PERFORMANCE EVALUATION OF SCHEDULING
ALGORITHMS ON BLUETOOTH PICONET AND
SCATTERNET NETWORK

by

KIN PONG, CHEUNG

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The Hong Kong University of Science and Technology
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the Degree of Master of Philosophy
in Computer Science

August 2002, Hong Kong
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This is to certify that I have examined the above M. Phil. Thesis and have found that it is complete and satisfactory in all respects, and that any and all revisions required by the thesis examination committee have been made.

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ABSTRACT

Bluetooth is an emerging communication technology that started as a simple cable replacement solution, but has quickly advanced to a promising solution for short range ad hoc networking. Compared to other wireless LAN technologies, Bluetooth has a number of distinctive features that significantly affect the performance of Bluetooth networks. However, there are still very few performance analyses of Bluetooth networks.
In this thesis, we first simulate the queuing delay of a single Bluetooth piconet traffic under the assumptions that (1) each piconet member uniformly communicates with all other members, and (2) each member receives data packets according to Poisson distribution. We also compare the 1-limited service, k-limited service, exhaustive service Fair Exhaustive Polling and skip-1 service scheduling with different traffic models such as exponential ON/OFF and bursty traffic. Simulation results show that exhaustive service offers better overall performance. We also consider scatternets that consist of two piconets linked through Master/Slave and Slave/Slave bridges respectively. In order to compare performance of both types of bridges, we have simulated the access delay and end-to-end delay for both local and non-local traffic, assuming that the traffic is bursty. We find that Slave/Slave bridge offers better overall performance.
CHAPTER 1

INTRODUCTION TO BLUETOOTH

1.1 Introduction

Bluetooth is a new low cost, low power wireless technology that has been designed to enable wireless communication between small, mobile devices. The first innovation regarding of Bluetooth was to replace the need for proprietary cables so as to enable device connectivity. For example, in order to transfer files from a palm computer to a laptop PC, a cable is needed in order to connect the palm to the laptop. If we use Bluetooth wireless technology in both the laptop PC and the palm computer, there is no need for cables to transfer data between devices. This idea can be expanded to include all hand held mobile electronic devices.

In addition to eliminating the need for cables to connect devices, Bluetooth enables devices to form small, ad hoc wireless networks. These wireless connections are established using a radio transceiver embedded within each Bluetooth device. The radio operates in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band which is globally available [3]. Bluetooth Radio is designed to operate in a noisy radio environment and a frequency hopping scheme is used which enables Bluetooth Radio modules to avoid interference from other signals in transmitting or receiving a data packet.

Bluetooth devices are organized in piconets that contain a master device and up to 7 slave devices. The master sequentially polls the slaves by sending them packets; the slaves can only talk to the master at the time of addressing, and only immediately
after being addressed by the master. This mechanism is known as Time Division Duplex (TDD).

1.2 Bluetooth Radio

The Bluetooth wireless interface is enabled via a radio transceiver which operates within the 2.4 GHz ISM band. Spectrum spreading is accomplished by frequency hopping in 79 hops displaced by 1 MHz, starting at 2.402 GHz and stopping at 2.480 GHz. The maximum frequency hopping rate is 1600 hops/s.

1.3 Connection Establishment

The Bluetooth Baseband Specification [3] defines point-to-point establishment as a two-step procedure. Inquiry Procedure is used to collect neighborhood information. Paging procedure is used to establish the connections between neighboring devices. During the page scan procedure a device assumes either the role of the master or of a slave. The scanning done by the slave unit is done on one frequency hop sequence which is determined by the hardware within the unit. The potential master unit scans using a page train. The page train is a way for the unit to cover all 32 possible frequency hops and to locate the slave unit which is listening on only one of those frequencies.

1.4 Frequency Hopped Spread Spectrum

In Frequency Hopped Spread Spectrum, the carrier transmission frequency of the modulated signal is not constant but changes periodically.
After each pre-defined time interval, the carrier hops from one frequency to another, which is determined by the Pseudo-Noise sequence. Hopset is the set of available frequencies the carrier can attain. The set of frequencies for hopping includes a number of frequency channels. The carrier transmits data by randomly hopping to different frequency channels.

1.5 Connection Modes

There are four possible connection modes for each Bluetooth device. In active mode, the Bluetooth device actively participates on the channel. Traffic within the channel is scheduled based on the needs of each active device within the piconet. The master also supports regular transmissions to keep all the slaves synchronized to the channel. When a Bluetooth device participates actively on a channel, it is assigned an Active Member Address (AM_ADDR) which is a 3-bit field. Because of that, there are only 7 active slaves within a piconet at any one time. The all zero address is reserved.

In hold mode, the communications with a slave are suspended for a period of time. Hold mode enables a device to keep its AM_ADDR and to support synchronous packets but not to support asynchronous packets. In Chapter 5, we will see how bridges connect to more than one piconet by entering into Hold mode.

A slave must listen at the beginning of each even-numbered slot to see whether the master is communicating to the device or not. In sniff mode, the master reduces the duty cycle of the slave's listening activity. This mode enables the unit to support synchronous and asynchronous packets and keep its AM_ADDR. This mode is primarily used to reduce the amount of power used by a device.
Park mode allows a unit to not actively participate in the channel but to remain synchronized to the channel and to listen for broadcast messages. A slave that enters the park mode gives up its active member address and is assigned an 8-bit Parked Member Address (PM_ADDR). Being 8-bits, there may be up to 255 parked slaves.

1.6 Link and Packet Types

There are two types of physical links in Bluetooth: Synchronous Connection-Oriented (SCO) and Asynchronous Connectionless (ACL). SCO and ACL links may be used on the same channel. SCO links may be used for voice communication and slave devices may transmit SCO data packets without being polled because SCO links have reserved time slots for transmission. A piconet supports up to three SCO links for voice communication. ACL links may be used for data transmission only and slaves must be polled before they can transmit data.

Traffic within the piconet is controlled by the master unit which divides bandwidth to each slave based on its application needs and available bandwidth. Each link between a master and slave may be of a different type than other links in a piconet. Furthermore, the link type between a master and slave may change during a session if the needs of the slave's application change. The packet types for ACL links of Bluetooth are shown in figure 1.5.1.
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>0-17</th>
<th>2/3</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM1</td>
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<td>0-27</td>
<td>no</td>
<td>1</td>
</tr>
<tr>
<td>DH1</td>
<td>2</td>
<td>0-121</td>
<td>2/3</td>
<td>3</td>
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<td>2/3</td>
<td>5</td>
</tr>
<tr>
<td>DM5</td>
<td>2</td>
<td>0-339</td>
<td>no</td>
<td>5</td>
</tr>
</tbody>
</table>

*Figure 1.5.1 ACL packet types.*

### 1.7 MAC layer

The channel of MAC layer in Bluetooth is divided into 625 μs intervals which are called slots. A different frequency hopping sequence is used for each slot. The master starts its transmission in even-numbered slots, while the slave transmission starts its transmission in odd-numbered slots. Packets can be 1, 3 or 5 slots long and are transmitted in consecutive slots. There is no direct communication between slaves, this is done through the master.

A master may address the slave even when there is no actual data to send, such packets are called POLL packets which occupy one time slot. A slave may respond to the master even if it has no packet to send, such packets are called NULL packets which also occupy one time slot. Slaves can talk to the master only when it is
addressed by the master in the preceding slot.

1.8 Scatternet

An ad hoc Bluetooth scatternet may be established by linking several piconets together. A piconet is defined as a group of devices consisting of at least one master and one slave unit which all share the same frequency hopping sequence. A scatternet is a collection of piconets linked together by a bridge. A bridge device may link two piconets by being a slave in two different piconets or it may be a slave in one piconet while being a master in another piconet. We will look in more detail, of bridges in Chapter 5.

1.9 Summary

In this chapter, we briefly describe the basics of Bluetooth. We discuss the Bluetooth radio, piconet and scatternet concepts, the packet types, MAC layer and connection establishment of Bluetooth.
CHAPTER 2

BLUETOOTH PROTOCOL AND SIMULATOR

2.1 Protocol Architecture

![Bluetooth Protocol Stack Diagram]

*Figure 2.1 Bluetooth Protocol Stack*

Figure 2.1 shows the organization of the protocols in the Bluetooth specification. These are the transport protocols developed by the SIG to carry audio and data traffic between devices. The core protocols of the bluetooth protocol stack include the following six protocols:

1. Baseband:
The Baseband layer is responsible for connection creation, frequency hopping sequence and timing, modes of operation such as power control and secure operation. It also responsible for medium access functions like polling, packet types, packet processing and link types.

2. Link Manager Protocol (LMP):

LMP is responsible for link set-up between Bluetooth units. It handles the control and negotiation of packet sizes used when transmitting data. The Link Manager Protocol also handles management of power modes, power consumption, and state of a Bluetooth unit in a piconet. Finally, this layer handles generation, exchange and control of link and encryption keys for authentication and encryption.

3. Host Controller Interface (HCI):

HCI provides a uniform interface method for accessing the Bluetooth hardware capabilities. It contains a command interface to the Baseband controller and link manager and access to hardware status. It also contains control and event registers.

4. Audio:

Audio transmissions can be performed between one or more Bluetooth units, using many different usage models. Audio data do not go through the L2CAP layer but go directly, after opening a Bluetooth link and a straightforward set-up, between two Bluetooth units.
5. Logical Link Control and Adaptation Protocol (L2CAP):

The Bluetooth logical link control and adaptation protocol, L2CAP, is situated over the Baseband layer and beside the Link Manager Protocol in the Bluetooth protocol stack. The L2CAP layer provides connection-oriented and connectionless data services to upper layers. The four main tasks for L2CAP are:

   a. Multiplexing: L2CAP must support protocol multiplexing, since a number of protocols (e.g. SDP, RFCOMM and TCS Binary) can operate over L2CAP.

   b. Segmentation and Reassembly: Data packets exceeding the Maximum Transmission Unit, MTU, must be segmented before being transmitted. This reassembly is performed by L2CAP.

   c. Quality of Service: The establishment of an L2CAP connection allows the exchange of information regarding current Quality of Service for the connection between the two Bluetooth units.

   d. Group abstraction: The L2CAP specification supports a group abstraction that permits implementations for mapping groups on to a piconet.

6. Service Discovery Protocol (SDP):

SDP defines how a Bluetooth client's application shall act to discover available Bluetooth servers' services and their Bluetooth characteristics. The protocol defines how a client can search for a service based on specific
attributes without the client knowing anything about the available services. The SDP provides means for the discovery of new services becoming available when the client enters an area where a Bluetooth server is operating. The SDP also provides functionality for detecting when a service is no longer available.

2.2 Bluehoc simulator

Bluehoc simulator is developed by IBM [2]. It provides a Bluetooth extension for Network Simulator (ver 2.1b8a). It allows users to evaluate how Bluetooth performs under an ad-hoc networking environment. The following Bluetooth layers have been simulated:

- Bluetooth radio.
- Bluetooth baseband.
- Link Manager Protocol.
- Logical Link Control and Adaptation Protocol (L2CAP).

There is one more layer, BTHost, which layered above L2CAP to act as a system to control the functionality of the above four layers. Simulation starts with the creation of a master node and several slave nodes. The master node starts the inquiry procedure. The transmission frequency depends upon the clock of the master and the general inquiry access code. The slaves respond to inquiry with FHS packets which contain the device address and the clock of the slave. When the required number of inquiry responses is obtained, the master starts paging the slave.

Once paging is over and the slave is tuned to the master hopping sequence, Link
Manager Protocol establishes an Asynchronous Connection-Less (ACL) link between the master and the slave. For this the master's LMP sends an LMP_host_connection_req to the peer LMP. When the master's LMP receives a response from the slave LMP it sends an HCI Event to BTHost indicating that the connection with the required device has (or has not) been created. In Bluehoc, it is assumed that there is only one flow per ACL connection.

After the communication from the LMP is over, it sends HCI_QoS_setup_complete_event to BTHost. The host then sends L2CA_Connect_Req to L2CAP. Signaling takes place between L2CAP peers. Each L2CAP channel has a connection identifier (CID) associated with it. For signaling the CID is 1. The L2CAP side that initiates connection establishment sends an L2CAP_connection_request and the other side sends an L2CAP_connection_response. Through this exchange each end can identify the other end through its CID. Several L2CAP connections can be established in this manner over a single ACL connection.

2.3 Improvement to Bluehoc simulator

The Bluehoc simulator currently only allows forward traffic going in one direction from master to slaves. The reverse traffic from slaves to master has been implemented by us with the following procedures:

1) L2CAP channel establishment from slaves to master.
2) Mapping the reverse channel to MAC level round robin scheduling.
3) Attaching applications (Poisson traffic) to slaves.
4) Starting slave to master applications.

We also improved the simulator by:
1) Implementing the Master/Slave bridge in forming scatternet.

2) Allowing different packet types to be transmitted in one application.

3) Adding agents to measure queuing delay for each packet and service time for each slave.

4) Implementing 1-limited service scheduling and exhaustive service scheduling.

5) Adding Poisson traffic and Exponential ON/OFF traffic.

2.4 Summary
In this chapter, we discuss the architecture of Bluetooth core protocol. We also briefly describe Baseband, Link Manager Protocol, Host Controller Interface, audio, Logical Link Control and Adaptation Protocol and Service Discovery Protocol. We also present the Bluehoc simulator and the ways that we have improved it.
CHAPTER 3

QUEUEING ANALYSIS OF BLUETOOTH

PICONET TRAFFIC

3.1 The System Model and Assumption

The performance of Bluetooth network on voice and data traffic deserve special attention, as is widely anticipated [22]. However, only few research [24], [14], [15], [16], [17], [18] has been done on analyzing the performance of Bluetooth at media access control (MAC) level. In this chapter, we will focus on this area.

![Diagram](image)

*Figure 3.1.1 (a) A single piconet with m members (one master and m-1 slaves)
(b) Downlink and uplink slot form a frame*

The system that we are modeling is a Bluetooth piconet with m members (one master and m-1 slaves), where 1 ≤ m ≤ 7. Figure 3.1.1a shows a single piconet with m members. Let us denote the piconet master as node 0, other slaves as 1 to m-1. We assume that the nodes will communicate with each other with equal probability. Packets will travel two hops if the packet is sent from one slave and destined to another slave. Packets only travel one hop if the packet is sent from master to slave or
vice versa. The master contains one downlink queue per slave and each slave contains one uplink queue, as shown in Figure 3.1.2

![Diagram](image)

*Figure 3.1.2 A Bluetooth piconet can be modeled with two sets of queues.*

Some work has been done on service policies based on polling systems [19], [20], [21] but they are not designed for Bluetooth network. In Bluetooth network, when 1-limited service scheduling is considered, the master will examine its queue sequentially no matter whether the queue is empty or not and each slave is addressed exactly once. If there is a data packet waiting in the downlink queue, this packet is sent in the downlink slot, otherwise, a POLL packet is sent. The slave responds with a data packet from its uplink queue, or a NULL packet if there is no packet in the uplink queue. We assume the packets arrive according to the Poisson process.

In exhaustive scheduling, the master will only start to address another slave when both the master and the slave it is currently addressing, have no packet in their queues. In other words, the master can address the same slave many times instead of only once in the case of 1-limited service scheduling.
3.2 The Simulation Model

A Bluetooth piconet simulator has been built using the bluehoc simulator that was mentioned in Chapter 2. We enhance the simulator by implementing the two-way communication between the master and the slave. Different traffic models like ON/OFF traffic model and burst traffic model are integrated into the simulator. 1-limited, exhaustive and k-limited scheduling policies have been implemented. The simulator operates at the MAC level, consistent with the queuing theoretic analysis presented above. We run the simulation by first forming a piconet and connecting the slaves to the master. Then, we run the simulation for 48000 time slots and the last 32000 time slots are collected as data for analysis.

3.3 Theoretical Analysis of 1-limited service scheduling

Dr Jelena Misic and Dr Vojislav Misic have analyzed this model using existing theory of M/G/1 queues with vacation [9]. We assume that each device generates bursts of packets that follow a Poisson distribution with arrival rate $\lambda$. All packets within a burst have the same destination node, and the distribution of destination nodes is assumed to be uniform. Then, the burst arrival rate for uplink queues $\lambda_u$ and downlink queues $\lambda_d$ will be:

$$\lambda_u = \lambda$$

$$\lambda_d = \frac{\lambda(m-2)}{m-1} + \frac{\lambda}{m-1} = \lambda$$

The probability distribution of packet burst length may be described with
probability generating function (PGF) $G_b(x) = \sum_{k=0}^{\infty} b_k x^k$, where $b_k$ is the probability that the packet burst length is equal to $k$; the mean value of the burst length is $\overline{B} = G_b'(1)$. The equivalent Laplace-Stieltjes transform (LST) of the probability distribution may be obtained by substituting the variable $x$ with $e^{-s}$ [23]; for example, the LST of the packet burst length PDF will be:

$$G_b^*(s) = \sum_{k=0}^{\infty} b_k e^{-ks}$$

The probabilities of packets being one, three, and five slots long are $p_1, p_3$ and $p_5$ where $p_1 + p_3 + p_5 = 1$. The corresponding probability generating function (PGF) is

$$G_p(x) = p_1x + p_3x^3 + p_5x^5$$

The first and second moments of packet length distribution are:

$$\overline{L} = G_p'(1)$$

$$\overline{L^2} = G_p^*(1) + G_p'(1)$$

and its LST is $G_p^*(s) = p_1 e^{-s} + p_3 e^{-3s} + p_5 e^{-5s}$.

Let the cycle time of the piconet (i.e. the time for the piconet master to service all of its slaves once) be $X_C$, the probabilities that the channel queues are not empty will be $P_d = \lambda_d \overline{B} X_C$ and $P_u = \lambda_u \lambda B X_C$ for the master and slave queues, respectively. The durations of the downlink and uplink communications may be described by:

$$G_d(x) = (P_d p_1 + (1 - P_d))x + P_d p_3x^3 + P_d p_5x^5 \quad (1)$$

$$G_u(x) = (P_u p_1 + (1 - P_u))x + P_u p_3x^3 + P_u p_5x^5 \quad (2)$$

The PGF for the piconet service cycle time will be:

$$G_{x_r}(x) = (G_d(x)G_u(x))^{(m-1)} \quad (3)$$
The first and second moment of the service cycle time may be obtained as:

\[ \overline{X_c} = G'_{X_c}(1) \]

\[ \overline{X_c^2} = G''_{X_c}(1) + G'_{X_c}(1) \]

In single server-multiple client systems, when the server finds an empty client queue, it goes on to service other clients, i.e. it take a vacation, which lasts until the next visit to this client [23]. In a Bluetooth piconet, a server vacation starts when the master polls a slave, finds its uplink queue to be empty (slave has replied with a NULL packet), and moves on to the next slave. The duration of the vacation period \( V_i \) may be described with the following PGF:

\[ G_{V_i}(x) = xG_d(x)(G_d(x)G_a(x))^{-2} \quad (4) \]

and its first and second moments are \( \overline{V_i} = G'_{V_i}(1) \) and \( \overline{V_i^2} = G''_{V_i}(1) + G'_{V_i}(1) \).

Finally, the LST for the distribution of the access delay at the slave queue as [8]:

\[ W_a^*(s) = \frac{1-V_i^*(s)}{sV_i^*} \cdot \frac{s(1-\lambda B X_c^*)}{s - \lambda + \lambda G_b(X_c^*)} \cdot \frac{1-G_b(X_c^*)}{B(1-X_c^*)} \quad (5) \]

where \( V_i^*(s) \) and \( X_c^*(s) \) denote the LST of the probability distributions of vacation time and cycle time, respectively. The average access delay at the slave is then calculated as \( \overline{W_a} = -W_a^*(0) \), or:

\[ \overline{W_a} = \frac{\lambda B X_c^2}{2(1-\lambda B X_c^*)} + \frac{B^{(2)} X_c}{2B(1-\lambda B X_c^*)} + \frac{V_i^2}{2V_i} \quad (6) \]

where \( B^{(2)} = E[B(B-1)] = G_b'(1) \) is the second factorial moment of burst length distribution.

Moreover, the burstiness of the traffic in the downlink queue will differ from the one in the slave queue because the bursts from different source slaves might become interleaved in the same downlink queue, which will in turn lead to an equivalent
decrease in burst length. The probability that two packet bursts from different slaves will not have the same destination, and hence will not be interleaved in the same downlink queue, will be \(1 - \frac{1}{(m-1)^2}\). Therefore, the equivalent mean burst length at the master downlink queue will be:

\[
\frac{1}{B_m} = \frac{1}{B} \left(1 - \frac{1}{(m-1)^2}\right) + 1 \cdot \frac{1}{(m-1)^2}
\]  

(7)

The burst rate has to be scaled so that \(\lambda_{dn} \overline{B_m} = \lambda_d \overline{B}\) and the same server utilization could be maintained.

The queuing delay at the piconet master may be described with an expression similar to (5), except that \(\lambda\) is replaced with \(\lambda_{dn}\), and the mean burst length is replaced with \(\overline{B_m}\).

### 3.4 Simulation results of 1-limited service scheduling

In this section, we run the simulation under 1-limited service scheduling. We assume that the mean burst length is equal to one. The results from simulation match with the analytical model in [12]. Mean access delay is obtained by taking the average of the access delay of all the slaves. Figure 3.4.1 and 3.4.2 shows the mean access delay vs data packet arrival rate. It contains 7 curves and each curve corresponding to piconet members ranging from 2 to 8. In figure 3.4.1, all packets are exactly one slot long. In figure 3.4.2, the packet size is uniformly distributed with mean packet length equal to 3. We find that the mean waiting times increases with packet arrival rate and piconets with more members have longer waiting time. Comparing figure 3.4.1 with 3.4.2, we
find that an increase in mean packet length leads to an increase in mean waiting time. The curve with higher packet length starts to have high waiting time at earlier packet arrival rate compared with low packet length.

Figure 3.4.1 Mean access delay for a piconet under 1-limited service scheduling policy, with all packets exactly one slot long.
Figure 3.4.2 Mean access delay for a piconet under 1-limited service scheduling policy, with mean packet length equal to 3 time slots long.

We examine the efficiency in our model by looking at the total number of time slots using in transmitting data packets (not included POLL and NULL packets) divided by the total number of time slots (data packets plus POLL and NULL packets). In figures 3.4.3 and 3.4.5, we find that efficiency is linear function of the packet arrival rate. We also find that the efficiency will approach its maximum value of 1 if the packet arrival rates approach critical values, which are shown in figures 3.4.1 and 3.4.2. This matches our previous results in figures 3.4.1 and 3.4.2.
Figure 3.4.3 Efficiency for a piconet under 1-limited service scheduling policy, with all packet length equal to 1 time slot long.

Figure 3.4.4 Efficiency for a piconet under 1-limited service scheduling policy, with mean packet length equal to 3 time slots long.
3.5 Theoretical Analysis of exhaustive service scheduling

In exhaustive scheduling, the master will only start to address another slave when both the master and the slave that it is currently addressing, have no packet in their queues. In other words, the master can address the same slave many times in the case of exhaustive scheduling. When there are only two members in the piconet, there is no difference between exhaustive service and 1-limited service scheduling. The exchange ends when both queues are empty, i.e., when the slave responds with a NULL packet to a POLL packet sent by the master [3]. The actual number of frames is equal to the number of packets in the downlink or the corresponding uplink queue, whichever is larger, plus one for the POLL-NULL sequence.

Dr Jelena Misic and Dr Vojislav Misic have analyzed this model in [9]. Let $X_{ms}$ denote the time to service a single channel, i.e., the time to empty both channel queues for one particular slave. The corresponding PGF is

$$X_{ms}(x) = e^{(\lambda_s + \lambda_d)X_s(x)(G_k(G_{sp}(x))-1)} \cdot e^{\lambda_s - \lambda_d}X_s(x)(G_k(x)-1) \cdot x^2$$

(8)

From previous notation, let $X_C$ denote the piconet service cycle time, its PGF is

$$X_C(x) = X_{ms}^{n-1}(x).$$

Then, the PGF of the server vacation time is

$$G_{V_s}(x) = x^2 X_{ms}^{m-2}(x)e^{\lambda_s X_s(x)(G_k(x)G_{sp}(x)-1)}$$

(9)

and its first and second moments are

$$\overline{V_s} = G'_{V_s}(1)$$

$$\overline{V_s^2} = G''_{V_s}(1) + G'_{V_s}(1)$$

The LST for the access delay probability distribution is:
\[ W_a^*(s) = \frac{1-V_e^*(s)}{sV_e} \cdot \frac{1-G_b(G_p^*(s))}{B(1-G_p^*(s))} \cdot \frac{s(1-2(m-1)\lambda B L)}{s - 2(m-1)\lambda + 2(m-1)\lambda G_b(G_p^*(s))} \]

(10)

which translates into the mean access delay of the form

\[ \bar{W}_a = \frac{2(m-1)\lambda B^2 L^2 + B^2 L}{2B(1-2(m-1)\lambda B L)} + \frac{V_e^2}{2V_e} \]  

(11)

### 3.6 Simulation results of exhaustive service scheduling

The mean access delay for the exhaustive service scheduling with different packet arrival rates is shown in figure 3.6.1. Compared with figure 3.4.1, we find that exhaustive service scheduling has higher access delay than 1-limited service scheduling under this traffic type. We also find that the efficiency under exhaustive service scheduling is a linear function of the packet arrival rate.

![Figure 3.6.1 Mean access delay for a piconet under exhaustive service scheduling policy, all packet length equal to one time slot long.](image)

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Figure 3.6.2 Efficiency for a piconet under exhaustive service scheduling policy, all packet length equal to one time slot long.

We define a run as a contiguous sequence of transmissions of packets between a master and a single slave. So, in 1-limited service scheduling, all runs are composed of a single downlink transmission from the master plus a single uplink transmission from the slave. While in the exhaustive service scheduling, a run may be composed of more than one downlink and uplink transmission pair which depends on the queue size of the master and slave.

Figure 3.6.3 shows the number of packets transmitted and the number of runs as functions of packet arrival rate, in a piconet with four members under the exhaustive service scheduling.

Under low packet arrival rate, the number of runs and the number of transmitted packets is almost the same. This is because most runs contain only a single data
packet and the gradient of the curve is nearly the same. When the packet arrival rate increases, most of the runs contain more packets and their mean length increases, which slow down the increases of the number of runs. After that, it reaches a broad plateau and it drops. Under high arrival rate, the queue size of both the master and slave is so large that a run may contains a long sequence of frames. This stops the master from serving other slaves and thus making large access delay.

![Graph showing number of packets and number of runs](image)

*Figure 3.6.3 Number of packets and number of runs in a piconet with m=4 members, operating under the exhaustive service scheduling policy with packet length =3.*

### 3.7 Summary

In this chapter, we have presented a simulation analysis of Bluetooth piconet traffic under the assumption that (1) each piconet member uniformly communicates with all other members, and (2) data packets arrive at each member according to Poisson distribution. Simulation results have been obtained in comparison of 1-limited service
and exhaustive service scheduling. The results match with the theoretical analysis presented in [12], [9].
CHAPTER 4

PERFORMANCE EVALUATION OF BLUETOOTH PICONET UNDER ON/OFF AND BURSTY TRAFFIC

4.1 The System Model and Assumption

In this chapter, the system that we are modeling is a Bluetooth piconet with m members (one master and m-1 slaves), where $1 \leq m \leq 7$ which is the same as the previous chapter. We assume that the nodes will communicate with each other with equal probability. The master contains one downlink queue per slave and each slave contains one uplink queue.

Besides 1-limited and exhaustive service algorithms, we have also implemented k-limited service algorithm, Fair Exhaustive Algorithm (FEP) [7] and skip-1 algorithm and comparison will be given in the latter section.

In Chapter 3, we assume that the mean burst length is equal to one. In this chapter, we will simulate traffic with different values of mean burst length. We will also try to model some other types of traffic, for example, the ON/OFF traffic.
4.2 The Simulation results for k-limited service

In this section, we compare the mean access delay for k-limited with exhaustive and 1-limited service scheduling. For exhaustive service scheduling, the master will continue to serve the same slave until all the packets in both the master queue and slave queue is empty. In k-limited service scheduling, the master will continue to serve the same slave until either all the packets in both the master queue and slave queue is empty or the number of frames exceeds k.

![Graph showing mean access delay for different service scheduling methods](image)

*Figure 4.2.1 Mean access delay of exhaustive, 1-limited and k-limited service scheduling for different packet arrival rate, lambda when m=5 and all packets with size equal to 1*
Figure 4.2.2 mean access delay of exhaustive, 1-limited and k-limited service scheduling for different packet arrival rate, lambda when m=4 and all packets with size equal to 1

Figure 4.2.1 and figure 4.2.2 shows the mean access delay of exhaustive, 1-limited and k-limited service scheduling for different arrival rate when there are four members in the piconet and all packets are exactly one time slot long. The mean burst length is again equal to one. We find that 1-limited and exhaustive service scheduling show the lower and upper bound among all the scheduling algorithms. When the packet arrival rate is moderate, the mean access delay of k-limited discipline between the 1-limited and exhaustive. When the packet arrival rate is high, we find that the mean access delay of k-limited move towards the lower bound (1-limited). This may due to the fact that the size of the queues in both the master and the slave is high under high arrival rate, master remains to serve for one particular slave and other slaves may need to wait longer and introduce high delay. While for k-limited service scheduling, even under high packet arrival rate, the number of frames that the master serving on one particular slave is limited by k, so, there is a
difference between them. Figure 4.2.3 shows the number of packets and number of runs in a piconet with four members, operating under the exhaustive, k-limited service scheduling policy with average packet length equal to three. We find that for k-limited service scheduling, the number of runs approaches plateau for higher packet arrival rate, lambda.

![Graph showing the number of packets and number of runs in a piconet with four members, operating under the exhaustive, k-limited service scheduling policy with packet length = 3.](image)

*Figure 4.2.3 Number of packets and number of runs in a piconet with m=4 members, operating under the exhaustive, k-limited service scheduling policy with packet length = 3.*

Besides the number of runs, we also compare the probability density distribution of access delay among 1-limited, k-limited and exhaustive service scheduling. Figure 4.2.4 - 4.2.7 show the distribution of access delay when there are six members in the piconet, mean packet length equal to three and mean burst length equal to one.
Figure 4.2.4 Probability density distribution of 1-limited service scheduling when there are 6 members, mean packet length = 3 and mean burst size = 1

Figure 4.2.5 Probability density distribution of 2-limited service scheduling when there are 6 members, mean packet length = 3 and mean burst size = 1
Figure 4.2.6 Probability density distribution of 3-limited service scheduling when there are 6 members, mean packet length = 3 and mean burst size = 1

Figure 4.2.7 Probability density distribution of exhaustive service scheduling when there are 6 members, mean packet length = 3 and mean burst size = 1
4.3 Simulation results of ON/OFF traffic

In this chapter, we try to model exponential ON/OFF traffic. During ON period, packets arrive according to the Poisson distribution. During OFF period, packet arrival is suppressed.

We define \( \gamma = \frac{\text{time(ON)}}{\text{time(ON)} + \text{time(OFF)}} \) and if \( \lambda \) is the packet arrival rate during ON period for each slave, then we have:

\[ \lambda \gamma = \text{constant}, \]

so that we can compare the performance of different scheduling algorithms under the same aggregate packet arrival rate.

Figure 4.3.1 shows the mean access delay of 1-limited service scheduling for different ON/OFF periods when there are three members in the piconet and the size of the packets are exactly one time slot long. No ON/OFF period means that all the time is ON period and there are no OFF periods. All different ON/OFF periods have the same aggregate packet arrival rate. This means that the arrivals of the packets are much more condensed for small activity periods compared to large activity periods. We find that although all the curves represent the same aggregate packet arrival rates, curves with higher ON-OFF ratio tend to have higher access delay. This can be explained by the larger number of packet arrival during the ON period and large queuing delay during the active period.
Figure 4.3.1 Mean access delay of 1-limited service scheduling for different ON/OFF period, when $m=3$ and all packets with size equal to 1

Figure 4.3.2 shows the mean access delay of exhaustive service scheduling for different ON/OFF periods when there are three members in the piconet and the size of the packets are exactly one time slot long. We find that 1-limited have smaller mean access delay than exhaustive service scheduling in the case of low ON/OFF ratio. The difference in mean access delay becomes smaller for higher ON/OFF ratio. When ON=20ms and OFF=80ms, their mean access delay is roughly the same. We can conclude that exhaustive service scheduling performs better with ON/OFF traffic compared with previous traffic pattern.
Figure 4.3.2 Mean access delay of exhaustive service scheduling for different ON/OFF period, when \( m=3 \) and all packets with size equal to 1.

We plot the graph of mean access delay vs \( \frac{1}{\gamma} \) in figure 4.3.3 for 1-limited service scheduling when there are seven members in the piconet. We find that the mean access delay shows an exponential growth when \( \frac{1}{\gamma} \) is getting smaller.
Figure 4.3.3 mean access delay vs $1/\gamma$ for 1-limited service scheduling when there are seven member in the piconet

4.4 Fair Exhaustive Polling (FEP) and skip-1 service

In previous section, we have compared 1-limited, k-limited and exhaustive service scheduling. In this section, we compare these three algorithms with Fair Exhaustive Polling (FEP) and skip-1.

There are two states for FEP, the active state and the inactive state. A polling cycle starts with the master moving all slaves to the active state, and then during each cycle, the master poll all the active slaves once. After each cycle, a slave is moved from the active state to the inactive state when the following conditions are BOTH fulfilled:

1) the slave responds with a NULL (no information to send)
2) the master sends a POLL to that slave (no information to send)

Figure 4.4.1 shows the decision graph of FEP service scheduling.
Figure 4.4.1 Decision graph of FEP service scheduling
A slave is moved to active state when the master has information to send to that slave. This is an iterative process that continues until the active state is emptied. And when all slaves get into inactive state, they will be put into active state again.

For skip-1 service scheduling, the master will skip the service of a particular slave for one cycle if BOTH of the following conditions happen:
1) the slave respond with a NULL in the previous cycle
2) the master has nothing to send to that slave in this cycle
If a slave has been skipped by the master for one cycle, the master will poll it again no matter whether the slave or master has something to send or not, so, that results in the name of skip-1.

4.5 Comparison of different service algorithms with ON/OFF traffic

![Graph showing mean access delay for 1-limited, skip-1, exhaustive and FEP service scheduling when there are seven members in the piconet when ON=20ms, OFF=100ms]
Figure 4.5.1 shows the performance of skip-1, FEP, exhaustive and 1-limited scheduling when there are seven members in the piconet when ON=20ms, OFF=100ms. In Section 4.4, we find that the performance of 1-limited and exhaustive service scheduling is roughly the same when ON=20ms, OFF=80ms. From figure 4.5.1, we find that exhaustive service scheduling begins to perform better than 1-limited when ON/OFF ratio increases. We also find that under this ON/OFF ratio, exhaustive scheduling performs the best compared with the other three.

4.6 Comparison of different service algorithms with bursty traffic

In Chapter 3, we consider the traffic where there are no ON/OFF periods and the number of packets per arrival is exactly one. In section 4.5, ON/OFF traffic is defined as the traffic pattern where packets are generated only during ON periods. In this section, we define bursty traffic as the traffic pattern which the number of packets for each arrival is more than one. Burst length is the number of packets for each arrival. It follows the geometric distribution with the probability generating function

\[ G_k(x) = \sum_{k=0}^{\infty} b_k x^k \] where \( b_k \) is the probability that the burst will contain exactly \( k \) packets [8].

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Figure 4.6.1 mean access delay for exhaustive service scheduling in bursty traffic when there are eight members in the piconet and mean packet length = 3

Figure 4.6.2 mean access delay for 1-limited service scheduling in bursty traffic when there are eight members in the piconet and mean packet length = 3
Figure 4.6.1 and 4.6.2 show the mean access delay for exhaustive service and 1-limited scheduling for bursty traffic when there are eight members in the piconet and mean packet length is equal to three. We simulate the traffic with different values of mean burst length. For example, traffic with mean burst length equal to three means that there will be three packets arrive at one moment on the average. As we expected, traffic with higher geometric mean tends to have higher mean access delay compared with traffic with lower geometric mean.

Figure 4.6.3 shows the comparison of skip-1, exhaustive, 1-limited and FEP service scheduling for bursty traffic when geometric mean equal to six, three members in the piconet and general packet length equal to three. We find that exhaustive service scheduling performs the best under this traffic pattern.

Figure 4.6.3 mean access delay for different service scheduling in bursty traffic when there are six members in the piconet and mean packet length =3
4.7 Summary

In this Chapter, we have compared 1-limited service, k-limited service, exhaustive service, FEP and skip-1 service scheduling in different traffic model such as ON/OFF traffic and bursty traffic. We find that exhaustive offers the best performance.
Chapter 5

PERFORMANCE OF BLUETOOTH BRIDGES IN SCATTERNETS

5.1 The System Model of Master/Slave bridge

When two or more Bluetooth piconets connected through bridges, such a network is called a scatternet. The bridge relays data packets from one piconet to another. Depending on the role of the bridge device in the piconet, two cases can be distinguished. In case of a Master/Slave (MS) bridge, the bridge device is the master in one piconet and a slave in another piconet. In case of a Slave/Slave (SS) bridge, the bridge device is a slave in both piconets.

![Diagram of two piconets connected through a Master/Slave bridge](image.png)

*Figure 5.1.1 Two piconet connected through a Master/Slave bridge*

When we consider two piconets $P_1$ and $P_2$ connected by MS bridge, there are $m_1$ and $m_2$ members respectively as shown in figure 5.1.1. In piconet $P_1$, there are one master and $m_1 - 1$ proper slaves. In piconet $P_2$, there are one master and $m_2 - 2$ proper slaves as one of the slaves is a bridge device as shown in figure 5.1.1
Proper slaves are the slaves that do not perform the role to be a bridge.

The bridge device acts as a master in piconet P2 for some period of time, during which it routes packet from one slave to another slave. It will queues packets with destination to piconet P1 which are waiting for exchange interval. The master in piconet P1 will perform the same role to route packet from and to its slaves and queues packets with destination to piconet P2. At some predefined time, the bridge switches to listening as a slave in piconet P2 and the master in piconet P2 will switch to communicate with the bridge. The packets which are queued at both the bridge and master in piconet P2 will be exchanged during that interval and again queued for later delivery to destination. After all the packets have been exchanged, the bridge device will switch back to act as a master in piconet P1 while master in piconet P2 will continue to serve its slaves. Figure 5.1.2 shows how this operation is being performed.

![Diagram](image)

*Figure 5.1.2 Queuing model of two piconets connected through an MS bridge*

The operation of the master nodes in both piconets to communicate with their proper slaves can be 1-limited service scheduling or exhaustive service scheduling which will be discussed later. However, for the packet exchanged between the master
of piconet \( P2 \) and the bridge device is done using exhaustive service mode. The reason is if we choose \( l \)-limited or \( k \)-limited service scheduling, we cannot guarantee all the packets queued in the bridge and master in piconet \( P2 \) have been exchanged. Secondly, since the communications in a Bluetooth piconet must be initiated by its master, slaves in piconet \( P1 \) cannot communicate during the exchange period. So, the bridge device should not be absent from piconet \( P1 \) for prolonged periods of time.

Since Bluetooth uses frequency hopping spread spectrum (FHSS) to combat interference, all members of the piconet hop simultaneously using the frequency sequence determined by the master. All transmissions are synchronized, in frequency and phase, with the time slot clock of the master. So, when the bridge device switches from the role of master in piconet \( P1 \) to a slave in \( P2 \), it has to switch from its own clock to the clock of the master in piconet \( P2 \). The same thing happens when the bridge switch back to act as a master in piconet \( P1 \).

In this model, we assume that proper slave generates batches or bursts of packets at time instants that follow Poisson distribution with arrival rate \( \lambda \). Neither the bridge device, nor the master device of \( P2 \), generate any traffic. The length of the packet burst follows the geometric distribution with the probability generating function

\[
G_b(x) = \sum_{k=0}^{\infty} b_k x^k
\]

where \( b_k \) is the probability that the burst will contain exactly \( k \) packets [8]. We assume that the proper slaves generate packets will length being one, three or five time slots long and the mean length is equal to three.
We define traffic locality as the proportion of traffic with destination that are within the same piconet as the source to that with destination that are not within the same piconet as the source. So, local traffic will be handled by only the masters while non-local traffic will be handled by the bridge device and also the masters. We further defined $T_1$ as the time for two successive exchange intervals as shown in figure 5.1.3.

![Figure 5.1.3 Operation of two piconets connected through an MS bridge](image)

As the packet exchange between the bridge device and the master in piconet $P2$ is done using exhaustive mode and controlled by the master device in piconet $P2$. NULL packets are sent by the bridge device if its queue is empty and POLL packet are sent by the master in piconet $P2$ when its queue is empty. We are informed the end of the exchange period by a NULL packet received in response to a POLL packet from master in piconet $P2$.

### 5.2 The Performance of Master/Slave bridge

Dr Jelena Misic and Dr Vojislav Misic present a theoretical analysis in [10], [11]. We find that our simulation results in ns2 running on a Linux platform match with their analytical results and simulation results using Artis Software Inc [1] simulation
engine.

In the following simulation, we assume that the packet exchange between the master in piconet $P_2$ and the bridge device is done in 1-limited service mode, round robin scheduling. So, the master will poll each slave sequentially but with a single frame, then moves on to serve another slave. In the following simulation, we assume that the mean packet length is equal to three and the mean burst length is equal to ten. We also assume that there are six proper slaves for each piconet.

![Graph showing mean access delay as a function of burst arrival rate and exchange interval]

*Figure 5.2.1 Mean access delay as a function of burst arrival rate and exchange interval for MS bridge using 1-limited service scheduling*
Figure 5.2.2 Mean local end-to-end delay as a function of burst arrival rate and exchange interval for MS bridge using 1-limited service scheduling.

Figure 5.2.3 Mean non-local end-to-end delay as a function of burst arrival rate and exchange interval for MS bridge using 1-limited service scheduling.
We plot the dependency of mean access delay, mean local end-to-end delay and mean non-local end-to-end delay on packet arrival rate and exchange interval for mean burst length equal to ten and traffic locality equal to 0.9 in figure 5.2.1 to 5.2.3. As can be seen from figure 5.2.1, for exchange interval below 40T, the mean access delay grows up while for exchange interval above 40T, the mean access delay are roughly the same. Similar behavior may be observed for local end-to-end delay and non-local end-to-end delay on the packet arrival rate in figure 5.2.2 and 5.2.3.

![Mean access delay as a function of burst arrival rate and traffic locality](image)

*Figure 5.2.4 Mean access delay as a function of burst arrival rate and traffic locality for MS bridge using 1-limited service scheduling*
Figure 5.2.5 Mean local end-to-end delay as a function of burst arrival rate and traffic locality for MS bridge using 1-limited service scheduling

Figure 5.2.6 Mean non-local end-to-end delay as a function of burst arrival rate and traffic locality for MS bridge using 1-limited service scheduling
The dependency of mean access delay, local end-to-end delay and non-local end-to-end delay on the packet arrival rate and traffic locality is shown in figure 5.2.4-5.2.6. The exchange interval is 100T. We find that under low packet arrival rate, all the delay variables are roughly the same for different traffic localities. For packet arrival rate greater than 0.0014T, all the delay variables increase when the traffic locality decreases.

![Figure 5.2.7 Performance parameters as functions of mean packet burst length, under constant aggregate arrival rate](image)

Figure 5.2.7 shows the impact of packet burst length on the mean access delay, local end-to-end delay and non-local end-to-end delay under constant aggregate arrival rate. In this simulation, we keep the aggregate packet arrival rate per slave constant and $\lambda \bar{B} = 0.015$, where $\lambda$ is the arrival rate and $\bar{B}$ is the mean packet burst
length.

We find that an increase in mean burst length lends to an almost linear increase in all delay variables. The non-local end-to-end delay which has to pass three hops experienced higher delay than local end-to-end delay which only passes two hops. We note that delays can reach rather high values, for values of mean burst length of 15 or above, end-to-end delays are over 800T or 0.5s. Consequently, smaller delay may be achieved by keeping the mean packet burst size as small as possible. This can be achieved by proper segmentation policies, which is a promising avenue for further research.

5.3 The System Model of Slave/Slave bridge

When we consider two piconets $P_1$ and $P_2$ connected by SS bridge, there are $m_1$ and $m_2$ members respectively as shown in figure 5.3.1. In both piconet $P_1$ and $P_2$, there are 1 master and $m_1 - 2$ proper slaves and a bridge device. The bridge device act as a slave in both piconets $P_1$ and $P_2$.

![Diagram showing two piconets connected through a Slave/Slave bridge](image-url)

*Figure 5.3.1 Two piconet connected through a Slave/Slave bridge*
The bridge device acts as a slave in piconet $P2$ for some period of time, during which it exchanges packets with master in piconet $P2$. It will queue packets with destination to piconet $P1$ which are waiting for exchange interval. The master in piconet $P1$ will serve the other slaves as usual. At some predefined time, the bridge switches to listening as a slave in piconet $P1$ and the master in piconet $P1$ will switch to communicate with the bridge. The packets which are queued at both the bridge and master in piconet $P1$ will be exchanged during that interval and will be queued for later delivery to destination.

![Diagram](image)

*Figure 5.3.2 Operations of two piconets linked through a Slave/Slave bridge*

As shown in figure 5.3.2, the bridge device will be a slave in $P1$ for some time $T_i$. After that, it will disconnect from $P1$ and act as a slave in $P2$ for some time $T_2$. Again, we will assume that only proper slaves generate traffic, all slaves have the same burst arrival rate and the probability of all destinations within a piconet is the same.
5.4 The performance of Slave/Slave bridge

Dr Jelena Misić and Dr Vojislav Misić have analyzed this model [10], [11]. We find that our simulation results in ns2 running on a Linux platform match with their analytical results and simulation results using Artis Software Inc simulation engine.

We have plotted the dependency of mean access delay and mean local end-to-end delay and mean non-local end-to-end delay on packet arrival rate and exchange interval, for mean burst length equal to 10; these diagrams are shown in figure 5.4.1 to 5.4.3. Overall, the dependencies follow the same shape as the corresponding variables in the scatternet with an MS bridge.

Mean access delay as a function of burst arrival rate and exchange interval (as bridge 1-limited)

![Diagram](image)

*Figure 5.4.1 Mean access delay as a function of burst arrival rate and exchange interval for SS bridge using 1-limited service scheduling*
Mean local end to end delay as a function of burst arrival rate and exchange interval (as bridge)

![Graph of local end to end delay as a function of burst arrival rate and exchange interval](image)

**Figure 5.4.2** Mean local end-to-end delay as a function of burst arrival rate and exchange interval for SS bridge using 1-limited service scheduling

Mean non-local end to end delay as a function of burst arrival rate and exchange interval (as bridge 1-limited)

![Graph of non-local end to end delay as a function of burst arrival rate and exchange interval](image)

**Figure 5.4.3** Mean non-local end-to-end delay as a function of burst arrival rate and exchange interval for SS bridge using 1-limited service scheduling
When comparing figure 5.2.3 with 5.4.3, we find that the end-to-end delay for non-local traffic for SS bridge increases with the exchange interval, $T_i$, especially for low burst arrival rate, unlike its MS bridge counterpart where the rate of increase is barely noticeable. This is due to the fact that bridge exchanges are spaced exactly $T_i$ apart, hence the non-local end-to-end delay virtually contains $2T_i$ as an additive component.

![Performance parameters as functions of mean packet burst length, under constant aggregate packet arrival rate.](image)

Same as before, we assume that each piconet has six active slaves and we plotted the impact of traffic burstiness by different mean packet burst length on various delay variables in figure 5.4.4. The aggregate packet arrival rate is fixed in all cases and $\bar{\lambda}B = 0.015$, while exchange intervals were $T_1 = T_2 = 100T$ and traffic locality is equal to 0.9.
We find that the access delay and local end-to-end delay are slightly lower than in the case of the MS bridge. The reason is in case of SS bridge, the master devices have time $T_1 + T_2 - \bar{T}$, to serve their slaves in their piconets while in case of MS bridge, the master devices only have time $T_1 - \bar{T}$, to serve their slaves in their piconets, where $\bar{T}$ is the mean value of bridge exchange time. Therefore, the packets will have to wait less at the master and slaves and the delays are lower.

We also find that the non-local end-to-end delay is higher in case of SS bridge. This is because packets with non-local destinations have to travel four hops in the case of SS bridge and three hops in the case of MS bridge. So, the extra hop in SS bridge introduces higher end-to-end delay. As we find that the relative increase in non-local end-to-end delay is smaller than the corresponding decrease in local end-to-end delay and access delay, we might say that SS bridge provide better overall performance.

5.5 The performance of Master/Slave bridge and Slave/Slave bridge using exhaustive service scheduling

The system model for both MS bridge and SS bridge will be the same as before. We will assume that the packet exchange for the bridges is done exhaustively. In this section, we will assume that master nodes in both piconets communicate with their proper slaves using exhaustive service. Under this policy, each master-slave channel is serviced for as long as necessary, until both the master and slave queues are empty.

The mean access delay as a function of burst arrival rate and exchange interval under exhaustive service for MS and SS bridge is shown in figure 5.5.1 and 5.5.2.
respectively. The mean end-to-end delay as a function of burst arrival rate and exchange interval under exhaustive service for MS and SS bridge is shown in figure 5.5.3 and 5.5.4 respectively. We do not show the local end-to-end delay, since it would provide little extra information except for the fact that it is lower than non-local end-to-end delay. Again, the agreement between our simulation results running in ns2 and the analytical results in [13] is quite good.

Figure 5.5.1 Mean access delay as a function of burst arrival rate and exchange interval for MS bridge using exhaustive service scheduling
Figure 5.5.2 Mean access delay as a function of burst arrival rate and exchange interval for SS bridge using exhaustive service scheduling

Figure 5.5.3 Mean non-local end-to-end delay as a function of burst arrival rate and exchange interval for MS bridge using exhaustive service scheduling
Figure 5.5.4 Mean non-local end-to-end delay as a function of burst arrival rate and exchange interval for SS bridge using exhaustive service scheduling

We get the same conclusion as in previous section that the access delay is lower for SS bridge, while non-local end-to-end delay is lower for MS bridge. Comparing with Section 5.2 and 5.4, we also find that the both the access delay and non-local end-to-end delay is lower under exhaustive service scheduling for both MS and SS bridge. So, we can conclude that exhaustive service scheduling performs better than 1-limited service scheduling under bursty traffic.

5.6 Summary

In this Chapter, we have analyzed the operation of Bluetooth scatternets by simulation. We considered scatternets that consist of two piconets linked through an MS and SS bridge respectively. We have obtained the average of access delay, local end-to-end delay and non-local end-to-end delay with respect to burst arrival rate, traffic locality and mean burst length.
We find that MS bridge provides lower mean end-to-end delay for non-local traffic. However, both end-to-end delay for local traffic and access delay at slave devices are lower for SS bridge configuration. We conclude that both MS and SS bridge topology under exhaustive service scheduling offers better overall performance than 1-limited service scheduling. The results presented here should help to improve the scatternet formation algorithms [4], [5], [25] which depend on choosing the bridge and the choice of holding time of the bridge.
CHAPTER 6
CONCLUSIONS AND FUTURE WORK

Bluetooth is an emerging communication technology that started as a simple cable replacement solution, but has quickly advanced to a promising solution for short-range ad hoc networking. The performance analyses of Bluetooth networks are still very few.

In this thesis, we have presented a simulation analysis of Bluetooth piconet with data packets arrive at each member according to Poisson distribution. We have simulated the model of 1-limited service, k-limited service and exhaustive service scheduling under uniform traffic, ON/OFF traffic and bursty traffic. Mean access delay, service time, end-to-end delay and number of runs have been measured.

We also investigated the performance of FEP and skip-1 service scheduling and compared them with the above scheduling scheme. In scatternet, we measured the performance of MS bridge and SS bridge and their results have been compared.

Further research topics related to the performance of Bluetooth networks might include similar analysis under variable rate traffic model and improvement on skip-1 service scheduling.
REFERENCES


