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Adaptive Intra-Piconet Scheduling for Supporting QoS on Scatternet Routes

Chorng-Horng Yang, Wu-Ping Ho

Abstract—**Bluetooth is a wireless communication technology which can be used for cable replacement. This paper proposes an adaptive intra-piconet scheduling (α-RMRR) for supporting Quality-of-Service (QoS) for scatternet routes. Firstly, two intra-piconet scheduling approaches were presented. However, these scheduling approaches do not fully support QoS on the scatternet route. The Round Robin (RR) approach is a fair scheduling but does not support QoS. The Exhausted Route-Member Round Robin (ERMRR) approach may support QoS on scatternet route but would suffer from the starvation problem. Thus, the proposed α-RMRR approach combines the RR and the ERMRR approaches into the α-Route-Member Round Robin (α-RMRR), which can support QoS on route-member slaves and provides good fairness for the slaves. Moreover, the simulation study was conducted to compare the scheduling delay of the three approaches. Our simulation results show that the α-RMRR is effective for supporting QoS with respect to the scheduling delay and good fairness on scatternet routes.**

Index Terms—**Bluetooth, Quality-of-Service, Scheduling, Scatternet.**

I. Introduction

Bluetooth is a short-range wireless technology [1] that operates in the unlicensed Industrial, Scientific and Medical (ISM) band at 2.4 GHz. Bluetooth provides interconnection between mobile electronic devices for personal area ad-hoc networks. In order to minimize the interference from other users in the same band, Bluetooth uses a frequency-hopping (FH) scheme that divides the band into 79 1-MHz channels. The channels use a Time Division Duplex (TDD) scheme, which divides each channel into consecutive time slots. Each time slot is a time period of 625 μs and the hop rate is 1600 hops/sec. Each packet is transmitted on a different hop frequency and the packet length may be 1, 3, or 5 time slot(s).

In a Bluetooth piconet, one device acts as the master and the other devices are slaves. The number of active slaves in a piconet can be up to seven. Devices in a piconet share the same hopping channels, which the channel is selected from the 79 hopping channels according to the FH sequence. The identity and system clock of the master determines the FH sequence. Each device selects the same hopping channel, and there creates a unique channel in a piconet. The Bluetooth air interface supports two types of links between a master and a slave. The Synchronous Connection-Oriented (SCO) links use a fixed bandwidth between the master and a single slave, and provide symmetrical connection for transmitting voice. And the SCO packets are never retransmitted. The other one is the Asynchronous Connectionless (ACL) links, which use the slots that are not reserved for SCO links to support point-to-multipoint links between the master and the slaves in a piconet. The ACL packet can be retransmitted if the packet was corrupted during transmission.

In the Bluetooth specification the Quality of Service (QoS) configuration has been proposed, but providing QoS in a scatternet is for further study. In addition, the traffic scheduling in piconet/scatternet is an important protocol that impacts on providing QoS in scatternets [2-5]. In this paper, several intra-piconet scheduling approaches that can be used for scatternet routes are investigated. (i) Round Robin (RR) approach: The master polls the slaves in a sequential and cyclic order. Obviously, the RR approach is a fair approach but it does not guarantee QoS on data transmission of the slaves that are members on a scatternet route. (ii) Exhaustive Route-Member Round Robin (ERMRR): ERMRR can guarantee the data transmission on the route members but suffer from the starvation problem of non-route-member (NRM) slaves. The ERMRR is an unfair approach, which serves route-member (RM) slaves with high priority and serves the NRM slaves when RM slaves have no data for transmission. Though the ERMRR is unfair, it can support QoS on scatternet routes. (iii) An approach, α-Route-Member Round Robin (α-RMRR), is proposed in this paper. The master executes ERMRR with the probability of α and executes the RR with the probability of 1-α. The value of α can be set by employing either a static approach or dynamic approach. Thus, the α-RMRR can support a trade-off between the fairness and the QoS by adjusting the value of α.

II. Related Work

A. Intra-piconet Scheduling Approaches

Several intra-piconet scheduling algorithms have been proposed in the literature [6-9]. These algorithms can be classified into two types: one is the intra-piconet scheduling approach without QoS guarantee and the other is the QoS-aware intra-piconet scheduling approach.

The Round Robin (RR) scheduling approach is a simple and famous scheduling approach that can be used in many applications. For the RR scheduling approach [10-12], the slaves are polled by its master in a sequential and cyclic order. Based on the rules of the RR scheduling, several intra-piconet scheduling approaches [13] are developed. The RR approach is a fair scheduling that each slave is polled by the master sequentially and periodically. However, the RR approach

Chorng-Horng Yang, Department of Information Management, I-Shou University, Kaohsiung City, Taiwan R.O.C.
Wu-Ping Ho, Department of Information Management, I-Shou University, Kaohsiung City, Taiwan R.O.C.

doesn't take the availability of data at the polled slave into account, so that it may waste a lot of time slots when the slave has no data packets for transmission. Hence, the Weighted Round Robin (WRR) [10-12, 14] in which each slave has its own weighting decides the cyclic order according to the weighting values for the slaves. Though WRR can improve the waste of time slots in RR, it may cause packet jitter at destination and ensure the fairness only over a long time. If a slave has a small weighting or the number of the slaves are large, it may cause the starvation problem.

The idea behind RR and WRR are the cyclic order with the weighting. They ignore the availability of data packets at the slave polled by the master. The Exhaustive Round Robin (ERR) considers not only the fairness but also the traffic in the piconet. It cleans up entire queue until that the traffic is empty. The master keeps polling the same slave until both the master and slave queues are empty. However, it may cause an unfair sharing of capacity between slaves.

The previous intra-piconet scheduling approaches does not consider the QoS in the piconet. Thus, Chen *et al.* proposed a QoS-based intra-piconet scheduling approach [3]. For this approach, each connection M_i is described by two parameters (C_i, D_i), where C_i is the maximum amount of messages (in time slots) in M_i and D_i is the relative transmission deadline in time slots. Moreover, $\rho(m)$ is a factor to evaluate the feasibility of the scheduling. We show the QoS scheduling as follows.

$$M' = \{M_i' = (C_i, D_i')\} \quad (2.1)$$

$$\rho(m) = \sum_{i=1}^{k} \frac{C_i}{D_i'} \leq 1 \quad (2.2)$$

In order to illustrate the QoS scheduling, we give an example as follows. Assume that there is a piconet with tree connections, m_1, m_2, andm_3. For these three connections, the corresponding QoS parameters are as follows.

$$M = \left\{ \{m_1, m_2, m_3\} \begin{cases} (C_1, D_1) = (1,7) \\ (C_2, D_2) = (1,11) \\ (C_3, D_3) = (2,9) \end{cases} \right.$$

After factorizing the QoS parameters for the connections, we get the new QoS parameters as fallows.

$$M' = \{m_1', m_2', m_3'\} \quad \begin{cases} m_1' = (C_1, D_1') = (1,4) \\ m_2' = (C_2, D_2') = (1,8) \\ m_3' = (C_3, D_3') = (2,8) \end{cases}$$

And,

$$\rho(m) = \frac{1}{4} + \frac{1}{8} + \frac{2}{8} = \frac{5}{8} \leq 1$$

Thus, it is possible to schedule the traffic in the three connections to meet their QoS requirements by adopting the WRR in the piconet. However, it may suffer from starvation problems.

B. Quality of Service

To support QoS in a Bluetooth scatternet [3] requires multiple mechanisms to cooperate together at different phases. At the beginning, Bluetooth devices run the scatternet formation procedure, which decides the role of each device to be either master or slave and either bridge or non-bridge [16][19-22]. After formatting the scatternet, the routing mechanism has to choose a proper route that meets the QoS requirements if two devices need a connection for exchanging data. Actually, such a route is a chain of master and slave devices. As mentioned in the previous Section, the master controls the data transfer in a piconet. Thus, scheduling the transmission of packets to the slaves at the master is essential to supporting QoS on the route. So, the formatting, routing and scheduling mechanisms must cooperate to support QoS in a scatternet. Moreover, the QoS parameters may include data rate, packet loss ratio, delay, delay jitter, etc. In this paper, we consider the QoS parameter, scheduling delay, for studying the provision of QoS in Bluetooth scatternets.

III. Adaptive Intra-Piconet Scheduling

This section discusses how the adaptive intra-piconet scheduling provisions QoS on scatternet routes. For route R_i with QoS requirements of D_i and B_i, the D_i can be decomposed into p_i components, $d_1^i, d_2^i, \cdots, d_{p_i}^i$, where p_i is the number of piconets on R_i. To support QoS on R_i the QoS-aware scheduling is required and the QoS-aware scheduling for scatternet routes is developed on basis of the intra-piconet scheduling approach.

The scheduling approaches in a piconet that can be used to implement the QoS-aware scheduling on scatternet routes are introduced as follows. Firstly, the following notations are used in this study.

$N_{i,k}^s$: The number of slave nodes in the k -th piconet on route R_i.

$S_{i,j}^k$: k-th slave in the j-th piconet on route R_i.

$S_{i,j}$: the j-th slave in the i-th piconet in the scatternet.

$MS_i(\cdot)$: Function of the membership of a node on a route R_i.

$C_b(R_i)$: The number of packets stored in the buffer of the slave on route R_i.

The fair and robust Round Robin (RR) scheme is described as follows. For the RR scheme each slave is polled by the master in a fixed and cyclic order. For the k-the piconet on route R_i , there are $N_{i,k}^s$ slaves. Suppose that the distribution of the packet size is the uniform distribution. The master sequentially polls the slaves $(1,2,\ldots,N_{i,k}^s)$. For each slave the polling priority is $\frac{1}{N_{i,k}^s}$. Suppose that there are four slaves in a piconet P1 on a route. Each slave is polled in a cyclic order so that the polling priority for each slave is $\frac{1}{4}$. And, the polling sequence is fixed as $s1 \to s2 \to s3 \to s4$.

Based on the RR scheme the Route-Member Round Robin (RMRR) scheme was proposed to guarantee the data transmission on the route. For the k-th piconet on route R_i, there are $N_{i,k}^s$ slaves. The membership of the slaves in the j-th piconet on route R_i is defined as follows.

$$\begin{cases} MS_i(S_{j,k}) = 1, & if\ S_{j,k} \in R_i \\ MS_i(S_{j,k}) = 0, & if\ S_{j,k} \notin R_i \end{cases} \quad (3.1)$$

For each slave in the k-th piconet on route R_i , the polling priority is defined as follows.

$$\begin{cases} \frac{1}{\sum_{k=1}^{N_{i,k}^S} MS_i(S_{j,k})}, if\ MS_i(S_{j,k}) = 1 \\ 0, otherwise \end{cases} \quad (3.2)$$

Though the RMRR scheme can guarantee the data transmission on the route, the fairness of using the bandwidth in a piconet for two or more routes through the piconet is not considered. Thus, an Exhaustive Route-Member Round Robin (ERMRR) scheme was proposed. The ERMRR scheme consists of two algorithms: the RR scheduling algorithm and RMRR scheduling algorithm. The C_b parameter is employed in the ERMRR scheduling. $C_b(S_{j,k}) > 0$ means that there are a lot of data packets (in time slots) stored in the buffer of $S_{j,k}$ and waited for transmission. And, $C_b(S_{j,k}) = 0$ means that buffer of $S_{j,k}$ is empty. The ERMRR scheduling is described as follows.

Step1: If there exists any slave $S_{j,k} \in R_i$ and $C_b(S_{j,k}) > 0$, then execute RMRR.

Step2: Otherwise, execute RR until $\exists S_{j,k} \in R_i$ and $C_b(S_{j,k}) > 0$ go to Step1.

Suppose that there is a route in the scatternet. When $C_b(S_{j,k}) > 0$ and $S_{j,k} \in R_i$, the master of a piconet polls the slaves that are the members of R_i with the polling priority of $\frac{1}{2}$ (i.e. RMRR scheduling). When all slaves that are the members of R_i meet the condition of $C_b(S_{j,k}) > 0$, the master executes RR scheduling with the polling priority of $\frac{1}{4}$ for other slaves.

In this paper a new scheme, α-RMRR, is proposed. The α-RMRR scheme adopts a parameter α to adaptively adjust the scheduling to execute RR scheduling or ERMRR scheduling. The following notations are used in this paper:

P: The probability of a slave generating packets in a time slot

α: The probability of executing ERMRR scheduling

β: The probability of executing RR scheduling (i.e., $\beta = 1 - \alpha$)

x: The probability of polling a slave

The slaves in a piconet are classified into two types: one is the route member (RM) slaves and the other is non-route-member (NRM) slaves. The α-RMRR scheduling is defined as follows:

Step1 : If $x \leq \alpha$ and there exists a slave $S_{j,k} \in R_i$ that satisfies the condition of $C_b(S_{j,k}) > 0$, then the master polling the RM slaves as the ERMRR scheduling.

Step2: Otherwise, execute RR scheduling to poll the NRM slaves until $x \leq \alpha$ and $C_b(S_{j,k}) > 0$ where $S_{j,k} \in R_i$, go to Step1.

The value of α can be determined by two ways: (i) static: α is fixed, when $x \leq \alpha$, execute RMRR. Otherwise, execute RR, (2) dynamic: α is set to be the ratio of total packets in the buffers of RM slaves to the total packets in the buffer of the NRM slaves. The definition of dynamic value of α is shown in Eq. 3.3.

$$\alpha = \frac{C_b(R_i)}{C_b(R_i) + \sum_{j=1}^{P_i} C_b(S_{j,k})}, \text{ where } S_{j,k} \notin R_i \quad (3.3)$$

IV. Simulation Study

A. Simulation Model

To evaluate the average packet delay for the proposed scheduling approaches, we make the following assumptions for the simulation study: (1) The packet size is fixed as 1 time slot, which is 625 μs. (2) The three scheduling approaches in a piconet was simulated. The piconet includes 7 slaves and the master can obtain the information about the number of packets in the buffer (queue) of each slave. (3) In the piconet, there are two slaves that are route members of a route in the scatternet. (4) Packet generating probability $\boldsymbol{p}$: The packet is generated for each slave in one time slot according to a uniformly distributed random process with the mean of $\boldsymbol{p}$. (5) The values of $\boldsymbol{\alpha}$: By varying the value of $\boldsymbol{\alpha}$, we can adjust the probability of master polling route members in $\boldsymbol{\alpha}$-RMRR and support QoS on the route. (6) The average scheduling delays for the three scheduling approaches for RM slaves and NRM slaves were compared**.**

The scheduling delay for a packet is defined as the time length that is from the time of generating the packet to the time of transmitting the packet. We conduct the simulation study on a Bluetooth piconet as shown in Fig. 1.

B. Simulation Results

This simulation study compares the scheduling delay of the three scheduling approaches with a fixed packet generating probabilities (p = 0.1). As shown in Fig. 2 to Fig. 5, the average scheduling delay of RR is larger than those of ERMRR and **α**-RMRR, and the RR does not guarantee the QoS in a piconet. It is obvious that the RR approach polls the slaves that have no data for transmission, so that incurs much

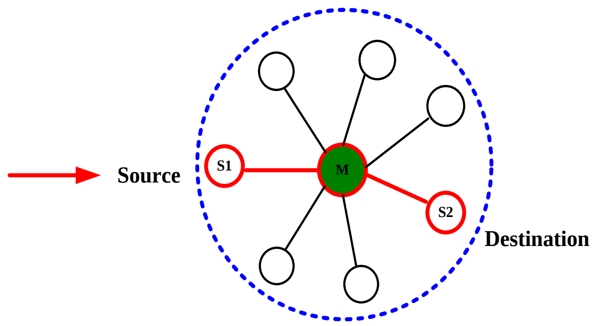

Fig. 1 A piconet for simulation study.

delay for the data transmission. However, the RR approach is fair and has less starvation problem. The average scheduling delay of the α-RMRR is between that of RR and that of ERMRR. If the value of α is smaller (say, 0.2), the α-RMRR acts as the RR. And, on the other hand, If the value of α is larger (say, 0.8), the α-RMRR acts as the ERMRR. Thus, the α-RMRR can support QoS on a route and provide better fairness than ERMRR does. On the other hand, the RR avoids the starvation problem. However, our proposed scheduling α-RMRR can keep the average packet delay in the middle of RR and ERMRR and can dynamically adjust the value of α to support the QoS requirement.

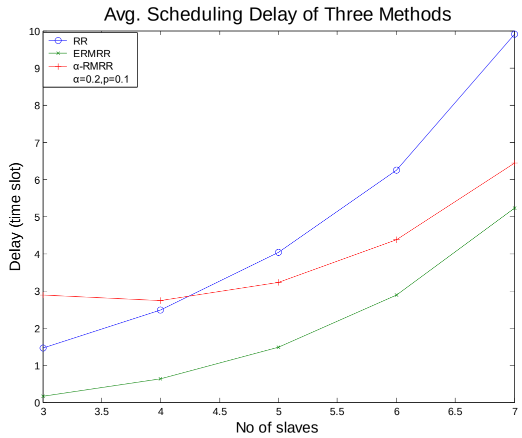

Fig. 2 Average scheduling delay (α=0.2)

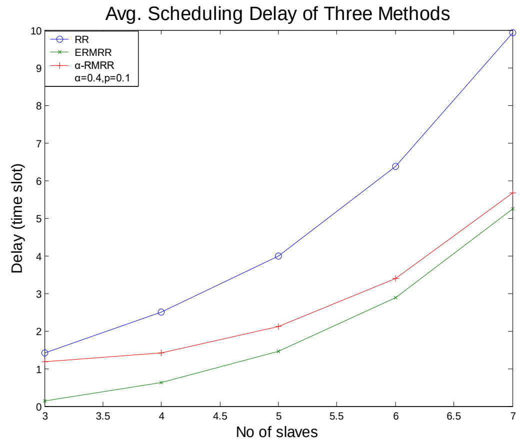

Fig. 3 Average scheduling delay (α=0.4)

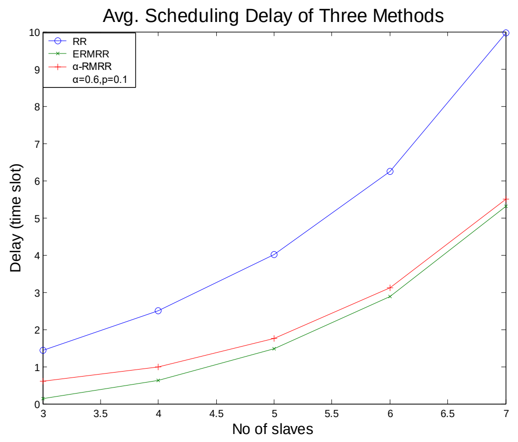

Fig. 4 Average scheduling delay (α=0.6)

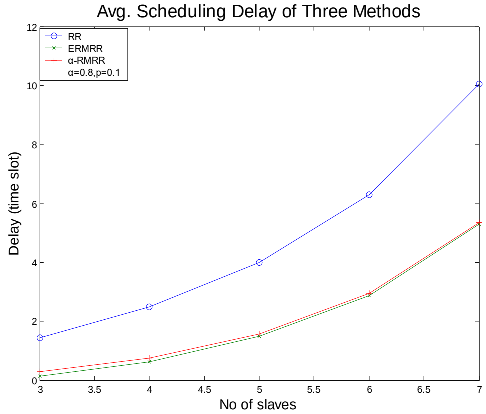

Fig. 5 Average scheduling delay (α=0.8)

V. Conclusions

This paper investigates the intra-piconet scheduling approaches, which can be classified into the non-QoS-aware approach and the QoS-aware approach. However, the inter-piconet scheduling for supporting QoS on scatternet is difficult to develop since the coordination of different piconets is hard. Thus, a QoS-aware intra-piconet scheduling approach to support QoS on scatternet route was proposed. Firstly, the traditional RR scheduling approach was presented and then the RMRR and ERMRR approaches were proposed. The RR approach is a fair scheduling but does not support QoS. On the other hand, the ERMRR approach can support QoS on scatternet route but suffer from the starvation problem for the NRM slaves. This paper proposed the α-RMRR approach, which combines the RR and the ERMRR approaches and supports QoS on RM slaves and provides good fairness for the slaves. A simulation study was conducted to compare the scheduling delay of the three different scheduling approaches and verifies the proposed α-RMRR approach. Our simulation results show that the α-RMRR may act as RR or ERMRR approaches by setting the value of α. Moreover, the proposed α-RMRR approach is effective for supporting QoS with respect to scheduling delay on scatternet routes.

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Chorng-Horng Yang, Department of Information Management, I-Shou University, Kaohsiung City, Taiwan R.O.C.

Wu-Ping Ho, Department of Information Management, I-Shou University, Kaohsiung City, Taiwan R.O.C.