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A Loop Reduction Method Utilizing Public Device Addresses of Master Terminals in Connection Procedures of Multiple Piconets for Bluetooth MANETs

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Abstract

Currently, research on Bluetooth-based mobile ad hoc networks (hereinafter referred to as Bluetooth MANETs) is being conducted. As an application of Bluetooth MANETs, a grass-root disaster information propagation system has been studied for the purpose of information distribution following disasters. Bluetooth standards include Classic Bluetooth (hereinafter referred to as Classic), which can transfer relatively large data packets, and Bluetooth Low Energy (hereinafter referred to as BLE), which can work with relatively low power consumption. So far, a rapid connection establishment method that combines Classic and BLE in a complementary manner (hereinafter referred to as the existing method) and the flooding-based data packet transfer method with delay- and disruption- tolerance have been proposed. In the existing method, a Bluetooth MANET is constructed by connecting multiple piconets, which consist of one master and multiple slaves. In the existing method, loops are easily formed in a Bluetooth MANET due to the establishment of connections between slave terminals in a piconet in an environment with high terminal density. Therefore, when the flooding-based data packet transfer method is used in the existing method, the amount of data packets increases and the processing load on the terminals increases. In this paper, we proposed a method to reduce the number of loops by controlling the connection establishment between slave terminals in a piconet for Bluetooth MANETs (hereinafter referred to as our proposed method). In addition, we have evaluated the effect of our proposed method on data packet transfer through simulation experiments. As a result, we confirmed that our proposed method can reduce the number of loops and the number of data packet transmissions while maintaining the time to complete the data packet dissemination at the same level as the existing method.

Keywords: Bluetooth MANETs, Piconet, Loop suppression, Public device address (PDA), Master

1 Introduction

Mobile Ad-hoc Networks (hereinafter referred to as MANETs) [1][2] are a technology that allows mobile communication terminals such as smartphones to communicate directly with each other without any communication infrastructure such as base stations. MANETs are expected to be utilized in environments where communication infrastructure is not available, such as during disasters.

Currently, research on MANETs based on Bluetooth [3] (hereinafter referred to as Bluetooth MANETs) [4][5] has been conducted, and the study and development of the grass-root disaster information propagation system [6] has been conducted as an application system of Bluetooth MANETs.

This system aims to reduce the damage caused by disasters by sharing and propagating disaster information such as photos taken by residents in the disaster area using Bluetooth MANETs. Since Bluetooth is a short-range wireless communication standard, the transmission range is limited and the connectivity changes frequently. In addition, since Bluetooth is a connection-oriented wireless communication standard, terminals are required to establish a connection with each other in advance to communicate. Therefore, in order to transmit information using Bluetooth MANETs, we must handle the disconnection between terminals due to the narrow communication range, and accelerate the connection establishment procedure between terminals. To address these issues, a new method has been proposed [7], which basically uses wireless multi-hop communication as used in MANETs, but also uses store-and-forward communication as used in delay-and-disconnection tolerant networks in environments where connections are dropped or connections between terminals are unstable. Also, for accelerating the connection-establishment procedure, a connection-establishment method that uses Classic Bluetooth (hereinafter referred to as Classic) and Bluetooth Low Energy (hereinafter referred to as BLE) in a complementary manner [8] (hereinafter referred to as existing method) has been proposed.

According to the research results in reference [8], the latency for connection between terminals using Bluetooth is reduced and the connectable time for establishing connection between terminals is improved compared to the case using only Classic. The effectiveness of the method in [8] is confirmed by experiments using a newly implemented simulator for a network of 100 devices. However, the method of establishing connections between terminals in [8] has been found to have a new problem to be solved. In Bluetooth, a star network called a piconet is assumed to be composed of one master and surrounding slaves managed by the master. However, as a result of confirming the behavior of Bluetooth MANETs in the existing method by simulation, we confirmed that an excessive number of loops are formed due to the establishment of connections between slave terminals in the piconet [9]. In general, when data packets are forwarded by broadcast in a network with loops, data packet collisions are more likely to occur. In addition, Bluetooth MANETs use the flooding-based data packet transfer method, which increases the amount of data packets and increases the processing load on the terminal. In this paper, we proposed a method to reduce the loops by controlling the connection establishment between slave terminals in a piconet in Bluetooth MANETs.

This paper is organized as follows: Sections 2 and 3 describe Bluetooth and Bluetooth MANET, respectively; Sections 4 and 5 describe our proposed method and simulation experiments; Section 6 describes and discusses additional experiments and results. Finally, in section 7, we summarize this paper.

2 Bluetooth

Table 1: Specifications of Classic and BLE

	Classic	BLE
Frequency	2.4 [GHz]	2.4[GHz]
Number of channels	79	40
Standard maximum speed	1[Mbps]	1[Mbps]
Effective maximum speed	0.7[Mbps]	0.27[Mbps]
Maximum packet size	1021[byte]	47[byte]
Maximum transmission power	100[mW]	10[mW]
Pairing	Required	Option
Broadcast when disconnected	impossible	possible

Bluetooth [10][11] is a short-range wireless communication standard that uses the 2.4 GHz ISM band. The features of Bluetooth are as follows: (1) Bluetooth consumes less power than other wireless communication standards such as Wi-Fi; (2) Since Bluetooth employs Frequency Hopping

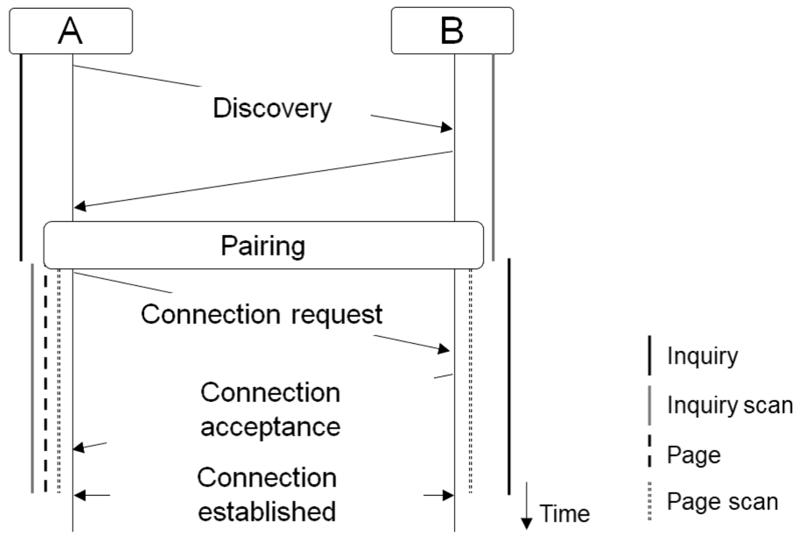


Figure 1: Connection establishment procedure for Classic

Spread Spectrum (FHSS) and Adaptive Frequency Hopping (AFH), which are one of the spread spectrum methods, it has high interference resistance and confidentiality. In addition, there are two Bluetooth standards: Classic [11], which was standardized before Bluetooth 3.0, and BLE [10], which was standardized after Bluetooth 4.0. Table 1 shows the characteristics of each standard in Bluetooth 4.1. In this section, we explain the Classic and BLE standards and the network to be constructed using Bluetooth.

2.1 Classic

Classic is a connection-oriented standard that allows bi-directional communication. Therefore, terminals need to establish a connection with their correspondence terminal in advance to transmit data packets. In addition, Classic requires a process called "pairing" between terminals before establishing a connection to improve security. Pairing refers to the authentication of connections between terminals, and since terminals that have been paired once become paired terminals thereafter, there is no need to pair the same terminals again. There are two types of Classic: Inquiry, which can detect surrounding terminals, and Inquiry Scan, which can detect itself. In addition, there are two states: Page, which is the state from the start of the connection establishment process until it is completed, and Page Scan, which is the state that can receive connection establishment requests. Figure 1 shows the procedure for establishing a Classic connection from terminal A:

1. Terminal A discovers terminal B in the Inquiry Scan state that exists within its communication range.
2. Terminal A performs its pairing process with the discovered terminal B.
3. After pairing is completed, terminal A is in PageScan only to terminal B and terminal B is in PageScan only to terminal A.
4. Terminal A is in Page and sends a connection establishment request to the discovered terminal B.
5. When terminal B accepts the request, a connection is established between terminals A and B.

In Classic, after a terminal is detected, pairing is performed with the detected terminal. If the pairing has been completed, the connection establishment request can be transmitted without

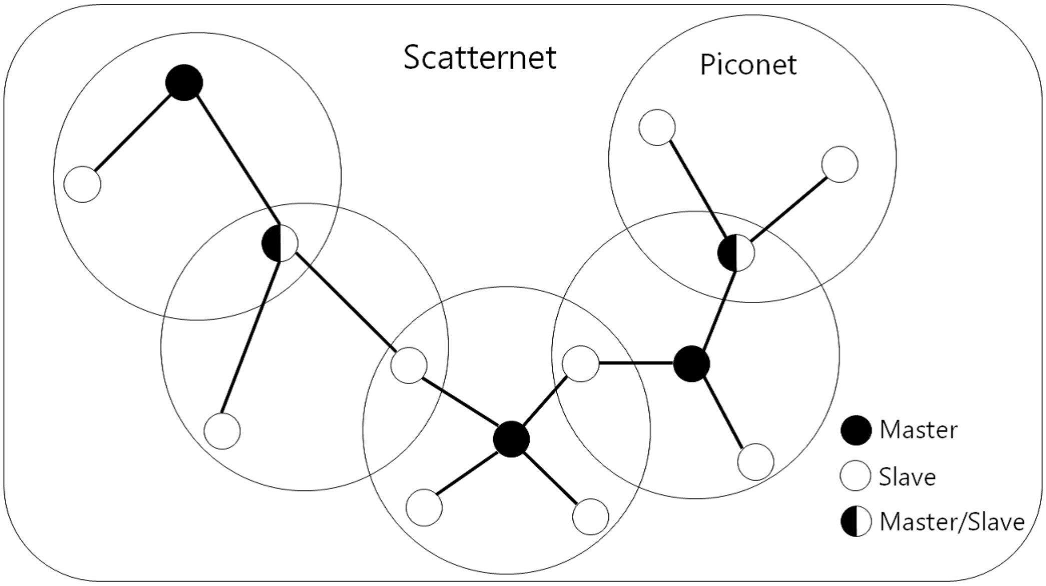


Figure 2: Example of piconet and scatternet construction

detecting the terminal. In addition, Page Scan is always performed only for terminals that have been paired.

2.2 BLE

BLE achieves low power consumption by significantly reducing the values of communication speed, transmission power, and data packet size compared to Classic. As shown in Table 1, however, BLE has a small maximum data packet size and, unlike Classic, does not have the capability of data packet fragmentation and transfer technology. In BLE, the terminal is identified using the 48[bit] address of the Bluetooth device, which is in the same format as the MAC address used in IEEE 802.11. There are two types of Bluetooth device addresses used in BLE: random device addresses and public device addresses (PDAs). The random device address is a device address that is randomly generated when an application starts. The PDA is uniquely assigned to each Bluetooth device according to the IEEE 802-2014 standard, and the pairing procedure is not mandatory but optional in BLE. A terminal using BLE sends advertising packets to surrounding terminals to notify their presence. The terminal under detection can detect, in return, the advertising terminal. Maximum size of an advertising packet is 31 [byte]. In BLE, connectionless unidirectional communication (hereinafter referred to as BLE-Broadcast) and connection-oriented bidirectional communication are available by using the unconnected broadcast function. We will explain BLE-Broadcast, which is related to the method used in this paper, in the following part.

BLE-Broadcast does not require the establishment of connections between terminals and can transmit information by broadcasting. In BLE, the state of a terminal that broadcasts advertising packets by BLE-Broadcast is called the advertising, and the state of a terminal that can receive advertising packets is called the scanning, and a terminal can be both the advertising and the scanning at the same time. The advertising terminal sends a data packets to all the scanning terminals in the surrounding area at once.

2.3 Networks constructed with Bluetooth technologies and their characteristics

In BLE, there is no limit to the number of slaves in a piconet, while in Classic, a master can hold up to seven slaves simultaneously. In the Bluetooth specification, the master is defined as the

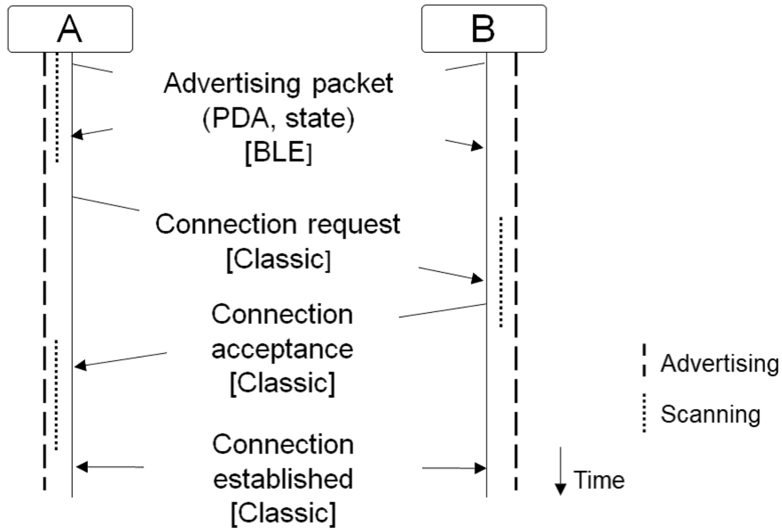


Figure 3: Procedure of connection establishment using the existing method

terminal that sends the connection establishment request and the slave is defined as the terminal that accepts the request. The master manages the FHSS channel used for communication with the slave, and controls the timing of communication with the slave by polling. Each terminal in a piconet can belong to multiple piconets, and the multi-hop network constructed by connecting piconets is called a scatternet. However, a terminal can belong to multiple piconets as a slave, but can belong to only one piconet as a master. Figure 2 shows an example of the construction of a piconet and a scatternet. In Figure 2, master/slave refers to a terminal that belongs to one piconet as master and to another piconet as slave. In Figure 2, multiple piconets are connected to form a single scatternet. Since each piconet uses the FHSS communication channel asynchronously in a scatternet, radio interference is likely to occur when many piconets are crowded in the same area. In reference [12], a method for constructing scatternets in ad hoc networks using Bluetooth is presented. This method aims to reduce the overhead of switching piconets by each master's controlling the number of slaves in a tree-type topology construction. In addition, in the survey paper in reference [13], a clustering method is introduced to reduce computation and communication costs in MANET configurations.

3 Bluetooth MANET

Bluetooth MANET is a MANET that uses Bluetooth for communication between terminals. Since Bluetooth MANETs use Bluetooth, which has low power consumption and high interference resistance, they have the advantages of (1) maintaining MANETs for a longer duration than other wireless communication standards such as Wi-Fi, and (2) reducing the influence of radio wave interference even in an environment with high terminal density where MANETs are expected to be used.

3.1 BLE-Broadcast assisted fast connection-establishment method

The current method for establishing a Bluetooth MANET is the BLE-Broadcast Assisted Fast connection Establishment described in reference [8]. In this section, we explain the connection establishment procedure between two terminals in the method of reference [8]. In the method of reference [8], to establish a Bluetooth MANET, BLE-Broadcast and Classic are used in a complementary manner to establish a Classic connection (the existing method). In the existing method,

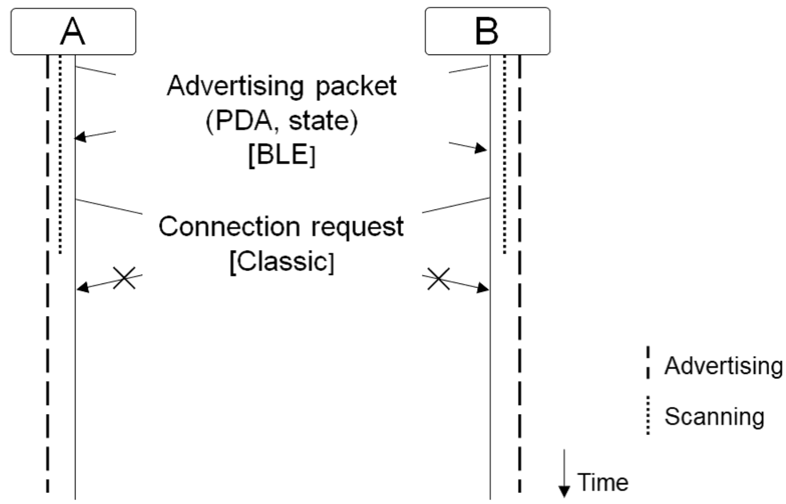


Figure 4: Example of conflicts

each terminal transmits its own PDA to the surrounding terminals by BLE-Broadcast. In the existing method, each terminal sends its own PDA to the surrounding terminals via BLE-Broadcast. When a deadlock occurs, the two terminals need to wait until a predetermined time elapses [14]. As a result, the time required to establish a connection increases. First, Figure 3 shows the connection establishment procedure in the existing method when there is no conflict between the connection establishment requests, i.e., when the two terminals are in different states. In the existing method, the advertising indicates the state in which the PDA of Classic and the advertising packet containing the state information are being sent, and scanning indicates the state in which the advertising packet can be received. In addition, each terminal is configured to periodically become scanning instead of always remaining scanning [15]. This is because if each terminal is scanning asynchronously and periodically, the frequency of both terminals executing the connection establishment procedure being advertising and scanning will decrease, and the frequency of conflict for connection establishment requests, which is the cause of connection establishment failures, will also decrease.

1. Terminal A in scanning discovers Terminal B in advertising.
2. Terminal A checks the status of terminal B and sends a request to establish a Classic connection to terminal B if it is scanning.
3. When terminal B accepts the request, a connection is established between terminals A and B.

In step 1, both terminals are the advertising, but only terminal A, which is the scanning, can receive terminal B's advertising packet and discover terminal B. In step 2, terminal A confirms that terminal B is not the scanning and performs the Classic connection establishment procedure based on terminal B's PDA. In Step 2, Terminal A confirms that Terminal B is not the scanning, and performs the Classic connection establishment procedure based on the received PDA of Terminal B. Next, Figure 5 shows the connection establishment procedure for a situation where the connection establishment requests conflict as shown in Figure 4, i.e., when two terminals are the advertising and the scanning and both receive advertising packets. Figure 5 shows the case where terminals A and B receive advertising packets in the advertising and the scanning modes, respectively. In this case, the PDA values of terminals A and B are assumed to be A>B.

1. Terminals A and B of the advertising broadcast advertising packets.
2. Terminals A and B of the scanning discover the source terminal by receiving the advertising packet.

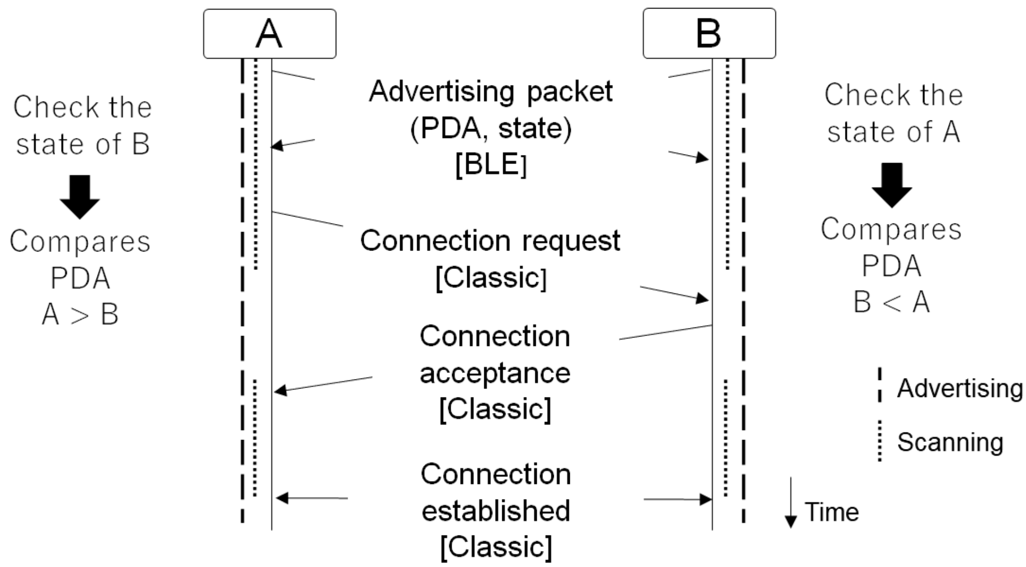


Figure 5: Example of the existing method to avoid conflicts

3. Terminals A and B check the status of the discovered terminal and send a connection establishment request if it is not scanning.

4. Terminal A, whose PDA value is higher than that of terminal B, sends a connection establishment request.

5. When terminal B accepts the request, a connection is established between terminals A and B.

In Step 2, terminals A and B receive each other's advertising packets and discover each other. In step 3, terminals A and B confirm that they are both scanning, and compare their own PDA values with the received PDA values. In step 4 and later, terminal A, which has a higher PDA value, sends a connection establishment request to terminal B and performs the connection establishment procedure. In the existing method, when a connection is established, the terminal that sends the connection establishment request becomes the master and the terminal that receives the connection establishment request becomes the slave. In other words, in Figures 3 and 5, when a connection is established, terminal A is the master and terminal B is the slave.

3.2 Data Packet Transfer Method in Bluetooth MANET

Since Bluetooth MANETs use Bluetooth, which has a narrow radio range, the connection establishment status between terminals changes frequently due to the movement of terminals. In addition, in a sparse environment, the number of terminals that can communicate directly by Bluetooth is limited, and data packet transfer by wireless multi-hop transmission may not be possible. On the other hand, in a dense environment, data packet transfer time becomes longer due to radio interference. To solve this problem, a data packet forwarding method that switches between epidemic routing and multi-hop forwarding has been proposed in reference [7]. In this method, when each terminal receives a data packet from an adjacent terminal and forwards the packet to another adjacent terminal, it forwards the packet to the terminal with which a connection has been established by wireless multi-hop forwarding. On the other hand, when the connection between terminals is not yet established, the data packet forwarding method is autonomously switched so that data packets are forwarded by store-and-forward based on Epidemic Routing using Summary Vector (SV) [16] after the connection is established.

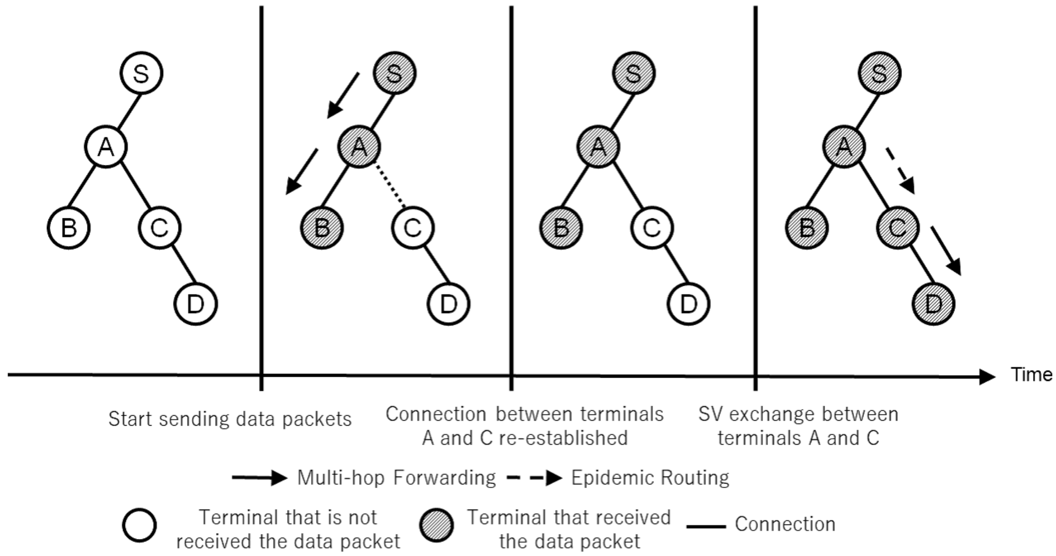


Figure 6: Example of the operation of a data transfer method that switches between epidemic routing and multi-hop forwarding

By exchanging SVs periodically and asynchronously, each terminal learns the data packets that are not held by the adjacent terminal and forwards only the difference data packets with the adjacent terminal. In this method, each terminal periodically sends its own SV to all terminals with which it has established connections. Figure 6 shows an example of the data packet forwarding method that switches between Epidemic Routing and wireless multi-hop forwarding. Terminal S starts to transmit a data packet. At this time, if the connection between terminals A and C is temporarily disconnected, the data packet is forwarded to terminal B by wireless multi-hop forwarding. Each terminal does not discard the data packet, but stores it in a buffer. After that, the connection is re-established between terminals A and C, and the time T_{SV} of terminal C's SV transmission interval arrives. Terminal C sends its own SV, and terminal A, which receives the SV, compares it with its own SV and sends a data packet that terminal C does not hold. Then, data packets are forwarded from terminal C to terminal D, with which a connection has been established, by the wireless multi-hop forwarding.

In addition to the above data packet forwarding method, Reference [7] proposes a forwarding function to speed up data packet forwarding in an environment where temporary disconnection is likely to occur. In this function, when a data packet is received, a certain short waiting time (hereinafter referred to as the multi-hop waiting time) is set and the data packet is stored in a buffer for wireless multi-hop transmission during the waiting time. If a connection is newly established or re-established with an adjacent terminal within the waiting time for multi-hop transmission, data packets are transmitted by wireless multi-hop transmission without exchanging SVs. By introducing the multi-hop waiting time transfer function, data packets can be transferred without waiting for T_{SV}, thus shortening the data packet transfer time.

3.3 Bluetooth MANET Simulator

Conventional research on Bluetooth MANETs has mainly focused on evaluation experiments using a few actual terminals, and few evaluation experiments have been conducted on a scale of several dozen or several hundred terminals. Therefore, the performance of Bluetooth MANETs in an environment where many terminals are moving and a network is being constructed is unclear, as in a real environment. The Bluetooth MANET simulator has been designed and implemented on QualNet ver.5.0 [17], which enables the performance evaluation of the connection establishment

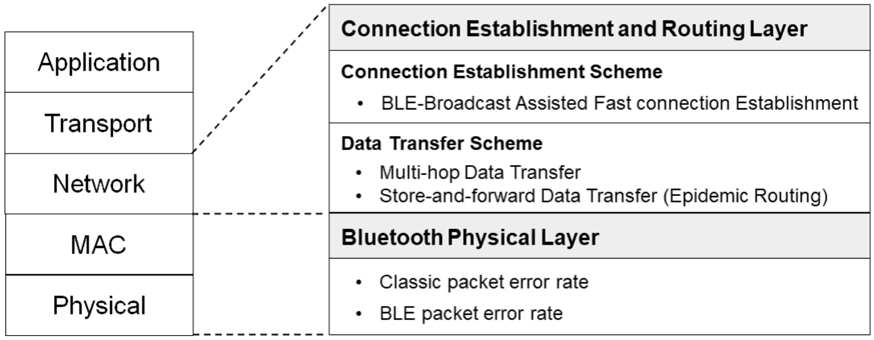


Figure 7: Configuration of the Bluetooth MANET simulator

method and data packet transfer method of Bluetooth MANET described in sections 3.1 and 3.2 [18]. Figure 7 shows the configuration of the Bluetooth MANET simulator, where the packet transmission/reception process of each layer from the physical layer to the application layer can be described in C++. In the Bluetooth MANET simulator, the behavior of the connection establishment method and data packet transfer method of Bluetooth MANET can be reproduced by modifying the network layer from the physical layer of QualNet. The Bluetooth MANET simulator consists of two layers: the Bluetooth Physical Layer, where packet loss due to Bluetooth radio interference is judged, and the Connection and Routing Layer, where terminals establish connections and transfer data packets in an autonomous and distributed manner. The Bluetooth MANET simulator consists of two layers: the Bluetooth Physical Layer, where packet loss due to Bluetooth interference is judged, and the Connection Establishment and Routing Layer, where terminals establish connections and transfer data packets autonomously. The implementation of each layer in the Bluetooth MANET simulator is described below.

3.3.1 Bluetooth Physical Layer

In the Bluetooth Physical Layer, it is possible to set parameters related to radio wave characteristics, such as Bluetooth transmission power and reception sensitivity, and by changing these parameters, it is possible to conduct experiments using terminals of different classes defined in the Bluetooth specification [10]. In addition, the Bluetooth Physical Layer abstracts the operation of FHSS in order to prevent the simulator from running slowly. Instead, we have implemented a way to set the packet loss rate of Bluetooth according to the experimental environment. In this simulator, the packet loss ratio of Classic and BLE can be set separately in order to evaluate the existing methods. The packet loss rate of each standard is set in advance based on reference [19][20] that investigates the error rate of packets caused by radio interference, etc. [15]. In the Bluetooth Physical Layer, the redundancy coding implemented in Bluetooth is not implemented, and it is assumed that packet loss always occurs when a packet error occurs, so that the error rate in reference [19][20] is directly set as the packet loss rate. In the following, we will discuss the results of our investigation. In the following, we show the error rates of the investigated Classic and BLE packets. In Classic, all 79 channels are allocated for data packet transmission, and the hopping frequency used for communication is determined and the transmission timing is controlled in each piconet. Therefore, the error rate changes depending on the number of adjacent piconets. When the number of adjacent piconets is n and the number of channels in a classic is $N_{channel}$, the error rate $P_{classic}$ due to radio interference can be expressed by equation (1) [19]. $N_{channel}$ is 79.

$$P_{classic} = 1 - (1 - (\frac{1}{N_{channel}}))^{2n} \tag{1}$$

On the other hand, in BLE, 37 channels are allocated for data packet transmission and 3 channels for advertising packet transmission out of the total 40 channels. In particular, since only three

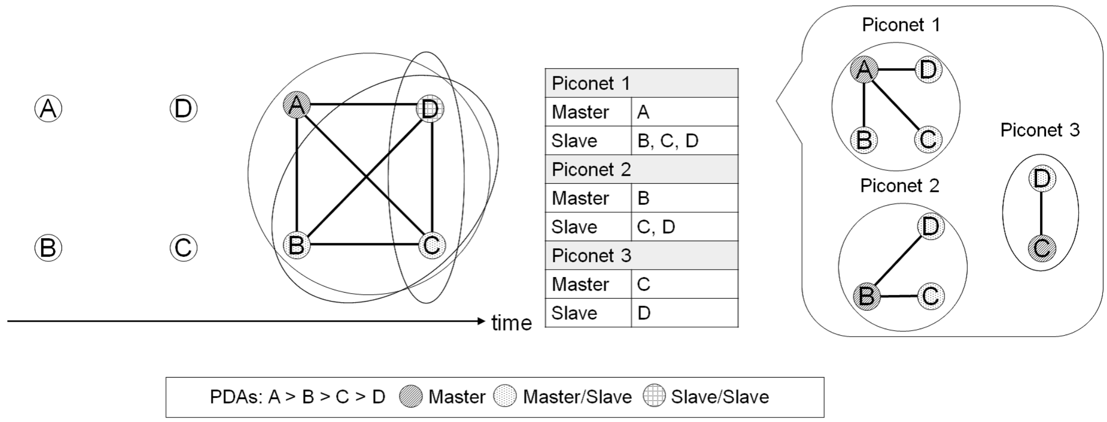


Figure 8: Example of Bluetooth MANET in the existing method

channels are allocated for the transmission of advertising packets, the error rate is higher than that for data packet transmission. The error rate P_{ble} in the transmission of BLE advertising packets can be calculated by equation (2) when the number of pairs of scanning and advertising terminals in the communication range is M and the probability of simultaneous transmission of advertising packets on the same channel is $2\alpha/\Upsilon_a$ [20].

$$P_{ble} = 1 - (1 - (\frac{2\alpha}{\Upsilon_a}))^{M-1} \tag{2}$$

α と Υ_a are defined in reference [20] as $\alpha = Round(A/\Delta)$ and $\Upsilon_a = Round(T_a/\Delta)$, where A is the advertising duration per channel, T_a is the time interval of the advertising event, and Δ is the unit time slot. In the existing method, a terminal has both roles of the scanning and the advertising. Therefore, when a particular scanning terminal and an adjacent advertising terminal are considered as a pair, there are as many pairs as the number of adjacent terminals, and the number of adjacent terminals and M of each terminal are equal. In this simulator, when evaluating the performance of the existing methods, the error rate P_{ble} in the transmission of advertising packets, which has a higher error rate than that of data packet transmission, is used as the error rate of data packets in the transmission of BLE-Connection, assuming an environment where the most radio interference occurs.

3.3.2 Connection Establishment and Routing Layer

The Connection Establishment and Routing Layer implements the packet exchange and terminal state switching of the connection establishment procedure in existing methods. It also implements a data packet forwarding method that switches between Epidemic Routing and wireless multi-hop forwarding as described in Section 3.2, and implements parameters for data packet forwarding such as SV transmission interval and multi-hop waiting time that can be freely set. The parameters for the Bluetooth packet loss rate, connection establishment method, and data packet transfer method described above can be set from the QualNet config file at the start of the simulation.

3.4 Problems with Bluetooth MANETs in dense terminal environments

This paper describes the issues of Bluetooth MANET applying the existing method in Section 3.1. As a result of investigating the behavior of the existing method in a large and dense network environment using a simulator, we found that the existing method creates excessive connections between slave terminals in a piconet, which leads to the formation of loops. We applied the existing method to Bluetooth MANETs in order to establish connections between terminals reliably and quickly in a sparse network, but in a dense network, the existing method easily creates loops due

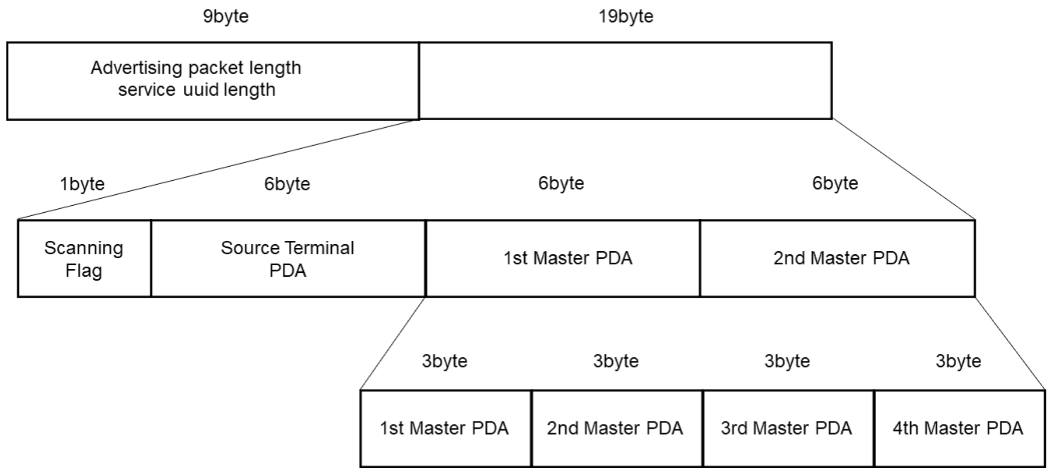


Figure 9: Payload format of advertising packets

to connections between slave terminals in the piconet.In the existing method, after discovering the source terminal of the advertising packet using steps 1 and 2 of the terminal discovery process by BLE described in Section 3.1, connections are established in step 3 without considering which piconet the source terminal of the advertising packet belongs to. As a result, a connection is established between slave terminals in the piconet, and loops is easily formed in the Bluetooth MANET.

Next, we explain an example of the construction of a Bluetooth MANET using the existing method in Figure 8. In Figure 8, there are terminals A-D within the communication range of each other, and if one of the terminals A-D becomes a representative master and all terminals belong to one piconet, all terminals can communicate. First, a Piconet1 with terminal A as the master and terminals B-D as slaves is constructed using existing methods. In the same way, Piconet2 is constructed with terminal B as the master and terminals C and D as the slave, and Piconet3 is constructed with terminal C as the master and terminal D as the slave, for a total of three piconets. As a result, connections are established between slave terminals B and C, B and D, and C and D in Piconet1, resulting in the formation of a loops. Thus, in the existing method, connections are newly established between slave terminals in a piconet even though they already belong to the same piconet. Furthermore, in the Bluetooth MANET using the existing method, the number of piconets to which a terminal belongs increases as the number of adjacent terminals increases. Therefore, if a Bluetooth MANET is constructed using the existing method in a dense terminal environment, the number of loops increases significantly with the increase in the number of piconets to which the terminals belong. In such a network, if the flooding-based data packet transfer method is used, the amount of extra data packets will increase, and the processing load of the terminals will increase. In fact, we have confirmed that when a topology with many loops are constructed using the existing method and data packets are sent using Android terminals, the operation of the application and Bluetooth becomes unstable and the application is forced to terminate.

4 Our proposed method to suppress loops[21]

4.1 Overview

Our proposed method is designed to suppress loops caused by excessive connection establishment between slave terminals in a piconet. In addition to the information contained in the advertising packets of the existing method, our proposed method includes the value of PDA of the piconet master to which the terminal currently belongs. Based on this information, the terminal that receives the advertising packet checks whether the sender terminal belongs to the same piconet as itself. It then

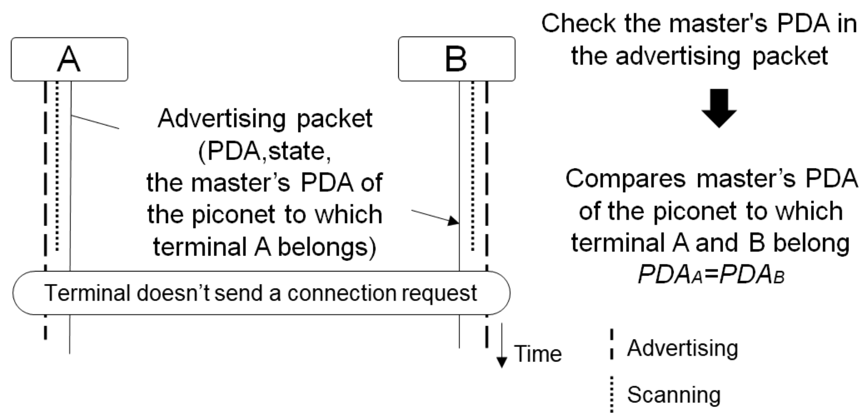


Figure 10: Procedure of loops reduction using our proposed method

sends a connection establishment request and decides whether to disconnect the connection. In this way, the problem of existing methods is solved.

4.2 Payload format of advertising packets

Figure 9 shows the payload format of the advertising packet in our proposed method. The size of the PDA is 6 *octets*, and the information included in the existing method uses 16 *octets* out of the payload size of 31 *octets* in the advertising packet. Therefore, in our proposed method, the number of PDAs that can be newly included in the advertising packet is limited to two due to the payload format of the advertising packet [21]. Through further investigation, we confirmed from reference [10] that the upper 3 *octets* of PDAs are Organizationally Unique Identifiers, and the lower 3 *octets* are terminal-specific addresses. This means that the upper 3 *octets* of the PDA can be cut off and the PDA can be identified only by the lower 3 *octets*, thus reducing the size of the PDA to half the 3 *octets*. As shown in Figure 9, we can add two new PDAs to the advertising packet, and our proposed method can include up to four PDAs in addition to the information of the existing method. Our proposed method in this paper adopts the second method introduced to include more master's PDAs of the piconet in one advertising packet, while our proposed method in reference [21] adopts the first method included two master's PDA in one advertising packet.

4.3 Connection control procedure between the slave terminals

Figure 10 illustrates the connection establishment control procedure between slave terminals in a piconet for loop suppression.

1. Terminal A of the advertising broadcasts an advertising packet.

2. Terminal B of the scanning discovers the source terminal by receiving the advertising packet.

3. Terminal B receives the advertising packet and compares the master's PDA of the piconet to which it belongs with the value of the master's PDA included in the advertising packet.

4. The value of the master's PDA of the piconet to which Terminal B belongs and the value of the master's PDA contained in the advertising packet match.

5. If they match, it is known that they belong to the same piconet, so the connection is not established. In addition, if a connection has already been established with the sender of the advertising packet, the connection is disconnected.

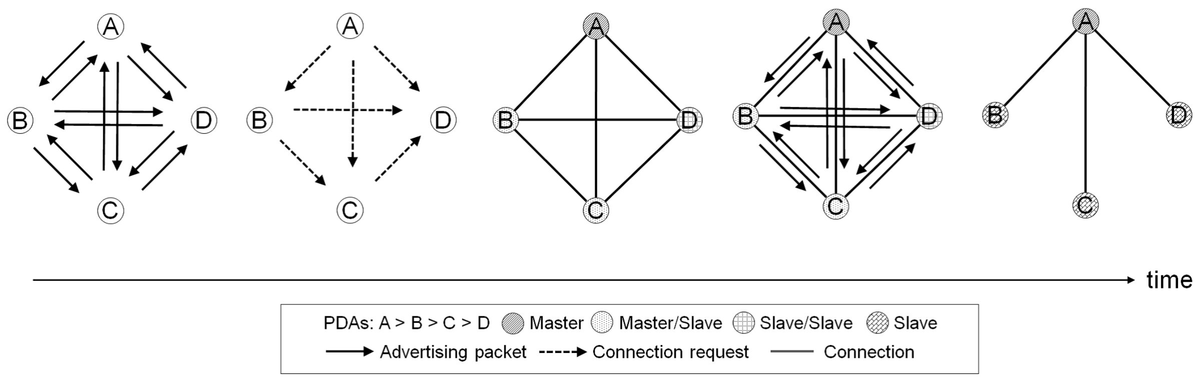


Figure 11: Example of Bluetooth MANET in our proposed method

Source PDA	1st Master PDA	2nd Master PDA	3rd Master PDA	4th Master PDA
A	None	None	None	None
B	A	None	None	None
C	A	B	None	None
D	A	B	C	None

Figure 12: Master's PDA in the advertising packet during loop control

In step (3), if the advertising packet does not contain the master's PDA to which the source terminal belongs, the connection is established with the source terminal using the existing method. If the values of the PDAs do not match in step (4), the connection is established with the source terminal using the existing method.

Next, Figure 11 shows an example of the construction of a Bluetooth MANET using our proposed method. In Figure 11, a piconet is not formed by terminals A-D at the beginning, and the advertising packet does not contain the information of the piconet master to which the terminal belongs.

1. Terminals A-D of the advertising broadcasts an advertising packet.

2. Terminals A-D of the scanninng discover the source terminal by receiving the advertising packet.

3. Since the advertising packet does not contain information about the piconet master to which the terminal belongs, the connection processing procedure of the existing method is performed, and the piconet including the loops are constructed.

4. Terminals A-D periodically send advertising packets. The advertising packets sent by each terminal include the master's PDA shown in Figure 12.

5. When terminals A-D receive an advertising packet, they compare the master's PDA of the piconet to which they belong with the value of the master's PDA in the advertising packet.

6. The value of the master's PDA of the piconet to which terminals B-D belongs and the value of the PDA of the master in the advertising packet match.

7. Terminals B-C, B-D, and C-D disconnect because they know that they belong to the same piconet to which terminal A is the master.

Thus, our proposed method can suppress loops by controlling the connections between slave terminals in a piconet. Therefore, even if the flooding-based data packet forwarding method is used, our proposed method can suppress the increase in the amount of data packets and reduce the processing load on the terminals.

5 Simulation experiments

5.1 Proportion of piconets with loops

5.1.1 Overview

In this experiment, to evaluate the performance of our proposed method, we implemented our proposed method on a Bluetooth MANET simulator and conducted simulation experiments for a proportion of piconets with loops on Bluetooth MANETs. Our proposed method is implemented on the Bluetooth MANET simulator to evaluate the performance of our proposed method. The average number of adjacent terminals was varied from 5, 10, 15, and 20, and the effectiveness of our proposed method was evaluated at each terminal density. In the following section, we define the piconet with loops and the proportion of piconet with loops.

Piconet with loops

A piconet with loops refers to piconets in which connections are established between slave terminals. A "loop" in this paper refers only to a length of "3" consisting of three terminals, and does not include a "loop" consisting of four or more terminals. Below is an example of a loop consisting of four or more terminals. Two slave terminals C and D will be in a loop (A-C-D-B-A); if A is master of C, B is master of D, A is master of B, and C becomes another master of D.

Proportion of piconets with loops

This is the proportion of number of piconets with loops to the total number of piconets in the field.

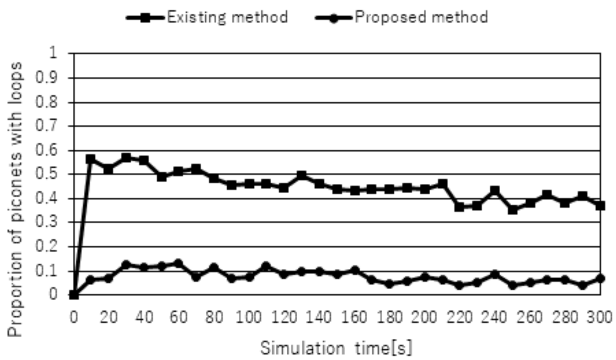
In the following sections, we describe the experimental environment and results.

5.1.2 Configuration of experiments

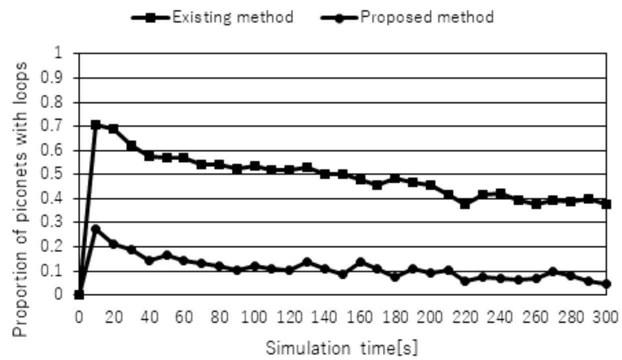
Table 2: Parameters for simulation experiments

Simulator	QualNet ver. 5.0[17]
Number of mobile terminals	32,63,95,125
Field size	$100[m] \times 100[m]$
Range of the radio wave	$22.4[m]$
Average number of adjacent terminals	5,10,15,20
Speed of mobile terminals	$4[km/h]$
Mobility model	Random Waypoint Model
Duration in “Scanning” + “Advertising”	$3[s]$
Duration in “Advertising” only	$7[s]$
Simulation time-length	$300[s]$
Number of trials	10

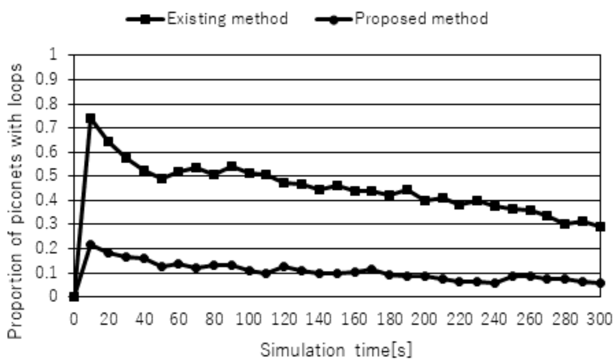
Table 2 shows the parameter values used in this experiment. In this experiment, we implemented the existing and our proposed method on QualNet ver. 5.0, and 32, 63, 95, and 125 terminals were randomly placed in a $100m \times 100m$ field. The value of PDA for each device is also determined randomly. The radio range of each terminal was set to $22.4m$ based on the transmission power and reception sensitivity from the specifications in [10][11]. Based on the size of the field and the number



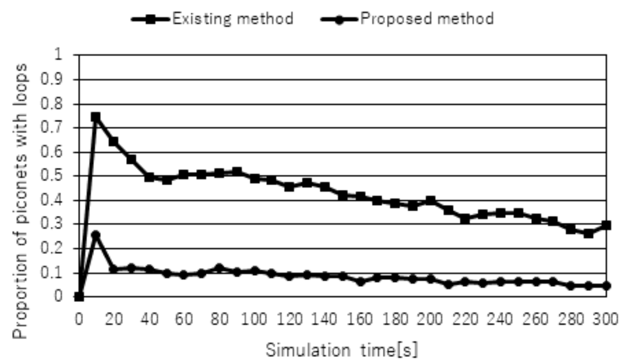
(a) Average number of adjacent terminals: 5



(b) Average number of adjacent terminals: 10



(c) Average number of adjacent terminals: 15



(d) Average number of adjacent terminals: 20

Figure 13: Proportion of piconets with loops when the average number of adjacent terminals is between 5 and 20

of terminals, we set the average number of terminals to be 5, 10, 15, and 20 within the reach of one terminal. The average number of adjacent terminals is calculated by the following equation.

$$\begin{aligned}(average\,number\,of\,adjacent\,terminals) &= (density\,of\,terminals) \times (range\,of\,the\,radio\,wave)\\ &= \frac{(number\,of\,termianls)}{(field\,size)} \times \pi(communication\,radius)^2\end{aligned} \tag{3}$$

In order to make the terminals mobile, each terminal moves according to the Random Waypoint Model (RWP) [22] at $4km/h$, which was the walking speed of a typical human. The average number of adjacent terminals was 15 or 20, assuming a dense environment such as an evacuation center during a disaster. In this environment, we conducted 10 experiments each during a simulation time of $300s$ to measure the proportion of piconets with loops for each method at each terminal density.

5.1.3 Experimental results and discussions

Figure 13 shows the proportion of piconets with loops for each method when the average number of adjacent terminals was between 5 and 20. Figure 13 shows that the proportion of piconets with loops in our proposed method decreased by 0.49 points at most when the average number of adjacent terminals was 5 compared to the existing method. The average difference of the proportion of piconets with loops for each method (hereinafter referred to as the average difference) was 0.37

points. When the average number of adjacent terminals was 10, the maximum decreased was 0.47 points, and the average difference was 0.38 points. When the average number of adjacent terminals was 15, the maximum decreased was 0.52 points, and the average difference was 0.35 points. When the average number of adjacent terminals was 20, the maximum decreased was 0.53 points, and the average difference was 0.33 points. Furthermore, regardless of the average number of adjacent terminals, the proportion of piconets with loops can be reduced to about 0.07 points in 300 seconds of simulation time. This was because our proposed method can reduce the loops caused by the connection establishment between slave terminals in the Bluetooth MANET piconet.From the above results, we believe that our proposed method can reduce the loops regardless of the terminal density.

Next, we discuss the experimental results. At the beginning of the simulation experiment, the proportion of piconets with loops are the highest. This is because at the beginning of the simulation, no piconet have formed and the advertising packet does not contain information about the master's PDA of the piconet to which it currently belongs, so connections are established between slave terminals in the piconet. In addition, as the average number of adjacent terminals increased, the proportion of piconets that have loops at the beginning of the simulation increased. This is because the more the average number of adjacent terminals, the more the number of terminals that can establish connections increased, and the more opportunities there are to establish connections between slave terminals in the piconet. In addition, the proportion of piconets with loops decreased in the existing methods. This is because the mobility of the terminals reduces the opportunities to establish connections between terminals.

5.2 Evaluation of data packet transmission performance

5.2.1 Overview

In the experiments in Section 5.1, we confirmed that our proposed method can reduce the proportion of piconets with loops compared to the existing methods. In this experiment, we measured the number of data packet transmissions to confirm the impact of the reduction in the proportion of piconets with loops on data packet transmissions, and confirmed whether the processing load on terminals can be reduced. In addition, it is important to disseminate data packets to as many terminals as possible in a short period of time during a disaster. Therefore, we measured the data packet dissemination rate and the time it takes to disseminate the generated data packets to all the terminals in the field. In the following, we show the number of data packet transmissions and the data packet dissemination rate.

Number of data packet transmissions

This is the average value of the number of data packet transmissions for each terminal.

Data packet dissemination rate

The data packets dissemination rate is defined as follows: the total number of terminals in the field is N, the number of unique data packets received by the i-th terminal during the simulation time T seconds is $x_i(i = 1, 2, 3 \cdots, N)$, and the number of unique data packets generated by M data packet generating terminals per unit time is m. is defined by equation (4).

$$(data\ packets\ dissemination\ rate) = \frac{\frac{1}{N}\sum_{i=1}^{N} x_i}{M \times T \times m} \tag{4}$$

In the following sections, we describe the experimental environment, results, and discussion.

5.2.2 Configuration of simulation experiments

In this experiment, 10 randomly selected terminals generate and send 10 data packets at the beginning of the simulation in the same environment as in Section 5.1.2. The data packet size set to 50 bytes. In this environment, we conducted 10 experiments to measure the number of data packet transmissions and the data packet dissemination rate for each method at each terminal density for a

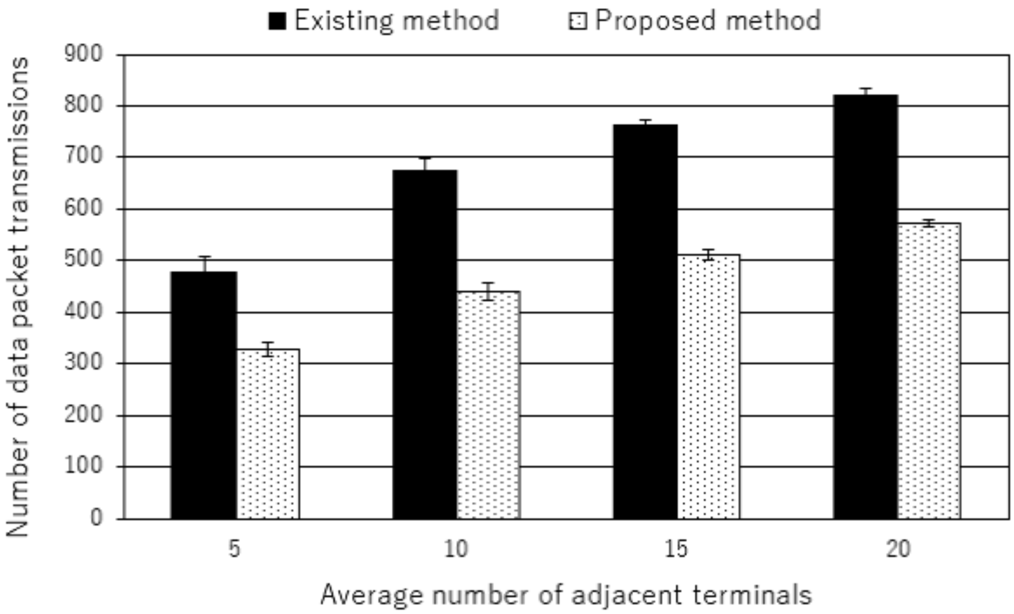


Figure 14: Number of data packet transmissions at each terminal density

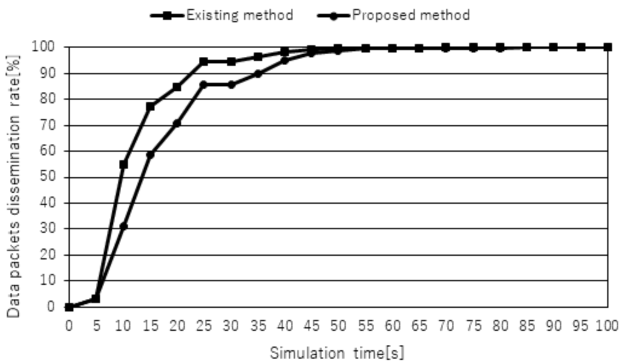
simulation time of 300 seconds. In this experiment, we measured the number of times data packets are transmitted in multi-hop communication, where the effect of loop generation is the largest. For this reason, no the multi-hop waiting time is set for data packets received by each terminal, and no data packets are stored in the buffer for wireless multi-hop transmission.

From equation (4), since each of the 10 terminals generates a unique data packet once every 10 seconds during the 300-second simulation time, the total number of data packets generated by the terminals is $M \times T \times m = 300$. For example, when the average number of unique data packets received by each of the 95 terminals in the field during the simulation time is 270, the data packets dissemination rate is 0.9. 95 indicates the number of terminals N in the field, and 270 indicates the average number of unique data packets received by each terminal $\frac{1}{N}\sum_{i=1}^{N} x_i$ in the simulation time.

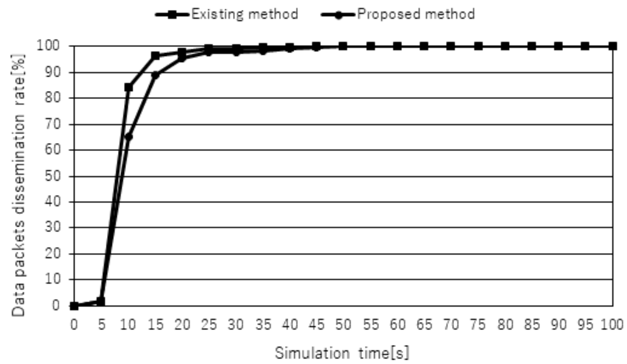
5.2.3 Results of simulation experiments

Number of data packet transmissions

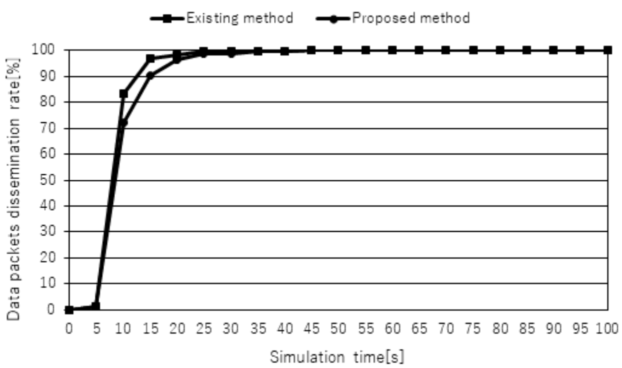
Figure 14 shows the number of data packets transmissions for each method when the average number of adjacent terminals was between 5 and 20. The error bars indicate the 95% confidence interval. Figure 14 shows that when the average number of adjacent terminals was 5, the number of data packets transmissions by the existing method was about 478.5, and that by our proposed method was about 329.3, a decrease of about 31%. When the average number of adjacent terminals was 10, the number of data packets transmissions by the existing method was about 675.2, while that by our proposed method was about 440.1, a decrease of about 35%. Furthermore, when the average number of adjacent terminals was 15, the number of data packets transmissions by the existing method was about 763.9, and that by our proposed method is about 511.8, which was about 33% less. Finally, when the average number of adjacent terminals was 20, the number of data packets transmissions by the existing method was about 820.3, and that by our proposed method was about 572.5, which was about 30% less. From these results, we confirmed that our proposed method can reduce the number of data packet transmissions more than the existing method by reducing the loops regardless of the terminal density. The reason why the number of data packet transmissions could be



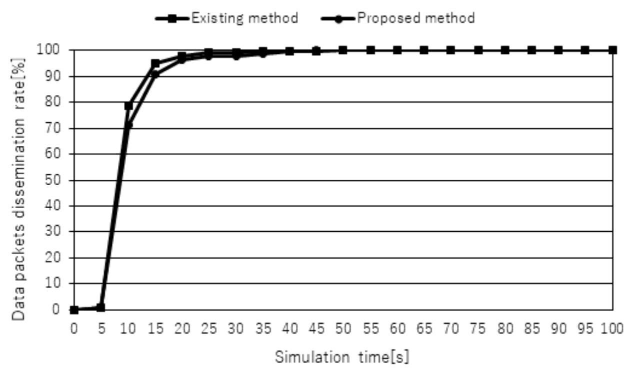
(a) Average number of adjacent terminals: 5



(b) Average number of adjacent terminals: 10



(c) Average number of adjacent terminals: 15



(d) Average number of adjacent terminals: 20

Figure 15: Change in data packets dissemination rate at each terminal density

reduced was that the number of unnecessary connections could be reduced by suppressing the loops. This reduction in the number of data packet transmissions is expected to reduce the data packet processing load on terminals.

Data packets dissemination rate

Since there is a possibility that data packets will not spread due to the suppression of the number of data packet transfers, we investigated the data packet dissemination rate. Figure 15 shows the variation of the data packet dissemination rate for each method with time when the average number of adjacent terminals was 5-20. Figure 15 shows that the data packet dissemination rate in our proposed method reached 100% regardless of the average number of adjacent terminals. In addition, we confirmed that our proposed method can keep the time to complete the data packet dissemination at the same level as the existing method regardless of the average number of adjacent terminals. These results suggest that our proposed method can disseminate data packets to all terminals in the field in the same amount of time as the existing method, regardless of the terminal density.

From the results of the number of data packet transmissions and the data packets dissemination rate, our proposed method can keep the time to complete the data packets dissemination rate at the same level as the existing method while suppressing the number of data packet transmissions.

6 Additional experiments

In the evaluation experiment in Section 5.1, our proposed method could not reduce the fraction of piconets with loops to zero. Therefore, as an additional experiment, in order to investigate whether our proposed method can reduce the proportion of piconets with loops to zero, we conducted an evaluation in an environment where there is no restriction on the payload size of advertising packets and no mobility by Bluetooth MANETs (hereinafter referred to as a fixed terminal environment). In the following sections, we describe the experiment, the experimental environment, and the experimental results.

6.1 Evaluation of the influence of the number of PDAs included in an advertising packet

In this section, we investigated whether the proportion of piconets with loops can be reduced to zero by eliminating the restriction on the payload size of advertising packets in our proposed method and including all PDAs of the masters of the piconets to which the terminals belong in the advertising packets. In our proposed method, the number of PDAs that can be included in an advertising packet is limited to four due to the restriction of the payload size of the advertising packet.

6.1.1 Configuration of simulation experiments

This experiment will be conducted in the same environment as in Section 5.1.2. There is no limit to the number of PDAs to be included in the advertising packet, and all PDAs of the piconet master to which the terminal belongs are included in the advertising packet. In such an environment, we conducted 10 experiments each during a simulation time of 300s to measure the proportion of piconets with loops for each method at each terminal density.

6.1.2 Results of simulation experiments

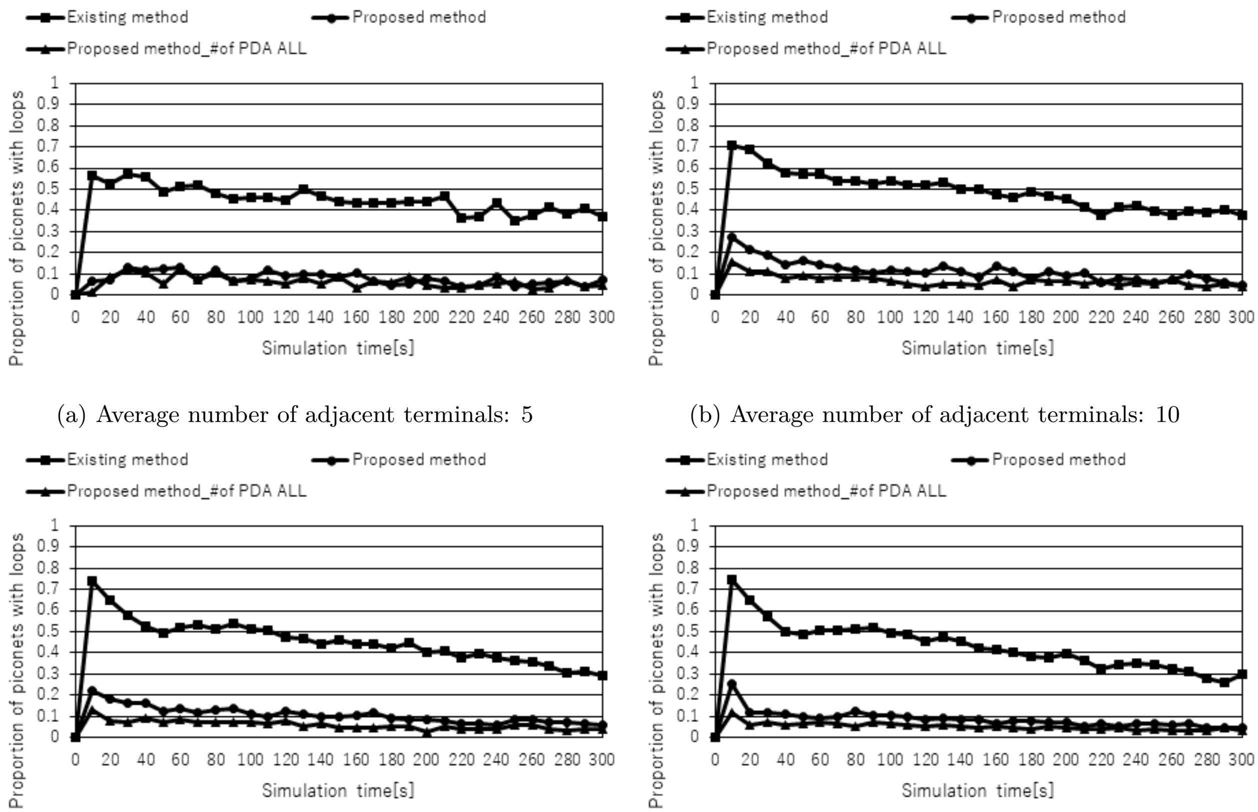
Figure 16 shows the proportion of piconets with loops for each method when the average number of adjacent terminals was 5-20 and the advertising packet payload size restriction was removed. In Figure 16, our proposed method without the constraint of the payload size of advertising packets was denoted as Proposed method_# of PDA ALL. Figure 16 shows that by increasing the number of PDAs in the advertising packet, our proposed method can reduce the proportion of piconets with loops at each terminal density. However, even when all the PDAs of the piconet master to which the terminal belongs were included in the advertising packet, the proportion of piconets with loops cannot be reduced to zero. This indicates that the reason why the proportion of piconets with loops cannot be reduced to zero is not due to the insufficient number of PDAs included in the advertising packet.

6.2 Evaluation of the influence of terminal movement

In this section, we investigated the effect of terminal mobility on the proportion of piconets with loops in our proposed method by eliminating terminal mobility and using a fixed terminal environment. In this section, we investigated the effect of terminal mobility on the proportion of piconets with loops in our proposed method.

6.2.1 Configuration of simulation experiments

In this experiment, each terminal was placed in a fixed terminal environment without mobility in the same environment as in Section 5.1.2. In such an environment, we conducted 10 experiments each during a simulation time of 300s to measure the proportion of piconets with loops for each method at each terminal density.



(a) Average number of adjacent terminals: 5

(b) Average number of adjacent terminals: 10

(c) Average number of adjacent terminals: 15

(d) Average number of adjacent terminals: 20

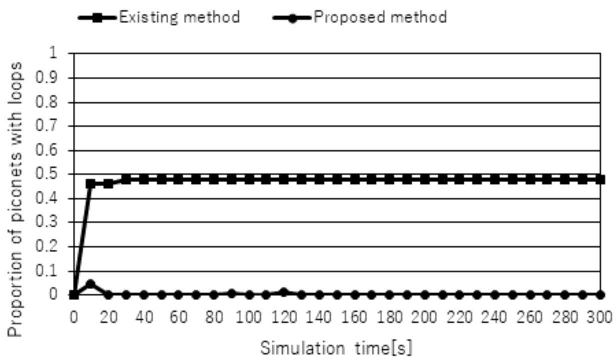
Figure 16: Proportion of piconets with loops at each terminal density when the advertising packet payload size is unconstrained

6.2.2 Results of simulation experiments

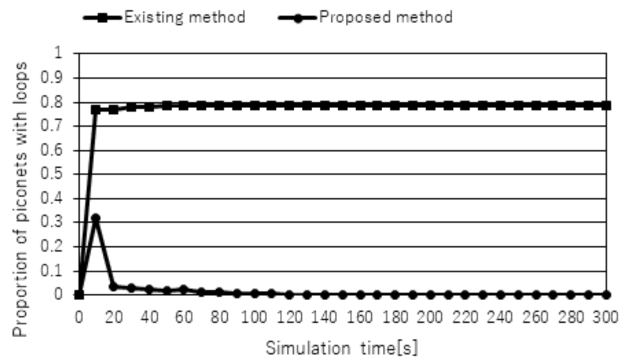
Figure 17 shows the proportion of piconets with loops for each method in a fixed terminal environment, where the average number of adjacent terminals was 5-20. As shown in Figure 17, the proportion of piconets with loops can be reduced to zero by eliminating mobility in a fixed terminal environment for each average number of adjacent terminals from 5 to 20. It is confirmed that our proposed method can reduce the proportion of piconets with loops to zero by changing the RWP to a fixed terminal environment.

6.2.3 Discussion

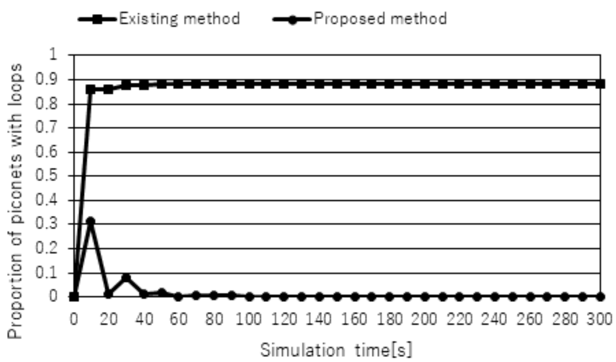
From the results of the evaluation experiments in Section 6.2.2, we confirmed that our proposed method can reduce the proportion of piconets with loops to zero by eliminating the mobility of terminals and creating a fixed terminal environment. On the other hand, the results of the evaluation experiments described in Section 6.1 show that our proposed method cannot reduce the proportion of piconets with loops to zero when the terminal moves according to the RWP, even if all the PDAs of the piconet master to which the terminal belongs were included in the advertising packet. This suggests that the mobility of the terminal may have an effect. One of the effects of mobility is that when a terminal moves according to the RWP, it moves out of the communication range of other terminals and locked into one of the roles of master or slave, but useless in either role due to its lack of connetcion. Next, when the terminal moves within the communication range of the other



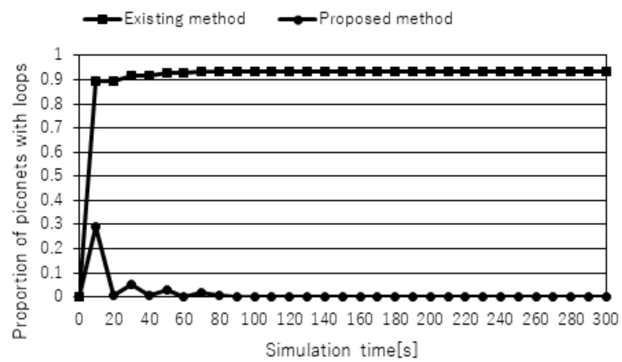
(a) Average number of adjacent terminals: 5



(b) Average number of adjacent terminals: 10



(c) Average number of adjacent terminals: 15



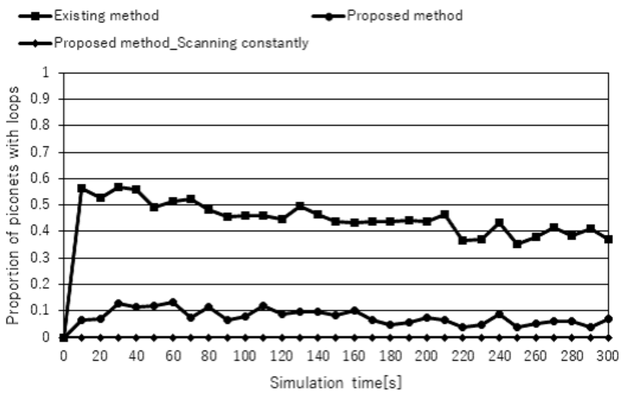
(d) Average number of adjacent terminals: 20

Figure 17: Proportion of piconets with loops in a fixed terminal environment for each terminal density

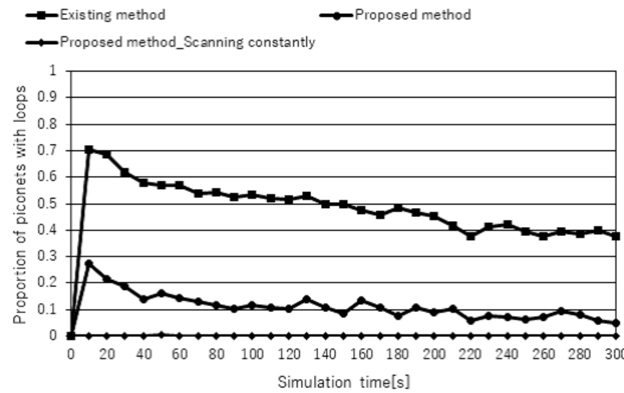
terminal again and establishes a connection, the advertising packet does not contain the information of the master's PDA of the piconet to which the terminal currently belongs, so the connection between slave terminals cannot be suppressed, resulting in the formation of loops. In addition, the existing and proposed methods cannot receive and process advertising packets when the terminal does not scanning, so they cannot break the loops that have already been formed. The experimental parameters in Table 2 show that the terminal is not scanning for 7 seconds out of 10-second cycle. In the case of a fixed terminal environment, if a loops exists, it will eventually move to the scanning state, and since it can receive and process advertising packets, it can break the loops. On the other hand, in the case of mobility, even if a loop exists, and if the terminal is not the scanning, it cannot receive and process advertising packets and moves without breaking the loops. The above shows that the proportion of piconets with loops is very small. This indicates that the scanning period of the terminal influences the proportion of piconets with loops. In this way, the scanning period of the terminal is affected.

6.3 Evaluation of the influence of the change in the scanning cycle

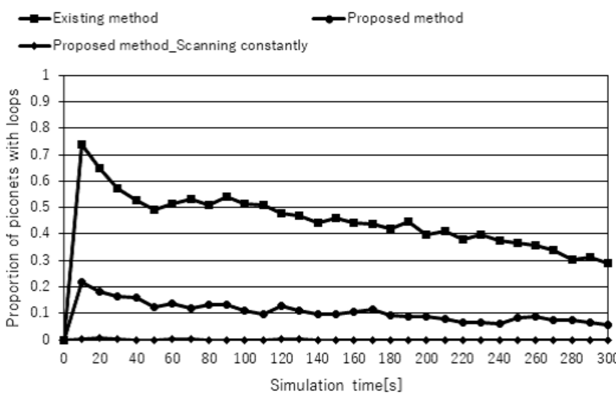
From Section 6.2.3, the scanning period causes loops to remain in our proposed method. Therefore, in this experiment, we change the scanning period as explained in Chapter 3, and investigate whether our proposed method can reduce the proportion of piconets with loops to zero by always scanning the terminals. The experimental environment and results are described below.



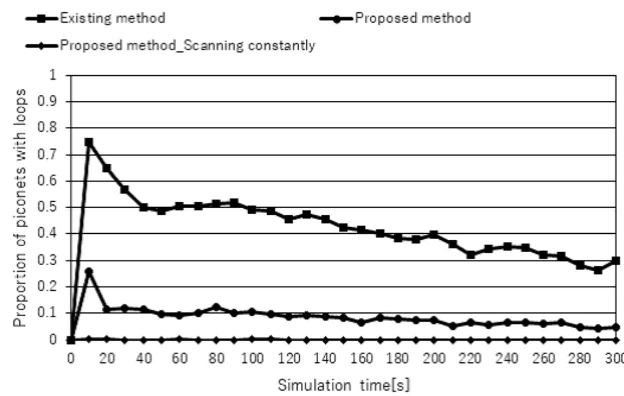
(a) Average number of adjacent terminals: 5



(b) Average number of adjacent terminals: 10



(c) Average number of adjacent terminals: 15



(d) Average number of adjacent terminals: 20

Figure 18: Proportion of piconets with loops when terminals are always scanning at each terminal density

6.3.1 Configuration of simulation experiments

In this experiment, the environment was the same as in Section 5.1.2, with the scanning period changed, and the terminals were assumed to be constantly scanning. In this environment, we conducted 10 experiments to measure the proportion of piconets with loops for each method at each terminal density for a simulation time of 300s.

6.3.2 Results of simulation experiments

Figure 18 shows the proportion of piconets with loops for each method, where the average number of adjacent terminals was between 5 and 20 when the terminal was always scanning in RWP. In Figure 18, our proposed method in which the terminal was always scanning is denoted as Proposed method_Scanning constantly. Figure 18 shows that the proportion of piconets with loops can be reduced to zero for each average number of adjacent terminals between 5 and 20. Thus, by changing the scanning period, to always scanning the loops can be broken reliably because the terminals can receive and process advertising packets by constantly scanning even if they are mobile. As a result, the scanning period of the terminal influences the proportion of piconets with loops.

7 Conclusion

In this paper, we proposed a method to control the connection establishment between slave terminals in a piconet in a Bluetooth MANET and to suppress the generation of loops. Through simulation experiments, we evaluated the effect of our proposed method on the data packet transmission, and confirmed that our proposed method reduces the proportion of piconets with loops. By reducing the number of loops, our proposed method reduces the number of data packet transmissions and keeps the time to complete the data packet dissemination at the same level as the existing method. As a result, our proposed method reduces the number of data packet transmissions while maintaining the time to complete data packet dissemination at the same level as existing methods. In the future, we will compare and evaluate our proposed method with methods that suppress the number of data packet transmissions by using MPR sets and probabilistic flooding. In addition, it is necessary to investigate the effect of our proposed method on data packet forwarding through experiments on actual machines.

Acknowledgment

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