대한산업공학회/한국경영과학회 2002 춘계공동학술대회
한국과학기술원(KAIST) 2002년 5월 3일-4일

A Traffic Adaptive MAC Scheduling for Bluetooth with Maximized throughput and Guaranteed fairness

Tae suk Kim, Sung-Gi Choi and Sehun Kim

Dept. of Industrial Engineering, Korea Advanced Institute of Science & Technology (KAIST), 373-1, Kusung-dong, Yusong-gu, Taejon, 305-701 Korea
Email: tskim@tmlab.kaist.ac.kr, sgchoi@tmlab.kaist.ac.kr, and shkim@tmlab.kaist.ac.kr
Tel: +82-42-869-2914, Fax: +82-42-869-3110

ABSTRACT : Bluetooth is an emerging technology expected to provide users with short range, low cost, pico-cellular wireless connectivity. The access to the medium for Bluetooth is based on a Master driven Time Division Duplexing (TDD) scheme. A slave transmits packets in the reverse slot only after the master polls the slave (or transmits a packet to the slave) in a forward slot. The master transmits packets to a slave in even slots while the slave transmits packets to the master in an odd slot. The way in which the master schedules packets transmission to slaves or polls them determines system performance. In this paper, we propose a traffic adaptive MAC scheduling scheme for Bluetooth. The proposed scheme adopts the ISAR (Intelligent Segmentation and Reassembly) policy, which adjusts the packet size to the traffic patterns, to adapt the polling frequency to the traffic conditions. Also for achieving fairness among master-slave connections our scheme includes a priority policy assinging prioritised service times to each connection. By considering a scenario where a Bluetooth master is used as wireless access point to the Internet, we show that our scheme improve the system throughput and average queue delay with regard to a naive Round Robin (RR) scheme.

1. Introduction

Bluetooth is a new low cost, low power wireless technology [1,2] that will allow users to interconnect their mobile phones, laptops, palmtops, headsets, and other electronic devices forming a small network usually referred to as the Personal Area Network (PAN).

One of the key issues in Bluetooth is MAC scheduling. The way in which a Master takes decisions regarding which a Slave to poll determines the performance of a system. The standard documents initially proposed a pure Round Robin (RR) scheme for the MAC scheduling [3]. Previous works [4, 5] have shown that the pure RR scheme may introduce bandwidth wastage. Therefore, efficient MAC scheduling schemes need to be designed.

To date, several MAC scheduling schemes for Bluetooth are proposed in the literature. The proposed schemes can be classified into two categories and have different strengths and weaknesses.

One is the Master-Slave Queue-State-Dependent Packet Scheduling scheme [6] which assumes that a Master knows if a Slave queue has packets to be transmitted so that only the non empty Master-Slave queues are considered by the Master. The priority policy (PP), the K-Fairness policy (KFP), the HOL-PP, and the HOL-KFP [6, 7] belong to this category. These schemes prevent the wastage of radio slots and give interesting results but assume the ideal scenario where a Master has the updated knowledge of Slave queues at all times by using an explicit signaling from a Slave to the Master which require additional bandwidth.

The other is variation of pure Round Robin scheme. The Exhaustive Round Robin (ERR), the Exhaustive Pseudo-cyclic Master queue length (EPM) and the Limited Round Robin (LRR) are included in this category. These schemes are practical schemes, which do not require the knowledge of Slave queues, and can be implemented without adding to new signaling messages from a Slave to a Master. But they still have bandwidth wastage in some traffic environments since the Master can't know the status of Slave queues.

In this paper, we propose a new and practical MAC scheduling scheme with an aim of achieving a high throughput with fairness bound. This paper is organized as follows: The following section describes Bluetooth MAC and SAR policies. In Section III we propose a new MAC scheduling scheme for Bluetooth. Section IV describes the simulation assumption and scenarios followed by the simulation results. Finally, Section V gives concluding remarks.

2. Medium Access Control in Bluetooth

2.1 MAC scheduling in Bluetooth

Bluetooth uses a TDD slot structure for resolving contention over the wireless links (Figure 1). There is a strict alternation of slots between a Master and Slaves. This implies that once a forward slot is assigned to the Master, the following reverse slot is assigned to the corresponding Slave. Thus, scheduling occurs in pairs of slots (i.e., the Master-Slave pair).

The channel access is managed according to a polling scheme. A Master decides which Slave is the only one to have the access to the channel by sending to him a packet. The Master packet may contain data or can simply be a polling packet. When a Slave receives a packet form the Master, it is obliged to transmit in the next time slot so as to acknowledge the Master transmission. The Slave packet may be a data packet or a NULL packet. There could be wastage of slots in the TDD scheme since if only one of the Master or the Slave has data to send, a slot gets wasted. Further, the fairness issue is complicated since service may be given to a Master-Slave connection even though it is not backlogged (i.e., Master and Slave do not, at the same time, have data to send).

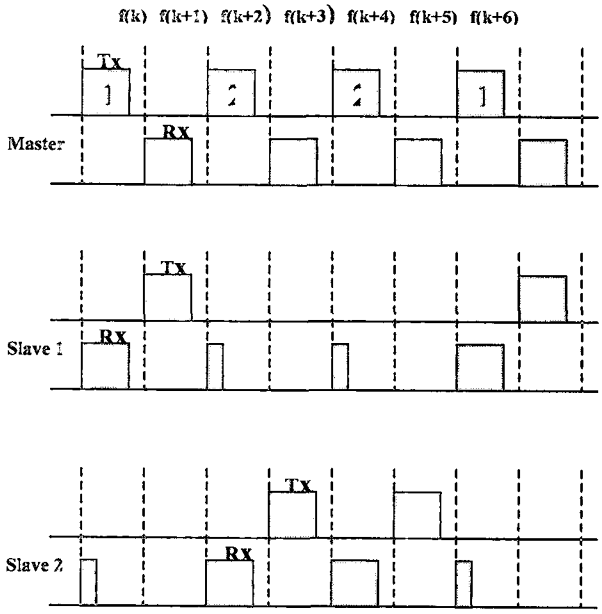

Figure 1. Bluetooth TDD slot structure

Considering the above problems, new and efficient scheduling policies are required by the Master driven TDD structure. These policies should be simple to implement (such as the round robin policy) in order to satisfy the low cost objective of the Bluetooth standard [3].

2.2 SAR in Bluetooth MAC

The Segmentation and Reassembly (SAR) incorporated in Bluetooth MAC is simple in design. The size of the MAC packets created by the SAR can vary among 1, 3 and 5 slot lengths both at a Master and a Slave [3]. Data packets of different sizes can be sent on the same connection. The distribution of data packet sizes is determined by a Bluetooth SAR policy. The data packet size distribution significantly effects the slot utilization. The naïve SAR policy (Random SAR) is to assign the data packet sizes (i.e., 1, 3 or 5) probabilistically. SAR policies have a significant effect on data scheduling as they govern the distribution of packet size.

To date, several SAR policies for Bluetooth are proposed in the literature [6, 7]. In [6] they showed that the ISAR performs better than the Normal SAR. The ISAR adapts the packet sizes to the traffic patterns. For example we can have a high data rate at on end (Master or Slave) while a low data rate at other end (e.g., FTP). In such a traffic pattern we have large MAC packets for a high data rate and smaller MAC packets for a low data rate. This results in overall lower delays, packet drops and throughput wastage. Our scheduling scheme adopts the ISAR as a SAR policy.

3. The Proposed Scheme

3.1 System Model

We assume one piconet where a Master is

used as wireless access point to the Internet (Internet Access Point). Slaves (can be either a PDA or a notebook) access the Internet via the Master. The main role of the Internet access point is to establish a wireless connection to each user device and forward user's packets to/from the wired network.

We also assume that the number of Slaves is limited to seven in order to remove the effect of parking that is required when more than seven slaves are to be connected to a Master. In addition, we assume a steady-state environment where no users join or depart the piconet. Also when there are N Slaves in a piconet N queues are assumed at the Master. For each Slave there is a corresponding queue at the Master.

3.2 Traffic adaptive MAC scheduling with efficient slot utilization

Our scheme aims to improve the system throughput and use the traffic adaptive MAC scheduling with high slot utilization based on the ISAR. 'Traffic adaptive' means that the scheme uses adaptive polling frequency for each connection whose value is changed based on the traffic rate.

3.2.1 The estimator for the size of the HOL packet at Slave queue

Since a MAC scheduling procedure is managed by a Master, the knowledge of the queues' status is only partial. The Master knows the status of all Master-to-Slave queues, but cannot have an updated information on the status of the Slave-to-Master queues even if an explicit signaling is provided. But by using the ISAR the Master can infer the size of the Head-of-Line (HOL) packet at a Slave queue from the size of the latest packet arrived from the Slave.

If a Master receives a 5 slots packet from a Slave, it is highly possible that the size of the next packet from the Slave will be also a 5 slots packet. Of course if the data rate at the Slave queue changes the estimation may be wrong. But in most of cases the change of the data rate is rare. Consequently the size of the latest packet from a Slave can be a good estimator for the size of the HOL packet at the Slave queue.

3.2.2 MAC scheduling algorithm

Master-Slave pairs are referred to on the basis of the size of the HOL packet at Master and the size of the latest packet arrived from Slaves (e.g., a 3-1 Master-Slave pair has a size three HOL packets at the Master queue and a size one latest packet arrived from Slaves.). As shown in Table 1, we classify Master-Slave pairs into nine classes based on the combination of slot utilization and the total number of the used slots for packet transmission during one polling interval. A Master-Slave pair with more slot utilization and used packet is given to higher priority. The Master-Slave pair with higher priority obtains more service times than the pairs with lower priority resulting in improvement of the system throughput by reducing slot wastage.

Class	Slot utilization	Used Slots for packet transmission and reception	Master - Slave States
class 1	100 %	10 slots	5-5
class 2	100 %	8 slots	5-3, 3-5
class 3	100 %	6 slots	5-1, 1-5, 3-3
class 4	100 %	4 slots	3-1, 1-3
class 5	100 %	2 slots	1-1
class 6	83.3 %	5 slots	5-0, 0-5
class 7	75 %	3 slots	3-0, 0-3
class 8	50 %	1 slots	1-0, 0-1
class 9	0 %	0 slots	0-0

Table 1. Master-Slave pair state classification

However, this policy may deteriorate the fairness among the Master-Slave pairs severely. To cope with this problem, we introduce the fairness bound K. Once the priorities among the Master-Slave pairs are identified, the Master determines the amount of time slots per each Master-Slave pair for K time slots interval. The allocation of time slots is based on the identified priorities. Note that this allocation procedure is completed before service. The pairs except the one with the highest priority are allocated to time slots enough for service during one polling interval. The remnants of K time slots left over allocating time slots for the pairs are given to the pair with the highest priority.

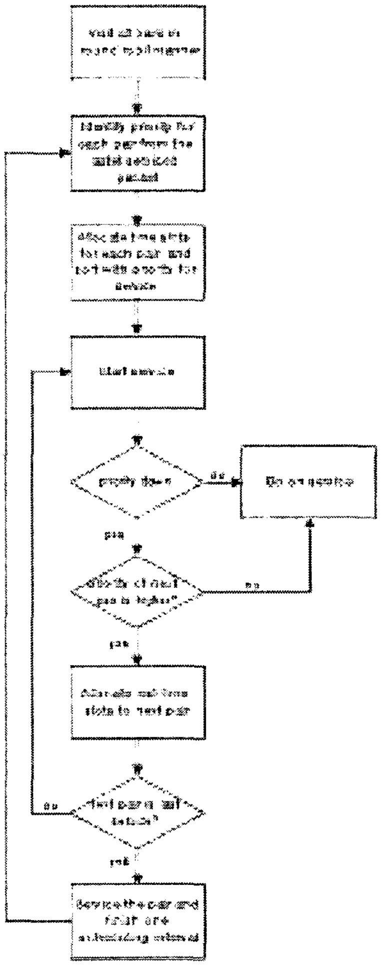

Figure 2. Flow chart of the proposed scheme

In the case that service class of the highest prioritized pair changes during packet transmission, the Master is needed to compares the priority of current services pair with that of the second highest prioritized pair. If the changed priority is lower than the second highest priority, then the rest of allocated time slots are sacrificed to the second one. Otherwise the service for current pair goes on. Also there may be several pairs with the same highest priority. In such a case, the rest left over allocating time slots for other lower pairs are equally divided and given to each pair. After the services for all Master-Slave pairs are finished in a round robin manner, the Master memorizes the last service class of each pair and utilizes this information for scheduling next time interval. This scheduling procedure is executed in every K slots. Figure 2 shows the flow chart of the proposed scheme.

4. Simulation Results

4.1 Assumptions in the simulation

We simulate a piconet environment consisting of five Slaves and a Master. For each Slave, there is a corresponding queue at the Master. The TDD slot length in Bluetooth is equal to 625 μsec. The data arrival process at the Master and Slave queues is assumed to be one of the following:

- Poisson
- three-state Markov Modulated Poisson Process (MMPP)

For the MMPP process, the transition probability from one state to another is equal to 0.01 and the probability of remaining in a state is 0.99. The service time of a data packet depends upon the packet length. A packet of size one occupies a single slot. The buffer size at the Slaves and Master queues is not limited. The simulation time is 10,000 TDD slots. We assume that there is no voice channel and all channels have no errors. For fairness bound we set K as 70.

Traffic Distribution				
Pair 1 (M1,S1)	**Pair 2 (M2,S2)**	**Pair 3 (M3,S3)**	**Pair 4 (M4,S4)**	**Pair 5 (M5,S5)**
(L, H)	(V, V)	(V, V)	(VH, L)	(L, L)
VH : very high data rate (0.39 packets/time slot) H : high data rate (0.2 packet/time slot) L : low data rate (0.01 packet/time slot) V : varying data rate with combination of VH, H and L				

Table 2. Traffic Distribution

Table 2 shows the traffic distribution for each Master-Slave pair. Pair 1 has a high arrive rate at the Slave queue and a low at the Master queue. MMPP traffic is generated at both Pair 2 and 3. Pair 4 has a very high arrive rate at the Master queue and a low arrive rate at the Slave queue. Pair 5 has a low arrive rate at both Master and Slave queue. We classify scenarios into eight categories based on the data arrival rate at the Master and Slave queue.

4.2 Simulation Results

We evaluate the performance of proposed scheme in terms of two measures: System throughput and Average delay. In Table 3, we compare the measures achieved by Round Robin policy (RR) and proposed scheme. AS the table shows, the proposed scheme outperforms the RR in both system measures. The proposed scheme tries to achieve maximum throughput in fairness bound K. The policy, which the proposed scheme executes, that gives more service times to higher prioritized pair results in better throughput performance than

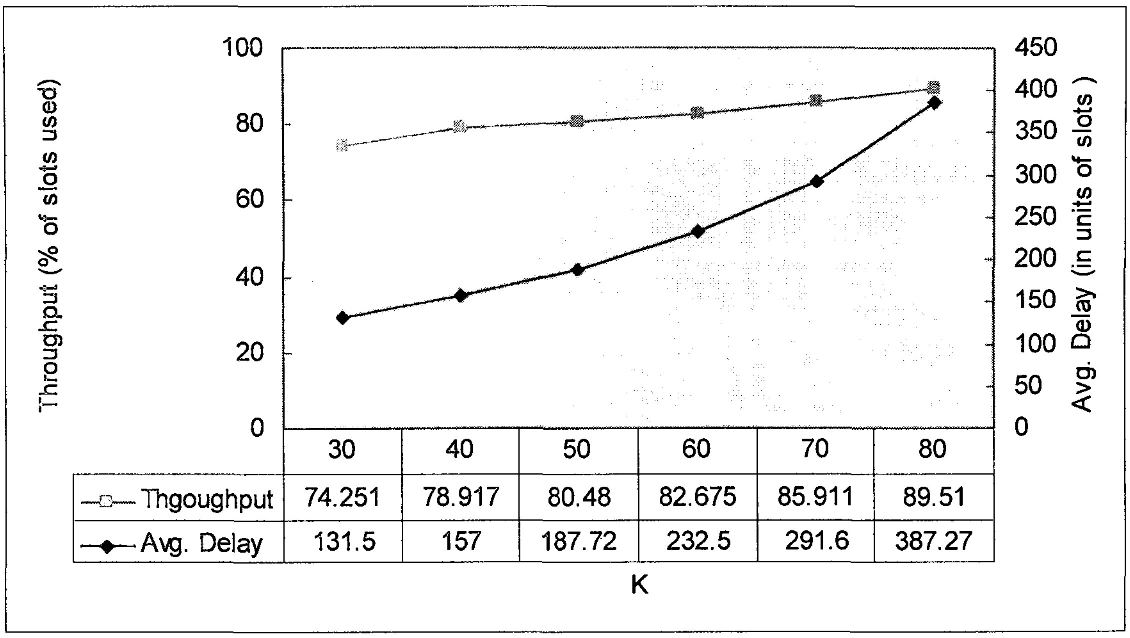

Figure 3. System performance with various K

the RR. Also smaller average delay is achieved since the proposed scheme based on ISAR services Master-Slave pair with a high arrive rate quickly.

Performance parameters	Our Scheme	Round Robin
System Throughput (% of slots used)	85.91	74.25
Avg. Queue Delay (in units of slots)	291.6	381.0

Table 3. Performance comparison

However, we notice that the value of K affects the system performance. The performance measures with various values of K are shown in Figure 3. As K is increased, the system throughput is also increased. This is caused by the fact that the increment of fairness bound is devoted to service the pair with the highest priority. But the average queue delay grows rapidly with the increment of K. The pairs with lower priority, which are sacrificed to the highest one, have more data in their queues with higher K since the ratio of their service times in K interval is decreased. As figure 3 shows, Average queue delays of both schemes are almost same when K is 80.

5. Conclusion

In this paper we have proposed a new and practical MAC scheduling scheme, which achieves high throughput and low queue delay. The proposed scheme utilizes the ISAR for a SAR policy. The ISAR policy enables the scheduling scheme to adapt the data traffic effectively without the explicit signaling. Also the proposed fairness bound guarantees least service time for every pair improving system throughput.

References

1. J.C. Haartsen, "Bluetooth: a New Radio Interface Providing Ubiquitous Connectivity", IEEE VTC 2000-Spring, pp. 107-111.

2. J.C. Haartsen, "The Bluetooth radio system", IEEE Personal Communications, vol. 7, no. 1, Feb. 2000, pp. 28-36.

3. "Specification of the Bluetooth System", version 1.1, December 2000, http://www.bluetooth.com/

4. N. Johansson, U. Korner, P. Johansson, "Performance Evaluation of Scheduling Algorithms for Bluetooth", IFIP TC Fifth International Conference on Broadband Communications '99, Hong Kong.

5. R. Bruno, M. Conti, E. Gregori, "WLAN technologies for mobile ad hoc networks", Proc. Hawaii International Conference on System Sciences, (HICSS-34), Maui, Hawaii, January 3-6, 2001.

6. M. Kalia, D. Bansal, R. Shorey, "Data scheduling and SAR for Bluetooth MAC", IEEE VTC 2000-Spring Tokyo, pp. 716-720.

7. S. Garg, M. Kalia, R. Shorey, "MAC Scheduling Policies and SAR Policies for Bluetooth: A Master Driven TDD Pico-Cellular Wireless System", MoMuC 99, pp. 384-387.