Model and Performance Evaluation of a Piconet for Point-to-Multipoint Communications in Bluetooth

Tae-Jin Lee, Kyunghun Jang, Hyunsook Kang and Jonghun Park
Network Solution Lab., Corporate R & D Center
Samsung Electronics Co., Ltd., Korea
{tjlee, khjang, iriskang, jonghun}@samsung.com

Abstract

We consider model and performance evaluation of the Bluetooth system supporting point-to-multipoint communications in a piconet. In order to support more than seven slave devices in a piconet, a park mode is considered and modeled. We evaluate the performance, i.e., throughput and delay, using simulations when multi-connections (both ACL and SCO connections) are present in a piconet. We show that the data rate may be less than 10 kbps when SCO connection(s) and more than six ACL connections are jointly supported in a piconet. In addition, if up to four ACL connections are supported, the average delay is shown to be maintained less than 10 msec. Our results serve as a guideline to the design of Bluetooth systems with throughput and delay requirements.

1 Introduction

Advances in wireless communication technology have extended our communication environment and delivered variety of services to users. In an effort to provide ubiquitous wireless communication services with inexpensive cost in a personal area, Bluetooth has been gaining much interest from various industries. More than 2000 industry members participate in the Bluetooth SIG (Special Interest Group) and it continues to grow [2]. As described in the Profiles of the Bluetooth Specification [4], Bluetooth is expected to provide numerous wireless services ranging from synchronization to networking between heterogeneous devices such as notebook PCs, PDAs, mobile phones, and headsets.

In order to truly make various devices communicate in a piconet, a small network consisting of a master and slave devices, it is required to employ point-to-multipoint communication functionality in Bluetooth-enabled devices. Although the Specification of the Bluetooth system [3] describes that Bluetooth has point-to-multipoint communication ability, few Bluetooth-enabled products have been known to have one-to-many communication capability so far. [1]

It is also vital to predict actual performance of Bluetooth systems so that it can be applied to the design of a system. Johansen et. al. [5] modeled Bluetooth for a few scenarios and evaluated performance. They focus on performance of a scatternet, *i.e.*, a set of piconets, in which each piconet consists of a few Bluetooth-enabled devices. In [7], performance evaluation under interference between piconets is addressed, in which each piconet has a single master and slave.

Performance of a piconet with more than seven devices supporting both ACL (Asynchronous Connection-Less) and SCO (Synchronous Connection-Oriented) connections has not been discussed. In this paper, we consider model and performance evaluation of a piconet consisting of more than seven slave devices with possible support of both ACL and SCO connections for point-to-multipoint communications. Our objective is to investigate the impact of SCO connections and a power saving mode, *i.e.*, a park mode, on the performance (throughput and delay) and adopt the result to the design of a system. This paper is organized as follows. In §2, we describe modeling of the Bluetooth system. We then evaluate performance of the system in §3. In §4, conclusion is followed.

2 Modeling

Bluetooth is a low power and low cost wireless communication system covering a small personal area within 10m. It operates in 2.4 GHz unlicensed radio frequency band and uses frequency hopping transceiver with the hopping rate of 1600 hoppings per second. It modulates signals using a GFSK (Gaussian Frequency Shift Keying) modula-

[1] Digianswer, National Semiconductor, Silicon Wave, and TTP-COMM have demonstrated point-to-multipoint communications at Bluetooth Congress 2000 in Monte Carlo.

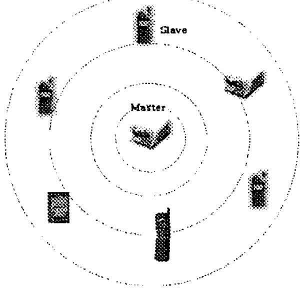

Figure 1. A piconet with one master and six slaves.

tion scheme and utilizes slotted TDD (Time Division Duplex) with the slot interval of 625 μsec. In a piconet, slaves with ACL connections are allowed to transmit data packets right after the TX slot of a master, only when they are explicitly "polled" by the master. ACL connections provide best-effort service. The maximum data rate one can achieve from an ACL connection between a single master and slave is 723 kbps. The number of slots for a packet can occupy can be one, three, and five according to the amount of data to be transmitted. For SCO connections, periodic slots are strictly reserved for SCO packets between a master and slave resulting in a guaranteed rate of 64 kbps. In addition, data packets can be protected by error correction codes depending on the status of wireless channel. Up to seven active slave devices can be supported in a piconet, and using a *park* mode, up to 255 devices can be supported. Piconets can form a scatternet to interconnect devices between piconets.

In this paper, we consider a piconet consisting of a single master and many slaves, see Fig. 1. Packet transmission and reception are synchronized by the system clock (625 μsec slot interval). We will focus on throughput and delay performance in point-to-multipoint communication environment. We try to simplify and abstract the system as much as possible while preserving the essence of the system which affects the actual performance of the system. We use BONeS simulation tool [1] to capture the behavior of the Bluetooth system. BONeS is the modeling and performance evaluation tool providing event-driven simulation environment and graphical user interface for the construction of functional blocks and simulation objects.

In order to poll multi-slaves, a polling list needs to be maintained in a master device. A master polls slaves in a round-robin fashion. In our model, multi-SCO connections (up to three SCO connections) can be supported. We also model scans (inquiry scan, inquiry response, and page scan), which are the series of a connection set-up procedure. [2] Through this scan model, we can evaluate the actual performance of the system in the presence of scan operations. Parameters for scan operations are given in Table 1.

	Parameter	Value	
Scan	$T_{inquiryscan}$	2.56	sec
	$T_{winquiryscan}$	11.25	msec
	$T_{pagescan}$	2.56	sec
	$T_{wpagescan}$	11.25	msec
Park	T_B	2.56	sec
	N_B	24	slots
	N_{B_sleep}	1	
	D_{access}	80	slots
	T_{access}	4	slots
	M_{access}	4	
	T_{park}	5	sec

Table 1. Parameters used in the simulation.

When there are seven active slaves in a piconet and a new device is about to enter the piconet, an existing slave may need to be parked since Bluetooth can support only seven active slaves. We propose a First-Active-First-Park scheduling mechanism for the parking/unparking of slaves. In the mechanism, the oldest active slave in the piconet is forced to enter a park mode first when parking of a slave is required due to a new connection (Fig. 2). In addition after some pre-specified parking time ($Tpark$) exceeds for a parked slave, the oldest one among active slaves is parked, and then the parked slave with expired parking time is unparked and enters the active slaves (Fig. 3). This scheduling mechanism will provide fair access to channel bandwidth to all the slaves in a piconet while admitting new connections. Parameters for a park mode are tabularized in Table 1.

3 Performance Evaluation

3.1 Throughput performance

Throughput performance is evaluated when there are one to ten slave devices, for which an ACL or SCO connection is established each. We assume that packets are always transmitted and received in the corresponding TX/RX slots. In other words, a master polls a slave with an ACL connection in a round-robin fashion and it transmits a packet to the polled slave. When a slave is polled by a master, the slave sends a packet to the master in the consecutive TX slot of the reception of the packet from the master. Various

[2] A master has to conduct inquiry/page scans at regular intervals, *e.g.*, 2.56sec, during connection state for possible inquiry/page signals from new devices trying to join a piconet. Inquiry response state follows after some random time if inquiry packets are successfully received during inquiry scan state [3].

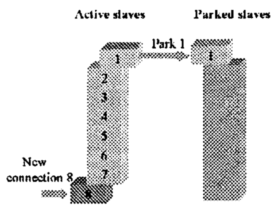

Figure 2. Before new device 8 joins a piconet, active slave 1 is parked.

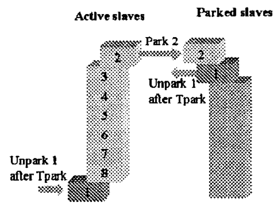

Figure 3. After *Tpark* for parked slave 1, active slave 2 is parked, and parked slave 1 is unparked and becomes an active slave.

packet types can be used for ACL connections when there are no SCO connections in a piconet. Only DH1 or DM1 packets are assumed to be transmitted if at least one SCO connection is present in a piconet. In order to see the maximum possible performance, asymmetric TX/RX is considered, where different packet types are used for down (master to slave) and up (slave to master) stream traffic. In our simulation, each master and slave is assumed to use a specific packet type, *e.g.,* DH5 for a master and DH1 for slaves.

First, we evaluate the performance of the system without SCO connections as the number of ACL connections increases, see Fig. 4 and 5, where DH5, DH3, and DH1 denotes DH5/DH1, DH3/DH1, and DH1/DH1, respectively, *i.e.,* packet types of master-to-slave/slave-to-master. Similarly, DM5, DM3, and DM1 denotes DM5/DM1, DM3/DM1, and DM1/DM1, respectively. When there is only one slave with an ACL connection, the data rate can reach 718 kbps, which is the maximum achievable performance when asymmetric DH5/DH1 packets are exchanged between a master and a slave. It shows 581 and 171 kbps for DH3 and DH1, respectively. As the number of slave devices increases, the data rate continues to decrease. When seven active slaves are in a piconet, the rate becomes 102, 83 and 24 kbps for DH5, DH3 and DH1, respectively. If a new slave comes into the piconet of seven active slaves, one of the existing slaves has to be parked and unparked regularly as explained in §2, and the resulting data rate of each slave becomes 88, 71 and 21 kbps for DH5, DH3 and DH1, respectively, due to the park and scan operations. It further decreases to 71, 57 and 17 kbps when the number of slave devices is 10. As for the DM5/DM1 connections, the rates are 474, 68, 58 and 47 kbps for one, seven, eight and ten slaves, respectively. We have observed graceful degradation of performance as the number of slaves increases. This indicates that the Bluetooth system can support many devices if the bandwidth requirement is not high.

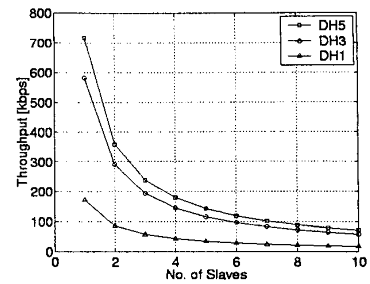

Figure 4. Throughput of ACL connections with DH packets and no SCO connections.

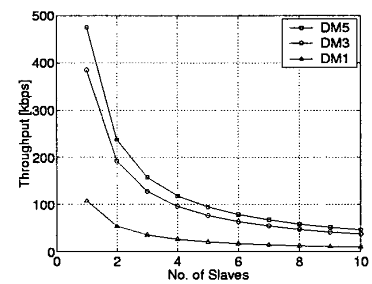

Figure 5. Throughput of ACL connections with DM packets and no SCO connections.

Next, throughput performance is evaluated when one SCO connection is present (DH-1HV3, DH-1HV2, DM-1HV3, and DM-1HV2), see Fig. 6 and 7. Since we have a SCO connection, 33 % of total available slots must be reserved for the voice (SCO) traffic [3]. So the number of slots available for ACL connections becomes smaller resulting in lowered performance for ACL connections. When one ACL and one SCO connection are established in a piconet, the rate of the ACL connection is 114 kbps (DH-1HV3), which can be compared with the rate of 370 kbps in previous simulation with two ACL connections (DH5). This 69.2 % decrease in throughput results from reduced available slots and packet size. Throughput performance becomes worse as the number of ACL connections increases. When six ACL connections and one SCO connection are supported, the rate shows 19 and 12 kbps for DH-1HV3 and DM-1HV3, respectively. If nine ACL connections and one SCO connection are supported using a park mode, the rate drops to 12 and 8 kbps for DH-1HV3 and DM-1HV3, respectively. The effect of degradation in throughput due to a

SCO connection is shown to become greater as the number of ACL connections increase, *e.g.*, 47 kbps for 10 ACL connections (DM5) vs. 8 kbps for 9 ACL and one SCO connections (DM-1HV3), which is 83.1 % decrease in throughput.

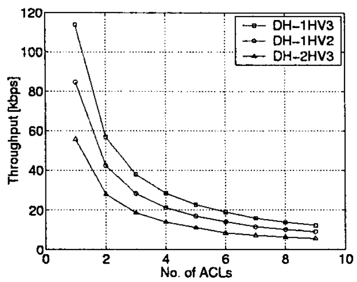

Figure 6. Throughput of ACL connections with DH packets and SCO connections.

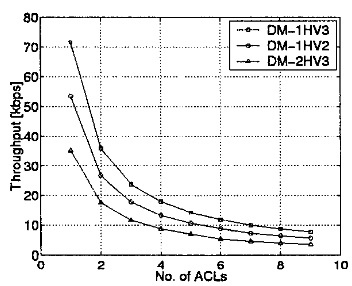

Figure 7. Throughput of ACL connections with DM packets and SCO connections.

Finally, when two SCO connections are supported (DH-2HV3 and DM-2HV3), performance is considered, see also Fig. 6 and 7. In this case, two SCO connections occupy more slots (67 % of total available slots) than one SCO connection, and thus lower data rates are expected. When four ACL connections with DM packets and two SCO connections with HV3 packets are in a piconet, performance already starts to become less than 10 kbps, *i.e.*, 8 kbps. It can even degrade to 3 kbps if more than eight ACL and two SCO connections communicate using a park mode in the piconet (DM-2HV3). In this case, 47 kbps for 10 ACL connections (DM5) reduces to 3 kbps for 8 ACL and two SCO connections (DM-2HV3), which is 93.6 % performance degradation. Thus, when many Bluetooth-enabled devices are contending channel bandwidth for both SCO and ACL connections in a piconet, these low data rates may not be suitable for some applications requiring high throughput.

3.2 Delay performance

Next, we evaluate delay performance. In the previous subsection, we have shown that SCO connections may significantly degrade system performance. Thus, if high throughput is required for the purpose of efficient data transmission like file transfers, one is likely to refrain from simultaneous support of SCO and ACL links. That is, use of only ACL connections would be a typical scenario for throughput-intensive applications. Thus, we investigate delay performance in such cases.

We consider one to seven slave devices with ACL connections in a piconet. In this scenario, packet types are adaptively selected among DM1, DM3 and DM5 according to the amount of data waiting for transmission in buffers. We consider only DM packets assuming that data packets are vulnerable to bit errors due to error-prone wireless channel characteristics. To ensure reliable data transmission, FEC (Forward Error Correction) and ARQ (Automatic Repeat Request) [3] are employed. We simulated simple wireless channel model, where BER (Bit Error Rate) is constant in a smulation. The BER of wireless channel is assumed to be 0.001.

As traffic sources, MMPP (Markov-Modulated Poisson Process) is used, which is shown to be well matched with multimedia traffic [6]. Each source is modeled by a two-state Markov chain, where on- and off-periods are exponentially distributed with mean of α^{-1} and β^{-1} sec, respectively. The rate transition matrix between on- and off-period is characterized by

$$Q = \begin{bmatrix} -\beta & \beta \\ \alpha & -\alpha \end{bmatrix}.$$

Thus the steady state probability of being in on-period $\pi_{on} = \beta/(\alpha + \beta)$. During on-period, packets are generated with Poisson arrival rate of λ_{on} packets/sec, and no packets are generated during off-period. Thus the average packet generation rate

$$\bar{\lambda} = \pi_{on}\lambda_{on}, \qquad \text{packets/sec.}$$

Let the average service rate of Bluetooth

$$\bar{\mu} = \lambda_{on}, \qquad \text{packets/sec}$$

and the traffic load $\rho = \bar{\lambda}/\bar{\mu}$. The average message size, average number of packets generated during on-period, is given by

$$\bar{m} = \alpha^{-1}\lambda_{on}, \qquad \text{packets.}$$

It is assumed that $\bar{m} = 250$ packets with the packet size of 100 bytes. If we assume symmetric TX/RX, the maximum rate for a single slave would achieve is 286.7 kbps. And if seven slaves share the bandwidth, 40.96 kbps is allocated to each slave. So we let average service rate of each connection $\bar{\mu} = 40.96$ kbps. One can then design $\lambda_{on}, \alpha^{-1}$, and β^{-1} to generate desired traffic. We have generated three types of traffic, *i.e.*, $\rho = 0.2, 0.5$ and 0.8, whose effective rates are 8, 22, and 33 kbps, respectively. For each direction, *i.e.*, master-to-slave and slave-to-master, there exists a traffic source and an associated data buffer.

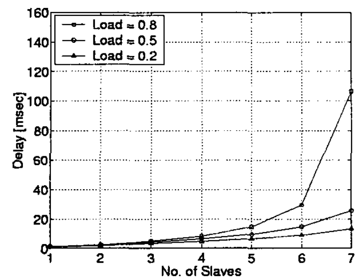

Figure 8. Average delay of packets from a master to slaves with no SCO connections.

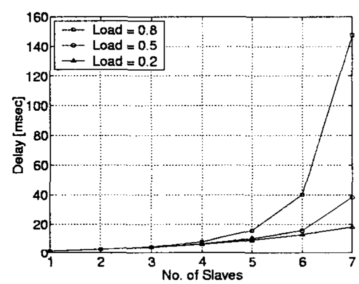

Figure 9. Average delay of packets from slaves to a master with no SCO connections.

Average packet delay, time between arrival of a new packet (data) into a buffer for transmission and reception of the packet at a receiver, is measured for each of traffic load as the number of ACL connections changes. Fig. 8 and 9 show the average packet delays measured at slaves and a master, respectively. Up to four ACL connections, the average delay is shown to be less than 10 msec, which is suitable for delay-sensitive applications, and it increases as the number increases. When the number of ACLs is five, the average delay still remains within 20 msec. When the traffic load is heavy, *i.e.*, $\rho = 0.8$, and the number of connections is seven, the delay would exceed 100 msec. Thus, one can estimate the average delay given traffic load and a number of slave devices, which can be used for the design of a system

4 Conclusion

We have modeled and evaluated the performance of a piconet in Bluetooth supporting point-to-multipoint communications. It has been shown that the performance of ACL connections may degrade significantly, *i.e.*, less than 10 kbps, when SCO connection(s) and more than six ACL connections are jointly supported. Thus, when many Bluetooth-enabled devices are contending channel bandwidth for both SCO and ACL connections in a piconet, resulting data rates may not be suitable for throughput-intensive applications. One can, however, control more than seven slave devices using a park mode with graceful degradation of performance. We have also shown that average delay experienced by a master and slaves is less than 10 msec if up to four slaves with ACL connections are supported. In order to guarantee low delay requirements, the number of slaves may need to be limited. Our simulation provides a performance metric when multi-slaves (both ACL and SCO connections) are supported using a park mode. These results can serve as a guideline to the design of Bluetooth systems with throughput and delay requirements.

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