

Bluetooth Scatternet Routing for Wireless Home Network

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Abstract

In this paper, we present a routing protocol for a wireless Bluetooth home network. In a house, we can use the protocol to connect electric appliances such as video, computer, refrigerator, etc. This will let us control the devices easily and it will be more convenient for human beings. Our protocol applies to the architecture proposed in [2]. We reduce the header length from 16 bits to 14 bits and decrease the number of hops in a longest routing path from 6 to 4 in some situations. We also analyze the performances.

Keywords: Wireless networks, Bluetooth, Ad Hoc Networks

1. Introduction

In an average household, people usually have a lot of electric appliances such as video player, computer, refrigerator, etc. When we use some of the electric appliances, they must be within a limited distance to us. Even we can use a wireless remote control such as infrared, the distance is still within certain limits. In general situations, a wireless remote control can only control several devices, but it is not good enough. In the future, each household will have more and more electric appliances. If we can make those devices connected with each other by a network, it will let us control the devices easily. To achieve this goal, assume each appliance is Bluetooth equipped. In [2], a general architecture for wireless home network is proposed. In this paper, we propose a routing protocol for this architecture. Such protocol can reduce the load of network and increase the performance of communication. Although a bottleneck may form in some root or subroot sometimes, the communication will not be affected within subtree of those roots.

The rest of this paper is organized as follows. Section 2 introduces the piconet and the scatternet. Section 3, we introduce the Bluetooth home network architecture. We propose our protocol in Section 4. We also analyze the performances in Section 5. Section 6 provides the conclusions.

2. Background

2.1 Piconets

If two Bluetooth devices establish a connection, they will create a type of personal area network called a piconet. Each piconet can include eight different Bluetooth devices.

In each piconet, one device serves as the master, while the other seven devices function as slaves. Any individual device can join, simultaneously, to multiple piconets. Figure 2-1 describes a typical piconet in action.

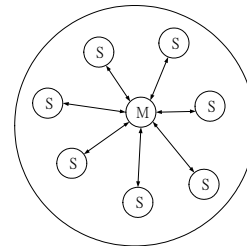


Figure 2-1: A piconet consists of one master device and up to seven slaves

2.2 Scatternet

Within each piconet, all the devices share the same frequency-hop channel, which is established by slaves synchronizing their internal clocks to the master unit's clock. This enables all the units in a piconet to hop from frequency to frequency in the same sequence, and establishes a unique identity for that piconet. Different piconets have different identities that are based on different frequency-hop channels. Thus multiple piconets can share the same physical space without interfering with each other.

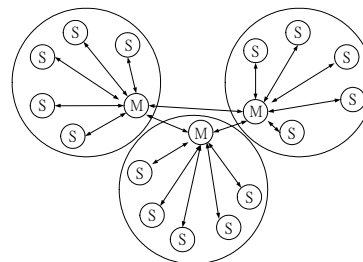


Figure 2-2: A scatternet composed of multiple piconets

All communications between different piconets are filtered through the individual piconet master devices in a scatternet. If there are 10 piconets, they contain 80 different Bluetooth devices. We could make those devices to be included in a single scatternet. Because Bluetooth only uses 79 frequencies in total, the network saturates beyond this number.

However, that multiple piconets share the same physical space. They can continue to operate independently each other without interfering. This is because each piconet operates on a different frequency-hop channel. The result is that the devices in piconet number one never share the same frequency as the devices in piconet number two.

3. Bluetooth Home Network Architecture

Our proposal uses a two level piconet hierarchy. Level 1 piconets are general piconets. They are used for communication among themselves. It is called a personal area network (PAN). Level 2 piconet is used for routing of PANs. It is called a routing area network (RAN). If there is a slave belonging to a PAN and a RAN at the same time, it is called a gateway slave. A gateway slave is not only working in a PAN but also working in a RAN simultaneously. In a PAN, master and gateway slaves need to be fixed. The other devices can be mobile nodes. In a RAN, the master is a router and it has to be fixed as well. An example of the two-level Bluetooth home network architecture is shown in Figure 3-1.

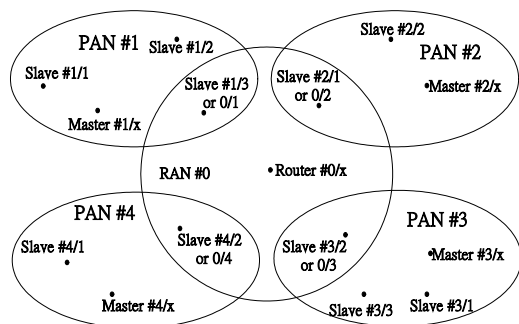


Figure 3-1: Bluetooth Home Network Architecture

4. Routing for Wireless Home Networks

At first, a RAN will be created. Then the master of RAN will assign addresses for its slaves, which will be gateways. The address is the Piconet Address (PA) of the slave when it becomes a gateway. The slave of RAN is in parked state and it will wait for a page from the master of PAN that it belongs to. When the master of PAN pages to the gateway, the master will

get PA from the gateway. In addition, each slave of a PAN is given a number as its Device Address (DA). Then slaves could get its PA from its master, which gets the value of PA from gateway. PA and DA combined is an address in the Bluetooth Home Network. The address is used for designing a packet header, which is used in the routing protocol. It also indicates a source or destination node in the Bluetooth Home Network.

The notation of Slave # m/n is used in Figure 3-1. m is the address of piconet, which is assigned by the RAN master node. The slave could get the value of m from its master and each node has the same value of m in the same piconet. n is the address of device, which is assigned by the PAN master node.

Each master will collect the information of its slaves. Then the information will be sent to the router. After the router receives the information from each master, it can make a routing map and send to each master. Thus each slave can get the routing map from its master. Using the routing map, each node can get all the information about PA and DA in the scatternet.

In Figure 3-1, we can find that the PA of RAN is set to 0. Because a gateway has two masters, it has two types of address. When it gets the address from the router, its PA must be zero. Both slave #1/3 and slave #0/1 point to gateway of PAN #1. If source node and destination node are in the same piconet, the gateway will use slave #1/3 as its address. Otherwise slave #0/1 will be used. We will explain these addresses in later sections.

4.1 Protocol Header Format

The routing packet header format is shown in Figure 4-1.

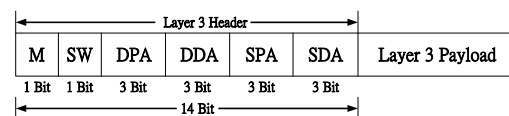


Figure 4-1: Packet Header Format

The first field is M (Master Flag). It indicates whether the destination node is a master in a PAN. If a packet will be transmitted to a master in a PAN, Master Flag of this packet will be set.

The second field is SW (Switch Flag). It defines whether the packets need to be switched between PAN and RAN. In addition, the field also indicates whether the packets have reached destination node. If this field is 1, any slave receiving the packet will automatically detect where the packet comes from. If the packet comes from PAN, the slave will send the packet to its master of RAN. Otherwise, the slave will

send the packet to its PAN. Then if the field is set to zero, it means that the packet belongs to the receiving slave.

The third field is the Destination Piconet Address (DPA). This field indicates which piconet is to be routed.

The fourth field is the Destination Device Address (DDA). The field indicates which node is the destination node within destination PAN. Each piconet is defined by DPA in a home network. Then each node is defined by DDA in a PAN. If the value is zero, it means that the packet needs to be broadcasted within destination PAN.

The fifth field is the Source Piconet Address (SPA). The field indicates the received device which piconet transmitted the packet.

The sixth field is the Source Device Address (SDA). The field indicates which node is the originating node within source PAN.

SPA-SDA and DPA-DDA are used to specify a unique source and destination node. Finally the payload is the information from higher layer such as application functions, control information, voice field, data field, etc.

4.2 Protocol Operation

We support both intra-piconet and inter-piconet communications. In addition, unicast and broadcast communications are also supported. If a destination device address (DDA) is zero, it means that the packet is a broadcast. Otherwise, the packet is used for unicast communication. In addition, we add a variable called Local Piconet Address (LPA). If a node is located within PAN #1, its LPA will be set to 1. Figure 4-2 shows the routing protocol for the master of PAN. Figure 4-3 shows the routing protocol for the master of RAN. The routing protocol for slaves is shown in Figure 4-4.

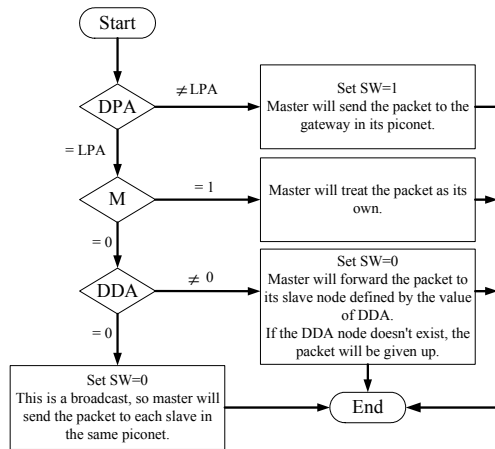


Figure 4-2: Routing protocol for master of PAN

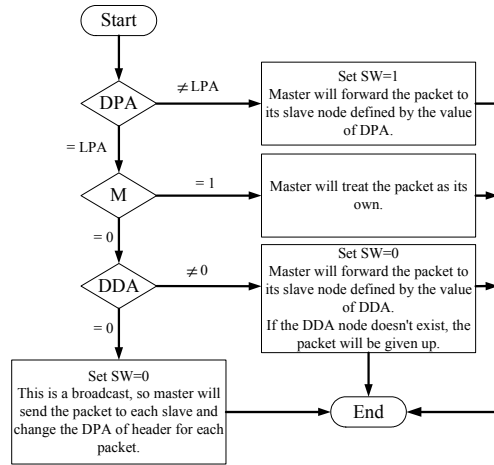


Figure 4-3: Routing protocol for master of RAN

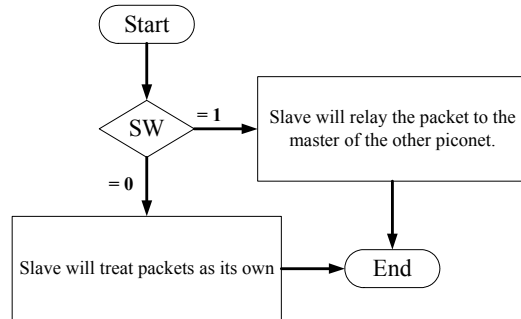


Figure 4-4: Routing protocol for slave

4.2.1 Intra-piconet Communication

In this section, we present an example for Intra-piconet communication. Figure 4-5 shows the example. Table 4-1 shows the packet header of Intra-piconet communication in each hop. The symbol X means “not applicable”.

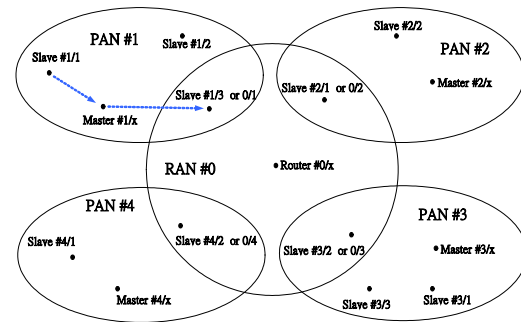


Figure 4-5: An example of Intra-piconet communication

Table 4-1: The packet header of Intra-piconet communication

Path	M	SW	DPA	DDA	SPA	SDA
Slave #1/1 to Master #1/x	0	X	1	3	1	1
Master #1/x to Slave #1/3	0	0	1	3	1	1

For this example, assume that slave #1/1 wants to send a packet to the gateway of PAN #1. The source node will use slave #1/3 as destination address because this is an Intra-piconet communication. At first, slave #1/1, the source node, creates a packet header shown in the first row of Table 4-1. Because the source node is slave #1 in PAN #1, both SPA and SDA are set to one. DPA is the same as SPA because the source and destination node are in the same piconet. DDA, which is 3, tells the master about the identity of the destination node. It is slave-slave communication, so M is set to zero.

The source node sends the packet to its master at first. When the master receives the packet, it will check DPA with its LPA. If the values of DPA and LPA are the same, the source node and destination node are in the same piconet. Thus SW flag of the packet is set to zero by master. Then the master checks M flag of the packet. In this case, the flag is zero, so the master continues to check DDA field of the packet. Because the field is not zero, master will forward the packet to a slave node defined by the DDA. After the slave receives the packet, it will check SW flag. If it is zero, the slave will receive the packets. Otherwise the slave will switch the packet to another network. At last, the packet will be received by slave #1/3.

4.2.2 Inter-piconet Communication

In this section, we present two examples for Inter-piconet communication. The first example demonstrates how to send a packet to the router. Figure 4-6 shows the route. Table 4-2 shows the packet header in each hop.

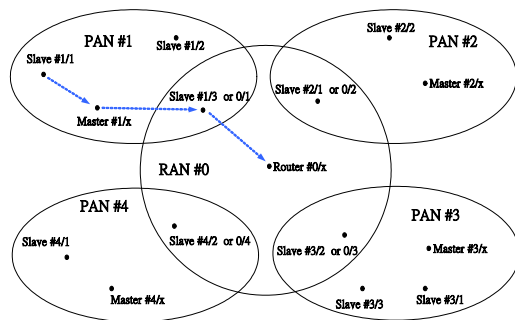


Figure 4-6: An Inter-piconet communication for router

Table 4-2: The packet header of Intra-piconet communication for router

Path	M	SW	DPA	DDA	SPA	SDA
Slave #1/1 to Master #1/x	1	X	0	X	1	1
Master #1/x to Slave#1/3	1	1	0	X	1	1
Slave#1/3 to Router #0/x	1	1	0	X	1	1

In this example, the slave #1 of PAN #1 wants to transmit the packet to the master of PAN #0, the router. The operation of the protocol along each hop is listed in Table 4-2. The destination node is a master node so M is set to 1. Because the destination node is in PAN #0, DPA is set to zero. The value of DPA is irrelevant because the destination node is a master. SDA and SPA are set to 1 as they indicate the source node and the originating piconet.

The source node sends the packet to its master first. When the master receives the packet, it will check DPA with its LPA. Because DPA is not equal to LPA in this case, the destination node is in other piconet. Thus the master sets SW flag of the packet to 1, and forwards the packet to its gateway. The gateway slave checks the SW flag. Because the value of SW flag is 1, a gateway node will relay the packet to the master of other piconet. When the master receives the packet, it will check DPA with its LPA. DPA is equal to LPA in this case so the destination node is in the same piconet. Then the master checks M flag of the packet. Because the flag had been set to 1 by the source node, the master of RAN will receive the packet.

4.2.3 Broadcasts

Broadcast is a basic and important function. If we want to send packets to every node without using broadcast, the load in the networks will be very heavy. Also the network will have a bottleneck near a master.

Our proposal not only provides a broadcast function in a piconet, which is also provided in [2], but it also has scatternet broadcast capability. Figure 4-7 shows the route when slave # 1/1 wants to broadcast in a piconet. Table 4-3 shows that packet header for each hop.

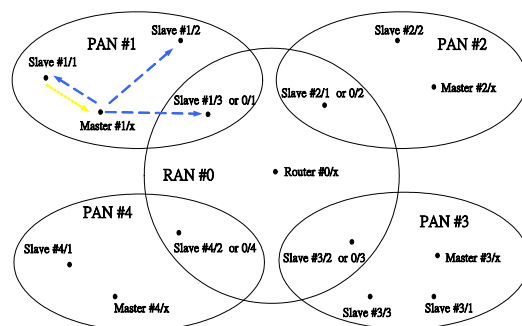


Figure 4-7: A broadcast in a piconet

Table 4-3: Packet header for a broadcast in a piconet

Path	M	SW	DPA	DDA	SPA	SDA
Slave #1/1 to Master #1/x	0	X	1	0	1	1
Master #1/x to Slave#1/1	0	0	1	0	1	1
Master #1/x to Slave#1/2	0	0	1	0	1	1
Master #1/x to Slave#1/3	0	0	1	0	1	1

Comparing to [2], our proposal adds scatternet broadcast function to improve the performance. In our proposal, a source node just sends a scatternet broadcast packet to router. Then the router will copy the packet and send to each master within the scatternet. Figure 4-8 shows the route for a scatternet broadcast. Table 4-4 lists the header of the packet for each hop.

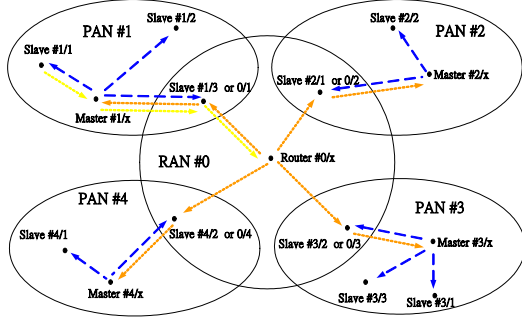


Figure 4-8: Our proposal to implement a scatternet broadcast

Table 4-6: the header of the packet for each hop

Path	M	SW	DPA	DDA	SPA	SDA
Slave #1/1 to Master #1/x	0	X	0	0	1	1
Master #1/x to Slave#1/1	0	0	1	0	1	1
Master #1/x to Slave#1/2	0	0	1	0	1	1
Master #1/x to Slave#1/3	0	0	1	0	1	1
Slave#1/3 to Router #0/x	0	1	0	0	1	1
Router #0/x to Slave#0/1	0	1	1	0	1	1
Slave #0/1 to Master #1/x	0	1	1	0	1	1
Master #1/x to Slave#1/1	0	0	1	0	1	1
Master #1/x to Slave#1/2	0	0	1	0	1	1
Master #1/x to Slave#1/3	0	0	1	0	1	1
Router #0/x to Slave#0/2	0	1	2	0	1	1
Slave #0/2 to Master #2/x	0	1	2	0	1	1
Master #2/x to Slave#2/1	0	0	2	0	1	1
Master #2/x to Slave#2/2	0	0	2	0	1	1
Router #0/x to Slave#0/3	0	1	3	0	1	1
Slave #0/3 to Master #3/x	0	1	3	0	1	1
Master #3/x to Slave#3/1	0	0	3	0	1	1
Master #3/x to Slave#3/2	0	0	3	0	1	1
Master #3/x to Slave#3/3	0	0	3	0	1	1
Router #0/x to Slave#0/4	0	1	4	0	1	1
Slave #0/4 to Master #4/x	0	1	4	0	1	1
Master #4/x to Slave#4/1	0	0	4	0	1	1
Master #4/x to Slave#4/2	0	0	4	0	1	1

5. Analysis and Results

At first, we evaluate the Ideal Throughput of our proposal. Let the scatternet contain $P+1$ piconets ($P \geq 1$) and each piconet contains S slaves (including Both non-gateway slaves and gateways). So the total number of devices in the Bluetooth scatternet is $S \cdot P + P + 1$. We shall derive the average number of hops distance that a data packet needs to travel before reaching its destination. This depends on the role of the source, which can be a slave, a master, or a router. Figure 5-1 shows each kind of nodes in our Bluetooth scatternet.

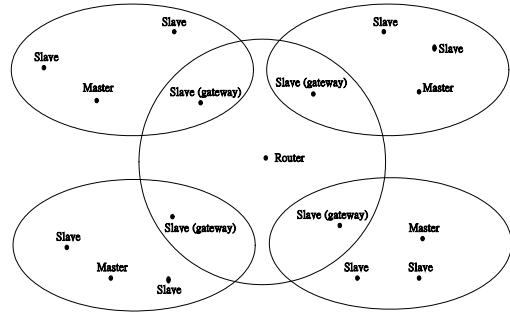


Figure 5-1: Each kind of nodes in our Bluetooth scatternet ($S=3, P=4$)

Table 5-1 summarizes the case when the source is a slave. In this table, destinations are classified into intra-piconet slave (including its gateway), intra-piconet master, inter-piconet slave (non-Gateway), inter-piconet master, router, or gateway.

Table 5-1: Source node is a slave

	No. of destinations	Distance
Intra-piconet slaves (include its gateway)	$c_{33} = S-1$	$d_{31} = 2$
Intra-piconet master	$c_{33} = 1$	$d_{32} = 1$
Inter-piconet slave (non-Gateway)	$c_{33} = (S-1)(P-1)$	$d_{33} = 5$
Inter-piconet master	$c_{34} = P-1$	$d_{34} = 6$
Router	$c_{35} = 1$	$d_{35} = 3$
Gateway	$c_{36} = P-1$	$d_{36} = 4$

Table 5-2 summarizes the case when the source is a master. In this table, destinations are classified into intra-piconet slave (including its gateway), inter-piconet slave (non-Gateway), inter-piconet master, router, or gateway.

Table 5-2: Source node is a master

	No. of destinations	Distance
Intra-piconet slaves (include its gateway)	$c_{m3} = S$	$d_{m1} = 1$
Inter-piconet slave (non-Gateway)	$c_{m3} = (S-1)(P-1)$	$d_{m2} = 5$
Inter-piconet master	$c_{m3} = P-1$	$d_{m3} = 4$
Router	$c_{m4} = 1$	$d_{m4} = 2$
Gateway	$c_{m5} = P-1$	$d_{m5} = 3$

Table 5-3 summarizes the case when the source is the router. In this table, destinations are classified into inter-piconet slave (non-Gateway), inter-piconet master, or gateway.

Table 5-3: Source node is a Router

	No. of destinations	Distance
Inter-piconet slave (non-Gateway)	$c_{i1} = (S-1)P$	$d_{i1} = 3$
Inter-piconet master	$c_{i2} = P$	$d_{i2} = 2$
Gateway	$c_{i3} = P$	$d_{i3} = 1$

Based on the above-mentioned tables, we derive the average distances d_s , d_m , or d_r for packets originated at a slave, a master, or a router respectively. It is shown in the following.

$$d_s = \frac{c_{s1} \cdot d_{s1} + c_{s2} \cdot d_{s2} + c_{s3} \cdot d_{s3} + c_{s4} \cdot d_{s4} + c_{s5} \cdot d_{s5} + c_{s6} \cdot d_{s6}}{c_{s1} + c_{s2} + c_{s3} + c_{s4} + c_{s5} + c_{s6}} = \frac{6SP - 4S + 3P - 1}{SP + P} \quad (1)$$

$$d_m = \frac{c_{m1} \cdot d_{m1} + c_{m2} \cdot d_{m2} + c_{m3} \cdot d_{m3} + c_{m4} \cdot d_{m4} + c_{m5} \cdot d_{m5}}{c_{m1} + c_{m2} + c_{m3} + c_{m4} + c_{m5}} = \frac{5SP - 4S + 2P}{SP + P} \quad (2)$$

$$d_r = \frac{c_{r1} \cdot d_{r1} + c_{r2} \cdot d_{r2} + c_{r3} \cdot d_{r3}}{c_{r1} + c_{r2} + c_{r3}} = \frac{3SP}{SP + P} \quad (3)$$

Because there are $S \cdot P$ slaves, P masters, and one router, the average traveling distance can be derived as follow.

$$D_{avg} = \frac{S \cdot P \cdot d_s + P \cdot d_m + 1 \cdot d_r}{SP + P + 1} = \frac{6S^2P - 4S^2 + 8SP - 2S + 2P}{S^2P + 2SP + S + P + 1}$$

For $1 \leq S \leq 7$ and $1 \leq P \leq 7$, the value of the average traveling distance D_{avg} is shown in Table 5-4. Figure 5-2 is Table 5-4 in graphical form.

Table 5-4: Average traveling distance for different P 's and S 's

$P \backslash S$	1	2	3	4	5	6	7
1	1.666667	1.833333	1.9	1.933333	1.952381	1.964286	1.972222
2	2.6	3.047619	3.277778	3.418182	3.512821	3.580952	3.632353
3	3	3.533333	3.807692	3.975	4.087719	4.168831	4.23
4	3.222222	3.794872	4.088235	4.266667	4.386667	4.472906	4.537879
5	3.363636	3.958333	4.261905	4.446154	4.569892	4.65873	4.72561
6	3.461538	4.070175	4.38	4.567742	4.693694	4.784053	4.852041
7	3.533333	4.151515	4.465517	4.655556	4.782946	4.874286	4.942982

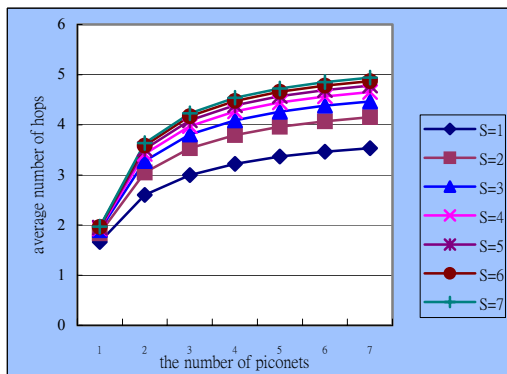


Figure 5-2: Average traveling distance for different P 's and S 's

Next we consider interferences between piconets. Assume that the maximum throughput of

a single piconet under an interference-free environment is T . Extending to a scatternet, different piconets that choose the same FH (Frequency Hopping) channel in the same time slot result in a collision. If we consider the worst case, each piconet is in the radio range of each other. Give that 79 frequencies are available in Bluetooth, the probability that a time slot of a piconet suffers no interference can be approximated by $Perm_{P+1}^{79} / 79^{P+1}$, where P is the number of piconets connected to router. The available network bandwidth is $T \cdot (P+1) \cdot Perm_{P+1}^{79} / 79^{P+1}$. Dividing this by the average traveling distance D_{avg} , we obtain the maximum achievable throughput T_{max} as [1].

$$T_{max} = \frac{T \cdot (P+1) \cdot \frac{Perm_{P+1}^{79}}{79^{P+1}}}{D_{avg}}$$

We use the Bluetooth nominal bandwidth $T=1$ Mbps and assume $1 \leq S \leq 7$ and $1 \leq P \leq 7$. The Ideal Throughput T_{max} is shown in Table 5-5. Figure 5-3 is Table 5-5 in graphical form.

Table 5-5: Ideal throughput T_{max} by varying P and S (Kbps)

$P \backslash S$	1	2	3	4	5	6	7
1	1184.81	1077.1	1039.307	1021.388	1011.423	1005.293	1001.248
2	1110.399	947.3091	880.7911	844.612	821.8573	806.2205	794.8119
3	1234.401	1048.077	972.5586	931.6236	905.934	888.3075	875.4619
4	1363.849	1158.043	1074.944	1029.99	1001.814	982.4988	968.4316
5	1468.584	1247.945	1159.055	1111.023	1080.94	1060.328	1045.321
6	1538.442	1308.39	1215.839	1165.866	1134.581	1113.151	1097.554
7	1569.867	1336.106	1242.155	1191.451	1159.717	1137.985	1122.17

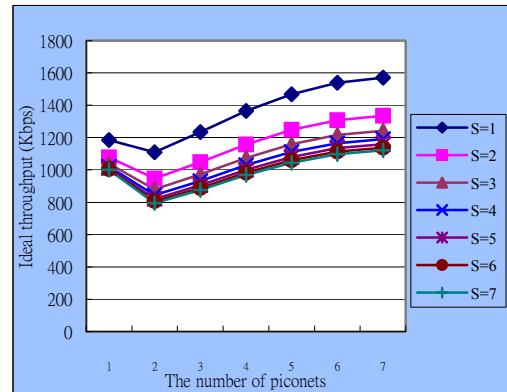


Figure 5-3: Ideal throughput T_{max} for different P 's and S 's

We compare the performance of our proposal with that of BlueRing [1]. The ideal throughput

of our proposal is better than BlueRing. Figure 5-4 shows the calculation results.

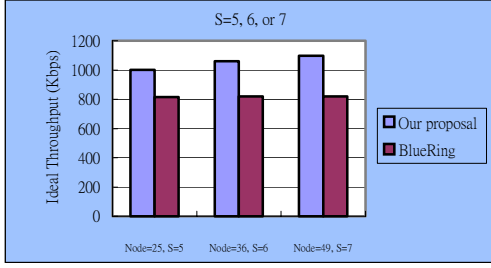
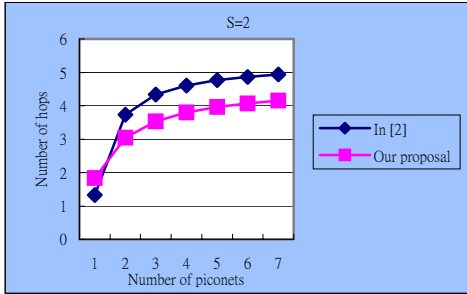
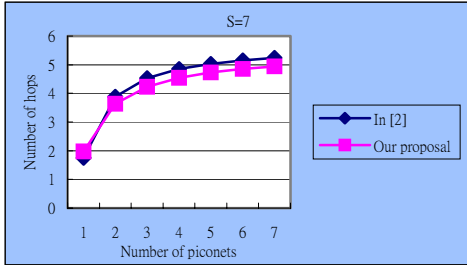


Figure 5-4: Our proposal compares with BlueRing for the ideal throughput

We compare the performance of our proposal with that of [2]. The average traveling distance of our proposal is better than [2]. Figure 5-5 shows the calculation results.



(a) Each piconet has 2 slaves



(b) Each piconet has 7 slaves

Figure 5-5: Our proposal compares with [2] about the number of hops in a unicast

Although the routing protocol of broadcast has been presented in [2], it is only for piconet. In our proposal, we present a new routing protocol for scatternet broadcast. Besides, we still support the piconet broadcast.

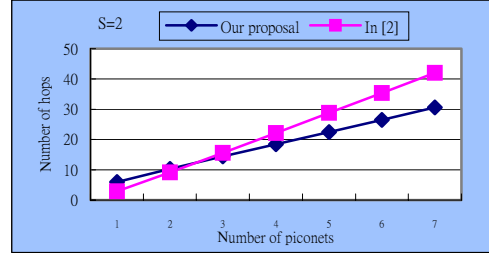
We want to derive the average number of hops that a data packet needs to travel before reaching its destination in a broadcast. This will depend on the role of the source, which can be a slave, a master, or a router. Table 5-6 summarizes these three cases.

Table 5-6: Broadcast distance for packets originated at a slave, a master, or a router.

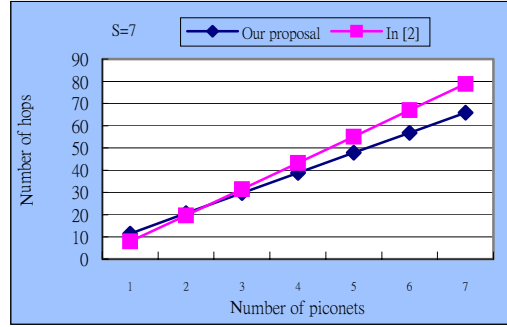
	No. of sources	Total distances
Source node is a slave	$c_{s1} = P \cdot S$	$d_{s1} = 3 + 2P + S \cdot P$
Source node is a master	$c_{s2} = P$	$d_{s2} = 2 + 2P + S \cdot P$
Source node is a router	$c_{s3} = 1$	$d_{s3} = 2P + SP$

Based on Table 5-6, we derive the average distances B_{avg} , as follows:

$$B_{avg} = \frac{c_{s1} \cdot d_{s1} + c_{s2} \cdot d_{s2} + c_{s3} \cdot d_{s3}}{c_{s1} + c_{s2} + c_{s3}} = \frac{S^2 \cdot P^2 + 2P^2S + 4SP + 4P + 2P^2 + SP^2}{P \cdot S + P + 1}$$



(a) Each piconet has 2 slaves



(b) Each piconet has 7 slaves

Figure 5-6: Our proposal compares with [2] about the number of hops in a broadcast

6. Conclusions

In this paper, we propose a method to extend and improve the performances of Bluetooth devices for the wireless home network in [2]. We reduce the packet header length and the number of hops needed for some routing paths. In addition, we add a scatternet broadcast function. In [2], the broadcast function is only designed for piconet. If some device needs to send a scatternet broadcast, it must send a lot of packets to each master within the same scatternet. Our proposal retains piconet broadcast function and supports a scatternet broadcast function. If a device needs to send a scatternet broadcast in our proposal, it only needs to send one packet to the router. Then the router will copy the packet to other masters in the same scatternet. We can reduce the number of packets in a scatternet broadcast.

Although our protocol can reduce the packet traveling distance and increase the throughput, a bottleneck may form in some

gateways or the router. It will affect the inter-piconet communication. How to avoid the bottleneck is an important problem.

If all the Bluetooth enabled devices are in each other's radio range, we can find a lot of scatternet formation protocols in the literature. However, those protocols can't be used in our home networks. In general situation, the communication distance of a Bluetooth device is 10 meters. Its covered area superficially is $\pi \cdot r^2$ where r is 10 meters. Thus the maximum area of a piconet is 314 square meters. However if all the Bluetooth nodes are in each other's radio range, the maximum area of a scatternet will be reduced to 78.5 ($5 \cdot 5 \cdot 3.14$) square meters. It is too small for our wireless home network.

Therefore, an interesting research topic would be to devise scatternet formation protocol that has no limits on the distances between Bluetooth nodes.

References

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