Congestion control of bluetooth radio system by piconet restructuring

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Abstract

Bluetooth is a low-cost and short-range wireless communication technology. Two or more bluetooth devices connected form a piconet and two or more piconets connected form a scatternet through relay devices. Without the consideration of traffic flows, a scatternet may operate with serious congestion problem. Congestion problem can be resolved by either reduced traffic flows or increased bandwidth provision. In bluetooth, new piconet can be dynamically constructed to increase system bandwidth. However, as the number of piconet is increased, collision problem among piconets becomes a serious problem. The objective of this paper is to resolve the congestion problems in a scatternet through piconet restructuring which perform both flow analysis and distributed role-switching technique. Advantages of the proposed piconet restructuring mechanism includes the following: (1) the communication bottleneck can be released; (2) the communication path is shortened; (3) the transmission latency is reduced; and (4) the lifetime of piconets can be increased. Experimental results demonstrated that the proposed method could effectively increase the transmission efficient in each piconet and increase the performance of an entire scatternet.

Keywords: Bluetooth; Piconet restructuring; Congestion control

1. Introduction

Recently, the advances of wireless technology have enriched daily life of human beings. As demonstrated by new consumer electronic products, the short-range wireless...
communication technology has been developed to replace the conventional cumbersome
cables. Various portable mobile devices can thus connect with each other through this
short-range wireless technology. Among lots of wireless technologies, bluetooth is a
representative of low-cost and low-power technology (Bluetooth Special Interests Group;
Pei et al., 2000; Baatz et al., 2001). Heterogeneous mobile devices thus can connect with
each other through bluetooth chips.

Devices equipped with bluetooth chips operate in unlicensed 2.4G industrial, science,
and medical (ISM), radio frequency. The radio frequency is divided into 79 channels with
width of 1 MHz in each sub-band. Bluetooth uses technologies of time division duplex
(TDD) (Kalia et al., 1999) and frequency-hopping spread spectrum (FHSS) to reduce the
probability of collusion. The number of frequency hopping is 1600 times per second, and
the length of each slot is 625 μs. According to the standard of bluetooth specification 1.1
(Bluetooth Special Interests Group), the atomic unit of bluetooth communication
architecture is a piconet. A piconet consists of one master device together with one to
seven slave device(s). The master device is responsible to the management of link
connections and packet transmissions. The wireless network, which includes two or more
piconets, is called a scatternet. Two or more piconets can be connected through relay
device. Through time division multiplex (TDM) mechanism, a relay device can switch
among different piconets to provide services such that multi-hop communication service
can be achieved (Bray and Sturman, 2001). A relay device can play roles of slave in two or
more piconets simultaneously; and a relay device can also play roles of master and slave in
different piconets. However, a relay device cannot play roles of master in two or more
piconets simultaneously.

In bluetooth radio system, each device exchanges packets with other devices through
TDD mechanism. The device, which plays roles of master, transmits packets in even
number of slots and receives packets in odd number of slots. On the other hand, devices,
which play roles of slave, transmit packets in odd number of slots and receive packets in
even number of slots. This simple master/slave communication model brings advantages of
simple operation together with low power consumption to bluetooth radio system.
However, the drawback of this model is that two slaves in a piconet cannot communicate
with each other directly. When two slaves in a piconet are going to communication, they
should first transmit packets to master in odd number of slots and master forward these
packets to destination slave in even number of slots. In previous works (Whitaker et al.,
2005; Tekkalmaz et al., 2006; Chiasserini et al., 2003), role change operations are used
to change roles of devices in a piconet according to the amount of intra-piconet traffic
flow. However, the traffic flows of inter-piconet communication are not taking into
consideration, so the throughput of entire scatternet is not optimized.

Other problems, which are caused by the freely matching of radio frequency in the
construction phase of scatternet, are large number of piconets and disconnected scatternet.
A partitioned network can happen when no relay device between two piconets exists. In
literature, (Bhagwat and Segall, 1999) had suggested to use Bernoulli trial to determine the
roles (master, slave or relay) of each device such that the basic requirements of a connected
scatternet and small number of piconets can be achieved. However, problems occur when
there are too few piconets in a scatternet. Although small number of hopping sequences
has low probability of collision, but too few piconets will lead to large number of devices
managed by a master in each piconet. Large number of devices in each piconet implies that
the average service time by master of each slave is low. Within a fixed time, the amount of
transmitted packets is decreased and the delay time is increased. In such a circumstance, the total throughput of entire system is poor and the power consumption of each master is heavy. If the power of master device is limited, the service time of master devices will thus be restricted. In terms of the total transmitted packets within a fixed time, small number of piconets implies the number of masters, which can transmit packets simultaneously, is also small. This means that the throughput of the entire scatternet cannot be optimized.

A piconet consists of at most eight devices; all communication activities among slave devices involve the services of master device. Because there are at most seven active slaves in a piconet, two slave devices located in different piconets require a routing path to communicate with each other. In literature, two approaches, Bhagwat and Segall (1999) and Marsan et al. (2002), was proposed to construct a routing path between two devices. In Bhagwat and Segall (1999), a flooding mechanism is proposed to search the destination. The source device broadcasts a route search packet. Each intermediated device receive this route search packet will rebroadcast it to neighbors. When destination device received the route search packet, it will return a route reply message to source device. A routing path can thus be constructed and two devices located in different piconets can communicate with each other. The drawbacks of approach Bhagwat and Segall (1999) is that only hop count is taken into consideration, important factors such as the architecture of scatternet and the traffic loads of intermediate nodes are ignored. The established routing path may have high delay time and low throughput due to traffic congestion in intermediate nodes. On the other hand, intermediate node with heavy traffics may deplete its power soon, so the lifetime of entire network is short. If architecture of congested piconet can be adjusted, a new scatternet, which is suitable for parallel computing, can achieve better performance. In such a circumstance, the load of master can be reduced, so the above problem can be avoided.

In this paper, a piconet restructuring mechanism based on role-switching technique (Bluetooth Special Interests Group; Whitaker et al., 2005; Tekkalmaz et al., 2006; Chiasserini et al., 2003) is proposed. The number of piconets and the role of devices can be determined automatically based on local traffic flow and relations between devices. When the traffic flow of some device is heavy or parallel transmission is required, the proposed approach can distribute the traffic load from one master to many masters such that the load and power consumption can be balanced. Furthermore, establishing new connection between slave devices can also achieve the objective of reducing length of routing path and delay time. The efficiency of data transmission within bluetooth can thus be improved.

The remaining parts of this paper are organized as follows: in Section 2, we will analyze the piconet structure of bluetooth system, describe the operation of role switching and discuss how the roles of device will affect transmission efficiency. A new piconet restructuring protocol, which can adjust piconet structure locally, and performance analysis will be discussed in Section 3. In Section 4, numerical results are given to demonstrate how the performance of scatternet can be improved via the proposed restructuring protocol. Finally, in Section 5, we will summarize the results of the proposed approach, discuss the inspiration of the results and describe the future work.

2. Backgrounds and basic concept

In bluetooth radio network, if two devices are within communication range, the inquiry/ inquiry scan and page/page scan operations can be applied to establish a new connection.
The device, which intends to play roles of master, executes the inquiry procedure and transmits ID packets to search other Bluetooth devices, which are within the transmission range. Those devices, which are dedicated to play roles of slave need to execute inquiry scan procedure to receive the ID packet, which is broadcasted by master device. After the slave device received the ID packet twice, it responses a FHS packet which contains its own 48-bits Bluetooth address and clock offset to the master device. In this circumstance, when the master device which state is inquiring receives this FHS packet, it will change its state to page state. Due to the required Bluetooth address and clock offset of slave has been collected by master, the master device can calculate the communication channel which is used by the slave device in page scan state. The communication link between the master and the slave device can thus be established and a piconet is formed in this circumstance.

**Fig. 1** illustrates this situation. Within a piconet, all slave devices and the master device use the same hopping sequence dominated by internal clock of master device. Each device uses TDD mechanism to transmit packets. The master transmit packets in even number of slots while receive packets in odd number of slots. On the other side, the slave devices will transmit packets in odd slots and receive packets in even slots. When two slave devices are dedicated to connect with each other, the forwarding service of master device is required to benefit the communication process.

Due to the upper bound of the number of active slaves in a piconet are 8; at least two piconets are required when the total numbers of devices are more than 8. In this situation, the relay device, which participates in more than two piconets, is required to connect piconets into a scatternet. As shown in **Fig. 2**, the roles of relay device can be categorized into two different classes. In the first class, the relay \( R_2 \) that participates in piconet \( P_2 \) and \( P_3 \) and play roles of slaves in both piconets is called slave/slave relay and is abbreviated as S/S Relay. When \( R_2 \) participates in piconet \( P_2 \), it should follow the planning and management of master in piconet \( P_2 \) while participates piconet \( P_3 \), it should follow the planning and management of master in piconet \( P_3 \). In the second class, the relay \( R_2 \) that plays roles of master in piconet \( P_1 \) and roles of slave in piconet \( P_2 \) is called master/slave relay and is abbreviated as M/S Relay. When \( R_1 \) participate in \( P_2 \), it will dominate the transmission and scheduling process of piconet \( P_2 \). But when \( R_1 \) participates in \( P_1 \), \( R_1 \) becomes a slave device and should follow the scheduling of master in piconet \( P_1 \). So when two devices located in different piconets, intermediate master and relay devices are required to establish a routing path. When relay device switch to another piconet, it should follow the hopping sequence of the master device in another piconet.

In Bluetooth network, the power level of the master device of a piconet decreases gradually due to its heavy traffic load. Without the master device, a piconet cannot function properly. The election of a new master in a piconet is required when the power of master device is exhausted. In other cases, when there are many routing paths pass through the same piconet, master must forward all packets of these routing paths. In this circumstance, many slave (relay) devices request forwarding service of master, the master

![Fig. 1. Illustration of a piconet structure.](image-url)
device become a bottleneck of this piconet. Under the consideration of traffic flow and communication pairs, if a new piconet can be separated from an existing piconet by role-switching technique, the workload of the bottleneck master device will be shared by the new master. The traffic load can be distributed to these two piconets and the performance of the piconet can be improved.

Fig. 3(a) illustrates the effects of role switching that one slave changes its roles and connects to another slave in the same piconets. In Fig. 3(a), device $M$ is the master device of this piconet and is responsible to forward packets among slave devices $A$, $B$, $C$, $D$, $E$ and $F$. In this piconet, there is large amount of traffic flow derived from many routing paths. These routing paths include path 1: $C \rightarrow M \rightarrow B$, path 2: $B \rightarrow M \rightarrow A$ and path 3: $G \rightarrow M$. In this circumstance, the master device $M$ is always responsible to forward packets among slave devices and is likely to be a bottleneck device in this piconet. If the structure of piconets can be locally adjusted according to the transmission source and destination of routing paths, advantages of load sharing of master device and parallel transmission can be obtained. For example, in Fig. 3(b), device $B$ changes its role from slave to master and establishes new connections to device $C$ and $A$, respectively. The congested traffic load in device $M$ then can be shared by device $B$. The operations of role switching and new connection establishments can reduce the amount of packet forwarding in master device, avoid the occurrence of transmission bottleneck, increase the lifetime of entire network, and reduce the length of routing paths.

The effect of role switching and new connection establishment operations on traffic flows of two piconets is illustrated in Fig. 4. In Fig. 4(a), device $A$ and $F$ are masters while device $B$ is relay of two piconets. There are three routing paths pass through this
scatternet; they are path 1: $A \rightarrow B \rightarrow F \rightarrow G$, path 2: $E \rightarrow A \rightarrow H$ and path 3: $I \rightarrow F \rightarrow D$, respectively. The hop counts of these routing paths are 4, 2, and 2, respectively. To share the traffic load of master device, we can choose one slave device from each piconet based on the communication flow and communication pairs. In Fig. 4(a), device $B$, $E$ and $I$ can be selected to share the work load and reduce the power consumption of master device $A$ and $F$. The resultant structure of scatternet is shown in Fig. 4(b). Those three routing paths are all changed by the operations. For example, the new hop counts of paths 1, 2, 3 are 3, 2 and 1, respectively and their paths are path 1: $C \rightarrow B \rightarrow G$, path 2: $E \rightarrow H$ and path 3: $I \rightarrow D$.

In the previous analysis, it is observed that the operation of role switching and new connection construction based on traffic flows can benefit the reduction of routing path length and the reduction of transmission latency. When a piconet is involved in a routing path, reducing the forwarding device can also avoid unnecessary power consumption. The transmission performance can be improved effectively. However, if the slave device constructs a new connection and break the old connection with master device, the total hop count of the new routing path may not reduce. For example, in Fig. 5, device $M$ is a master of piconet. There are three routing paths pass through this piconet, they are path 1: $E \rightarrow M \rightarrow D$, with hop count 2; path 2: $M \rightarrow A$, with hop count 1 and path 3: $D \rightarrow M$, with hop count 1. If device $E$ is taken over by device $D$ according to traffic load and transmission targets, then the new resultant piconet will be as in Fig. 5(b). Although the hop count of

![Fig. 4. Analysis of communication pairs in two piconets. (a) In this piconet, device A and F are master devices. (b) In this piconet, device A, B, I, E and F play roles of master.](image-url)
path 1 is reduced from 2 to 1, i.e. from $E \to M \to D$ to $E \to D$, but the hop count of path 3 increases from 1 to 2, i.e. from $D \to M$ to $D \to E \to M$. The total hop counts remain the same; the objective of path reduction cannot be achieved in this case.

From the analysis on Fig. 5, it is observed that although the construction of new connection among slave devices by completely piconet division can disperse the traffic flow, but the objective of hop count reduction cannot be achieved. We also observe that in Fig. 5(b), if device $D$ changes its role as master in new piconet and maintains the connection with old master in the original piconet structure, the hop count of routing path will not increase, that is the path will not enlarger $D \to M$ from to $D \to E \to M$. The total hop count can be reduced from 4 to 3. The device, which changes its role as master without changing the original piconet structure and share, the traffic load of original master will be called an auxiliary master. When some slave is dedicated to be an auxiliary master, the operation of role switching can be applied to change the role of device. The device thus can connect with other slave devices.

In the following example, Fig. 6 is used to describe the packet exchanging information of the role-switching operation between two devices in the link management protocol (LMP) layer. When the master device wants to send role-switching request to the slave device, the master device will send a LMP\_switch\_req packet to slave device. After a short period, the slave device will reply a LMP\_slot\_offset packet which contains difference of clock offset to master device. Then master device can perform role-switching operation with slave device to achieve the objective of piconet merging.
From the above analysis, it is concluded that the traffic load of master can be shared and the performance of piconet can be improved by changing the communication targets among slaves without destruction of the original piconet structure. The second advantage of piconet restructuring is that the amount of forwarding packets in master device can be reduced due to the transmission targets is changed. The power consumption of master device is reduced and the lifetime of piconet can be increased. In the following, we will propose a dynamic transmission targets changing protocol according to the historical traffic flow in the environment where there exist many routing paths in a scatternet. By choosing a suitable slave device as auxiliary master and select suitable slave devices communication with the auxiliary master directly, advantages of reducing traffic load of master device, reducing the hop counts of routing paths, decreasing the transmission delay, balancing the power of master device, increasing the lifetime of piconet, and reducing the bandwidth consumption can be achieved.

In the following, we will define terms and data structure formally.

**Definition.** Auxiliary master: Auxiliary master is a slave device in original piconet and can directly connects with other slave devices in the same piconet and share the workload of master device.

**Definition.** Data flow matrix: Data flow matrix (DFM) is a square matrix which records the traffic flow between pairs of devices in a piconet within a given time interval $T$. Each element in the $i$th row and $j$th column of matrix is denoted by $a_{ij}$, for $i, j = 1, \ldots, n$, where $a_{ij}$ represents the amount of traffic from device $i$ to device $j$. The number $n$ denotes the total number of devices in a piconet.

**Definition.** Packet error rate: The value packet error probability, $PER(p)$, denotes the probability of collision within communication range when there are $p$ piconets within communication range. The formula to compute $PER(p)$ is

$$PER(p) = 1 - \left(\frac{78}{79}\right)^p.$$  

**Definition.** Restructuring request packet: To adjust the piconet architecture dynamically, the master device will broadcast the restructuring request packet to inform the slaves which the auxiliary master dominates to establish connection. The restructuring request packet contains fields of $\langle Page-BD_ADDR, PageScan-BD_ADDR, Clock, TimeSlot \rangle$. The field $Page-BD_ADDR$ records the $BD_ADDR$ of those slaves, which should enter, $Page$ state while the fields of $PageScan-BD_ADDR$ and $Clock$ record the $BD_ADDR$ and $Clock$ of those slaves, which should enter $PageScan$ state.

3. Dynamic piconet combination and decomposition

In bluetooth radio system, selecting different slave device, as auxiliary master will affect performance of the entire piconet profoundly. The proposed approach selects the suitable auxiliary master according to the transmission pair and historical traffic load of the piconet. Through changing transmission pair, reducing length of routing path and changing roles of devices, the transmission efficiency of entire bluetooth radio system can
be enhanced. When a master detects heavy traffic load within piconet, it can select a slave to play roles of auxiliary master which can change its hopping sequence and perform role-switching operation of establish new connections to other slaves.

Fig. 7 illustrates the role-switching operation in a piconet. In Fig. 7(a), if the master device $M$ selects device $B$ to be an auxiliary master, device $M$ can send a role-switching request to device $B$. After device $M$ sends the role-switching request, device $M$ also informs slaves $A$, $C$, $D$, $E$, $F$, $G$ and $M$ to switch to page scan state and sends $BD\_ADDR$ and Clock information to device $B$. Then device $B$ enters page state and uses the received $BD\_ADDR$ and Clock information to establish new connections to device $A$, $C$, $D$, $E$, $F$ and $G$ to form a new piconet, as shown in Fig. 7(b). The new piconet consists of master device $B$ and slave devices $A$, $C$, $D$, $E$, $F$ and $G$. The connections among new master and slave devices thus can be are established.

3.1. Single piconet restructuring

As two slaves cannot communicate directly within a piconet, the master should involve in the communication process between any two slave devices. When multiple routing paths pass through the same piconet, the master device will experience the heavy traffic load problem and become the bottleneck node of a network. The system performance will decay if the traffic load of some device is heavy. In this section, we propose an auxiliary master selection protocol, which selects suitable auxiliary master based on historical traffic flow analysis. The auxiliary master selection protocol can be used to improve system performance.

The determination of an auxiliary master in a piconet is based on the analysis of data flow matrix (DFM). The two slave devices with the largest amount of traffic between them are candidates of auxiliary master. One of them is selected to be a auxiliary master to share the traffic load of current master device. If the traffic flow changes frequently, the number of auxiliary masters may change dynamically to share the traffic flow. In the proposed protocol, we propose to distribute traffic flow of the routing path with heavy traffic from the master device.

The operation of piconet restructuring can be illustrated in Fig. 8. Due to master device involves all communication process within a piconet, the master can compute a cumulated amount of traffic between any two devices within piconets. So it can estimate the traffic flow of each link and store in its internal $DFM$. For example, in Fig. 8(a), the master device $M$ forwards traffics among slaves $A$, $B$, $C$, $D$, $E$, $F$ and $G$ and records the amount of traffic among them. The results are illustrated in Table 1. To determine the suitable slave to be an auxiliary master, the master device chooses the slave, which can maximize the amount of parallelism and to release the traffic bottleneck.
3.1.1. The restructuring operation in a single piconet

The improvement of system performance depends on the piconet restructuring operation. We will use Fig. 8(a) to continue the principle and process of the reconstructing operation. Table 1 shows the traffic flow of the piconet in Fig. 8(a). The total amount of packets transmitted and received for slave \( k \) can be computed using the following formula:

\[
P_k = \sum_j a_{kj} + \sum_i a_{ik} \quad \text{for} \quad k = 1, 2, \ldots, 8. \tag{2}
\]

For example, the values in the first column and the first rows represent the amount of transmitted and received number of packets of device \( A \). The following formula can be used to compute the total amount of traffic transmitted and received by device \( A \):

\[
P_1 = \sum_j a_{1j} + \sum_k a_{k1}.
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Table 1

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Fig. 8. Traffic load analysis in a single piconet. (a) Traffic load in a piconet. (b) Structure of piconet after the first restructuring operation. (c) Structure of piconet after the second restructuring operation.
After the values of $P_k$ (for $k = 1, 2, \ldots, 8$) are all computed, master can select the $a_{mn}$ which satisfies the following rule:

$$(m, n) = \arg \max_{i,j} (a_{ij} + a_{ji}) \quad \text{for} \quad i, j = 1, \ldots, 8. \quad (3)$$

The values $m$ and $n$ represents IDs of devices, which need to construct a direct link to improve system performance. If total traffic in device $m$ is larger than device $n$, i.e., $P_m \geq P_n$, then $m$ is selected as an auxiliary master. Otherwise, $n$ is selected as an auxiliary master. Assume that the ID of master device in piconet be denoted by number 1. If the value of $m$ or $n$ is 1, then the routing path will use the original master to service this routing path. In Fig. 8(a), assumed that the values $m$ and $n$ fulfill Eq. (3) are (2) and 1, respectively. The corresponding devices are device $B$ and $A$, respectively. After device $M$ selects the first pair of devices to perform piconet restructuring, the rows and columns corresponding to the traffic flow of device $A$ and $B$ are reset to 0, as shown in Table 2. Repeat the above procedure until one of the following conditions occurred.

1. There are only one non-zero entry in $DFM$.
2. The largest traffic flow $a_{ij} + a_{ji}$ corresponding to device $i$ and $j$ is smaller than a threshold $T$, where $T$ represents the transmission bottleneck of master device.

The final $DFM$ after piconet restructuring for Fig. 8(a) is shown in Table 3.

After the internal computation about the restructuring operation in master $M$ has completed, master $M$ will send a restructuring request packet to inform all slaves to perform piconet structure adjustment. In the example shown in Fig. 8(a), after device $A$, $B$, $C$ and $E$ received the restructuring packet, the devices $B$ and $C$ which are responsible to be auxiliary masters will perform role-switching operation with device $D$ and $E$, respectively. A shortcut routing paths will be constructed to benefit the transmission process of routing paths. The result is shown in Fig. 8(b).

Due to increasing the number of piconets will also increase the probability of data collision. The lifetime of the new piconet managed by auxiliary master thus depends on the amount of traffic flow the auxiliary master should share. In the proposed protocol, the lifetime of each piconet restructuring operation is determined by the amount of traffic flow of the first selected communication pair in the restructuring computation. However, due to the increasing of packet error rate, the total number of slots needed to complete the

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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>60</td>
<td>0</td>
</tr>
</tbody>
</table>
sharing of traffic flow is as follows:
\[ L(p) = \left( 1 + \text{PER}(p) \right) \times \max_{i,j} (a_{ij} + a_{ji}). \] (4)

For example, in Fig. 8, assume the number of piconets within transmission range after first restructuring operation is 4, and the maximum amount of traffic flow \( \max_{i,j} (a_{ij} + a_{ji}) \) is 90. Applying these two values into Eqs. (1) and (4), the computed time slots are \((1 + 0.037) \times 90 \approx 94\). After 94 slots, master device will perform restructuring operation and arrange the next piconet restructuring operation. The result is shown in Fig. 8(c). In Fig. 8, after two restructuring operation, the DFM matrix become zero matrix. During these two restructuring operation, the lifetime of new piconets are 100 and 90, respectively. So, the total amount of time slots required to transmit data to all destinations can be reduced from 670 to 190 slots. On the other hand, due to the amount of packets forwarded by master is decreased; the power consumption is reduced from 1340 to 775. To compute the cost of power consumption, we will first compute the traffic flow between master–slave pair and slave–slave pair.

The traffic flow between master and all slave devices is
\[ F_{MS} = \sum_i a_{i1} + \sum_j a_{ij}, \] (5)

while the traffic flow between slave and slave device is
\[ F_{SS} = \sum_i \sum_j a_{ij}. \] (6)

So, the power consumption of original piconet \( p \) is
\[ POWER_{ORG} = 2(F_{MS} + 2F_{SS})(1 + \text{PER}(p)) \] (7)

and the power consumption of the piconet \( p' \) after RRP is
\[ POWER_{PRP} = 2(F_{MS} + F_{SS})(1 + \text{PER}(p')). \] (8)

The detail procedures of the proposed single piconet restructuring protocol are as follows:

**Step 1:** Master \( M \) records the amount of packets \( m \) it forwarded during time interval \( t \). Let \( \delta \) denote the traffic overload threshold. If \( m > \delta \), and the probability of packet lost is smaller than \( \beta \), then perform the restructuring operation.

<table>
<thead>
<tr>
<th>M</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
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<tbody>
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<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>F</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>60</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3
Contents of DFM after the first restructuring operation
Step 2: After internal restructuring computation is completed, master device $M$ sends restructuring request packet to all slaves.

Step 3: After each slave received restructuring request packet, the slave which is assigned to be auxiliary master should perform role switching and connect to the selected devices to construct a new piconet.

Step 4: After the time interval $t + 1$, all devices including auxiliary master should return to its original states. The amount of traffic transmitted between device $i$ and $j$ during the last time interval $t$ should be send to master, master will return to step 1 and start a new cycle of piconet restructuring if the traffic load is heavy.

Fig. 9 illustrates how the single piconet restructuring protocol operates. In a constructed piconet, master device will compute the amount of transmitted packets $m$ and packet error rate $e$. If $m > \alpha$ and $e < \beta$, then master will trigger the piconet restructuring operation, where $\alpha$ is a threshold representing traffic load and $\beta$ is a threshold denoting the tolerable packet error rate. The master device will perform internal computation and select suitable slaves to become an auxiliary master to share traffic load of master device. Then the master will broadcast the restructuring request packet to slave $s_1$ and $s_2$, where $s_1$ and $s_2$ are the suitable devices after master performing internal computation. Slaves $s_1$ and $s_2$
then can use the information in the restructuring operation and role-switching technique to create a new piconet. Assume \( s_1 \) is responsible to be auxiliary master and \( s_2 \) is the corresponding slave, then \( s_1 \) should enter page state and \( s_2 \) should enter page scan state. When \( s_1 \) and \( s_2 \) are connected, \( s_1 \) becomes an auxiliary master and \( s_2 \) becomes a \( S/S \) relay. Now, \( s_1 \) can communicate with \( s_2 \) directly without the service of original master device. After the time of the arrange slots is out, \( s_1 \) and \( s_2 \) will disconnect their link and return to slave states in original piconet. If the traffic load is heavy again, the master device can trigger another piconet restructuring operation.

### 3.2. Multiple piconet restructuring

In a single piconet, the DFM matrix can be used to select auxiliary master to share traffic load of master device. However, in a scatternet, the class of a relay may be a \( M/S \) relay and the number of slaves it dominates may be 7. In this circumstance, this relay cannot be selected to be an auxiliary master due to the constraint of at most 7 slaves in a piconet. To solve this problem, the master device can select the slave device with light traffic flow as auxiliary master to serve the routing path with heavy traffic. The proposed protocol will give the routing path with heavy traffic high priority to construct direct link using auxiliary master approach. The established network thus can be optimized. The example shown in Fig. 10(a) can be used to illustrate the operation of the proposed protocol in a scatternet environment.

In the scatternet shown in Fig. 10(a), device \( E, D \) and \( L \) are relay devices and are responsible to inter-piconets packet transmission. From the amount of forwarded packets, master device can compute the transmission pair and their traffic flow in piconet \( P_4 \). When the traffic is congestion in \( P_4 \), master \( M \) can perform restructuring computation according to its DFM. In Fig. 10(a), assume that the path with largest traffic flow is \( E\Rightarrow M\Rightarrow L \). Due to the number of slaves managed by device \( E \) and \( L \) are all 7, the connection between \( E \) and \( L \) cannot be established directly. In this circumstance, master \( M \) perform restructuring computation and find device \( B \), which accumulated traffic \( P_k \) is minimum to be an auxiliary master. After \( B \) performs role switching and connects to \( E \) and \( L \), respectively, the routing path, \( E\Rightarrow M\Rightarrow L \), is updated to be \( E\Rightarrow B\Rightarrow L \). The traffic load of master \( M \), piconet \( P_4 \), can thus be released. The new scatternet is shown in Fig. 10(b). However, when slave devices in a piconet are all either \( M/S \) relay or \( S/S \) relay, then only relay device can be selected to perform role switching. Fig. 11(a) reveals this condition. In this example, the traffic in master is congestion; master \( M \) performs restructuring computation to select the routing path, \( E\Rightarrow M\Rightarrow L \), with largest traffic flow as mention previously. From DFM, the most suitable slave is selected to be an auxiliary master. After the slave performs role-switching operation and connects to the associated slave, the final resultant scatternet is shown in Fig. 11(b).

The detail operations of the proposed multiple piconet restructuring protocol are summarized as follows:

**Step 1:** The master device \( M \) records the number of packets it forwarded, the roles of its slave and relevant information. During a time interval \( t \), when the number of forwarded packet \( m \) is larger than \( x \) and the packet error rate \( e \) is less than \( \beta \), the master will trigger a restructuring computation according to its DFM.
Step 2: Master device $M$ performs restructuring computation and finds devices $i$ and $j$, which fulfill Eq. (3). According to the parallelism of routing paths passing through this piconet, the roles of slaves and the relevant information, master can compute the feasibility of establishing direct connection. If it is infeasible to find the suitable device, then master chooses another slave, according to minimum $P_k$, roles of slaves and other relevant information, to be an auxiliary master to perform role-switching operation to connect those devices, which cannot establish direct connections.

Step 3: Master device broadcasts the computed restructuring results to all of its slaves using the restructuring request packet.

Step 4: After the slave device $m'$ is chosen to be an auxiliary master and slave $i, j$ which fulfill Eq. (3) received the restructuring request packets, those devices which are arranged to be auxiliary master then perform role-switching operation to establish direct connections among slave devices.

Fig. 10. The analysis of traffic load in a scatternet environment. Structure of piconet (a) before restructuring operation and (b) after restructuring operation.
Step 5: After the time interval $t + 1$ has passed, all devices involved in the new piconet restructuring will return to its original piconet and return to its original roles. The traffic flow of each slave will be sending to master again. Master will trigger another piconet restructuring operation if the traffic flow is heavy again.

In this section, we have explained the operation of signal and multiple piconets restructuring protocol. The heavy traffic of master devices in piconet can be shared by new auxiliary master device. The total hop count of routing path can thus be reduced. In the following section, we will discuss the characteristics of the proposed restructuring protocol and use experimental results to demonstrate the improvement on system performance using the proposed piconet restructuring protocol.

4. Performance study

In previous sections, we have proposed a dynamic piconet restructuring protocol (PRP), which adjusts structure of piconets in a dynamic and distributed manner using
role-switching operation. The slave device, which experiences heavy traffic flows, is chosen to be an auxiliary master to share the workload of master device. To evaluate the performance of the proposed PRP, we construct a simulation environment to investigate important factors, which affect the system performance and measure the performance of entire system.

The environment of experiments is as follows. The size of the environment is 10 by 10 m. All devices are located within 10 m, i.e. they are all within transmission range. For a fixed number of devices, the location, $BD\_ADDR$ and internal clock of each device is randomly generated. The traffic flow between any two devices is generated randomly also. The routing operation is performed using shortest path routing, which construct a routing path with minimum number of hops. Assume the role-switching operation takes 50 time slots and all transmission using DH1 data packets. The factors of external interference and fading are ignored in the following experiments.

4.1. Transmission efficiency for various packet types

The proposed piconet restructuring protocol creates new piconets to share the traffic load of master devices. However, increasing the number of piconets will also increase the packet error rate. Before the performance of the proposed piconet restructuring protocol can be inspected, the relation between packet error rate and number of co-located piconets should be examined. According to Eq. (1), packet error rate for DH1 packets under $p$ co-located piconets is

$$PER_{DH1}(p) = 1 - \left(\frac{78}{79}\right)^p,$$

Due to DH3 and DH5 use 3 and 5 slots to transmit data, their packet error rate will be

$$PER_{DH3}(p) = 1 - \left(\frac{78}{79}\right)^{3p},$$

and

$$PER_{DH5}(p) = 1 - \left(\frac{78}{79}\right)^{5p},$$

respectively.

Fig. 12 shows the packet error rate for DH1, DH3, and DH5 packets under various numbers of co-located piconets. Because DH3 and DH5 use more slots to transmit data, their packet error rates are higher than DH1. According to bluetooth specification (Bluetooth Special Interests Group), the length of payload for DH1, DH3, and DH5 packets are 28, 185, and 341 bytes. Although DH3 and DH5 have higher packet error rates than DH1 packet, but they can carry more payload than DH1 packets. To justify the efficiency of each type of packets under various numbers of co-located piconets, we define
the effective payload as

\[
\text{Payload}_{\text{Effective}} = \frac{\text{Payload length}}{\text{Number of slots} \times (1 + \text{PER})}. \tag{9}
\]

Although the payload length, packet error rate, and number of slots for DH1, DH3, and DH5 are all different, using Eq. (9) the effective payload can be defined as the expected successful transmitted amount of data for each slot. The effective payload for DH1, DH3, and DH5 packets under various numbers of piconets is shown in Fig. 13.

From Fig. 13, we observe that when the number of co-located number of piconets is under 3, DH5 has the highest effective payload. However, as the number of co-located piconets is increased, DH3 outperforms DH5. When the number of co-located number of piconets is larger than 33, DH1 becomes the most effective packet type. However, the packet error rate becomes 0.33 for DH1 packets under 33 co-located piconets. It is not practical to construct so many co-located piconets under a scatternet, so using DH3 and DH5 packets can get good system throughput. In fact, the number of co-located piconets is difficult to determine, so a simple way to estimate the packet error rate will be count the ratio of packet collision detected by master device in each device.

4.2. Performance of piconet restructuring protocol under various traffic loads

In the following experiments, 30 bluetooth devices are distributed under 10 × 10 square area. The scatternet is constructed as shown in Table 4. There are six piconets in original scatternet. For device, which plays roles of slaves in more than one piconet, is a relay
device. For example, device 2 participates in piconets $P_0$ and $P_1$; device 2 is a relay node between piconets $P_0$ and $P_1$.

The traffic load is simulated by various numbers of flows. In each flow, two devices are randomly selected as source and destination to deliver 1 kbytes data. The shortest path routing algorithm is used to find a route from source to destination. When the route is constructed, the traffic loads for all links on the route are added by the data rate 1k. The threshold to trigger the piconet restructuring protocol is set as 20k. As the number of generated flows is increased, the traffic load of each link will also increase too. When master detects a communication pair which traffic load is larger than threshold, the piconet restructuring protocol is initiated. Fig. 14 shows the relation between the number of piconets and number of flows. Without piconet restructuring, six piconets exists in this scatternet. If piconet restructuring protocol is applied, the number of piconets is increased from 6 to 7 when the number of flows exceeds 70. When the number of flows is increased to 160, another piconet is constructed.

![Effective payload for various packet size](image)

**Fig. 13.** The relations between effective payload and number of co-located piconets for packets DH1, DH3, and DH5, respectively.

**Table 4**
A constructed scatternet using 30 bluetooth devices under 10 x 10 square area

<table>
<thead>
<tr>
<th>Piconet no.</th>
<th>Master</th>
<th>Slaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$</td>
<td>0</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>$P_1$</td>
<td>6</td>
<td>2, 7, 8, 9, 10</td>
</tr>
<tr>
<td>$P_2$</td>
<td>11</td>
<td>7, 12, 13, 14, 15</td>
</tr>
<tr>
<td>$P_3$</td>
<td>16</td>
<td>12, 17, 18, 19, 20</td>
</tr>
<tr>
<td>$P_4$</td>
<td>21</td>
<td>17, 22, 23, 24, 25</td>
</tr>
<tr>
<td>$P_5$</td>
<td>26</td>
<td>22, 27, 28, 29</td>
</tr>
</tbody>
</table>
The benefits of new created piconets are as follows. First, the average path length is shortened. As shown in Fig. 15, when the number of flows exceeds 70, the average path length is reduced. The reason why the route is shortened is that a new piconet is created, so
that two slaves that initially cannot transmit data can now establish a direct link. When the number of flows is more than 170, another shortcut path is constructed, so the average path is shortened again. Second, the delay times is reduced when new piconets are created.

![The relation between delay and number of flows using DH1 packets](image1)

**Fig. 16.** The relation between delay times and number of flows using DH1 packets.

![The relation between average delay and number of flows using DH3 packets](image2)

**Fig. 17.** The relations between average delay times and number of flows using DH3 packets.
The relations between delay time and number of flows for DH1, DH3, and DH5 packets are shown in Figs. 16–18. When the number of flows exceeds 70, a new piconet is created to share the traffic load of master, so the transmission delay can be reduced.

Fig. 18. The relations between average delay times and number of flows using DH5 packets.

Fig. 19. The relation between number of piconets and threshold.
4.3. Selection of threshold to trigger piconet restructuring protocol

The proposed piconet restructuring protocol is trigger by threshold $T$. When the traffic load of a link is larger than $T$, a new piconet is constructed to share the heavy traffic load. To investigate the effect of threshold, the following experiment is conducted. The number of flows is set to be 100; the threshold is changed from 1 to 30k. The relation between the number of constructed piconets and various thresholds is shown in Fig. 19. The number of piconets is large when the threshold is small while the number of piconets is small when the threshold is large. Increasing the number of piconets will also increase packet error rate. New piconets will not be constructed when a master detect that increasing the number of piconets does not contribute to share the traffic load within piconets.

5. Conclusion

In this paper, we have proposed a distributed and dynamic piconet restructuring protocol, which can adjust structure of scatternet locally to share the traffic load of master device. The traffic load of master device is shared by piconet restructuring computation such that slave device with the largest amount of traffic can act as an auxiliary master and involve the communication process among slaves directly. Experimental results reveal that the proposed approach bears the following advantages: the number of hops of routing paths can be reduced; the bottle neck of network can be released; the transmission delay time can be reduced; the power consumption of master device is balanced with other devices; the lifetime of piconet can be increased and the bandwidth efficiency is increased. The proposed protocol constructs new piconets while maintaining the original network topology.

References


