# QoS Adaptive Inter-piconet Scheduling in Bluetooth Scatternet for Wireless PANs

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**Abstract.** Every bridge node participating in multiple piconets and forming a scatternet should schedule the inter-piconet traffics in an efficient manner. Frequent piconet switching due to short polling intervals for the links of a bridge node leads to considerable time slots loss caused by the guard time and power consumption for transceiving and processing. On the other hand, restrained piconet switching may result in failures of fulfilling QoS (Quality of Service) requirements for some links. In this paper, we present a QoS aware inter-piconet scheduling scheme minimizing the piconet switching events within guaranteed QoS requirements. According to simulation results, the proposed scheme is confirmed to have great improvement in throughput and number of switching events over the credit scheme as current inter-piconet scheduling scheme for the scatter mode.

## 1 Introduction

Any two or more Bluetooth-enabled products that come within range of each other can set up a piconet, which is composed of a single master and up to seven active slaves [1] [2]. To support full duplex transmission between the master and slaves Bluetooth adopts a Master-driven TDD (Time Division Duplex) in the baseband MAC layer; The Master can send packets to a slave in even-numbered slots, while the slave can only send packets to the master in odd-numbered slots immediately after receiving packets from the master. Meanwhile a Bluetooth device can participate in more than one piconet and form a scatternet, multi-hop ad hoc network. A node maintaining connections with multiple piconets, i.e. bridge node, may have a master role in a piconet of its own and slave roles in one or more other piconets. A bridge node is required to schedule inter-piconet connections effectively since the consequence of its scheduling has an immediate effect on scatternet performance [5].

In this paper, we propose an inter-piconet scheduling scheme of which basic operations follow those of the credit scheme. The proposed scheme adjusts the access rates for each link according to links' QoS requirements and meets the requirements strictly. For this purpose, two scheduling parameters $s_i$ and $T_{pp}$, which are entitled the starting time and the interval times between two successive present points for each link $i$, respectively, are adaptively determined by proposed rules, not arbitrary and fixed respectively as in the case of the credit scheme. Then we have found that the maximum access rates for every link guaranteed by the credit scheme become identical to $(M+1)T_{pp}$, where $M$ is the number of inter-piconet links. For the justification of this result we present two lemmas and a theorem. If the guaranteed maximum rate is lower than the minimum rates required by QoS for every link, then unnecessary piconet switching events are inevitably incurred. To resolve this problem, we offer additional time slots for transmitting packets to some links so that the guaranteed maximum rates are increased to the extent of the QoS for each link being satisfied. For this purpose, we present integer optimization problems that maximize the number of the total additional time slots under constraints that the minimum rates for each link should be fulfilled. A heuristic approach based on local search method for the problems and a strategy that applies the obtained solution to the credit scheme are presented. We also evaluate the proposed scheme through simulation and confirm the superiority over the credit scheme in terms of the number of piconet switching.

## 2 QoS adaptive scatternet scheduling mechanisms

At the start of the credit scheme, let $L_i$ be the $i$-th link to be serviced out of $M$ links. We assume that all the initial time slot of the other $M-1$ links start during the first two slots of $L_1$. Let $d_i(\geq 0)$ denote the difference in time slots between starting times of the first time slot of $L_1$ and $L_i$. We assume that, without loss of generality, $d_1(=0)\leq d_2\leq d_3\leq\cdots\leq d_M$. The starting time of initial PP for $L_i$, $s_i$, for $1\leq i\leq M$, is then set as follows:

$$s_i=(i-1)k+d_i, \qquad (1)$$

where $k$ is an even integer not less than 2.

For every $L_i$, $T_{pp}$, which is defined as an interval between two subsequent presence points (PPs) in slot [2], is assumed as follows:

$$T_{pp}=k\cdot M+2. \qquad (2)$$

Note that $T_{pp}$ is the same for all the links. Throughout this paper we follow the recommendation $T_{pp}=N_{switch\_th}$ in [2]. Let $c_i$ to be the credit of $L_i$ at $d_i$. Then the following condition for $c_i$ is assumed to be satisfied:

$$c_1\geq c_2\geq\cdots\geq c_M \quad \text{and} \quad (3)$$
$$c_i\leq c_j+k \quad \text{for } \forall i,j.$$

Since every credit for all the links is set to 0 at the beginning for the credit scheme [3] [4], every link at starting time $s_1$ automatically satisfies (3).

Then we have the following:

**Theorem 1.**

For $L_i$, $p_i^{\max}=(M+1)T_{pp}$,

where $p_i^{\max}$ is the maximum poll intervals of $L_i$. We omit proof on this theorem due to short of pages.

From the theorem, we consider the problem of time slot assignment with QoS constraints and Qualified values (TAQQ) as follows:

**Problem TAQQ**

$$\text{maximize} \quad \sum_{i=1}^{M} r_i$$

$$\text{subject to} \quad \sum_{i=1}^{M} r_i - r_j \leq T_{scatter\_poll\_j}-(M+1)T_{pp}, \quad \textit{for each } j=1,2,\cdots,M$$

$$r_i \text{ is a common multiple of } M \text{ and } T_{pp}(\geq 0)$$

where $r_i$ and $T_{scatter\_poll\_i}$ are additionally assigned time slots and QoS parameter for link $i$, respectively. For this problem, we propose a heuristic approach referred to as QoS guaranteed additional time slot assignment (QATA). Procedure of the QATA is summarized as follows:

**Algorithm QATA:**

Step 1 (acquisition of initial solution):

1. Rename $L_i$ for $1\leq i\leq M$ such that

$T_{scatter\_poll\_1} \le T_{scatter\_poll\_2} \le \cdots \le T_{scatter\_poll\_M}$.

2. Assign additional time slots for $L_2$ which amount to

$$r_2 = \left\lfloor \frac{T_{scatter\_poll\_p} - (M+1)T_{pp}}{\gcd(M,T_{pp})} \right\rfloor \cdot \gcd(M,T_{pp}), \text{ and}$$

$r_i$ for $\forall i \ne 1$ and 2 is set to 0.

3. Set $r_1$ to as

$$r_1 = \min_{\forall j \ne 1} \left( T_{scatter\_poll\_j} - (M+1)T_{pp} - \sum_{i(\ne 1)} r_i + r_j \right).$$

4. Make a set $(r_1, r_2, \cdots, r_k)$ and give the set to step 2.1 as an input.

Step 2 (neighborhood search):

1. If $r_2 > 0$, find the set $(r_1^k, r_2^k, \cdots, r_M^k)$ such that $\sum_i r_i^k$ is maximal for $3 \le k \le M$ (if more than one such a set exit, then a lexicographically greater set is selected),

where

$$\begin{cases} r_2^k = r_2 - \gcd(M,T_{pp}) \\ r_l^k = r_l \quad \text{for } l \ne 1 \text{ and } k \\ r_k^k = r_k + \gcd(M,T_{pp}) \\ r_1^k = \min\limits_{\forall j \ne p} \left( T_{scatter\_poll\_j} - (M+1)T_{pp} - \sum\limits_{i(\ne 1)} r_i + r_j^k \right) \end{cases}$$

Otherwise, go to step 2.3.

2. If $\sum_i r_i^k > \sum_i r_i$, then go to step 2.1 with $(r_1^k, r_2^k, \cdots, r_M^k)$ as an input.

Otherwise, go to step 2.3.

3. Select $(r_1, r_2, \cdots, r_M)$ as the final solution.

## 3 Numerical Results

We adopt the scatternet topology of Fig. 4 as our scenario for the simulation. Four piconets, which are coordinated by the master M1, M2, M3 and M4, respectively, are connected each other by a bridge node, which is a slave node for all of the linked piconets.

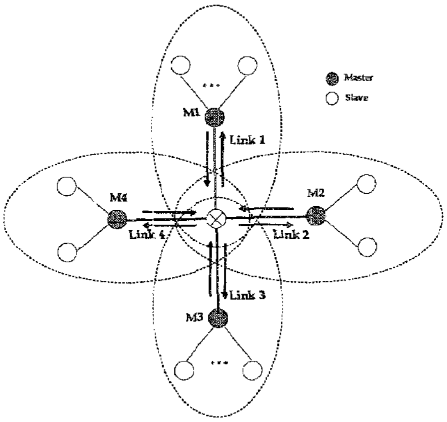

Figure 1: Scatternet topology for the simulation scenario

Based on the fact that a switching between two links consumes power-related resources such as transceiving and processing power, the energy efficiencies of several schemes are implicitly compared by showing the number of switching events for each of them in Figure 2.

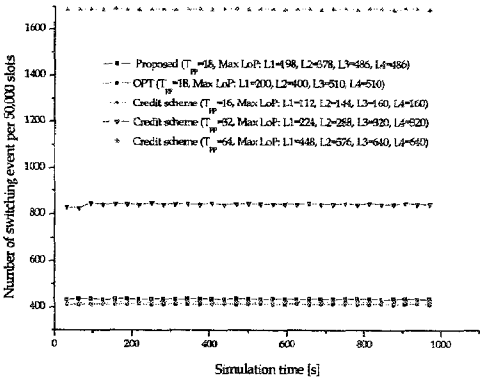

Figure 2: Number of piconet switching events

Compared to the credit scheme with $T_{pp} = N_{switch} = 16$, the number of switching events of the proposed scheme is almost a quarter of that of the credit scheme although its minimum service time, i.e. $N_{switch\_th} (= T_{pp})$, is just two more slots than that of the credit scheme. To validate the fulfillment of QoS for each link through the credit scheme as the number of switching is decreased, we increase $T_{pp}$ of the credit scheme two and four times. In the case of $T_{pp} = 32$, the credit scheme does not completely fulfilled the QoS of link 1 since the maximum poll interval of the link is greater than 200. Although the number of switching events is positioned between those of the proposed and the optimal in the case of $T_{pp} = 64$, the QoS of all the links except for link 4 are shown not to be guaranteed by the credit scheme. Figure 2 demonstrates the benefit of the proposed scheme in that the scheme achieves the number of switching as low as the optimal at the same time satisfying the QoS requirements of all the links.

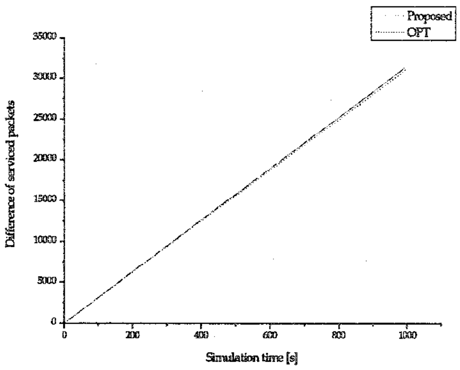

Figure 3: Throughput gain

Figure 3 shows the differences of serviced packets between the credit scheme and the proposed scheme and between the credit scheme and the optimal during incurred the simulation time. From the figure, the relative gain of throughput of the proposed scheme is linearly increased, as we expected, since the gap of total number of switching events, which incurs the guard time loss, between the credit scheme and the proposed scheme is greater as the simulation proceeds. The gap of serviced slots between the proposed and optimal is, however, so slight that the gap attains about 350 time slots at 1,000 seconds of simulation times.

## 4 Conclusions

In this paper, we propose a scheduling mechanism to achieve a thrifty use of wireless resources under given QoS requirement for each link of a bridge node in Bluetooth scatternet. The proposed scheme provides each link with time slots for transmitting data as many as additional time slots for each link does not guarantee some links' QoS requirements. In conclusion, since the overhead of the proposed scheme is so low as to be simply realized from the credit scheme with the coordination of inter-piconet timing and distribution strategy we expect that the proposed scheme can be easily applied to the current Bluetooth specification and the scatter mode.

## References

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