Identifying Invalid Nodes in Bluetooth Mesh Networks by Using the Bayesian Probability Classification Algorithm and Time to Live

Ta-Te Lu
Department of Computer Science and Information Engineering
Chien Hsin University of Science and Technology
Taipei, ROC
ttlu@uch.edu.tw

Yi-Hsuan Li
Department of Computer Science and Information Engineering
Chien Hsin University of Science and Technology
Taipei, ROC
m10613004@gapps.uch.edu.tw

Bo-Yu Jheng
Department of Computer Science and Information Engineering
Chien Hsin University of Science and Technology
Taipei, ROC
m10713027@gapps.uch.edu.tw

***Abstract*—Bluetooth mesh networks improve existing star networks by overcoming the problem of network service unavailability during single-node failure and enabling transmission for multiple Bluetooth devices. The flooding method does not consider transmission paths and merely transmits messages using advertisement channels (Channels 37, 38, and 39) to all nodes within its range using random paths in Bluetooth mesh networks. Time to live (TTL) and the Bayesian probability classification algorithm calculated the probabilities of the paths to identify invalid nodes. Invalid nodes influence overall network transmission performance. This study examined transmission time in single-path and multipath topologies for each radio channel (37, 38, and 39) and invalid nodes in a Bluetooth mesh network. Their roles were adjusted to improve network performance. The experimental results showed that replacing invalid nodes decreased the average return time by 18% for the single-path topology. Similarly, for the multipath topology, the modification of invalid nodes reduced the average return time by 27%.**

Keywords—Bluetooth mesh network, flooding, invalid nodes, time to live

I. INTRODUCTION

Bluetooth is a wireless communication technology that features low cost and low power consumption. Bluetooth is generally suitable for short-distance transmission between two nodes, suitable only for small networks [1-3]. In June 2016, the Bluetooth Special Interest Group introduced Bluetooth 5, with increased Bluetooth transmission speed and distance (i.e., from 50 m to 300 m). In June 2017, the Bluetooth Special Interest Group officially announced supporting mesh network topology to extend the transmission distance.

Bluetooth low energy (BLE) transmission uses 2.4-GHz industrial, scientific, and medical (ISM) bands that require no authorization; its minimum and maximum spectrum frequencies are 2402 and 2480 MHz, respectively, and it contains 40 channels. Each BLE channel is 2-MHz wide [1–3]. The advertisement channels are channels 37, 38, and 39 in different ISM band regions (i.e., 2402, 2426, and 2480 MHz for Channels 37, 38, and 39, respectively) used for broadcasting in Bluetooth mesh networks [4].

The flooding method may lead to packet delays and packet losses because of the invalid nodes involved. Therefore, experiments with different topologies (i.e., single-path, multipath topologies) conduct to locate invalid nodes. Different topology (i.e., single-path, multipath topologies) tests were performed for Channels 37, 38, and 39 to assess their stability. Radio channels that sent messages and topology provisions were adjusted to locate invalid nodes. This study aimed to locate these invalid notes, and their paths were adjusted to improve performance.

This paper comprises five sections. Section I introduces the research background, motivation, objective, and the overall structure and direction of this study. Section II introduces the literature on Bluetooth mesh network technology. Section III describes the research methods employed in this study. Section IV presents an analysis and discussion of the experimental results, and Section V provides the study conclusion.

II. LITERATURE ON BLUETOOTH MESH NETWORK TECHNOLOGY

From bottom to top in Bluetooth system layers, the layers are the bearer layer, network layer, lower transport layer, upper transport layer, access layer, foundation model layer, and model layer. The bearer layer defines how nodes transmit network messages. Currently, there are two bearers: the advertising bearer (ADV bearer) and the generic attribute profile bearer (GATT bearer). For devices not connected within a network, messages are sent to the devices using the ADV bearer. For devices connected to a network, message types determine the receipt of the messages. Identical message types indicate the receipt of the messages, and the connected devices ignore the message indicating the messages to receive. Because the ADV bearer cannot connect devices from different networks, the GATT bearer sends messages between devices from different networks.

The GATT bearer utilizes the proxy protocol to transmit and receive protocol data units (PDUs). The network layer defines the address types and formats of network messages transmitted, and it offers relay and proxy features. Nodes that support relay send network PDUs using the ADV bearer, whereas those that offer proxy features send network PDUs using both ADV and GATT bearers. The lower transport layer breaks messages into different segments and reorganizes them. The upper transport layer encrypts, decrypts, and verifies data and defines how transmission control messages and friend features. The access layer uses data formats, controls the encryption and decryption processes performed by the upper transport layer, and verifies the received data before forwarding messages to the upper transport layer. The foundation model layer defines the states, messages, and models required to provision and manage mesh networks. The model layer defines the models used in standard user scenarios and operations in the specifications of the Bluetooth network model.

The nodes have four types in the Bluetooth mesh network topology. These node types are as follows: a. Low-power nodes: Low-power nodes must be used with friend nodes. These nodes are not responsible for transmitting messages. b. Relay nodes: Relay nodes receive messages and resend these messages through broadcasting or group broadcasting methods. Message caches are employed to decrease the number of identical messages received. The hop count can be as high as 127. c. Friend nodes: Friend nodes assist low-power nodes and send messages only when required. d. Proxy nodes: BLE devices send and receive messages using the GATT bearer, and they receive and forward mesh messages from/to the advertising bearer. Proxy nodes also offer proxy services.

Darroudi et al. [6] noted that star networks do not support communication between multiple surrounding devices in traditional Bluetooth, and their maximum transmission distances are limited. Vijay et al. [7] embedded BLE devices in cargos to extend mesh networks. The networks could be connected using programmable logic controllers to expand the network scope, offering IoT solutions for continuous monitoring and item tracking. Nikoukar et al. [8] investigated the received signal strength indicator (RSSI) values of BLE radio channels. They experimented in four environments with varying environmental interferences, environment sizes, obstacles, and reflectors. They used a log-distance path loss model to predict path signal losses in disrupted environments; the goal was to achieve accurate indoor positioning. Murillo et al. [9] measured and compared flooding- and connection-based Bluetooth network transmission methods and they measured items such as packet delivery ratio (PDR), terminal-to-terminal delays, and power consumed by devices. The results showed that flooding-based transmission could effectively reduce transmission time delays and the power consumed by devices during data transmission. Prasetyo et al. [10] proposed adjusting Bluetooth scanning and broadcasting times methods. They asserted that mesh networks improve the limitations of Bluetooth coverage because beacons can be used as relay nodes to transmit data, increasing the transmission distance and facilitating transmission to the target nodes. The Bluetooth Special Interest Group has introduced new technology to support mesh networks [2]. A unique characteristic of mesh networks is that the links between network nodes can be changed, whereas the links built fixed to use routing- or ring-based operations. Baert et al. [11] proposed Bluetooth mesh network standards and presented them in simulations, statistical analyses, and graphics, highlighting the existing problems of mesh networks. Lee [12] presented an energy detection-based method to achieve regular broadcasting.

III. Research Methods

A. Bayes' theorem

Bayes' theorem is to calculate the probability of the occurrence of a specific event, given that another event has occurred. Detailed descriptions are as follows.

The equation for calculating the odds of event A occurring given that event B has occurred is as follows:

$$\mathrm{P(A|B)} = \frac{P(A \cap B)}{P(B)} \quad (1)$$

The equation for calculating the odds of event B occurring given that event A has occurred is as follows:

$$\mathrm{P(B|A)} = \frac{P(A \cap B)}{P(A)} \quad (2)$$

If the odds of event B occurring is not zero, then the odds of event A occurring can be expressed as follows:

$$\mathrm{P(A|B)} = \frac{P(B|A)P(A)}{P(B)} \quad (3)$$

Bayes' theorem determines the least frequently used path out of all known paths; the identified path is an invalid node. Detailed descriptions are as follows in Section G.

B. Analyses of Radio Channel Characteristics

For analyses of radio channel characteristics, messages were transmitted 500 times to understand the RSSI transmission situations of Channels 37, 38, and 39 (Fig. 1). Each radio channel obtained the RSSI values, and the results showed that the average RRSI value differed between the radio channels. For instance, the average RRSI values of Channels 37, 38, and 39 were −54.3 ± 10.7, −53.6 ± 12.4, and −52.9 ±14.1 dBm, respectively.

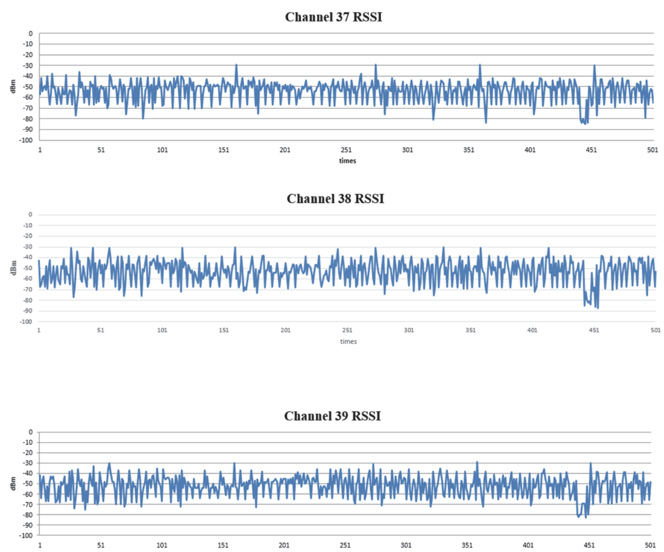


Fig. 1. RSSI values of Channels 37, 38, and 39

C. Effects of Invalid Nodes

The denser the node arrangement in mesh networks is, the higher the delivery ratio becomes. However, faster transmission rates also increase the probability of packet collisions, resulting in delays and losses [13-14]. In addition to the number of nodes, node provisioning can cause delays. For example, delays will occur if the nodes possess unfavorable relay abilities and are arranged in critical positions (Figs. 2 and 3).

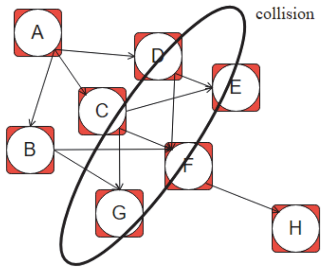


Fig. 2. Delays resulting from collisions

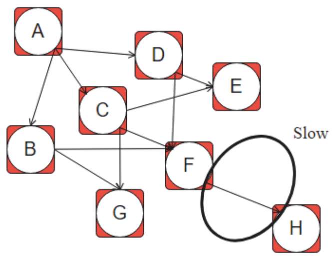


Fig. 3. Delays resulting from node problems

D. Determining the Return Time Using Timestamps

Timestamps are the basis for determining the transmission time. Because the timestamp of each node is asynchronous, the transmission nodes record the timestamps when they send messages. Similarly, the receiving nodes record the timestamps when they receive messages, where the transmission nodes return the timestamps. The transmission timestamp difference (R_t) and the return time (R_s) use Eq. (4) and Eq. (5):

$$R_t = T_r - T_s \quad (4)$$

$$R_s = \frac{R_t}{f_0} \quad (5)$$

T_r is the timestamp (returned to the transmission node) when the receiving node receives a message; T_s is the timestamp when the transmission node sends a message; f_0 is the default value (i.e., 32768 in this study) of the development board frequency.

E. Field Tests

For the field tests, experiments determine the effects of the experimental environments and antenna angles (0° and 90°), in which node locations switch and the antenna is placed horizontally (0°) and vertically (90°).

F. Calculating the Hop Count Using Time To Live

Time to live (TTL) is a method through which Bluetooth mesh networks control the number of relays. Users can also use this parameter to infer how many nodes are involved in transmitting data. The equation is as follows:

$$hop = InitTTL - RxTTL \quad (6)$$

Here, *InitTTL* is the initial value (10 in this study), whereas *RxTTL* is TTL recorded when receiving messages.

G. Parameters and Use of the Bayesian Probability Classification Algorithm

According to Bayes' theorem detailed in Section A, the Bayesian probability classification algorithm calculates the probability of an event occurring, given that another event has occurred. In this study, the return time (Section D) and the hop count (Section F) as the parameters used in the Bayesian probability classification algorithm. The return times determined the nodes at which the data arrived first. Through TTL, the node hop count was substituted into the Bayesian probability classification algorithm to calculate the probability of possible paths. TTL calculations identify and calculate all possible paths, as shown in Eq. (7)

$$P(n_i) = P(n_i)P(x_1|n_i) \quad (7)$$

Here, $P(n_i)$ is the probability of n_i, and x_1 is the return time of this path.

H. System Flowchart

First, one node sends messages and records the timestamps. Subsequently, the receiving node records the TTL of the messages and the return time. Next, the node records the timestamps of when the return messages are received (Section D). According to TTL, each node determines the hop count and path (Section F). The nodes determined the paths taken and the time spent on them based on their hop count and timestamps, respectively. Finally, the data were substituted into the Bayesian probability classification algorithm to calculate the path value (Section G).

IV. Experimental Results and Verification

In this study, the Bayesian probability classification algorithm was used to identify invalid nodes, and their roles were adjusted accordingly to increase overall performance. The experiment process had two parts. The first part involved entering the initial settings (mainly through a mobile app), and the second part entailed implementing the system procedure. Detailed information is provided below.

A. Process for Entering the Initial Settings

The internal settings of the provisioned nodes (e.g., app keys, subscription addresses, publication addresses, and model control operations) are set using the app, and the AppKey (32 bytes) and subscription addresses (range: 0xC000-0xFEFF) of the server. On the client, publication addresses (range: 0xC000-0xFEFF) are set in addition to AppKey and subscription addresses. In this study, the subscription and publication addresses were set to 0xC001.

B. The system procedure

In this experiment, timestamps were recorded twice: when a client transmitted a message and received the message from the server. In figure 4 (marked by the red box), the start_timer_cnt is 9937870; stop_timer_cnt is 9938655; Rt is 785 (Eq. (4)). Based on subsequent calculation, Rs = 785/32768 = 0.023 s. When nodes receive a message, they record the TTL of the message to determine how many nodes the message has passed.

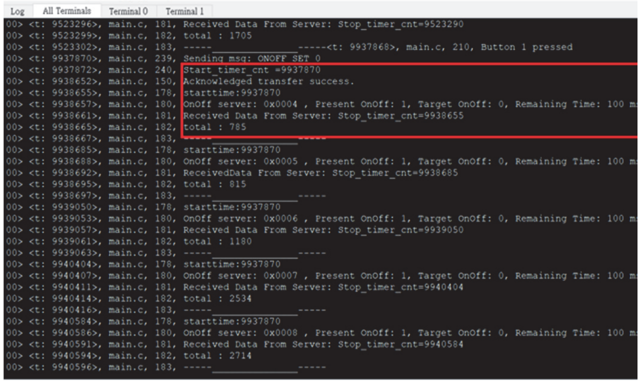


Fig. 4. Timestamp display screen

C. *Transmission Time of Each Radio Channel that Used Single-Path Topology*

We used nine development boards in single-path topology, and the experiment was in an unshielded open space (measuring 15 m × 10 m) in Sanying Ceramics Riverside Park. The development boards were placed on a 70-cm-tall table and featured linear topology, and nodes were placed 62.5-cm apart (the distance between Nodes A and I was 5 m). Observations were made using nRF Sniffer, and packets collected were displayed using Wireshark. Channels 37, 38, and 39 transmitted 50 broadcasts each in the experiment. The channels transmitted one broadcast, which contained three packets every second. The size of each packet was 58 bytes, and the data was obtained from transmitting the 50 packets to calculate the average transmission time of each channel (Fig. 5). In the figure, the sudden increases in the transmission time may be caused by increases in RSSI values and radio channel instability. The average time required by Channels 37–39 to transmit 50 packets using the linear (single-) path topology was 108 ms, whereas the transmission times of Channels 37, 38, and 39 were 105, 109, and 111 ms, respectively. The results showed that in the linear (single-) path topology, the average transmission time of Channel 37 was the shortest. Because the RSSI value of Channel 37 was more stable than those of Channels 38 and 39.

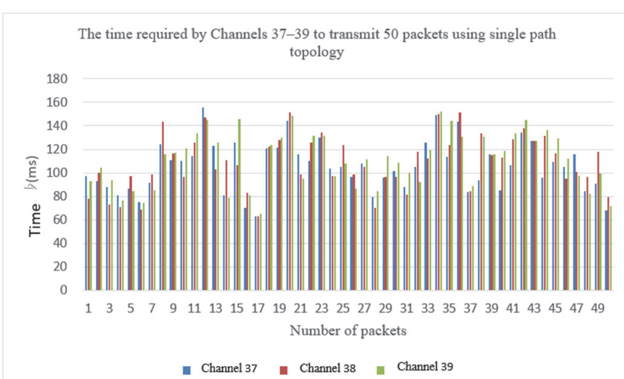


Fig. 5. Time required by Channels 37–39 to transmit 50 packets using single-path topology

D. *Experimental Environments for Identifying Invalid Nodes in Single-Path Topology and Analysis of the Nodes*

In Experiment 2, six development boards identified invalid nodes in single-path topology (Fig.6), and the experiment was in an unshielded open space (measuring 15 m × 10 m) in Yangming Park. The development boards were placed on a 47-cm-tall plastic chair, and data were transmitted from Node A to Node F (Fig. 6), passing through Nodes B, C, D, and E. Of all the distances with optimal reception, the longest one was selected as the distance between nodes. In the experiment, Channels 37, 38, and 39 transmitted 50 broadcasts, producing the average node return times shown in Fig. 7(a). The return times of Node_B and Node_F averaged 0.024 and 0.103 s, respectively. Because a fixed transmission direction was adopted, the farther away the nodes were, the longer the time they took to return broadcasts. The average return time of all the nodes (from Node_B to Node_F) was 0.059 s. The return times of all nodes identified the invalid nodes in Table 1. Because transmission and reception ability differed between nodes, those with poorer transmission and reception ability may affect overall mesh network transmission performance. In the experiment, the average return time of Node D was 0.024 s, which was considerably slower than those of other nodes. Therefore, following invalid node analysis, Node D (the invalid node) was replaced with a new Node G because the average return time of Node G (i.e., 0.021 s) was similar to those of other nodes. As shown in Fig. 7(b), an experiment was performed after the replacement. According to the results, the average return times of Nodes B and C were similar to those observed in Fig. 7(a), whereas the average return time of Node D improved substantially. The average return time of the refined overall network was 0.048 s, representing a decrease of 18%.

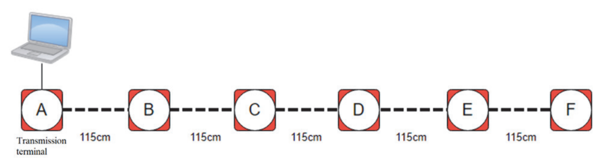
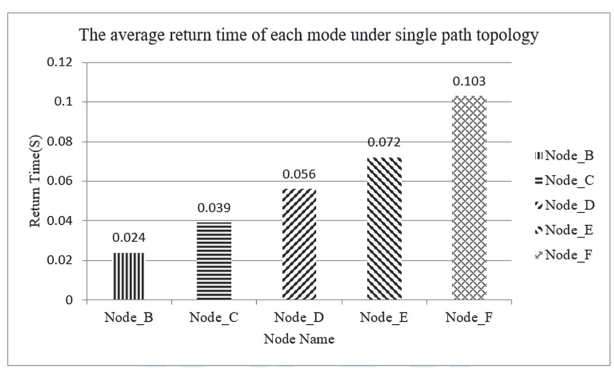


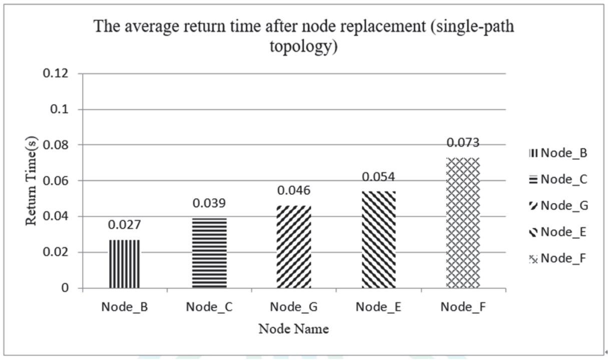
Fig. 6. Test environment of Experiment 2 for identifying invalid nodes

Table 1. The return times of the nodes (a round trip)

Node	A to B	A to C	A to D	A to E	A to F
Return Time(s)	0.019	0.02	0.024	0.02	0.021



(a)



(b)

Fig. 7. Average return time of each mode under single-path topology (a) original (b) invalid node replacement

E. Transmission Times of Radio Channels in Multipath Topology

In Experiment 3, nine nodes were placed in a multipath topology (Fig. 8). Node A transmitted 50 broadcasts to Node I at a rate of one broadcast, which contained three packets every second. The size of each packet was 58 bytes, and the average packet transmission times of Channels 37–39 were calculated (Fig. 9). The average time required by Channels 37–39 to transmit 50 packets using the multipath topology is 85 ms, whereas those required by Channels 37, 38, and 39 are 81, 86, and 89 ms, respectively. Fig. 9 indicates the experimental results that Channel 37 had the shortest average packet transmission time in the multipath topology. Because the flooding method did not consider transmission paths, it merely transmitted messages to all nodes that could be reached within its range.

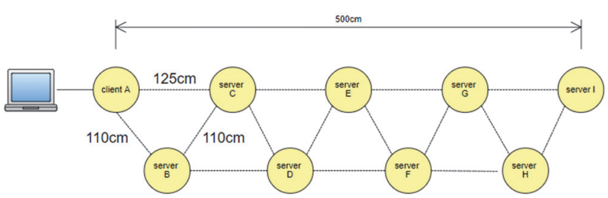


Fig. 8 Radio channel environment in Experiment 3(multipath topology)

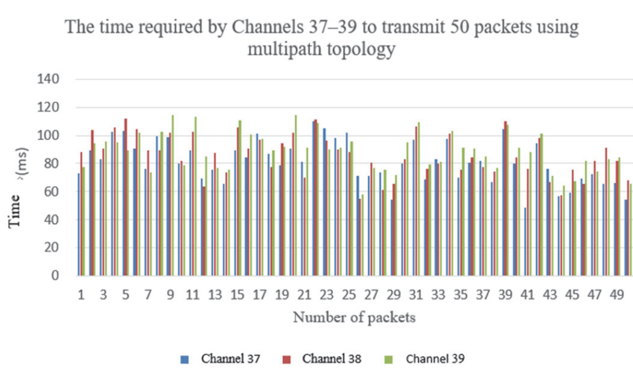


Fig. 9. Time required by Channels 37–39 to transmit 50 packets using multipath topology

F. Experimental Environments for Identifying Invalid Nodes in Multipath Topology and Analysis of the Nodes

The effect of the transmission interval was assessed using nRF Sniffer. The transmission intervals were set at 1 s and 5 s; the test was conducted for 2 min. Figure 10 shows the experimental environments for identifying invalid nodes in the multipath topology. The nodes were placed 115-cm apart, and nodes with quick and slow average return times were placed on the left and right sides. In the triangle topology, the TTL of Nodes B and D was 9; the TTL of Nodes C, E, and F was 8; and the default value was 10. The average return times of BCE (0.0287 sec; left half) and DFE (0.039 sec; right half) indicated that the average return time of BCE was shorter than that of DEF.

The PDRs of nodes in the multipath topology were compared (Fig. 11). According to the results, the average PDR of each node was 86% and 92% when the interval was 1and 5 s, respectively. The Bayesian probability classification algorithm identifies invalid nodes in the multipath topology, and TTL was utilized to derive data transmission paths. The results indicated that out of 50 transmissions, AB and AD were used 37 and 13 times, respectively, producing the path probabilities of 0.74 and 0.26, respectively. According to the calculation result, Node D had the lowest probability value of classifying as an invalid node s. Its role was changed from a relay node to a general node. Subsequent tests were performed, which showed that for Node F (a relay node that changed from Node D to Node E), its overall return time decreased by 27%. The new average return times of all the nodes are shown in Fig. 12, confirming that changing or switching the roles of invalid nodes increased the mesh network transmission time.

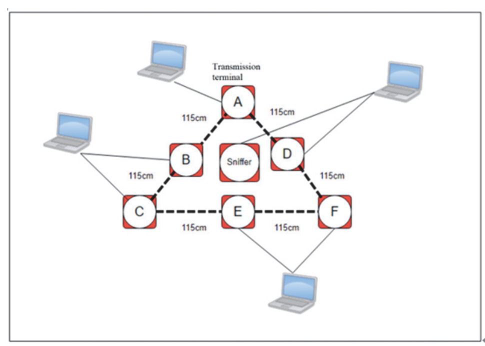


Fig. 10. Searching for invalid nodes in multipath topology

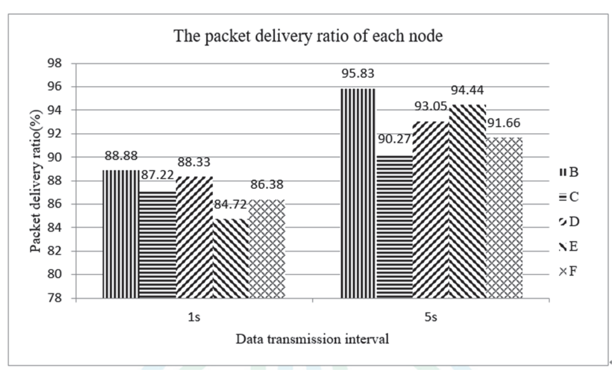


Fig. 11. Packet delivery ratio of each node

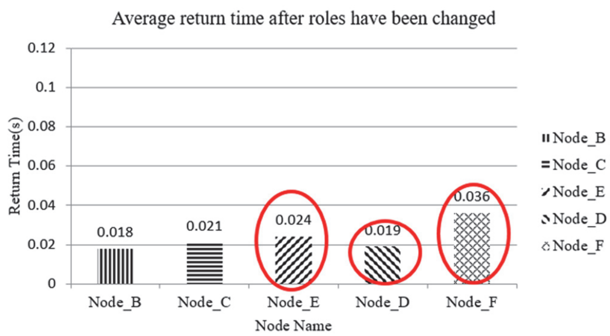


Fig. 12. Average return time after roles have been changed

V. Conclusion

This study investigated the packet transmission and delivery ratios in a Bluetooth mesh network with single-path and multipath topologies. The experimental results demonstrate that invalid nodes affected network transmission performance in a Bluetooth mesh network. Time to live and the Bayesian probability classification algorithm proposed to calculate and identify invalid nodes in these topologies and their roles were adjusted accordingly to increase overall performance. The experimental results showed that the replacement of invalid nodes decreased the average return time by 18% and 27% for the single-path topology and the multipath topology, respectively.

Acknowledgment

This work was supported by the Ministry of Science and Technology, [Project number most 110-2221-E-231-001].

References

[1] P. Pierleoni et al., "Performance Improvement on Reception Confirmation Messages in Bluetooth Mesh Networks," in IEEE Internet of Things Journal, pp. 1-15 June 2021.

[2] Bluetooth Mesh Networking - An Introduction for Developers https://www.bluetooth.com/bluetooth-resources/bluetooth-mesh-networking-an-introduction-for-developers/.

[3] D. Perez-diaz-de-cerio, A. Hernandez-solana, M. Garcia-lozano, A. V. Bardaji, and A. J. Valenzuela, "Speeding up bluetooth mesh," in IEEE Access, vol. 9,pp. 93267-93284 June 2021.

[4] S. M. Darroudi and C. Comez, "Bluetooth low energy mesh networks: A survey," in Magnetism, Sensors vol.17, pp. 1467-1485, June 2017.

[5] J. A. Prasetyo, A. Yushev, and A. Sikora, "Investigations on the performance of bluetooth enabled mesh networking," Institute of Reliable Embedded Systems and Communication Electronics, Offenburg University of Applied Sciences, D77652 Offenburg, Germany, pp. 26-27, Sept. 2016.

[6] S. M. Darroudi and C. Gomez, "Bluetooth Low Energy Mesh Networks: A Survey", Sensors Vo.17, pp. 1467-1485, June 2017.

[7] R. Vijay et al., "A Heterogeneous PLC with BLE Mesh network for Reliable and Real-time Smart Cargo Monitoring", IEEE International Symposium on Power Line Communications and its Applications (ISPLC), pp. 3-5, April 2019.

[8] A. Nikoukar, M. Abboud, B. Samadi, M. Gunes, and B. Dezfouli, "Empirical analysis and modeling of bluetooth Low-energy (BLE) advertisement channels," in 17th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), pp. 20-22 June 2018.

[9] Y. Murillo et al., "Bluetooth now or low energy: Should BLE mesh become a flooding or connection oriented network?," in IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Oct. 2017.

[10] J. A. Prasetyo, A. Yushev, and A. Sikora, "Investigations on the Performance of Bluetooth Enabled Mesh Networking", Institute of Reliable Embedded Systems and Communication Electronics, Offenburg University of Applied Sciences, D77652 Offenburg, Germany, pp. 26-27, Sept. 2016.

[11] M. Baert, J. Rossey, A. Shahid, and J. Hoebeke, "The bluetooth mesh standard: an overview and experimental evaluation," in Sensors, vol. 18, pp. 1-24, July 2018.

[12] J. Lee, "Broadcast audio transmission for bluetooth LE on an interfered ISM Band," in IEEE Internet of Things, vol. 6, pp. 6140-6150, Aug. 2019.

[13] B. Liu, Z. Yan, and C. W. Chen, "Medium access cotrol for wireless body area networks with QoS provisioning and energy efficient design," in IEEE Trans. on Mobile Computing, vol. 16, pp. 422-433 Ferb. 2017.

[14] N. Ahmed, H. Rahman, Md.I. Hussain, "A comparison of 802.11ah and 802.15.4 for IoT," in ICT Express, vol. 2, pp. 100-102 Sept. 2016.