s_{15} are deployed in different rooms. The path p_5 that has the maximum quality is chosen as the best emergency path. This is because the sensors contained in path p_5 have a higher forwarding probability and lower traffic flow and share more general sensors. As a result, the probability that they are triggered by the same event is very small. For the purpose of energy conservation, the path should be shared with the sensors as much as possible to save energy.

Figs. 9 and 10 compare the MRT-BLE, LBMMRE-AODMV, and the proposed JECP in terms of the average retransmission ratio and the path length from the emergent sensors s_{10}, s_{13}, s_{15}, and s_{17} to the gateway G, respectively. The same simulation environment with the same source and destination nodes is used, and the result is obtained from the

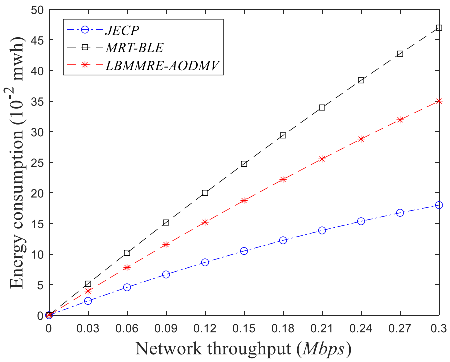


Fig. 11. Comparison of JECP, MRT-BLE, and LBMMRE-AODMV in terms of the average energy consumption of all emergent sensors.

average of results of 100 repeated experiments. The MRT-BLE transmits the data by choosing different time schedules to avoid the collision. The proposed JECP outperforms the MRT-BLE and LBMMRE-AODMV mechanisms. The main reason is that sensors s_{10} and s_{13} are deployed in the same room, and the proposed JECP constructs disjoint paths for them to avoid the occurrences of collision. As a result, the proposed JECP reduces the number of retransmissions and hence requires a smaller number of time slots for packet transmission.

Fig. 11 aims to compare MRT-BLE, LBMMRE-AODMV, and the proposed JECP in terms of the average energy consumption of all emergent sensors. The network throughput varies ranging from 0 to 0.3 Mb/s. As shown in Fig. 10, the proposed JECP outperforms the MRT-BLE and LBMMRE-AODMV mechanisms in all cases. The main reason is that the proposed JECP constructs the shared path for those emergent sensors deployed in different rooms, aiming to reduce the number of awake sensors. This also reduces the number of sensors that participate in the packet forwarding. As a result, the average energy consumption can be saved.

Fig. 12(a) and (b) shows the transmission success ratio and the lifetime of the emergent sensor s_{10} by varying the transmission throughput ranging from 0 to 0.3 Mb/s, respectively. It is clearly observed that the transmission success ratio is decreased with the increase in transmission throughput. This occurs because the number of collisions is increased with the transmission throughput. The proposed JECP outperforms the MRT-BLE and LBMMRE-AODMV mechanisms. This occurs because the proposed JECP constructs the disjoint path for those emergent sensors that are deployed in the same room, aiming to reduce the occurrences of collisions. This helps improve the transmission success ratio. As shown in Fig. 12(b), the lifetime is also decreased with the network throughput. The reason is that the number of packet retransmissions is increased with the number of collisions. The energy consumption for packet retransmission can be saved for prolonging the lifetime.

Fig. 13 further investigates the impact of the transmission throughput on the lifetime of different emergent sensors. The network throughput varies from 0 to 0.3 Mb/s. All the compared mechanisms have the common trend that the lifetime

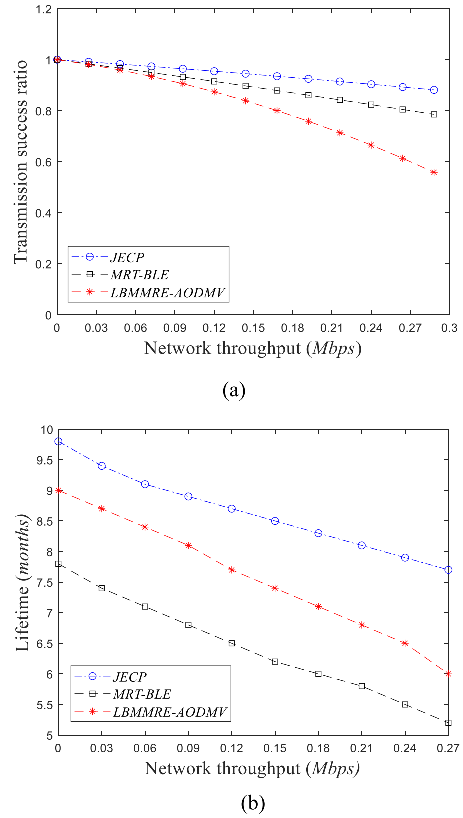


Fig. 12. Comparison of JECP, MRT-BLE, and LBMMRE-AODMV in terms of transmission success ratio and lifetime for the emergent sensor s_{10}. (a) Transmission success ratio. (b) Lifetime.

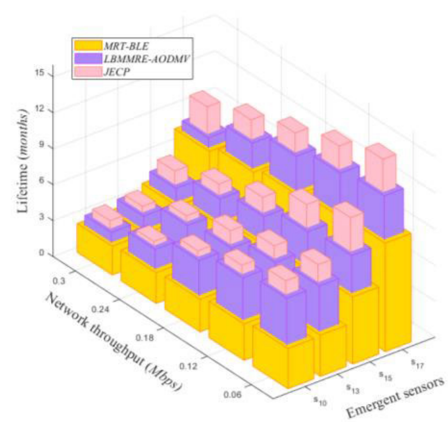


Fig. 13. Comparison of MRT-BLE, LBMMRE-AODMV, and JECP in terms of lifetime.

decreases with the network throughput. This occurs because the number of collisions is increased with the transmission throughput. The emergent sensors need to spend more energy to retransmit the packets. In comparison, the proposed JECP has the longest lifetime. The reason is that the proposed JECP reduces the number of awake sensors and the number of collision occurrences.

VI. Conclusion

This article proposes a path construction mechanism, called JECP, for Bluetooth mesh networks. The proposed JECP aims to conserve energy and avoid collision for the emergent sensors. Initially, it uses broadcasting to establish a temporary path, aiming to transmit the information for role identification for each sensor. Then, the proposed JECP establishes a dedicated emergency path for each emergency sensor. The disjoint paths are constructed to avoid collision for the emergent sensors deployed in the same room, because they can be easily simultaneously triggered by the same event. On the other hand, the proposed JECP constructs the best emergent path that shares the general sensors as much as possible to save energy consumption for the emergent sensors deployed in different rooms, which are triggered by the same event with a very small probability. The experimental results show that the proposed JECP outperforms the existing mechanisms. Future work will further consider the other variable parameters of emergency transmission problems in the Bluetooth network, which include different types of emergency events, different needs for emergency communication, and many more.

REFERENCES

[1] J. Wannenburg and R. Malekian, "Body sensor network for mobile health monitoring, a diagnosis and anticipating system," *IEEE Sensors J.*, vol. 15, no. 12, pp. 6839–6852, Dec. 2015.

[2] T. D. Mendes, R. Godina, E. M. Rodrigues, J. C. Matias, and J. P. Catalão, "Smart home communication technologies and applications: Wireless protocol assessment for home area network resources," *Energies*, vol. 8, no. 7, pp. 7279–7311, 2015.

[3] J. Lloret, A. Canovas, S. Sendra, and L. Parra, "A smart communication architecture for ambient assisted living," *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 26–33, Jan. 2015.

[4] J.-H. Chen, Y.-S. Chen, and Y.-L. Jiang, "Energy-efficient scheduling for multiple latency-sensitive Bluetooth low energy nodes," *IEEE Sensors J.*, vol. 18, no. 2, pp. 849–859, Jan. 2018.

[5] *Mesh Profile Specifications 1.0*, Bluetooth SIG, Kirkland, WA, USA, Jul. 2017.

[6] D. Hortelano et al., "Reducing the energy consumption of the friendship mechanism in Bluetooth mesh," *Comput. Netw.*, vol. 195, pp. 1–16, Aug. 2021.

[7] A. S. Brandao, M. C. Lima, C. J. B. Abbas, and L. J. G. Villalba, "An energy balanced flooding algorithm for a BLE mesh network," *IEEE Access*, vol. 8, pp. 97946–97958, 2020.

[8] L. Leonardi, G. Patti, and L. L. Bello, "Multi-hop real-time communications over Bluetooth low energy industrial wireless mesh networks," *IEEE Access*, vol. 6, pp. 26505–26519, 2018.

[9] G. Patti, L. Leonardi, and L. Lo Bello, "A Bluetooth low energy real-time protocol for industrial wireless mesh networks," in *Proc. IECON*, Florence, Italy, Oct. 2016, pp. 4627–4632.

[10] Z. Guo, I. G. Harris, L.-F. Tsaur, and X. Chen, "An on-demand scatternet formation and multi-hop routing protocol for BLE-based wireless sensor networks," in *Proc. WCNC*, New Orleans, LA, USA, Mar. 2015, pp. 1590–1595.

[11] P. Pierleoni, A. Gentili, M. Mercuri, A. Belli, R. Garello, and L. Palma, "Performance improvement on reception confirmation messages in Bluetooth mesh networks," *IEEE Internet Things J.*, vol. 9, no. 3, pp. 2056–2070, Feb. 2022.

[12] D. Han, L. Xu, R. Cao, H. Gao, and Y. Lu, "Anti-collision voting based on Bluetooth low energy improvement for the ultra-dense edge," *IEEE Access*, vol. 9, pp. 73271–73285, 2021.

[13] P. Shabisha et al., "Security enhanced emergency situation detection system for ambient assisted living," *IEEE Open J. Comput. Soc.*, vol. 2, pp. 241–259, 2021.

[14] F. Alvarez, L. Almon, H. Radtki, and M. Hollick, "Bluemergency: Mediating post-disaster communication systems using the Internet of Things and Bluetooth mesh," in *Proc. IEEE Global Humanitarian Technol. Conf. (GHTC)*, Seattle, WA, USA, Oct. 2019, pp. 17–20.

[15] S. A. Alghamdi, "Load balancing maximal minimal nodal residual energy ad hoc on-demand multipath distance vector routing protocol (LBMMRE-AOMDV)," *Wireless Netw.*, vol. 22, no. 4, pp. 1355–1363, May 2016.