A Bluetooth Group-Scatternet Formation Algorithm for Efficient Routing

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Abstract

In this paper, we propose a novel algorithm, Group-Scatternet Formation Algorithm (GSFA), is proposed for scatternet construction. GSFA consists of two phases, piconet formation and group-scatternet formation. An efficient routing protocol based on the resulting scatternet of GSFA is also presented in this article. The experimental results show that two-group and three-group scatternets are suitable for the networks with more than 50 devices and for that with less than 50 devices, respectively. The proposed GSFA also outperforms BTCP, TREE, and LINEAR in terms of delay and network throughput.

1. Introduction

Bluetooth is the major low power technology employed in wireless personal area networks (WPAN), especially for short-range wireless ad hoc network communications. Bluetooth operates in the unlicensed Industrial-Scientific-Medical (ISM) band at 2.4 GHz employing a frequency-hopping spread-spectrum (FHSS) technique, where the hopping is performed on 79 RF channels spaced 1 MHz apart. The transmission in the Bluetooth system is based on slotted Time Division Duplex (TDD) scheme, where each slot is 0.625 ms long [1].

In Bluetooth network, every device is identified by its own device address named Bluetooth Device Address (BD_ADDR). One master and up to 7 active slaves form a piconet. The master is responsible for determining the hopping sequence and initiating the connection to slaves. Master-to-slave and slave-to-slave transmissions always start in even-numbered and in odd-numbered time slots, respectively. Multiple piconets in the same area form a scatternet. A device may serve as a relay to participate in more than one piconet on a time-sharing basis. The relay can be the master in one piconet and the slave in other piconets. Figure 1 shows an example of Bluetooth scatternet. The link formation process between the master and slave is described in detail in [1].

A good scatternet topology is an important issue in a Bluetooth network since it can reduce the routing overhead and improve the overall network performance. However the Bluetooth specification doesn't make any mention of scatternet formation. Several Bluetooth scatternet formation schemes have been reported.

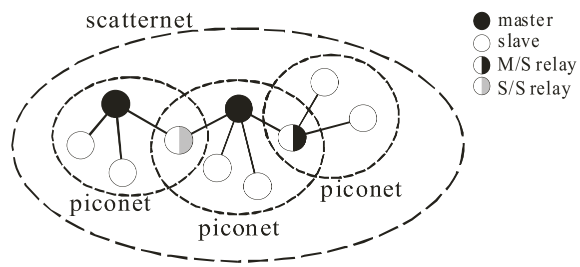

Figure 1. The example of a Bluetooth scatternet with three piconets.

In [9], a clustering algorithm in which a piconet is regarded as a cluster first elects a device as the super-master. Then the super-master collects the information of all devices to generate the piconet. Eventually the connections between two piconets are established to form the scatternet.

A Bluetooth Topology Construction Protocol (BTCP) is proposed in the earlier report [5]. Coordinator election, Role determination, and the actual connection establishment are three major phases in BTCP. BTCP generates multiple routing paths, and the shorter routing path is guaranteed. However BTCP incurs more links and piconets. This approach limits the network to 36 nodes, thus the solution is not feasible for large networks.

Two algorithms, Blueroot Grown Bluetree and Distributed Bluetree, are addressed in [4]. Because the parent nodes in Bluetree are very likely to be the bottlenecks, the resulting scatternet exhibits an inherent deficiency. The drawback of the scheme proposed in [6] is that the piconets may have more than 7 slaves in the resulting scatternets. Several techniques proposed in [7] are used to solve the problems in [6]. However these techniques may be unfeasible because the additional facilities like GPS receiver are required.

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In addition to the metrics the proposed Bluetooth scatternet approaches consider, the goal of this paper is also to minimize the overhead for search packet flooding and to improve the performance for routing. We propose a novel algorithm called Group-Scatternet Formation Algorithm (GSFA) for Bluetooth scatternet formation. The main idea of GSFA is to group the devices according to the congruent relation to their BD_ADDRs. Consequently, the source node can send a search packet directly to the group that the destination node belongs to.

In comparison with the existing solutions, GSFA has the following good properties: (1) GSFA is a distributed scatternet formation algorithm. (2) GSFA is robust because it supports multiple routing paths between any two nodes. (3) The resulting scatternet topology is connected. (4) The allover network is not flooded with search packets for the destination discovery. (5) GSFA has no limitation with regard to number of devices. Moreover, GSFA can really improve the network performance.

This paper is organized as follows. Section 2 mentions our network model and some notations. In Section 3, we elaborate on the proposed GSFA. Following that, we present the simulation results in Section 4 and conclude the paper in Section 5.

2. Network Model and Notations

In the section, we first focus on the properties that the resulting Bluetooth scatternet satisfies. Then we give the notations used in the following sections.

2.1. Bluetooth Scatternet Properties

A good scatternet has some properties such as less piconets, less relay devices, and connected. It is necessary to conform to these properties when designing a faster and robust algorithm for Bluetooth scatternet formation. Here, we propose and discuss the following properties, and the resulting scatternet topology has to satisfy.

Number of piconets

In Bluetooth network, all piconets share the same set of 79 channels of the 2.4 GHz ISM band. More piconets would incur the extra collision, and reduce the network performance. Thus a scatternet with a minimum number of piconets is necessary for routing and maintenance.

Number of relay devices

A relay device is shared with some piconets, and holds active member addresses (AM_ADDR) of these piconets. More relay devices would result in more piconets. As the above properties mentions, less piconets is preferable to constructing Bluetooth scatternet. Thus the minimum number of relay devices should be also concerned.

Connected assurance

To ensure that one Bluetooth device can communicate with others, a path between any two devices is required.

Relay device selection

The master is responsible for intra-piconet communications, thus we has to lighten the load of the master possible. To avoid reducing the network performance, it is reasonable to select the slaves to act as relay devices.

2.2. Notation

We consider an interference-free Bluetooth network in which any two devices are in single-hop distance. The Bluetooth devices' addresses are uniformly distributed. The following two relays are defined for piconet connection.

Internal Relay (IR)

Internal relay is a relay between two piconets within the same group. It is a slave randomly assigned by the master. Each piconet has only one internal relay.

External Relay (ER)

External relay is a relay between two piconets within the different groups. It is a slave randomly assigned by the master. Each piconet has only one external relay.

The basic notations used in the paper are defined in Table 1.

Table 1. The number of *ER*s in the different group.

Notation	Description
N	The number of Bluetooth devices in the network
N_g	The number of groups in the network
B_x	The BD_ADDR of node x

In GSFA, congruence grouping is a critical idea fro scatternet formation. Let g_i be the group that node x belongs to. The suffix i is the group id calculated from

$$i = B_x \bmod N_g$$

Let G_i be the set of nodes that belong to g_i. G_i is obtained by

$$G_i = \{B_x \mid B_x \bmod N_g = i,\ 0 \le i \le N_g\text{-}1,\ i \in Z\}$$

3. Group-Scatternet Formation Algorithm

In the initial network, all Bluetooth devices are separated into groups according to the congruent relation between their BD_ADDRs and the number of groups. Before communicating with other devices, a Bluetooth device has to be assigned as the master or slave. The master/slave role determination is discussed in various studies [2] [3], and is out of scope of this paper. Here we apply the approach proposed in [2] to determine the role of all slaves.

3.1. Piconet Formation

The main idea of this phase is to generate the as less number of piconets as possible. As a result, a distributed mergence procedure called intra-group piconet mergence is used to combine two piconets to reduce the number of piconets. The rule applied in the procedure is that for two piconets, the piconet with more slaves merges the other. If the number of slaves of two piconets equals, either one randomly selected merges the other. The details are specified as follows.

Let S(x) be the set of slaves of master x, and |S(x)| be the number of elements in S(x).The value of |S(x)| is between 0 and 7. The AM_ADDR field in FHS packet is not used during the inquiry and inquiry scan procedures. We keep |S(x)| in AM_ADDR field for piconet mergence. In any piconet, two links are reserved for IR and ER connection. The maximum number of slaves are allowed to connect with the master is 5 in this phase. Consequently, the piconet mergence procedure would form the piconets with at most 5 slaves as possible. Figure 2 illustrates three cases during the piconet mergence.

If the number of slaves of the master reaches to 5, or there is no any communication made in any two devices for the predefined period, we proceed to the second phase described in next section to form a group-scatternet. The example generated from this phase is shown in Figure 3.

3.2. Group-Scatternet Formation

During this phase, all masters have to create their own relay table to record the group(s) that they connect to. The relay table stores the AM_ADDRs of all ERs and their group id. Figure 4 shows an example of the relay table. The main objective is that when looking for the routing path, a master first checks its relay table. If the group id of the destination is in the relay table, the packet is delivered into this group directly. This manner not only speeds up the routing path establishment, but also reduces the search packets flooded in the network.

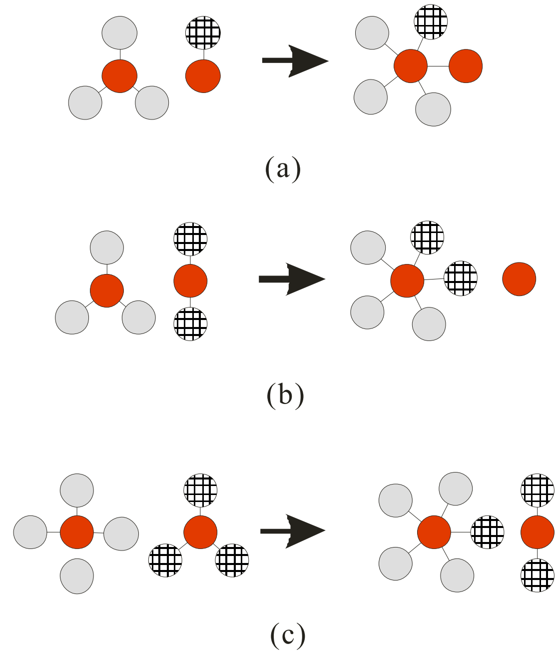

Figure 2. Three cases of piconet mergence. The left and right sides of the arrow are the statuses before piconet mergence and after piconet mergence, respectively.

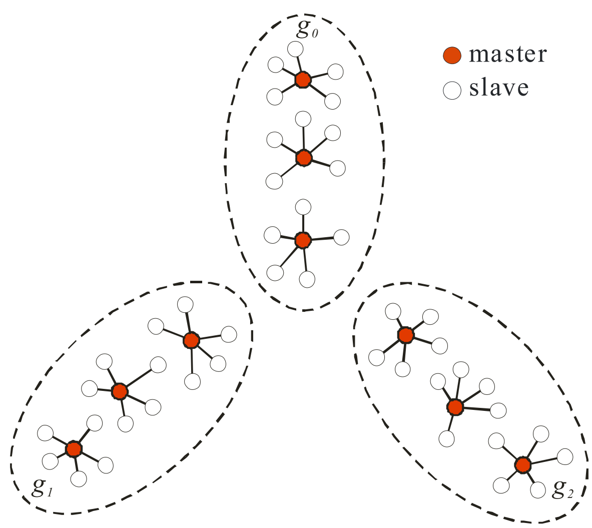

Figure 3. An example generated from the phase of piconet formation. The number of groups is 3, and the group id is numbered clockwise form 0 to 2. There are three piconets within each group.

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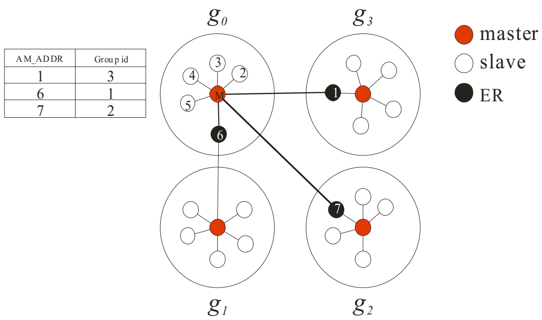

Figure 4. An example of relay table.

This phase consists of two parts, intra-group piconet connection and inter-group piconet connection. They are performed in distributed fashion. To speed up the route discovery and routing are two major objectives in this paper. We employ ring and complete connected on intra-group and inter-group piconet connection, respectively.

During the intra-group piconet connection, assume that a group has three piconets, P_1, P_2, and P_3. M_1, M_2, and M_3 are the masters of P_1, P_2, and P_3, respectively. IR_1, IR_2, and IR_3 are the masters of P_1, P_2, and P_3, respectively. Ring topology means that each piconet has a direct link to two other piconets, and a wraparound connection between the piconets at the end. Hence M_1 will make the connection to IR_3 according to Bluetooth link formation process. The connections between M_2 and IR_1, as well as M_3 and IR_2 are established in the same manner. Figure 5 shows a result of intra-group piconet connection.

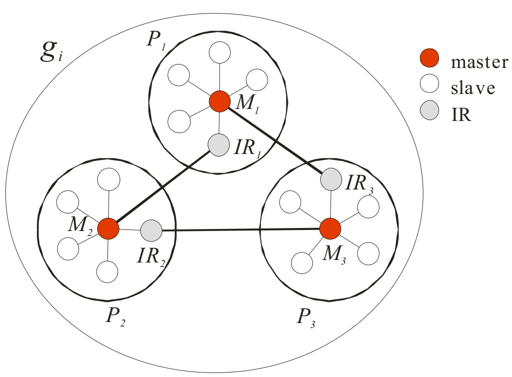

Figure 5. A ring topology with three piconets within a group.

In Section 2, we mention that connected assurance is one of the criteria for developing an efficient scatternet formation algorithm. Consequently, the scatternet based on GSFA is generated by connecting the groups in complete fashion. That is every piconet has link to other piconet within the different groups. Figure 7 shows a resulting group-scatternet generated by GSFA.

For each piconet, the number of links of master connecting to the slaves is at most 7. Two links have to be reserved for intra-group piconet connection. The rest (i.e., at most 5) of links are allowed to connect to the piconet(s) within the other group(s). Namely, these links are all reserved for ERs. It is quite obvious that the number of the groups in the network is limited to 6. All cases of group interconnection are illustrated in Figure 7. The number of ERs in the different groups is shown in Table 2.

A robust and efficient routing scheme on the scatternet generated by GSFA is proposed. Due to lack of space, the elaborate description of routing protocol is represented in [8].

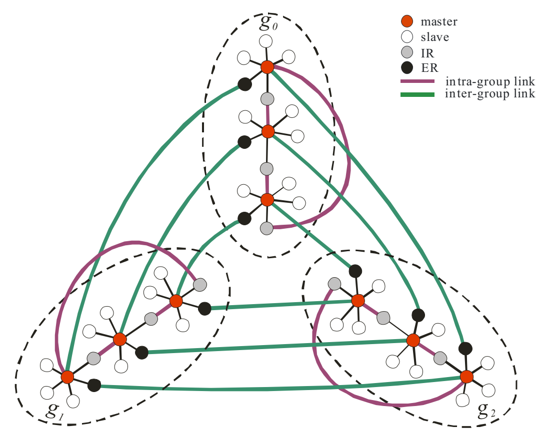

Figure 6. A resulting group-scatternet generated by GSFA.

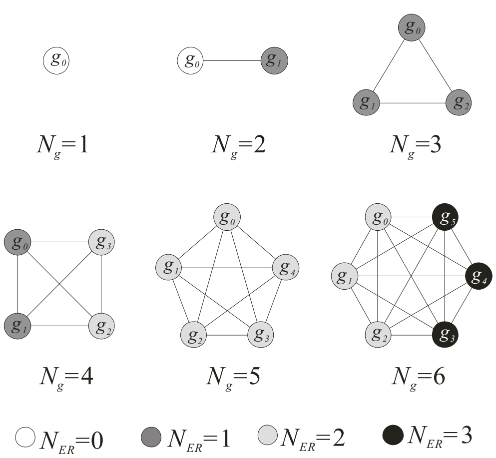

Figure 7. All cases for group interconnection. N_{ER} is the number of *ER*s.

Table 2. The number of *ER*s in the different group.

N_g	Group id	No. of *ER*	N_g	Group id	No. of *ER*
1	0	0	1	-	-
2	0	0	2	1	1
3	0, 1, 2	1	3	-	-
4	0, 1	1	4	2, 3	2
5	0, 1, 2, 3,	2	5	-	-
6	0, 1, 2	2	6	3, 4, 5	3

4. Simulation results

In our simulation model, the topology of the Bluetooth network is initialized according to the number of devices assigned in advance. The BD_ ADDR and the hopping sequence of each device are also produced randomly. We focus on the variations in the significant metrics for each number of nodes 10, 20, 36, 50, 80 and 100. The metrics we concerned are number of piconets, links, and scatternet construction time as well as network throughput and delay. In addition, to simulate the network throughput and the transmission delay, the Poisson distribution with arrival rate 20 packets per second per node and the exponential distribution with the mean 500 are involved to determine the frequency of data transmission and the length of data, respectively. Besides, we investigate the performance of GSFA by comparing with some solutions proposed in [5], [6] and [7].

Figure 8, Figure 9, and Figure 10 show the results that more groups incur more piconets, links, and construction time. It is obvious that more ERs for inter-group connections are produced. And more links accompany more construction time.

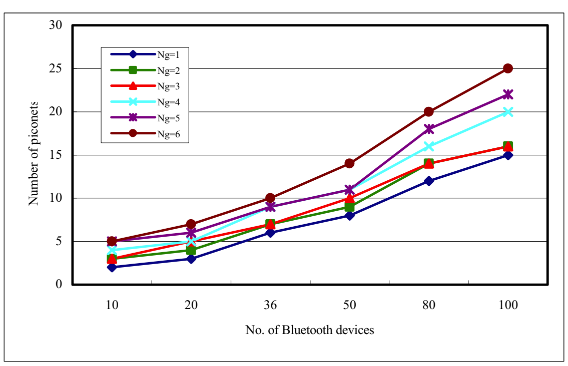

Figure 8. Number of piconets for the different number of nodes with N_g is 1, 2, 3, 4, 5 and 6.

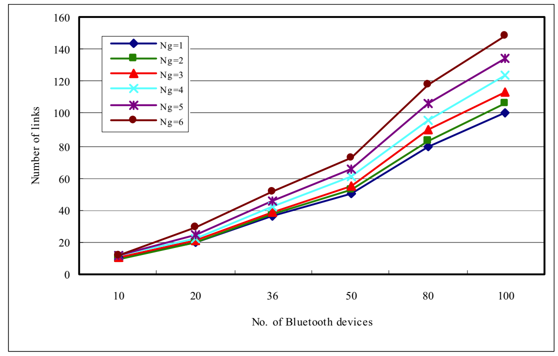

Figure 9. Number of links for the different number of nodes with N_g is 1, 2, 3, 4, 5 and 6.

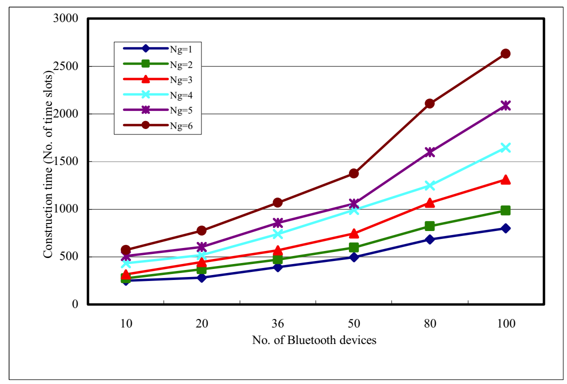

Figure 10. The scatternet construction time for the different number of nodes with N_g is 1, 2, 3, 4, 5 and 6.

In Figure 11, we find that the more groups, the higher the throughput. That's because more paths exist in the network and more search packets received in the destination. It's evidently that more groups may cause less delay because of less hop counts. The result is revealed in Figure 12.

From the above simulation results, the scatternet with more groups leads to high network throughput and lower packet delay, while more piconets and links are generated. When applying two or three-group scatternet, we find that the construct time, the number of piconets and links are slightly more than that produced by GSFA without any group, however the network throughput significantly increases. In comparison with the network with more than three groups, the construct time increases, and the improvement in the network throughput is not outstanding. Consequently we summarize that two or three-group is suitable for scatternet formation.

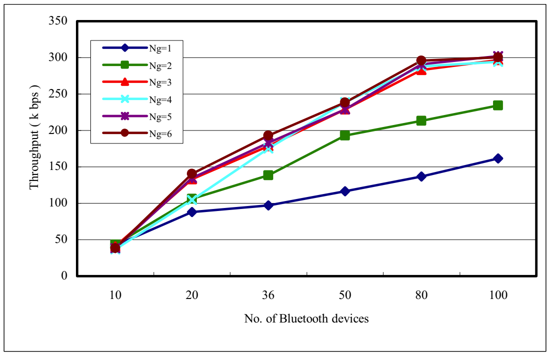

Figure 11. Throughput for the different number of nodes with N_g is 1, 2, 3, 4, 5 and 6.

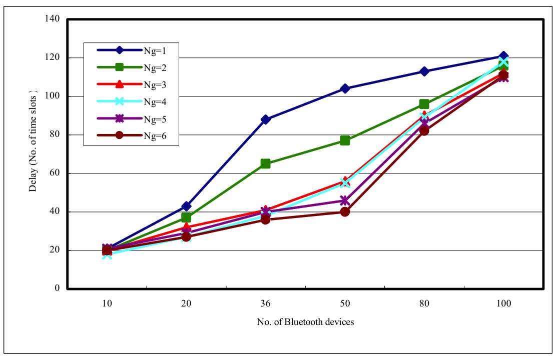

Figure 12. Delay for the different number of nodes with N_g is 1, 2, 3, 4, 5 and 6.

Some additional experimental results are illustrated in Figure 13, Figure 14, Figure 15, Figure 16, and Figure 17. It is apparent that the performance of GSFA is superior to those of other approaches. We find that two-group and three-group scatternet topologies are the best alternatives for the nodes that are over 50 and for that are less than 50, respectively.

5. Conclusions

In this paper, we explicate a distributed method named GSFA to construct the Bluetooth group-scatternet. GSFA depends on the congruent relation of BD_ ADDRs of all devices to divide all devices into groups. Then two major phases, piconet formation and group-scatternet formation are performed. The scatternet topology based on GSFA is fully connected because at least one link exists between any two groups. In addition, the resulting group-scatternet is robust as a result of multiple paths between any two devices. Moreover, the search packets need not to be flooded in the resulting network for routing.

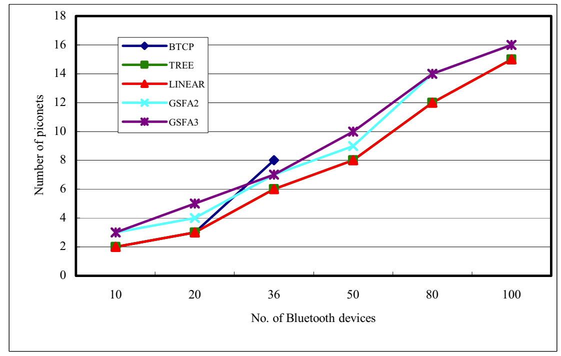

Figure 13. Number of piconets for the different number of nodes with different approaches.

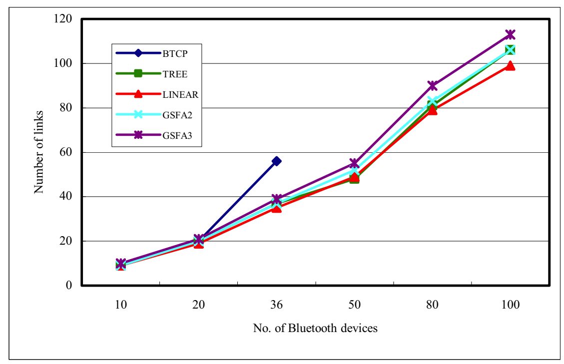

Figure 14. Number of links for the different number of nodes with different approaches.

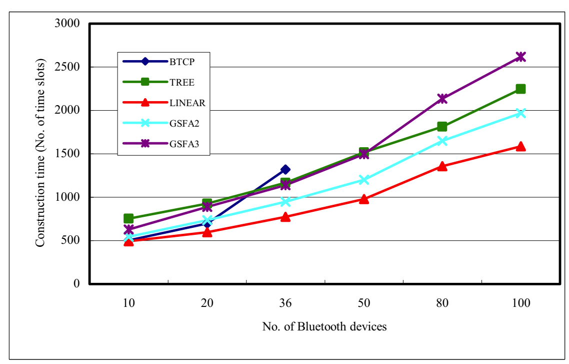

Figure 15. The scatternet construction time for the different number of nodes with different approaches.

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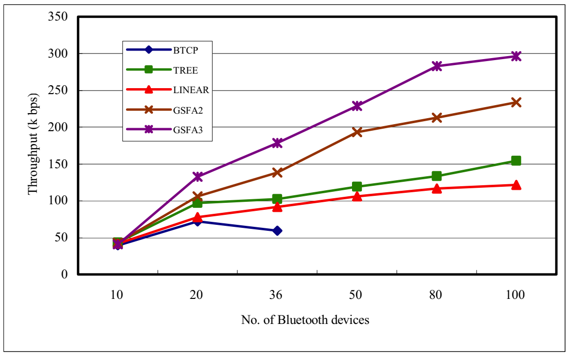

Figure 16. Throughput for the different number of nodes with different approaches.

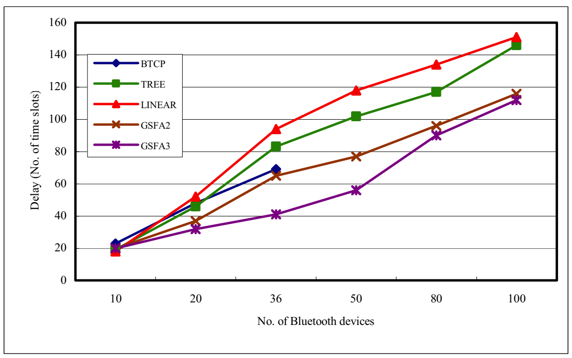

Figure 17. Delay for the different number of nodes with different approaches.

Through the experiments, the scatternet is constructed quickly by GSFA in comparison with other related works. The performance of GSFA with two or three-group is also better than that of using BTCP, TREE, and LINEAR in most cases. Three-group scatternet topology is especially suitable for the network with less than 50 nodes, while two-group scatternet is preferred when the number of nodes exceeds 50.

In Bluetooth network, the packets frequently occur between the devices with the same service. In case these devices are located within the same group, data communications between them may be speeded up. Thus, our feature work is also to evaluate the feasibility of grouping the Bluetooth devices by the services they provide.

Acknowledgement

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