Solidring: A Novel Bluetooth Scatternet Structure

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Summary

Designed as a short-range wireless communication technology, Bluetooth enables voice and data communication between devices. A Bluetooth scatternet enables more devices to be included and covers a larger area. A number of scatternet structures have been designed, taking into consideration easy initialization, simple routing or lower energy consumption, etc. However, another important factor, that of time delay has been ignored until now. In this paper, we propose a new scatternet structure, called the Solidring, and a routing algorithm to achieve a lower time delay. In the Solidring, more routes exist between devices and these routes are shorter on average than those in other structures. In addition, the routing algorithm avoids crossing devices as much as possible. These characteristics help to reduce the time delay. Simulation results show that the Solidring can provide a significantly lower time delay.

Key words:

Bluetooth, scatternet structure, Solidring, time delay.

1. Introduction

As an emerging technology, Bluetooth has received much attention in recent years. It is a promising new technology for short-range wireless communication, developed and promoted by the Bluetooth SIG (Special Interest Group). By using the unlicensed 2.4 GHz ISM (industrial, scientific, medical) band, Bluetooth devices knowingly communicate within a local area. Intended as a replacement for interconnecting cable, Bluetooth is capable of both voice and data communication. In addition, Bluetooth has the characteristics of low cost and low energy consumption [1, 2].

Before communication is possible, Bluetooth devices form a mini network, called a piconet, in which one device acts as the master to manage the piconet and the other devices serve as slaves. A piconet supports 1 master and up to 7 slaves, with the result that only 8 devices can be included.

On account of the limited number of devices, one piconet is usually not sufficient for real applications. To solve the problem, the Bluetooth specification defines an extended network structure, called a scatternet, to interconnect overlaying piconets as one network. A Bluetooth device can act as master in one piconet and as slaves in several other piconets simultaneously. A device existing in several piconets is known as a bridge device. Using such bridge devices, piconets connect with one another to build a scatternet.

Scatternets are generally implemented in two different environments. In the first environment, not all Bluetooth devices can communicate directly with one another, and must therefore communicate through multihop routes provided by the scatternet. The second environment is a single hop environment, in which devices can communicate with one another directly, but if there are more than 8 Bluetooth devices, one piconet cannot include all the devices. Setting up temporary piconets results in many problems and lowers the performance, and thus, a well managed scatternet is necessary in a single hop environment.

A complete scatternet structure includes both the network formation and corresponding routing algorithm. The network formation ascertains how the Bluetooth devices should combine to form the scatternet, while the routing algorithm provides the communication routes. Inside a scatternet, most of the communications are transmitted through multihop routes, in which the data is forwarded through individual hops. This process is one of the sources of time delay, because Bluetooth devices must execute communication switching processes to maintain data transmission. The other source of time delay is crossing devices. When two or more communications pass through the same device, they block each other and generate a time delay. The details of this are described in Section 3.

Most of the available scatternet structures have been designed with more emphasis on easy initialization, simple routing or lower energy consumption, etc., while ignoring the time delay [3-13]. In this paper, we propose a new scatternet structure, called the Solidring, together with its routing algorithm to minimize the time delay. The underlying principle of the Solidring is to combine a number of ring structures into a hyper ring structure. Compared to a ring structure, the Solidring typically has shorter routes and provides more routes for communications. Its routing algorithm is designed to avoid crossing devices as far as possible. Simulation results show that the Solidring can provide significantly lower time delays in a single hop environment.

The rest of the paper is organized as follows. Section 2 explains the Bluetooth communication mechanism. In Section 3, the time delay in a scatternet is described and analyzed in detail. Solidring and its associated routing algorithm are presented in Sections 4 and 5, respectively. Simulation results are introduced and analyzed in Section 6. Finally, conclusions are presented in Section 7.

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2. Bluetooth Communication Mechanism

Bluetooth technology has been developed and promoted by the Bluetooth SIG as a global solution to short-range wireless communication operating in the unlicensed 2.4 GHz ISM band. Bluetooth radio employs a fast (1600 hops/s) FH-CDMA technique. A set of 79 channels with 1-MHz carriers has been defined at 2,402 + k MHz (k= 0, 1, … , 78). A pseudorandom hopping sequence with a hop dwell time of 625 seconds is derived from the BD Address (Bluetooth Device Address) and is unique to each device.

Before communicating, Bluetooth devices must construct a mini network, called a piconet. The initiating device positions itself as master and creates the piconet with a pseudorandom hopping sequence determined by its BD Address. The master detects neighboring devices and invites them into the piconet. Participating neighbors serve as slaves in the piconet and follow the hopping sequence and timing of the master. Each slave establishes a point-to-point link with the master via a two-step procedure that includes an inquiry process and a paging process. The initialization steps are illustrated in Fig. 1, while the details of the inquiry and paging processes are described in the next few paragraphs.

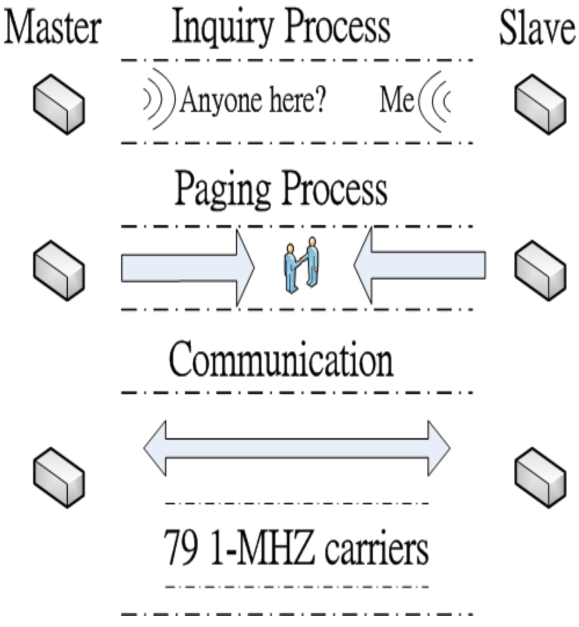


Fig. 1. Initialization steps

Inquiry Process: This process discovers the existence of neighboring devices and collects relevant information from them, such as BD Address and clock. In this process, the master device continually probes different hop channels and listens for responses. Neighboring devices scan the inquiry channel periodically. When a neighboring device detects the master for the first time, it enters a random backoff state to prevent other neighbors from responding at the same time. The master device then obtains the BD Address and clock information from its neighbors.

Paging Process: With the BD Address and clock information of its neighbors, the master can contact a desired neighbor via the paging process. This is very similar to the inquiry process. The page hopping sequence is decided by the BD Address and clock of the paged neighbor. The master estimates the current scan frequency of the neighbor, enabling the neighbor to detect the invitation from the master quickly and thus reducing the paging delay.

After setting up a synchronization and physical channel via the inquiry and paging processes, data transmissions can be carried out and a piconet is initialized. Within the piconet, only master-slave pairs are able to communicate. A slave is forbidden to communicate directly with other slaves and thus all inter-slave communications must pass through the master device.

It must be emphasized that the transmission channel of a piconet is fundamentally determined by the clock of the master. This means that a device cannot act as the master in two piconets simultaneously, because in this case, the two piconets would have the same communication channel, resulting in significant co-channel interference between the piconets [1, 14, 15].

The Bluetooth specification allows a device to be the master in one piconet and slaves in several other piconets simultaneously. Devices that exist in several piconets are called bridge devices, and these interconnect piconets to form a scatternet.

Figure 2 illustrates two cases of bridge devices. In case 1, the bridge device acts as a slave in both piconets and is called a slave/slave bridge. In case 2, the bridge device is called a master/slave bridge, because it acts as a slave in piconet 1 and the master in piconet 2. All bridge devices are classified as one of these two types.

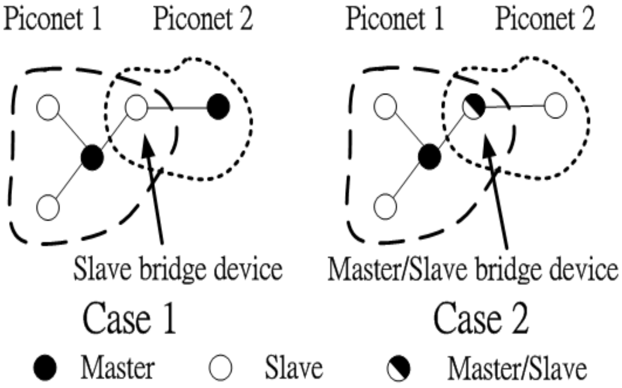


Fig. 2. Two classifications of bridge devices

3. Time Delay in a Scatternet

Within a scatternet, most of the communications are carried out using multihop routes that include a number of Bluetooth devices. Along the route, data is forwarded through Bluetooth devices one by one. During the transmission, posterior devices have to wait for the data transmitted from anterior devices. Such a data transmission process generates considerable time delays. Furthermore, the time delay increases proportionally to the route length, which is equal to the hop number along the route. A way to reduce this time delay is to shorten the route.

A further problem is that bridge devices must frequently switch between piconets and this switching process also results in time delay. For example, suppose that a bridge device exists in two piconets. After receiving the data from an anterior device, the bridge device must send the data to its posterior device. However, as it is not active in the same piconet as the posterior device, a switching process must be carried out. Thus, the bridge device suspends itself in the first piconet and waits to become active in the new piconet. During the switching process, a time delay will result if the new and old piconets do not have synchronized time slots. This time delay is expected to be up to one time frame, 1.25 ms, as defined in the Bluetooth specification. Any number of bridge devices may exist along a route and each of these repeats the switching process with a time delay of up to 1.25 ms. As a result, the accumulated time delay can become significant.

The example illustrated in Fig. 3 depicts 4 Bluetooth devices with data being transmitted from device 1 to device 4. Devices 1, 2 and 3 form piconet 1, while devices 3 and 4 are part of piconet 2. The time delay includes transmitting times of all hops and the switching process of device 3. Originally, device 3 is active in piconet 1. In transmitting data to device 4, device 3 must suspend itself in piconet 1 and switch to piconet 2. The time delay along the route is generated according to the description given previously [16, 17].

The time delay along the route is generated by the Bluetooth and scatternet mechanisms themselves and as such is an inherent property of Bluetooth and scatternet. The best solution is to shorten the route, thereby decreasing the time delay accordingly.

Time delay also emanates from crossing devices, through which different communications pass simultaneously. When two or more communications pass through the same crossing device, the data transmissions are handled one by one. This means that some communications have to wait for others to complete. Communications could thus be postponed a long time, causing the time delay to be even greater than that along the route.

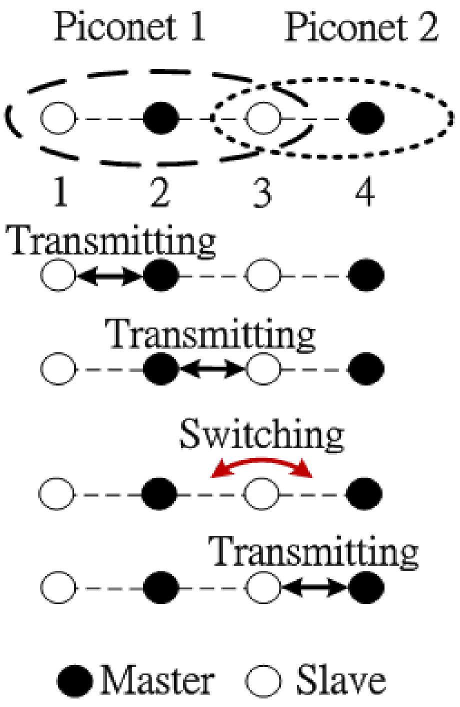


Fig. 3. Time delay from the switching process

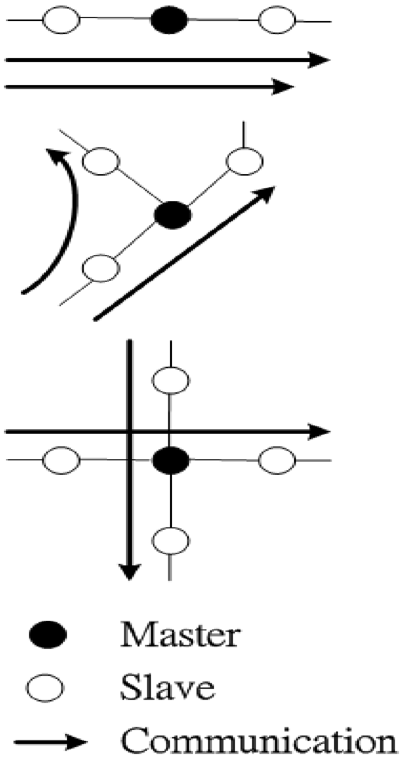


Fig. 4. Examples of crossing devices

Figure 4 shows several examples of crossing devices. In each case, one or more crossing devices exist through which different communications pass. Within the crossing devices, communications are executed one by one. Some communications are transmitted earlier, while others have to wait, thus causing huge time delays in certain cases [18].

In conclusion, there are mainly two kinds of time delay in a scatternet. One is the time delay along the route, which is generated inherently by Bluetooth and the scatternet. The other comes from the crossing devices. When two or more communications pass through the same device, they will influence each other and prolong the communication time.

There are several methods to decrease the time delay. Shortening the route can reduce the number of switching processes and shorten the time delay. Providing more routes between each pair of devices is helpful in eliminating crossing devices. The routing algorithm should also be optimized to avoid crossing devices as far as possible.

4. Solidring Structure

Based on the previous discussion, a new scatternet structure called the Solidring has been designed to shorten the time delay as much as possible. The underlying design principles are to shorten the route and provide more routes for communications. Combined with its routing algorithm, the Solidring can provide a shorter time delay for each communication.

The structure is designed for a single hop environment. All Bluetooth devices are assumed to be within a single hop and can communicate directly with one another. The construction process of the Solidring structure is organized as the following 2 phases.

Phase I. Group Ring Construction

In Phase I, Bluetooth devices are divided into N groups, where N is a preassigned even number. Initially, each device divides its BD Address by the group number N to obtain a remainder that determines to which group the device belongs. For example, if the remainder is 0, the device is assigned to group 0; likewise, if the remainder is 3, the device is assigned to group 3. In this way, devices are distributed among the N groups. Figure 5 gives an example of device assignment, with N set to 4. Devices are allocated to one of 4 groups, depending on the remainder obtained, 0, 1, 2, or 3.

In addition, the groups 0, 1, … , N-1, are categorized as even and odd groups. A device with either the maximum BD Address in an even group or the minimum BD Address in an odd group acts as the leader of that group.

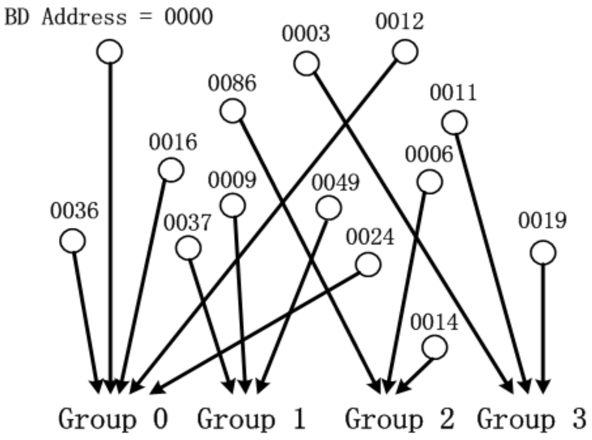


Fig. 5. Device assignment with a group number of 4

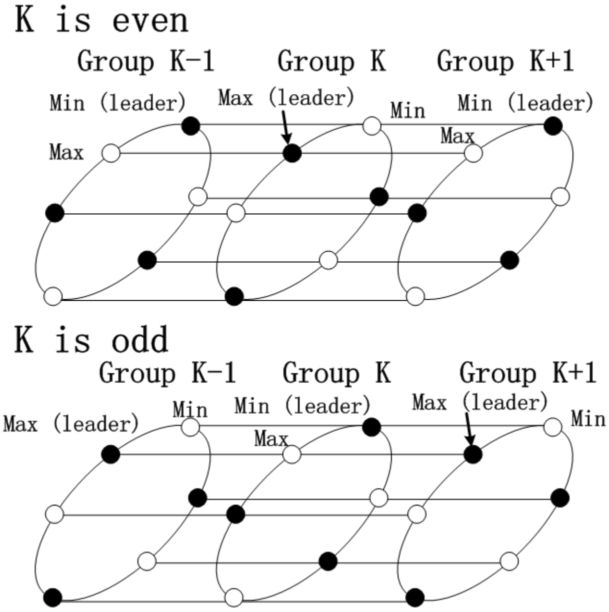


Fig. 6. Groups connecting with one another

Within an even group, the leader sorts the devices according to BD Address. The devices are then connected sequentially in a chain from largest to smallest BD Address. Once all devices have been joined in the chain, the device with the smallest BD Address is connected to the leader to close the chain. The group ring is thus formed and the leader is able to broadcast to all other groups.

Within an odd group, the process is similar, but with opposite rules. The leader of an odd group links the devices from smallest to largest BD Address to form a chain. The device with the maximum BD Address connects with the leader to close the chain. The group ring is thus formed and the leader is also able to broadcast to all groups.

Phase II. Solidring Construction

Once all group rings have been formed, they connect with one another to construct the Solidring structure. Groups *k-1* and *k+1* are neighbors of group *k*, where *k* is a group index in the range [0, N-1]. Specifically, group 0 and group *N-1* are treated as neighbor groups. Neighbor groups connect with each other as follows. In an even group, the leader connects with the two devices having the maximum BD Address in the neighboring odd groups. In an odd group, the leader notifies the device with the maximum BD Address to connect with the leaders of the two neighboring even groups. These connections then proceed one by one along neighboring group rings from the largest BD Address to the smallest BD Address and devices are connected one by one, as shown in Fig. 6.

Once all neighbor groups have been connected with one another, a Solidring structure, as shown in Fig. 7, is constructed. As mentioned previously, the Solidring is a combination of rings that provides both a shorter route and more routes for communications. The routing algorithm is described in Section 5. Simulations are presented in Section 6 to prove that the Solidring provides significantly lower time delays and higher network performance in a single hop environment.

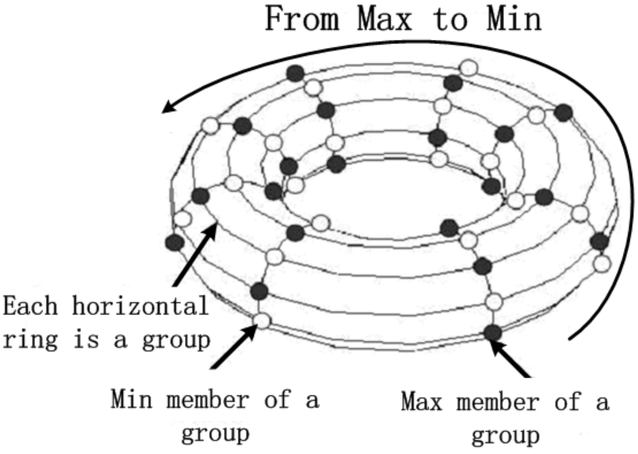


Fig. 7. Solidring structure

5. Routing Algorithm

As described previously, the Solidring structure is constructed under a very strict rule whereby the topological position of each device is determined by its BD Address. Due to this characteristic, the routing algorithm is designed to be simpler and more efficient.

The routing algorithm is implemented in 3 steps, which correspond to finding an available route, a shorter route and a better route, respectively.

Step 1: In this step, the routing algorithm seeks an available route. When one device tries to communicate with another, the BD Address of the destination device is divided by the total group number N. The remainder indicates to which group the destination device belongs. The source device sends a RDP (route-discovery-packet) directly to the specified destination group. On arrival at the destination group, the RDP will be forwarded along the group ring. Having received the RDP, the destination device sends back a RRP (route-reply-packet) to the source device through the newly discovered route. The related information of the route is included in the RRP. This process is illustrated in Fig. 8(a).

Step 2: The aim of this step is to find a shorter route. Because the topological position of a device can be calculated approximately, the source device can predict a shorter route by changing some links along the original route. For example, assuming that the Solidring consists of 8 groups, if the source and destination exist in groups 2 and 8 respectively, the shortest route between the two groups is 2 hops, by passing through group 1 to group 8, and not 6 hops by passing through groups 3, 4, 5, 6, and 7 to group 8. The source device can improve the communication route by following the predictions. A new RDP that includes the potentially shorter route is then sent out. The function of the RDP is to verify the predicted route. If the route does not exist, some links along the route will be changed to seek an approximate shorter route. The final route will be included in a new RRP and sent to the source device. In this step, a shorter route is selected for the communication, as shown in Fig. 8(b).

Step 3: In this step, the routing algorithm tries to find a better route. Taking into consideration crossing devices, a shorter route may have an abnormally longer time delay than a longer route. Thus, a shorter route does not always equate to a better route. The available bandwidths of links should be taken into consideration. In the Solidring, each device keeps a record of current existing communications, expectant communication time lengths and communication requests. Each device can then decide whether to accept a communication request, with the precondition that it has available bandwidth. If a device refuses a communication request, it sends the RDP back to its anterior device to check another equivalent link. Through this process, the RDP arrives at the destination device with the information of the potential routes. The destination device can then select a comparatively less busy and shorter route. The route information is written into the RRP and sent back to the source device. The process in this step is shown in Fig. 8(c).

After completing the 3 steps, the final route is chosen. It is expected to be shorter and avoids passing through crossing devices. Both of these characteristics are helpful in keeping the time delay small.

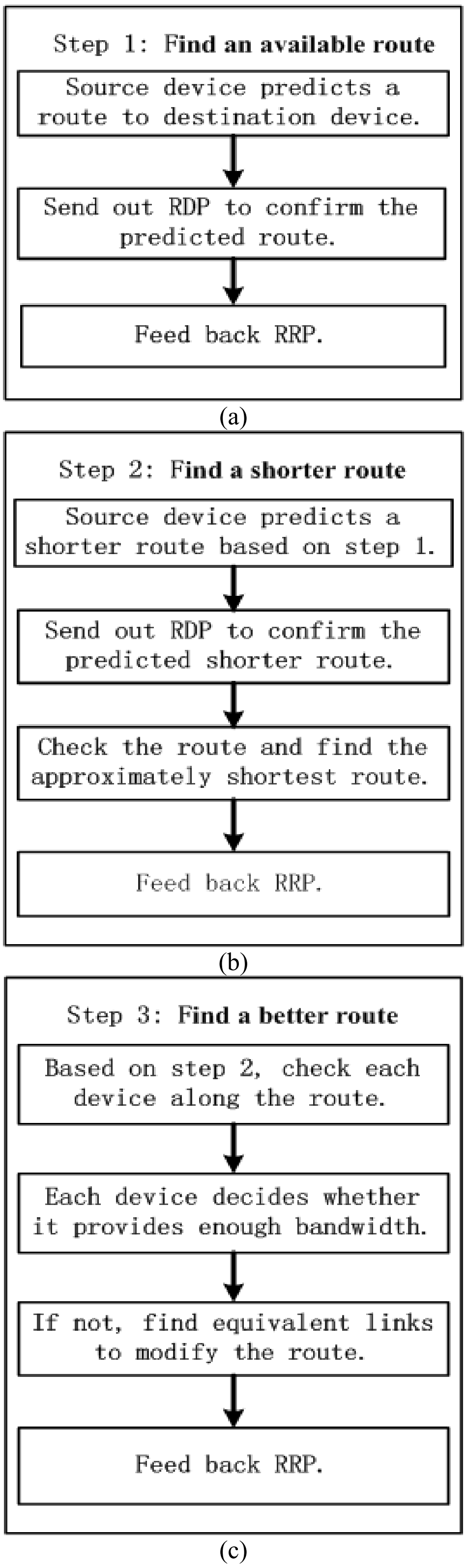
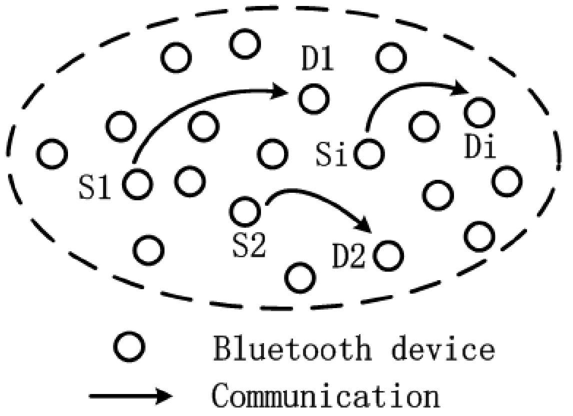


Fig. 8. Steps in routing algorithm

In the design of the Solidring and its routing algorithm, time delay is the primary focus. All the characteristics, such as additional routes, shorter routes and avoiding crossing devices, etc., are effective in lowering the time delay. In the next section, simulation results are presented and analyzed to prove that the Solidring provides significantly lower time delays and higher network performance in a single hop environment.

6. Simulation Results

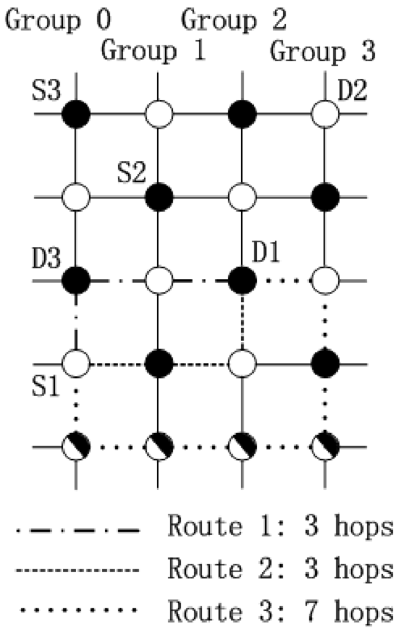
The simulations are programmed in C++. Two of the most popular scatternet structures, the tree [19-21] and ring [22, 23] are simulated and compared with the Solidring. In the simulations, networks are randomly generated with different device numbers of 20, 25, 30, … , 100. In the networks, all devices can communicate directly with one another, which means that any device is located within a single hop. Moreover, device pairs are randomly generated to implement communications. An example network is shown in Fig. 9.



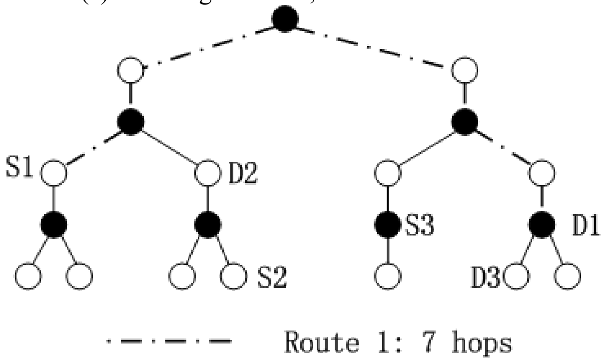
Simulator randomly generate communication pairs, (S1,D1), (S2,D2),…,(Si,Di),…

Fig. 9. Random network and device pairs with device number = 20.

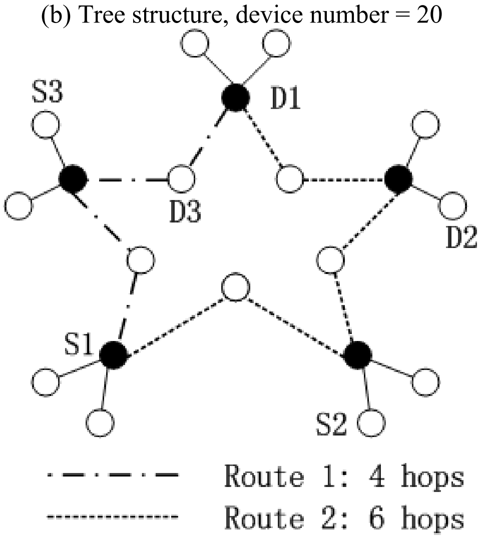
Under these conditions, the three structures are constructed. Figure 10 shows the formation of the three structures with a Bluetooth device number of 20. In Fig. 10(a), 20 devices are divided into 4 groups and organized as a Solidring structure. Because the Solidring is a 3D structure, only a section of the graphic is shown in Fig. 10(a). If there are more devices, the group number in the Solidring structure would be increased accordingly. Figs. 10(b) and (c) illustrate the tree and ring structures respectively, with a device number of 20. Fig. 10 shows the three structures with a device number of 20 only. The three structures become increasingly complicated with greater device numbers.



(a) Solidring structure, device number = 20



(b) Tree structure, device number = 20



(c) Ring structure, device number = 20

Fig. 10. Examples of the three structures

Randomly generated device pairs communicate in the three structures and the respective communication factors are then compared. For example, a device pair is generated with BD addresses of S1 and D1, as shown in Fig. 9. The device specified as S1 communicates with D1 in the tree, ring and Solidring structures. In other words, the same pairs are made to communicate in the three different structures.

Three factors are compared in the simulations: the route number, route length and time delay.

The route number indicates how many routes exist for a specified communication. Figure 10 also illustrates the route numbers for S1 and D1. In the Solidring, there are 3 routes between S1 and D1, instead of 1 route and 2 routes in the tree and ring, respectively. Table 1 provides details of the routes for S1 and D1 in the three structures. More routes mean that there are more alternatives allowing devices to communicate, which is helpful in lowering the time delay. Thus, it is preferable for the route number to be large.

Table 1(a). 3 routes in the Solidring structure

	Route length	*Time delay*	*Recommend*
Route 1	3 hops	0.9 s	○
Route 2	3 hops	1.1 s	
Route 3	7 hops	2.4 s	

Table 1(b). 1 route in tree structure

	Route length	*Time delay*	*Recommend*
Route 1	7 hops	2.9 s	△

Table 1(c). 2 routes in ring structure

	Route length	*Time delay*	*Recommend*
Route 1	4 hops	1.5 s	△
Route 2	6 hops	2.6 s	

The route lengths between S1 and D1 differ greatly in the three structures. As mentioned previously, route length has a close relationship with the time delay. Observing the data provided in Table 1, shorter routes tend to have a lower time delay. In the example, the Solidring has the shortest route length of 3 hops, lower than both the tree and ring structures.

Time delay is not only determined by the route length, but is also influenced by the circumstances along the route. In some cases, a longer route may even achieve a lower time delay than a shorter yet more congested route. The main reason for this is the bandwidth along the route. Initially, no communication exists and each link provides the full bandwidth for communications. Later, some bandwidth is occupied by communications. This means that the available bandwidth of a link decreases, as shown in Fig.11.

The available bandwidth of a link varies with time in the range [0kbps, 512kbps]. An example of the change in available bandwidth is illustrated in Fig. 12.

In the simulations, the available bandwidth of all links changes with time, as shown in Fig. 13, and not all links are able to provide enough bandwidth for a specified communication. Sometimes, a communication is blocked and the time delay increases sharply, especially when passing through crossing devices. This is why the route number is important for lowering the time delay. With more routes, a communication can select a comparatively less congested route and lower the time delay.

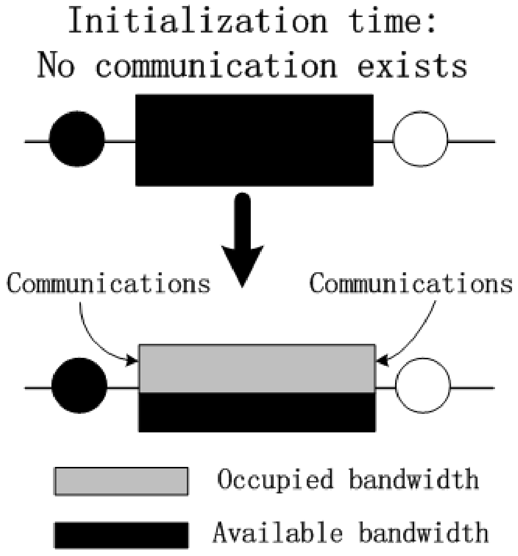
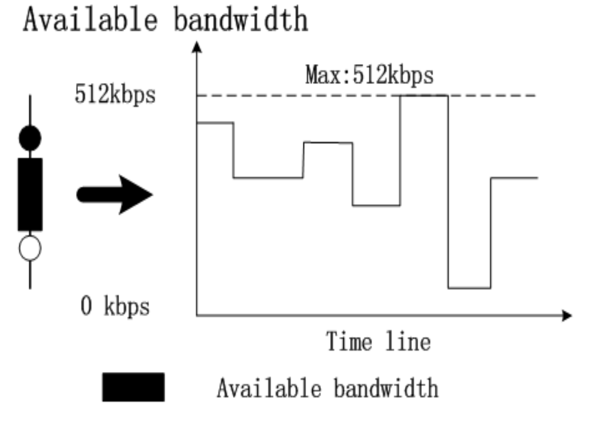
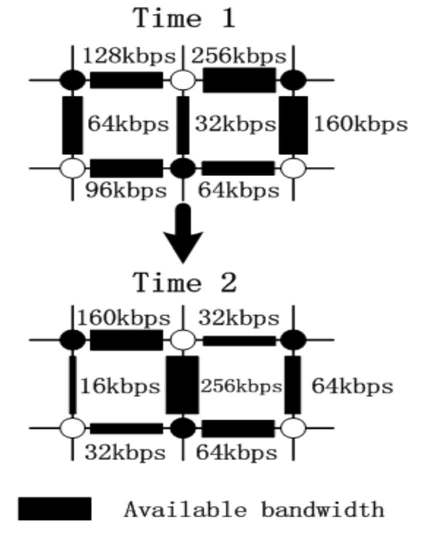


Fig. 11. Available bandwidth of a link



The bandwidth range of a link is from 0kbps to 512kbps.

Fig. 12. An example of how the available bandwidth changes in a link



Available bandwidth of each link changes from time to time.

Fig. 13. Change in available bandwidth of each link

The simulations were carried out thousands of times and the average values for route number, route length and time delay were compared. For *n* communications, the average values of the three factors are calculated using the following equations.

Average Route Number = (Route Number 1 + Route Number 2 + … +Route Number n)/n (1)

Average Route Length = (Shortest Route Length 1 + Shortest Route Length 2 + … + Shortest Route Length n)/n (2)

Average Time Delay = (Shortest Time Delay 1 + Shortest Time Delay 2 + … +Shortest Time Delay n)/3 (3)

The following paragraph provides comparisons of the three factors for the three structures. These comparisons indicate that the Solidring performs better with respect to all three factors, namely average route number, average route length and average time delay.

Figure 14 gives the comparative graph of average route numbers for the three structures. Considering the topology of the tree structure, there is only one unique route between each pair of devices. In the ring structure, there are exactly two routes between each pair of devices. Because the Solidring structure extends in all directions, there are many routes between each pair of devices, as illustrated in Fig. 10(a). As described previously, more routes provide more alternatives and possibly comparatively less congested circumstances for communication. With reference to this factor, the Solidring performs better than both the tree and ring structures.

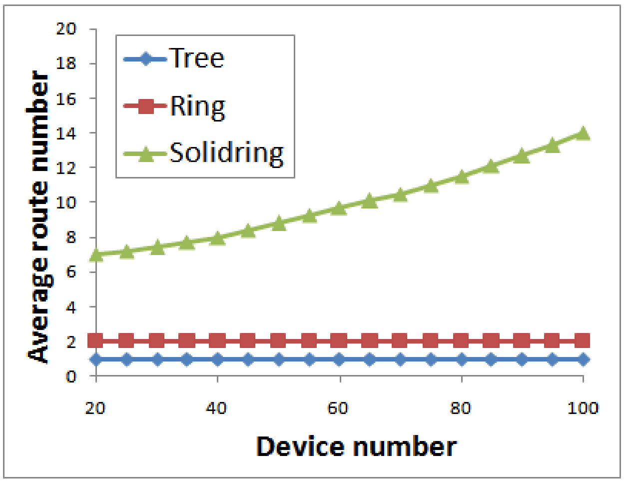


Fig. 14. Average route number

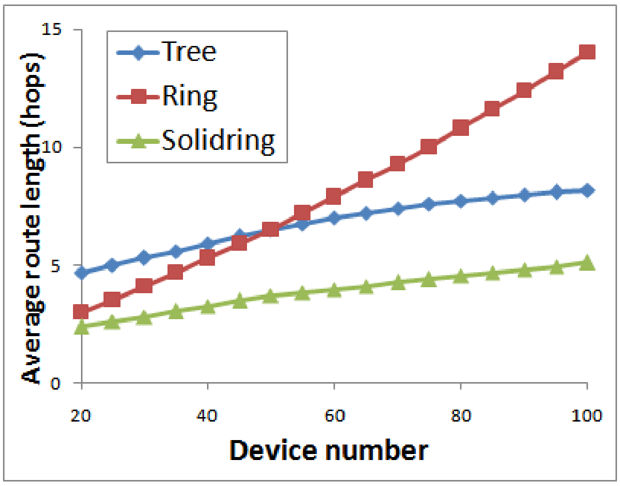
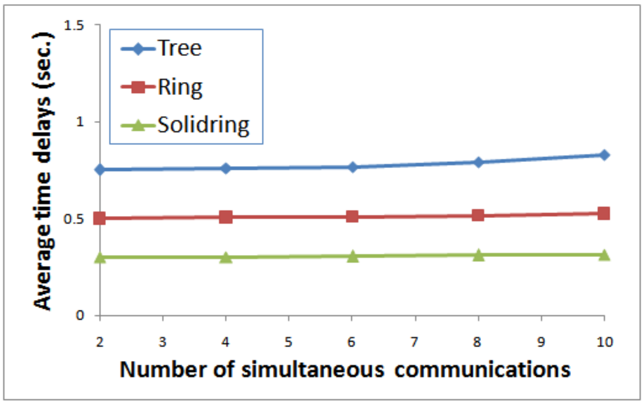


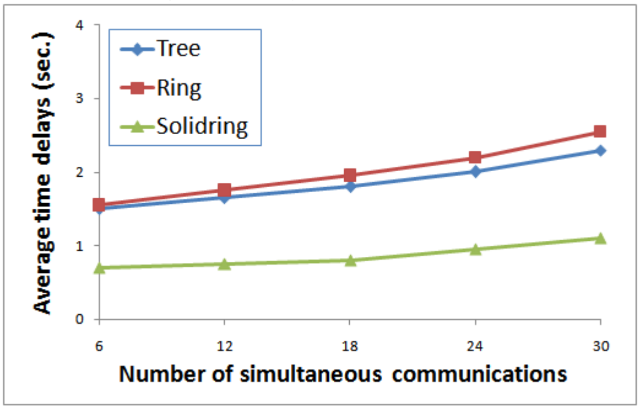
Fig. 15. Average route length (hops)

Figure 15 compares the average route lengths of the three structures. As mentioned previously, route length is closely related to time delay. Shortening the route length lowers the time delay. The simulation results show that the ring has the longest average route length of the three structures. This is reasonable as a ring structure only has one unique route, the ring itself. The route length grows sharply as device numbers increase. The tree structure also has a longer route length than the Solidring structure. In this comparison, the Solidring performs best of the three structures.

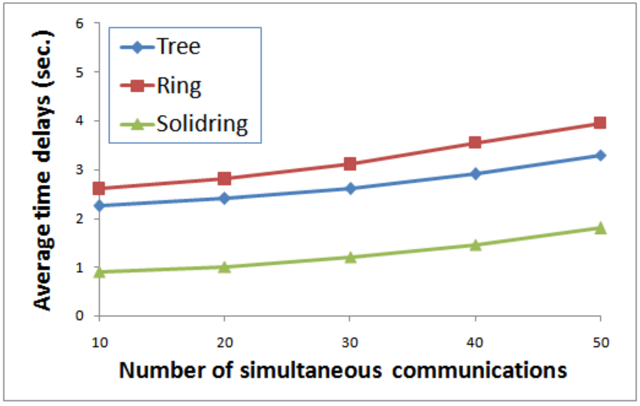
Additionally, the simulations measure and compare the average time delays of the three structures. For the simulations, communications are generated randomly with total data size between 1,000 kb and 10,000 kb and data rate between 64 kbps and 512 kbps.



(a) Average time delay, device number N = 20



(b) Average time delay, device number N = 60



(c) Average time delay, device number N = 100

Fig. 16. Comparisons of average time delay

We simulated three cases with device number N = 20, 60, and 100, respectively. In each case, we introduced simultaneous communications that are carried out during the same time span and may interfere with one another. It is expected that in a scatternet with more devices, the number of simultaneous communications would also be greater. We set the number of simultaneous communications according to the device number N, to make the comparisons clearer. For N = 20, the number of simultaneous communications is set to be 2, 4, 6, 8, and 10. For N = 60, the number is set to be 6, 12, 18, 24, and 30. For N = 100, the number is set to be 10, 20, 30, 40, and 50. Figure 16(a) shows the average time delays of the three structures when the total device number is 20. The figure shows that the Solidring achieves a smaller average time delay than the other two structures. In addition, the Solidring has a shorter average route and more available routes. As a result of these characteristics, the routing algorithm has more alternatives to allow a comparatively less congested and shorter route to be chosen for each communication. As a result, the average time delay is shortened significantly. Figs. 16(b) and (c) also illustrate that the Solidring achieves a smaller average time delay than the other two structures, when the total device numbers are 60 and 100, respectively.

The analysis of the simulation results proves that the Solidring can provide more routes, a shorter route length and comparatively less congested circumstances, resulting in a shorter average time delay.

7. Conclusion

In this paper, a new scatternet structure, the Solidring and its routing algorithm have been proposed. The Solidring is implemented in the single hop environment, where it can lower the time delay and improve the network performance remarkably.

At initialization of the scatternet, a group number N is preassigned in accordance with the number of Bluetooth devices. Each device obtains a group index, which is the remainder of dividing the BD Address by the group number N. According to the group index, devices are distributed to N groups, each of which constructs a ring structure. Finally, all rings are connected to build the Solidring structure.

The Solidring outperforms other structures in terms of lower time delay and higher network performance. Simulations have been carried out to compare the performance of the Solidring and two classic structures, the tree and ring.

In the simulations, Bluetooth devices are organized as Solidring, tree and ring structures, respectively. Device pairs are randomly generated and communications are implemented in the three structures. During the simulations, three factors, namely route number, route length and time delay, are recorded.

Compared with the tree and ring structures, more routes exist between devices in the Solidring, as it extends in all directions and most links can be replaced. The average route length in the Solidring is also shorter than that in the ring and tree structures, which is helpful in reducing the time delay. Together with its routing algorithm, the Solidring provides a comparatively less congested and shorter route for each communication. Time delay is shortened significantly in the Solidring.

In conclusion, the Solidring, together with its algorithm, performs better in terms of lower time delay and higher network performance.

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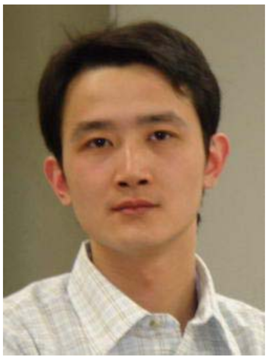

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