

中文摘要

隨著最近無線技術的發展，短距離的無線傳輸技術逐漸成爲一股新的潮流，而且也提供使用者越來越多方便的服務。其中藍芽技術的出現使得原先單機的裝置可以容易地進入網路環境。隨著最新版的藍芽標準 1.1 版在 2000 年十二月制訂後，相關的產品預期將很快地出現在市場上。

在藍芽無線系統裡，藍芽裝置會被組織成 Piconet。而各自獨立的 Piconet 也可以互相連接，進一步形成 Scatternet。Scatternet 中裝置的數目和其所使用頻寬分配機制都是影響效能的重要因素。在本篇論文中，我們提出三種不同的頻寬分配機制，同時評估在藍芽環境中，不同網路拓撲和和使用不同頻寬分配機制的效能，其中效能包括平均傳輸量和封包延遲時間。

Abstract

With the recent advance in wireless technologies, short-range wireless transmission gradually becomes a new trend, and provides users with more convenient services. One renowned example will be the standardization of Bluetooth specification that provides previously standalone devices the network services. As the latest revision of Bluetooth specification version 1.1 in December of 2000, the compliant products are expected to rapidly fill the market.

In Bluetooth wireless systems, Bluetooth devices are organized in piconets. A set of piconets can be grouped and interconnected as a scatternet. As anticipated, both the number of devices in a scatternet and bandwidth allocation schemes will affect the system performance. In this thesis, we will experiment three kinds of bandwidth allocation schemes to evaluate their performances, including throughputs and delays, under different system topologies. Discussions on their pro-and-con will also be provided.

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Chapter 1 Introduction

Recently, much attention has been placed on home- and personal-area network (PAN) devices with low-cost radio technologies such as HomeRF and Bluetooth [1][2]. Short-range radio technologies enable users to easily interconnect their handheld devices such as cellular phones, palm devices or notebooks. In specialty, Bluetooth focuses on providing a low-cost short-range radio link to mobile and stationary devices.

1.1 A Brief of Bluetooth System

Bluetooth is a short-range radio technology operating at the 2.4GHz unlicensed ISM (Industrial-Scientific-Medical) band. The modulation scheme is GFSK (Gaussian Frequency Shift Keying). Microwave ovens and other wireless technologies such as HomeRF and IEEE 802.11 also operate at this ISM, which may be sources of interferences. Bluetooth system uses the frequency hopping technique, combined with forward error correction coding scheme, to overcome the interference. The communication range is possibly from 10 cm to 10 m, but can be extended to 100 m, which is controlled by the transceiver power in the range of -30 dBm to 20 dBm with a nominal value of 0 dBm.

Bluetooth devices are organized in, so-called, piconets. There is exactly one Bluetooth device in each piconet that acts as a master, who can admit up to seven active slaves. A Bluetooth device is allowed to participate in more than one piconet at anytime but it can be a master in only one piconet. This network which consisting of

several overlapping piconets is called a scatternet, as depicted in Figure 1-1.

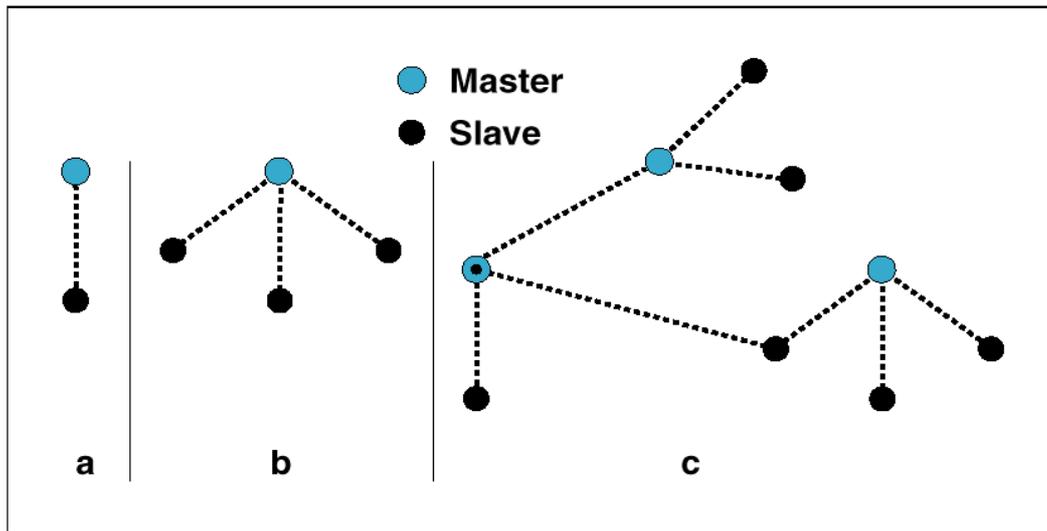


Figure 1-1: Bluetooth network scenario: (a) a piconet with a single slave; (b) a piconet with multi-slave; (c) a scatternet.

Within a piconet, Bluetooth devices use a slotted time-division duplex (TDD) scheme for transmission, where each slot is 0.625 ms in duration. Each time slot is numbered according to the clock of the piconet master. The master and slave alternatively transmit by following the TDD scheduling. Specifically, the master shall start its transmission in even-numbered time slots only, and the slave shall start its transmission in odd-numbered time slots only (cf. Figure 1-2). Packets transmitted by the master or the slave can be extended over up to five time slots (cf. Figure 1-3).

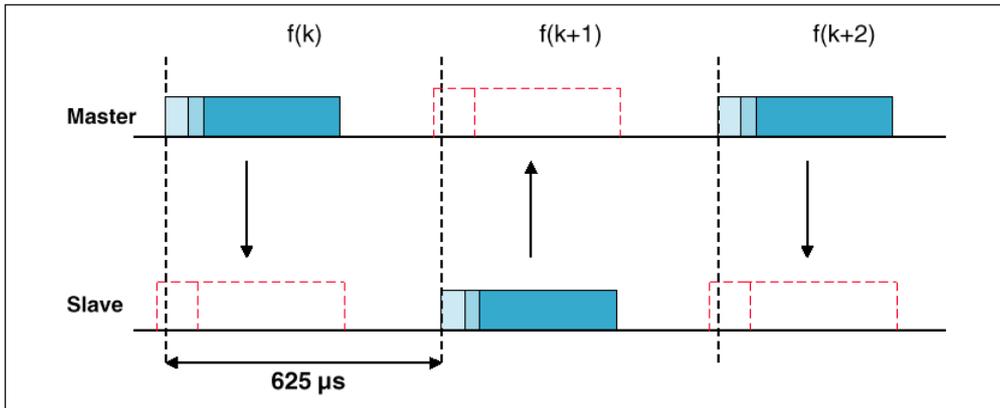


Figure 1-2: TDD and timing

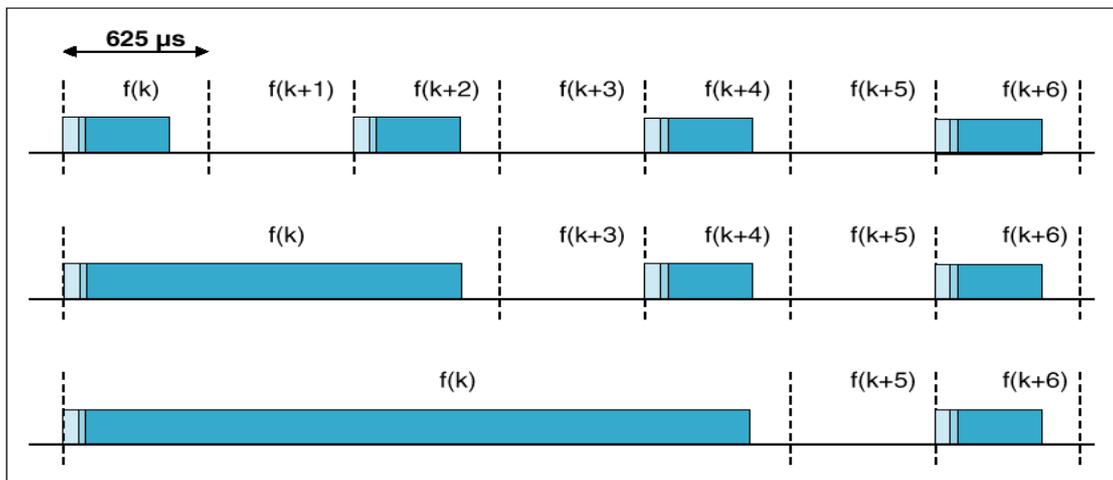


Figure 1-3: Multi-slot packets

The basic packet format is shown in Figure 1-4. Each packet consists of 3 parts — the access code, the header, and the payload. The access code and header are 72 bits and 54 bits in length, respectively. The payload may range from zero to a maximum of 2745 bits.

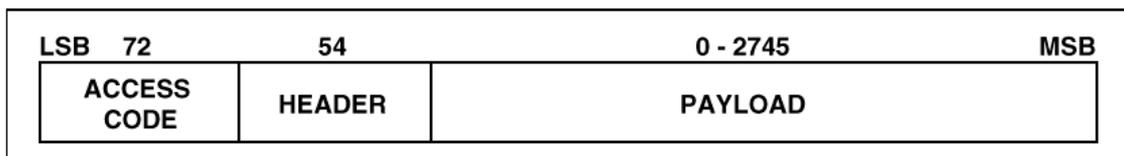


Figure 1-4: Standard packet format

The access code consists of a preamble, a sync word, and possibly a trailer, as depicted in Figure 1-5. The preamble and trailer are fixed zero-one patterns used to facilitate DC compensation. The sequence is either 1010 or 0101. The sync word is derived from the Lower Address Part (LAP) of the Bluetooth device.

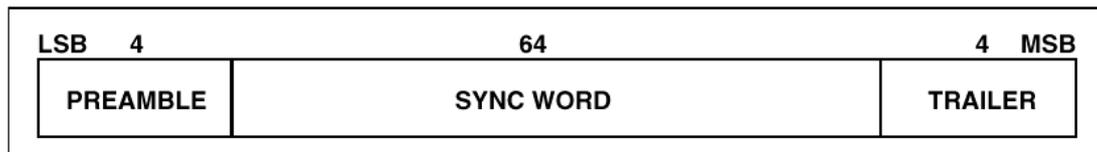


Figure 1-5: Access code format

Figure 1-6 shows the header format. The header consists of 6 fields:

- **AM_ADDR:** The AM_ADDR contains 3-bits active member address used to distinguish the active members participating on the piconet. The all-zero address is reserved for broadcasting packets from the master to the slaves.
- **TYPE:** The 4-bits type code specifies which packet type is used.
- **FLOW:** This bit is used to control the flow of packets over the packet-switched link.
- **ARQN:** This bit is used for acknowledge indication.
- **SEQN:** This bit is used to sequence the packet stream.
- **HEC:** 8-bits header error check.

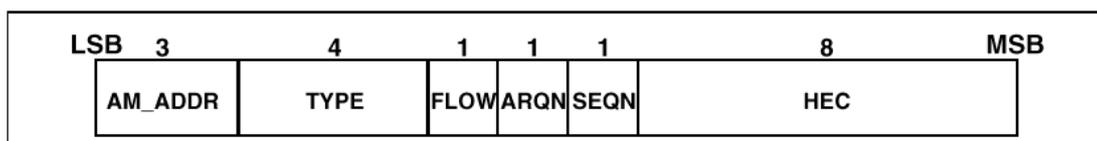


Figure 1-6: Header format

Figure 1-7 shows a state diagram that illustrates the states used in the Bluetooth

link controller. There are two major states: STANDBY and CONNECTION, and seven substates, which are page, page scan, inquiry, inquiry scan, master response, slave response, and inquiry response. The substates are used to add new slaves to a piconet.

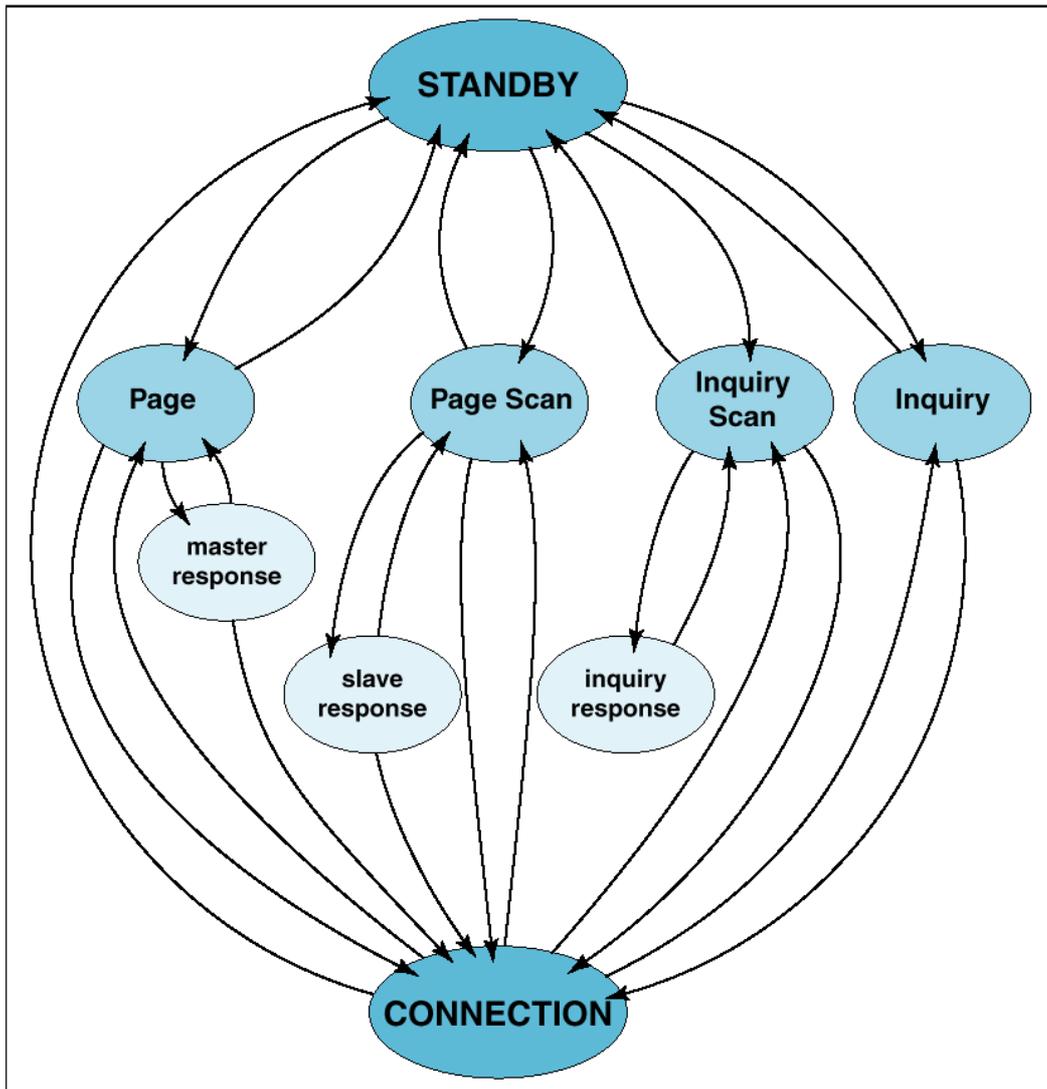


Figure 1-7: State diagram of Bluetooth link controller

The STANDBY state is the default state in the Bluetooth device. In this state, the device is in the low-power mode.

In the CONNECTION state, the connection has been established and packets can

be transmitted or received.

The inquiry, inquiry scan, and inquiry response are parts of the inquiry procedure. The inquiry procedure enables a device to discover which devices are in range, and what their device addresses and clocks are.

The page scan, page, master response, and slave response are parts of the paging procedure. With the paging procedure, a real connection can be built after discovery.

1.2 Contributions

In this thesis, we experiment three kinds of bandwidth allocation schemes. Their performances, including average system throughput and queuing delays, over fixed- and dynamic network topologies are simulated. Pro-and-con of these schemes are also remarked.

1.3 Thesis Overview

This thesis is organized as follows:

Chapter 2 illustrates the simulation model, including three bandwidth allocation schemes, and simulation flow.

Chapter 3 describes the simulation assumption and presents the simulation results.

In chapter 4, we summarize the simulation results and point out some possible future works.

* The figures in this chapter are all quoted from [1].

Chapter 2 Simulation Model

2.1 Simulation Flow

The simulation system flow is depicted in Figure 2-1. After the initialization of the Bluetooth devices, the system enters the system simulation loop. When the pre-setup time is reached, the simulation stops.

Within the simulation loop, every device checks its `Arrival_Time` timer that is generated according to exponentially distribution. If the timer is zero, the device creates a new data packet and put it into the device queue (also a new `Arrival_Time` will be generated and loaded into the timer). When the device queue is full, the newly generated packet will be dropped. As shown in the flowchart, if the `Arrival_Time` timer is not zero, it will be decremented by one.

Afterwards, every device checks its `PageScan_Period` timer. If the `PageScan_Period` timer is not zero, it will be reduced by one, and the flow continues; otherwise, the device examines its current state and takes necessary follow-up actions. In case the current state is Normal under zero `PageScan_Period` timer, the device sets the current state to `PageScan`. However, if the current state is not Normal, the device resets the `PageScan_Period` timer. This procedure ensures that every device will periodically enter the `PageScan` state with accurate period. In the end, each device checks its current state, and enter the process corresponding to its current state.

Figure 2-2 graphically illustrates the system state transitions. The following sections will devote to the detail of each process.

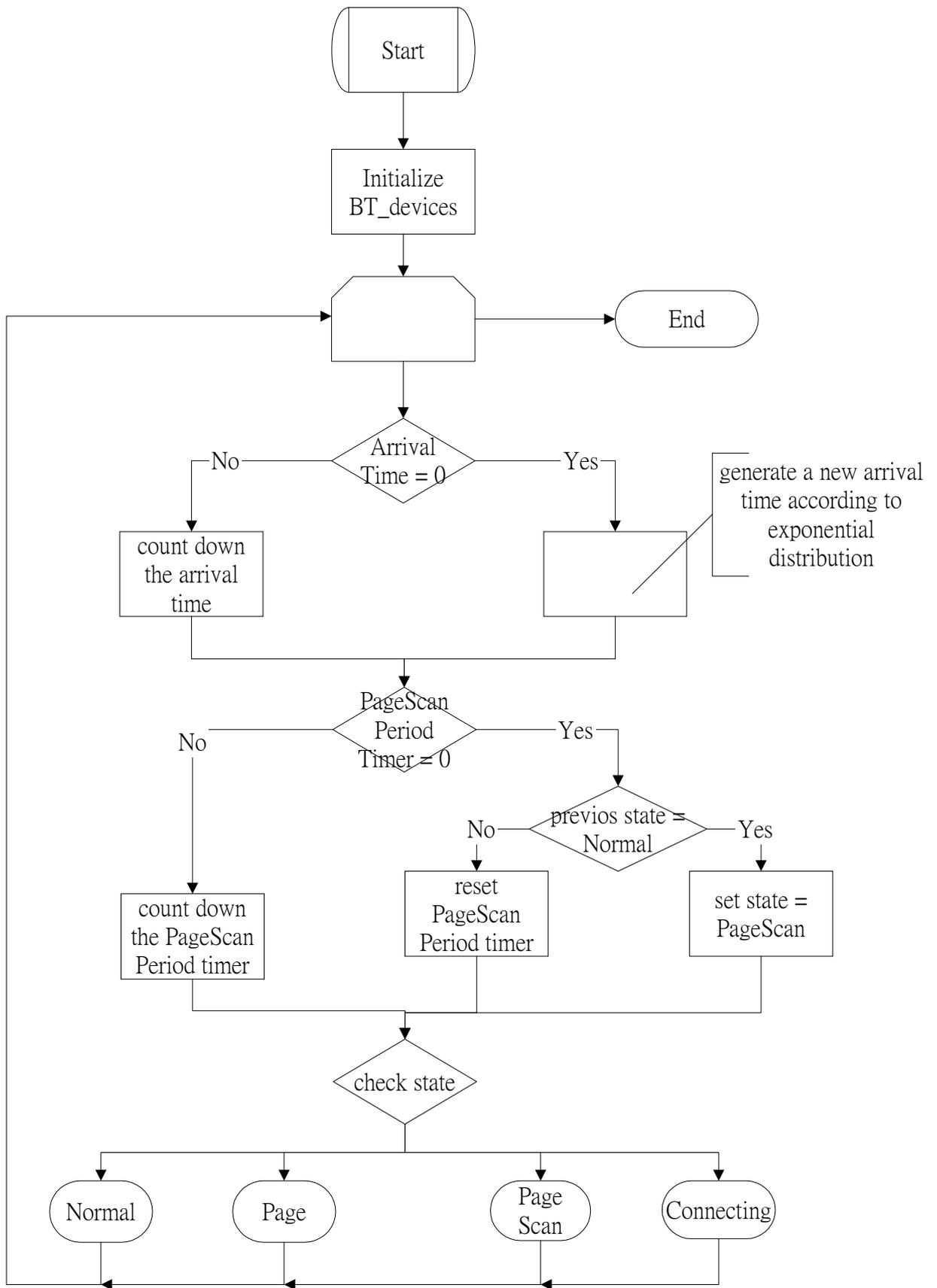


Figure 2-1: Flowchart of system simulation

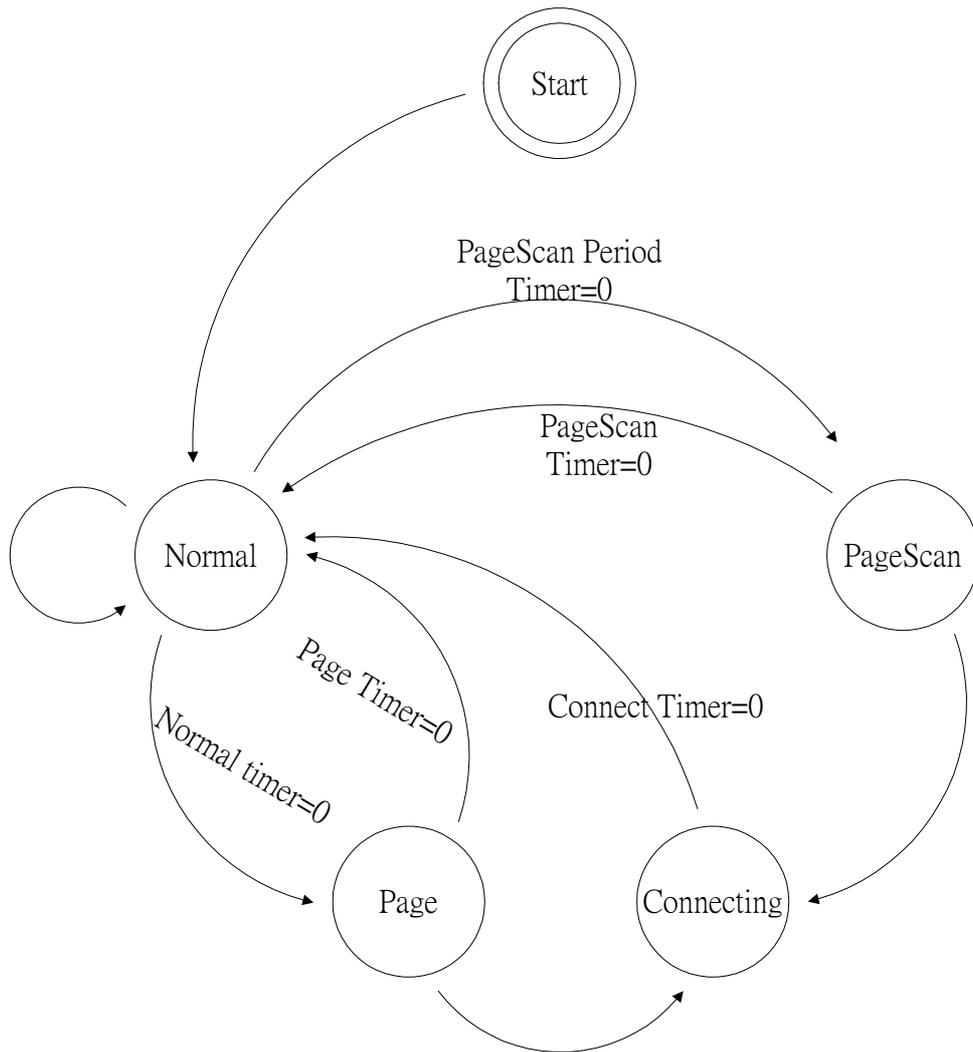


Figure 2-2: System state transition diagram

2.2 Normal process

The Normal process consists three part – Normal_time timer check, master role activity part, and slave role activity part.

First, each device counts down the Normal_time timer in every system cycle. When the timer is counted down to zero, the device's state is set to Page, and goes into the Page process at the next cycle.

Then, as a master role, the device allocates the bandwidth, and decides the slave to be polled. As a slave role, the device waits for its master's polling command, and returns a packet to the master, if there is any in its queue.

In the Bluetooth specification [1], no bandwidth allocation scheme is specified. Therefore, we will experiment three frequently adopted schemes – Round Robin Polling, FIFO, and combination of the former two. Details will be introduced in the sequel.

2.2.1 Round Robin Polling (RRP) bandwidth allocation scheme

Figure 2-3 illustrates the Round-Robin Polling bandwidth allocation scheme. The master polls each of its slaves in the slave list in a round-robin fashion. Of course, whenever there is a packet in the master's queue destined to the slave, it will be transmitted to the slave; otherwise, a pure Poll command will be transmitted.

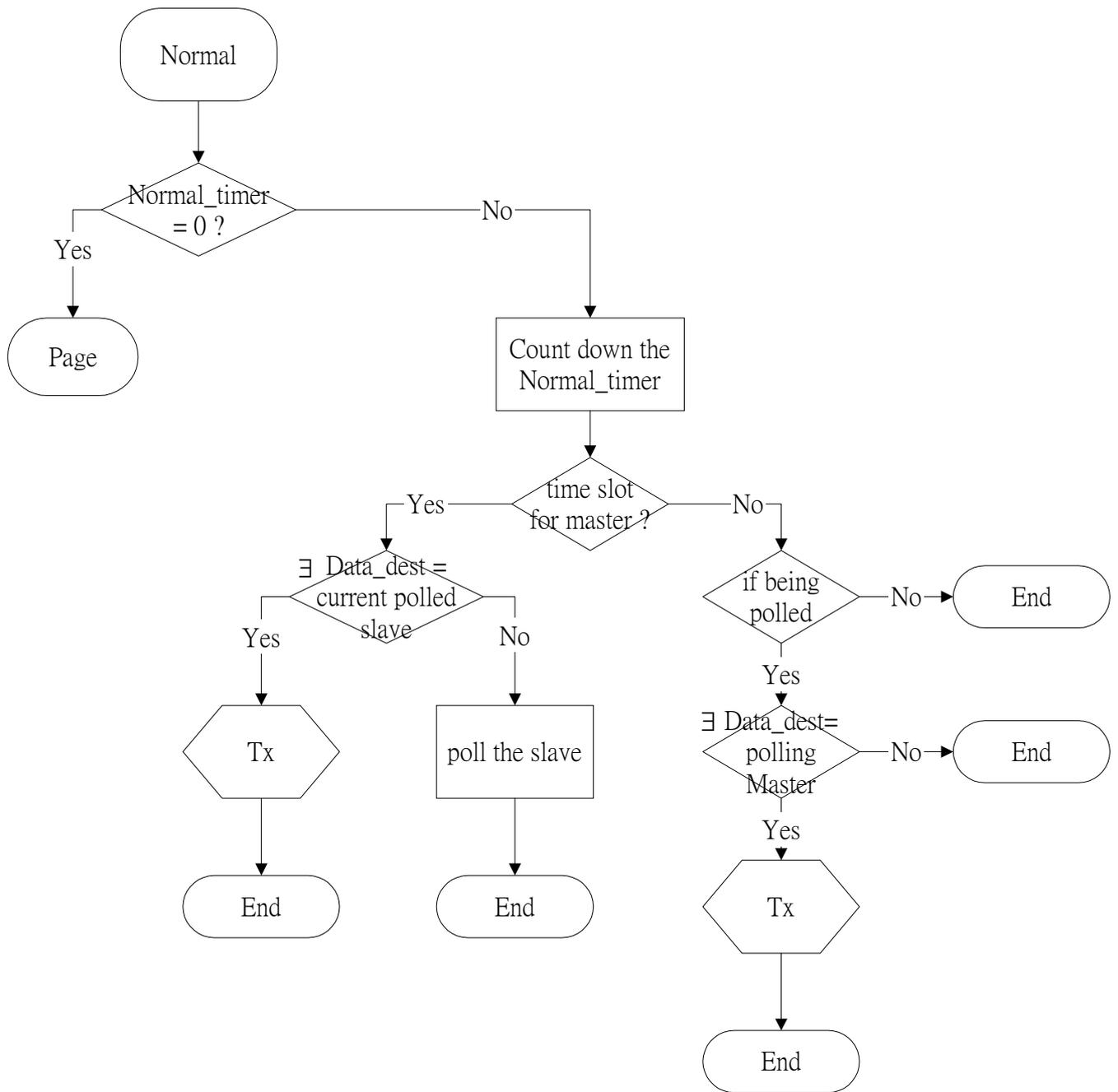


Figure 2-3: Normal process with Round Robin Polling bandwidth allocation scheme

2.2.2 FIFO bandwidth allocation scheme

Figure 2-4 describes the first-in-first-out (FIFO) bandwidth allocation scheme. The master examines the packets in its queue in a FIFO fashion. If the top packet destined to one of its slaves, it will be transmitted; otherwise, the master will end the Normal process.

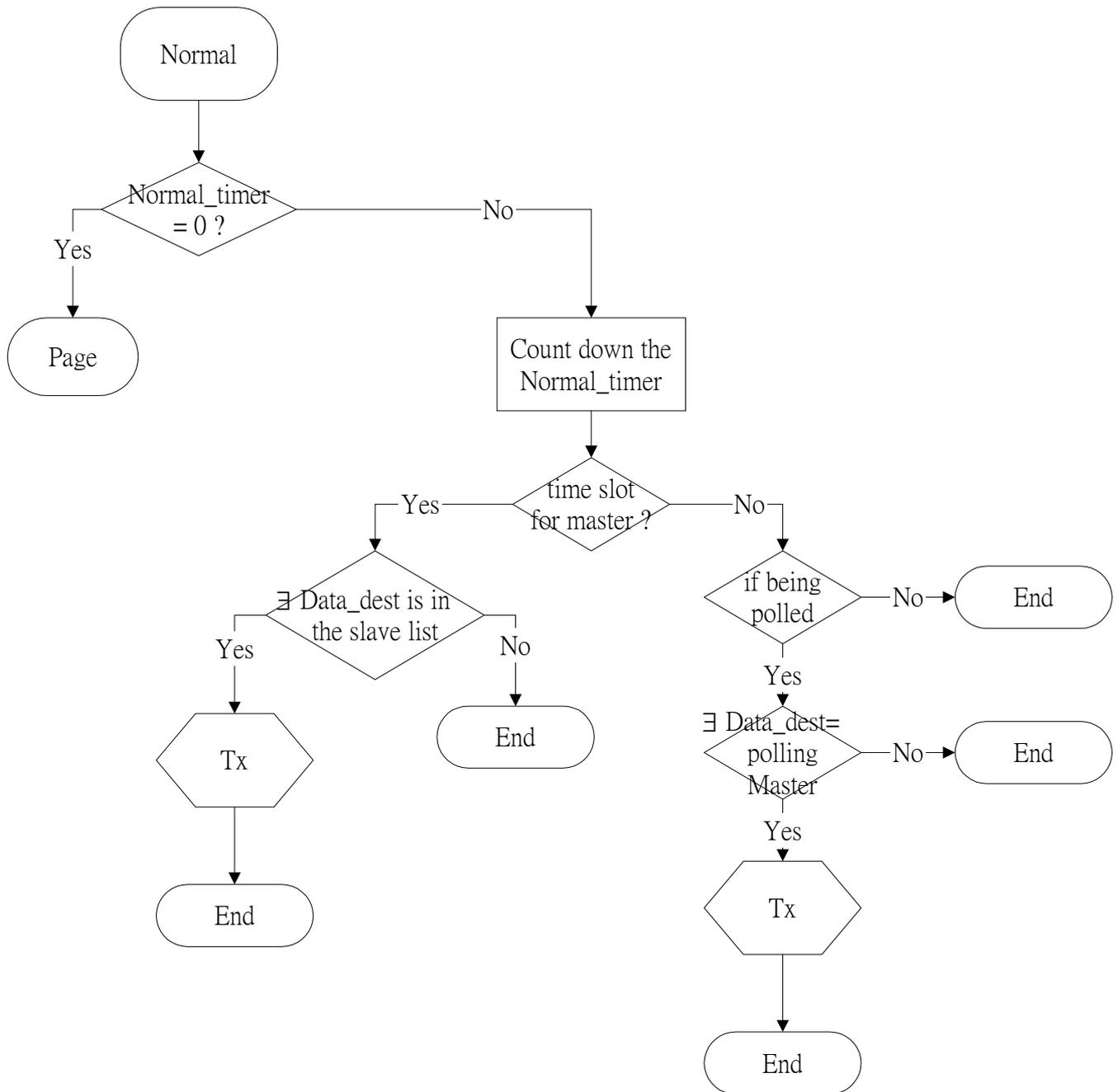


Figure 2-4: Normal process with FIFO bandwidth allocation scheme

2.2.3 Combined RRP and FIFO bandwidth

allocation scheme

As shown in Figure 2-5, this scheme alternatively use the RRP and FIFO bandwidth allocation schemes.

2.3 Page process

To simplify the simulation, we assume that each Bluetooth device knows the MAC addresses of all the other devices; hence, it is not necessary to concern the inquire process specified in Section 10.6 of Bluetooth specification [1].

In our simulation, the master in the Page process sets up the devices it intend to page, and waits the response of these devices at its PageScan process for a maximum time of 2048 slots. This choice of 2048 slots is from Section 10.6.3 of [1] as R1 mode. When the Page_timer counts down to zero, the device will go back to the Normal state at the next cycle. Figure 2-6 describes this process.

2.4 PageScan process

In the PageScan process, the device examines all other devices to find if anyone is paging it. If there exists a device that is paging it, our simulation will update the paging device's slave list and the paged device's master list. Then both devices enter the Connecting state at the next simulation cycle. If there is no device paging it before

the expiration of the PS_timer, the device will go back to the Normal state at the next cycle. The PS_timer initial value is 16 slots, which is specified in the section 10.6.2 of [1]. We assume the PageScan device only listen at a single hop frequency. Figure 2-7 illustrates this process.

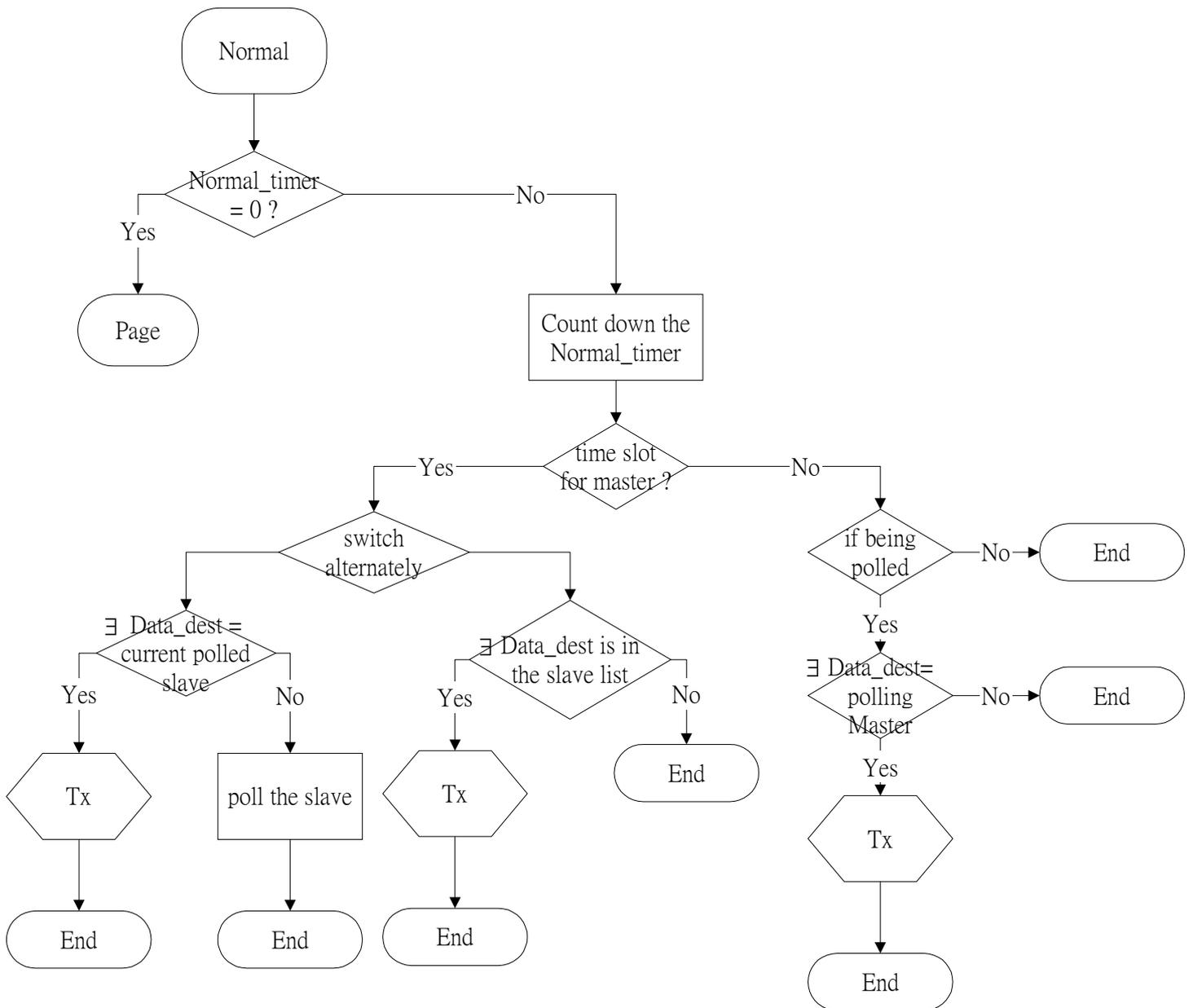


Figure 2-5: Normal process with combined bandwidth allocation scheme

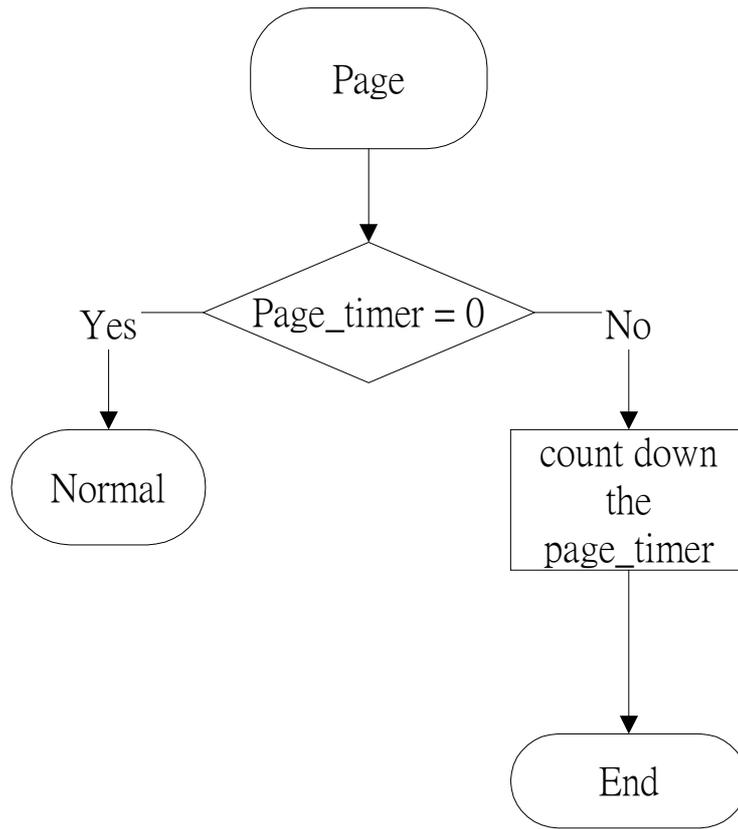


Figure 2-6: Page process

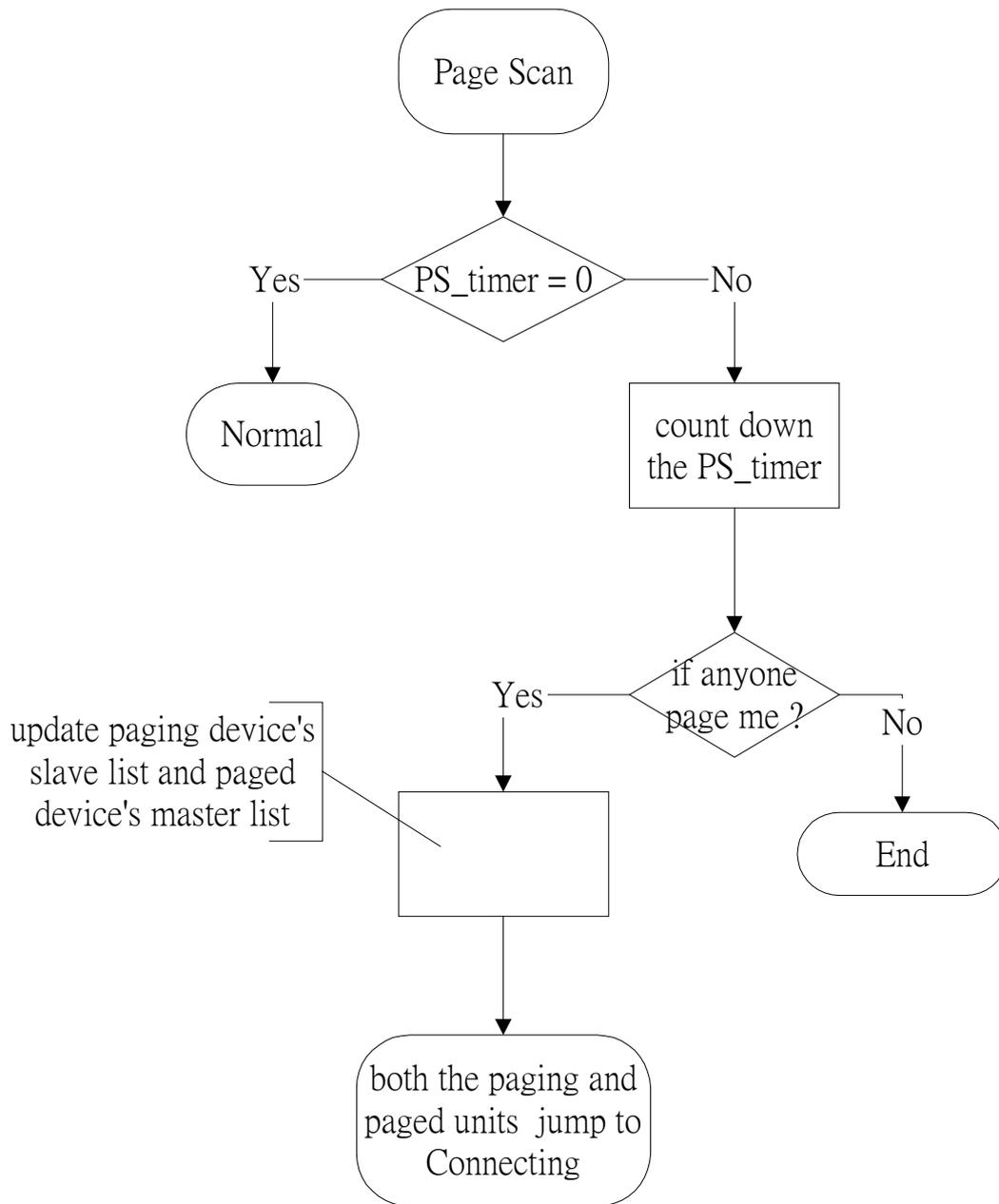


Figure 2-7: PageScan process

2.5 Connecting process

According to the standard [1], if the paging master and the paged slave meet at some slot time, the master will enter the “master response” procedure, and the slave, the “slave response” procedure. After some sequences of information exchange, both devices enter the CONNECTION state. We simplify the “sequence of information exchange” and “entrance of the Connection state” as a Connect_timer counting down to zero. The Connect_timer’s initial value is assumed to 8 slots. This value is referred to Part B Figure 10.6 and Part C Figure 4.1 of [1]. After the Connect_timer counts down to zero, the devices go back to the Normal state at the next cycle. Figure 2-8 illustrates the Connecting process.

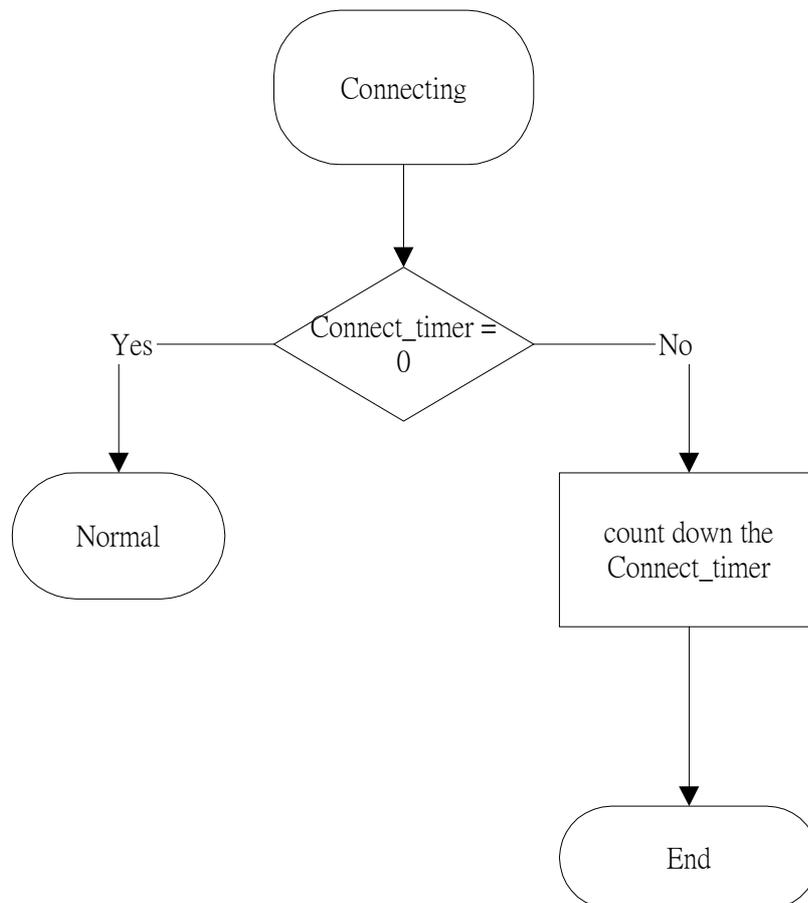


Figure 2-8: Connecting process

Chapter 3 Simulation Results

3.1 Basic Assumptions

We will simulate using four different populations of Bluetooth devices, i.e., 5, 10, 20 and 30. Each device may act as a master or a slave. The role of master or slave can be fixed or dynamically decided by Page and PageScan processes. Each device as a master can admit at most 7 active slaves, and can be the slave of other Bluetooth device. The individual data arrival process is assumed to be Poisson distributed. The packet generated is only one slot in length. The buffer size at the Bluetooth device is either 20 or 40 packets. When the buffer overflows, the next incoming traffic will be blocked. We assume a completely synchronized Baseband, i.e., the time slot of every device is aligned to each other.

Simulation was lasted for 480000 TDD slots (which is equivalent to 5 minutes in duration). We studied the throughputs and queuing delays of two network topologies - fixed and dynamic, and three bandwidth allocation policies for different values of Poisson mean interarrival time (unitted by slots).

3.2 Throughputs of fixed topology network

In Figure 3-1, we simulated the throughput of a piconet consisting of 5 Bluetooth devices that form a piconet of one master and four slaves. The results are listed in Table 3-1.

Figure 3-2 shows the throughputs of a scatternet consisting of 3 piconets corresponding to three bandwidth allocation schemes. Figure 3-3 illustrates its topology, which consists of 10 devices. In Figure 3-2, we observe that the RR-Polling and Combination schemes have similar performances, but the FIFO scheme is actually a little worse in performance. We will interpret the results in Section 3.4.

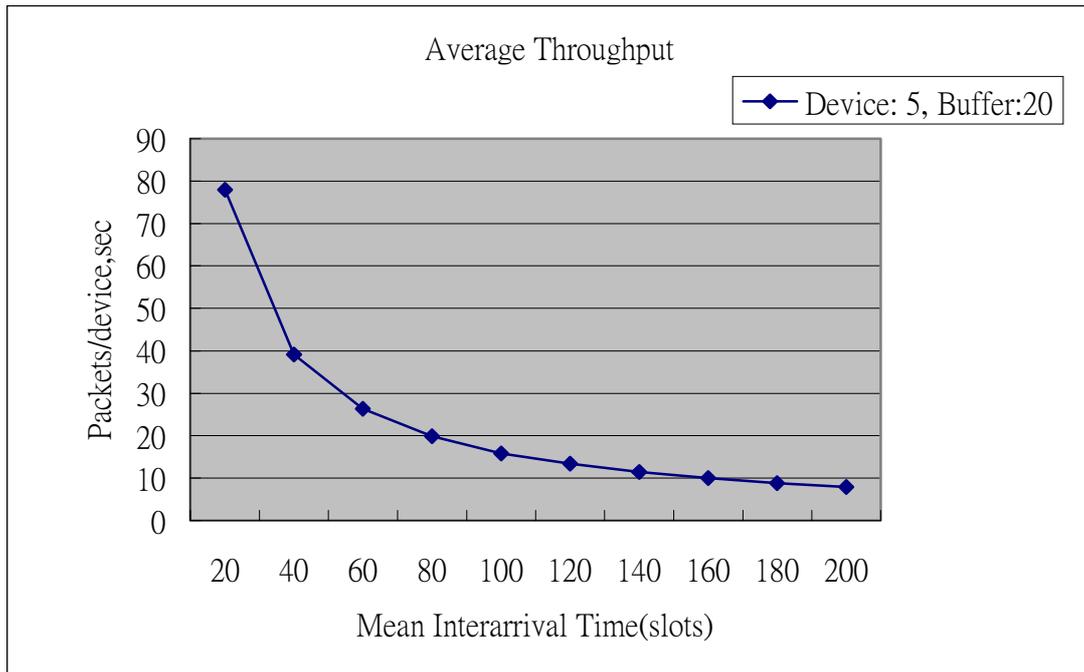


Figure 3-1: Average throughput of a piconet consisting of one mater and four slaves

BT Device	5	Buffer	20							
InterArrival Time	20	40	60	80	100	120	140	160	180	200
Drop Packets	0	0	0	0	0	0	0	0	0	0
Successful Packet	116909	58736	39541	29834	23670	20125	17162	15041	13231	11901
Average Throughput	77.9	39.2	26.4	19.9	15.8	13.4	11.4	10	8.8	7.9
Data Rate (Kb/s)	17.45	8.78	5.91	4.46	3.54	3	2.55	2.24	1.97	1.77

Table 3-1: The collected data of Figure 3-1

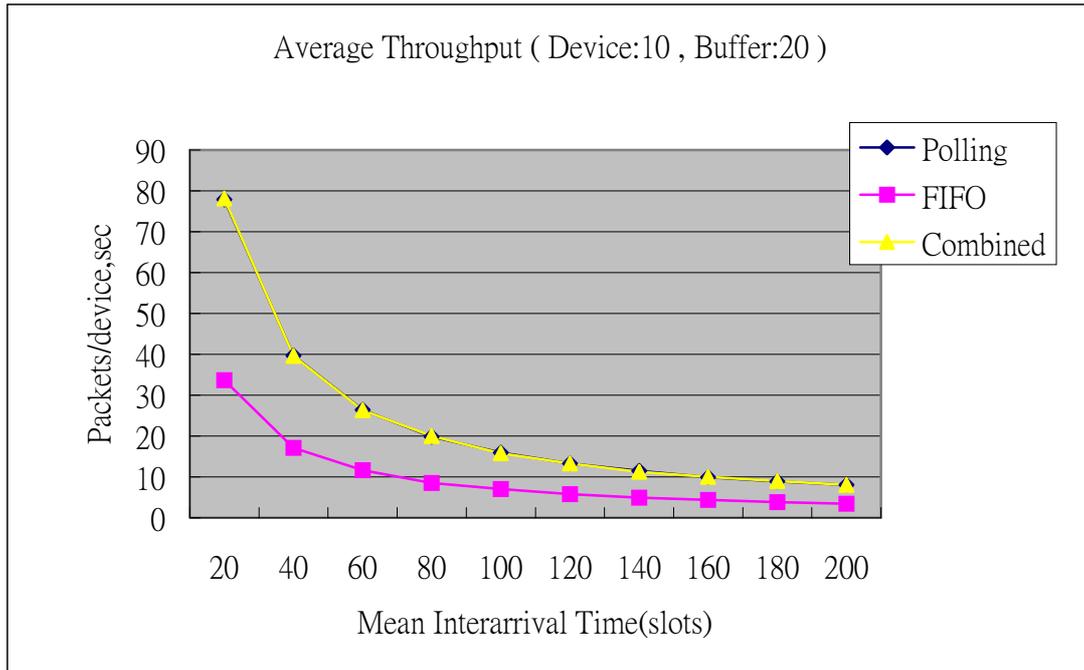


Figure 3-2: Average throughput of a scatternet consisting of 3 overlapping piconets as shown in Figure 3-3

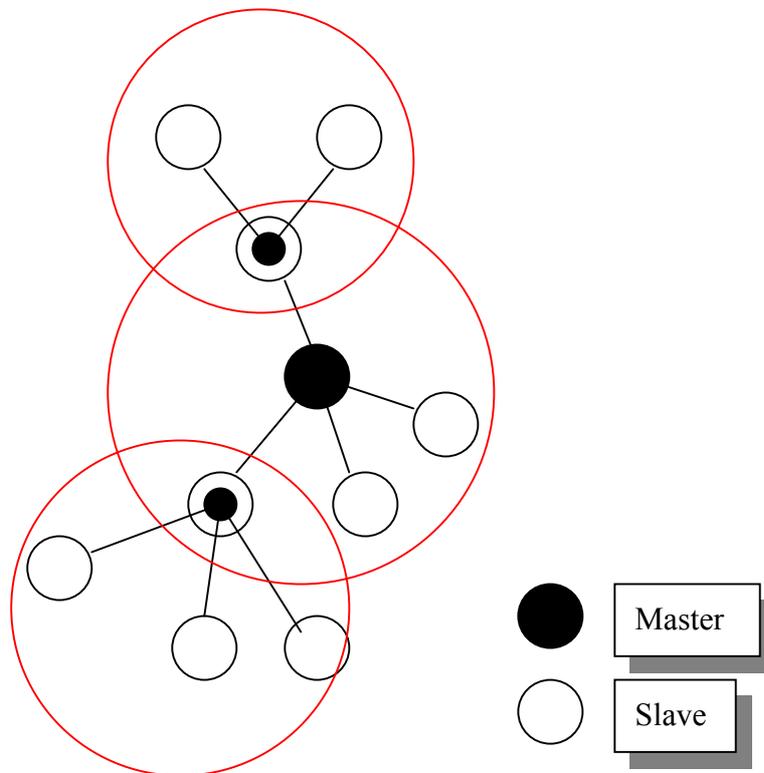


Figure 3-3. Topology of three overlapping piconets.

3.3 Throughputs of dynamic topology network

Figure 3-4 and Figure 3-5 respectively show the throughput and number of dropped packets for a dynamic topology network with different buffer sizes. The Round-Robin Polling bandwidth allocation scheme is used. First, we notice that a dynamic topology network with more than 20 devices exhibits a significant throughput degradation. Specifically, the throughput is only 30 percents of that for a dynamic topology network with 10 devices. The major reason for this phenomenon is due to that the packet destination is uniformly selected from all devices. Therefore, the packets whose destinations are not in the current master or slave list have to stay in the queue until the Page/PageScan processes have built the Baseband link, which could quickly overflow the buffer. This situation becomes worse if the number of devices is raised to 30.

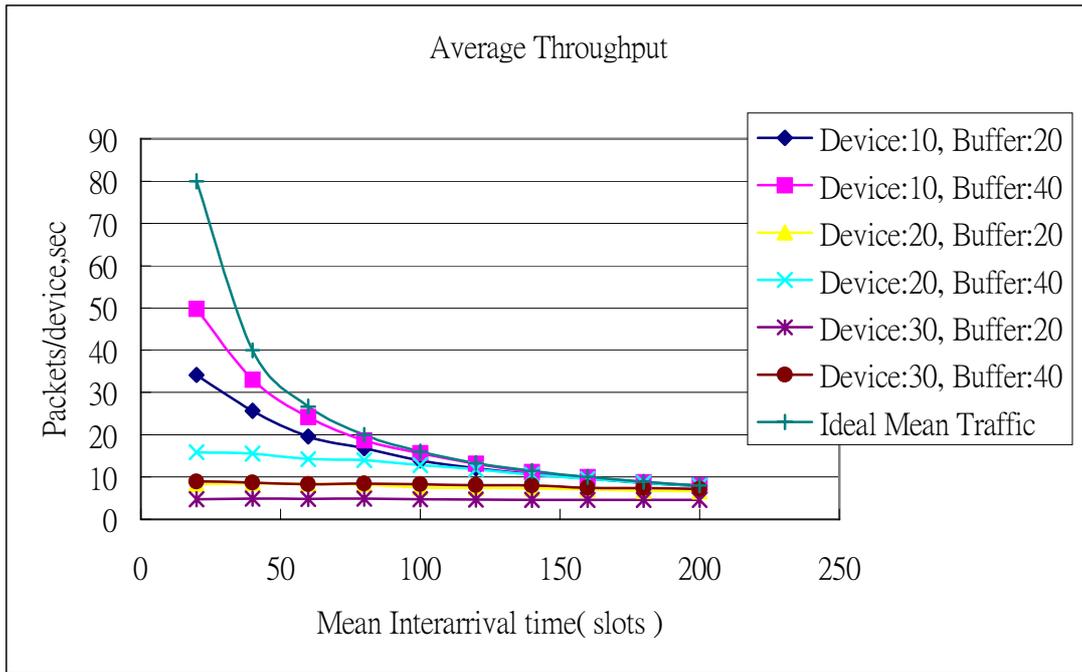


Figure 3-4: Average throughput of dynamic network topology with Round-Robin Polling bandwidth allocation scheme

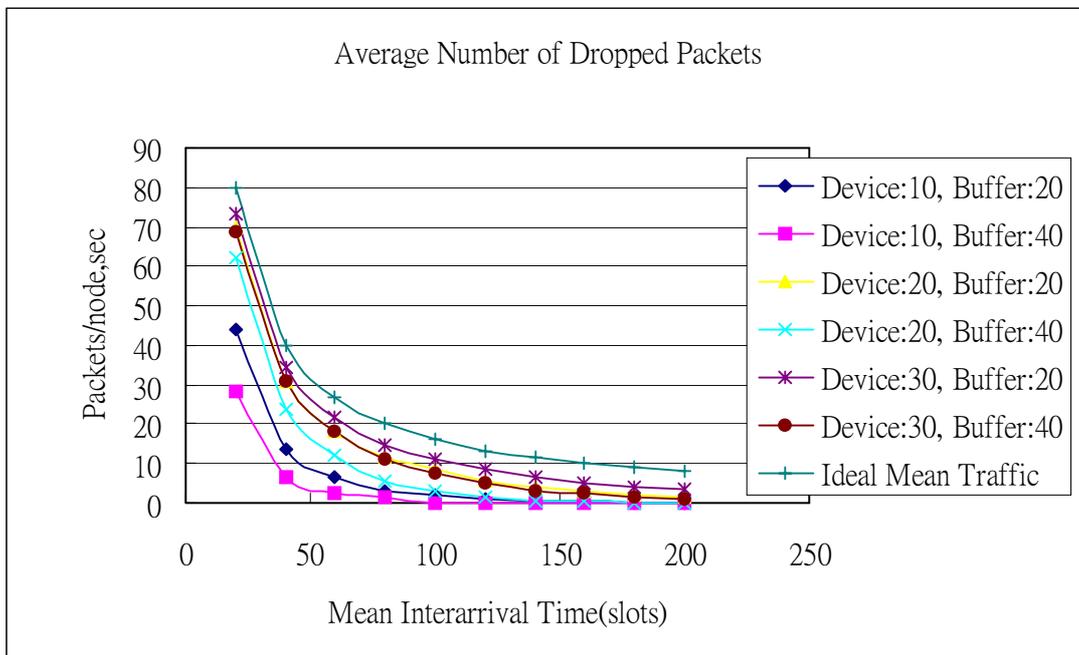


Figure 3-5: Average number of dropped packets of dynamic network topology with Round Robin Polling bandwidth allocation scheme

Figure 3-6 and Figure 3-7 respectively show the throughput and number of dropped packets for different network and buffer size with FIFO bandwidth allocation scheme. Because the network consisting of 30 devices does not provide meaningful reference data, we eliminate their simulation results from these figures. From these figures, the FIFO bandwidth allocation scheme gives a throughput of about 85% as compared to the Round Robin Polling scheme when the traffic load is heavy. This is because the Round Robin Polling scheme will poll all the slaves even if the master does not have packets for some slaves. This will give these slaves the chances to return their traffic to the master. In contrary, the FIFO scheme will poll the slaves only when the master has packets for that slave; the packets queued in the slave may therefore suffer a long delay. So the masters using Round Robin Polling scheme have lower blocking probability, and its throughput is higher than that of the FIFO scheme. Similar to the results in the previous simulations, the network consisting of more than 20 devices has significant throughput degradation, which is almost 30 percent of the throughput for the network with 10 devices.

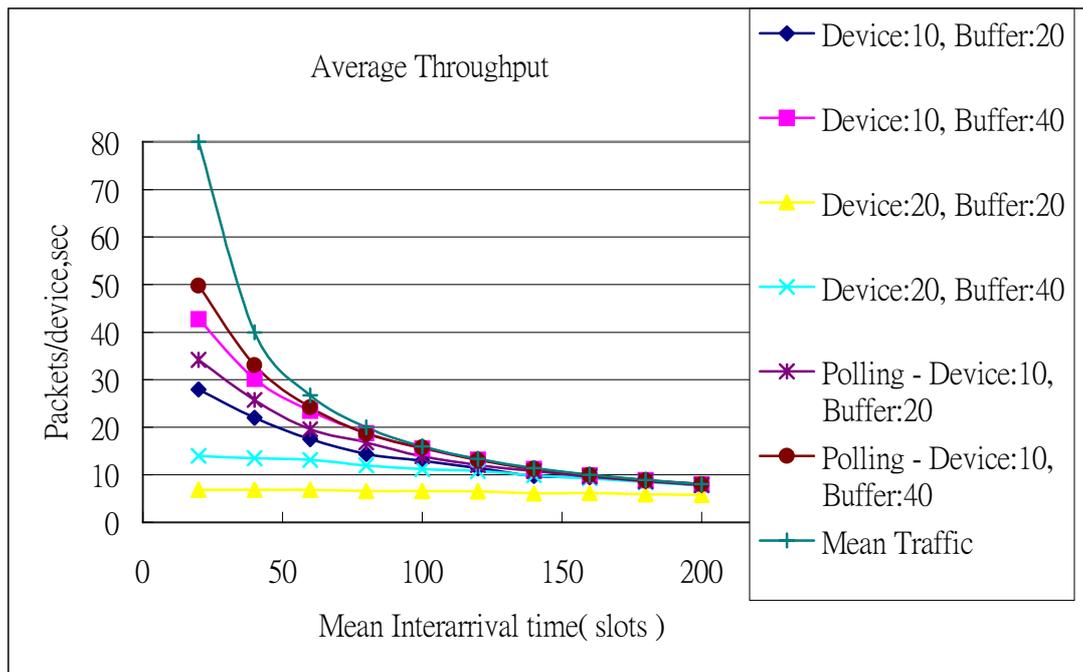


Figure 3-6: Average throughput of dynamic network topology with FIFO bandwidth allocation scheme

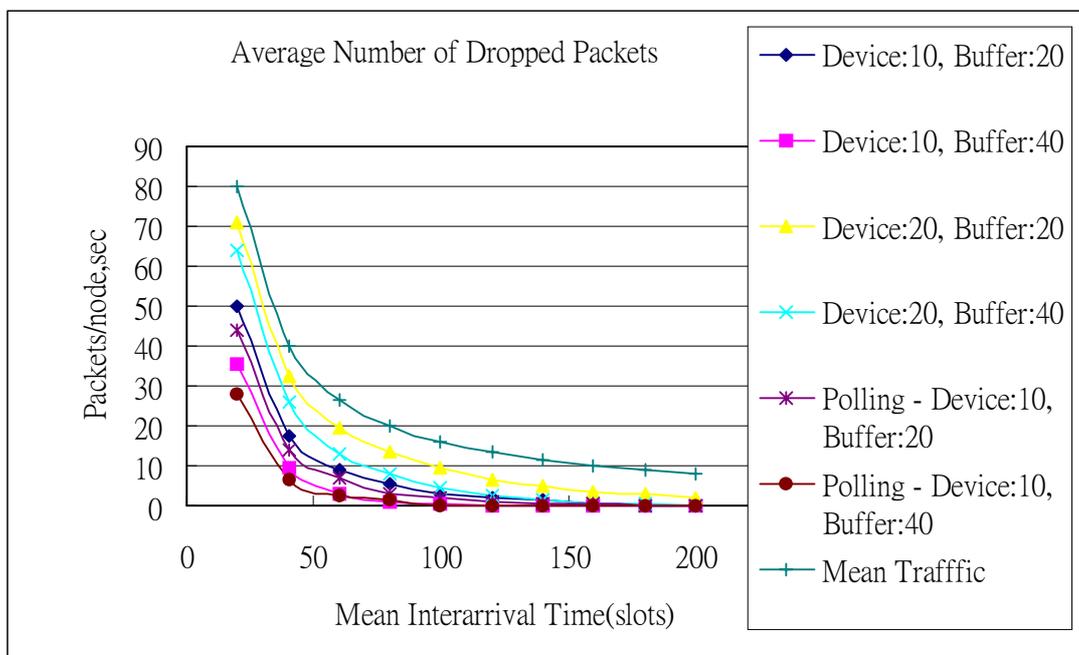


Figure 3-7: Average number of dropped packets of dynamic network topology with FIFO bandwidth allocation scheme

Figure 3-8 and Figure 3-9 respectively show the throughput and the number of dropped packets of different network and buffer size with the combined bandwidth allocation scheme – a combination of Round Robin Polling Scheme and FIFO scheme. The combined scheme gives similar performance as compared to Round Robin Polling scheme. As expected, the Polling part dominates the performance. The reason that the throughput of the combined scheme is a little lower than the Round Robin Polling scheme is actually the same as the one for the throughput of the FIFO scheme being lower than the RR-Polling scheme.

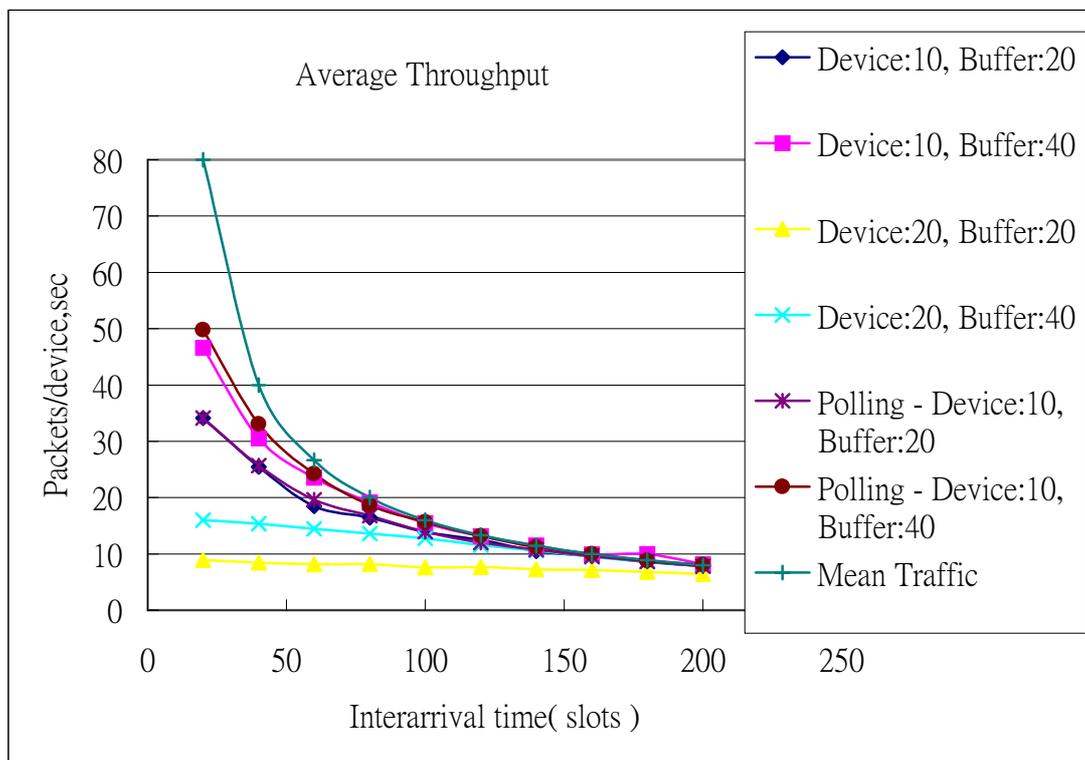


Figure 3-8: Average throughput of dynamic network topology with combination bandwidth allocation scheme

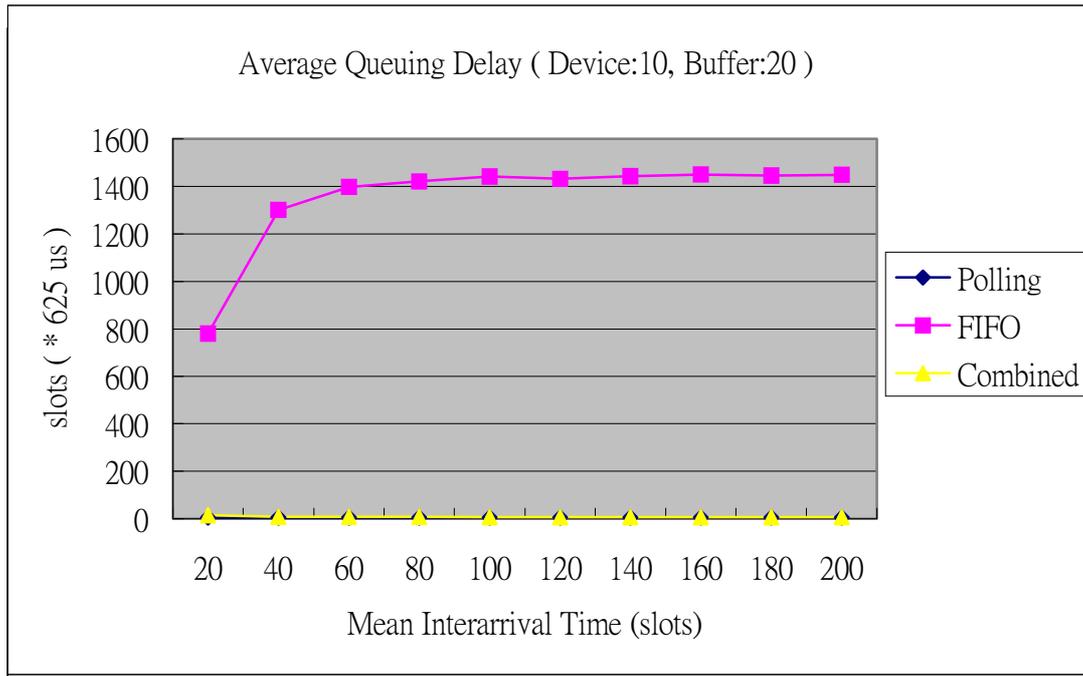


Figure 3-9: Average number of dropped packets of dynamic network topology with combination bandwidth allocation scheme

3.4 Queuing Delay of fixed topology network

In Figure 3-10 we see the average queuing delay performance of a scatternet consisting of 3 piconets with three bandwidth allocation methods. The scatternet topology is illustrated in Figure 3-3. The Polling and Combination methods have the similar low queuing delay, but the FIFO has not. The reason is FIFO is not like Polling fairly treat all slaves, even no suitable packets need to send, the master using Polling still give the chance to polled slaves to send the packet to master. So the packets in the slave FIFO queue may experience higher queuing time.

Figure 3-10: Average queuing delay of fixed scatternet consisting of 10 devices that constitute 3 piconets

3.5 Queuing Delay of dynamic topology network

Figure 3-11 shows the average queuing delay of dynamic topology network consisting of 10 devices, and the buffer of each device is of 20 packets. Due to the reason mentioned above, the FIFO scheme should have the highest queuing delay. Besides, the combined scheme and Round Robin Polling scheme have comparable queue delays.

One may question that why the queuing delay in Figure 3-11 grows as the traffic load decreases. This can be justified below. In our simulation, the distribution of packet destination is uniform, and no timeout mechanism is presumed. Accordingly, the packets whose destinations are not in the current slave or master lists may stay in the queue for quite a long time. Until the destined devices get into the list via Page and PageScan procedures, these packets can then be sent. Theoretically, under the condition of infinite queue, the number of such packets will increase as the traffic load rises, and thus the average queuing delay should be getting higher as load increases. However, in the simulation, the buffer size is fixed, and is relatively small. So when the buffer is full, the packets whose destinations are not in the current master or slave lists are also blocked. As a result, the number of such kind of packets will not increase in proportional to the load (cf. Figure 3-12). Consequently, as the traffic load increases, the large queuing delay of such kind of packets is averaged out by the increasing number of successfully transmitted packets; thus, the average queuing

delay decreases as the load increases.

Figure 3-12 shows the distribution of packet delay time of the scatternet consisting of 10 devices whose buffer size is of 20 packets. The bandwidth allocation scheme is the Round Robin Polling. We can see the proportion of the large-delay-time packets under different loading does not increase with traffic load. Under light load, the proportion of large-delay packets is indeed larger due to the fewer successfully transmitted packets; thus, the average queuing delay becomes higher under light traffic load.

Figure 3-13 shows the average queuing delay of dynamic topology network consisting of 10 devices, and the buffer of each device is of 40 packets. The average queuing delay increases as the traffic load decreases, which meet the interpretation in the previous paragraph.

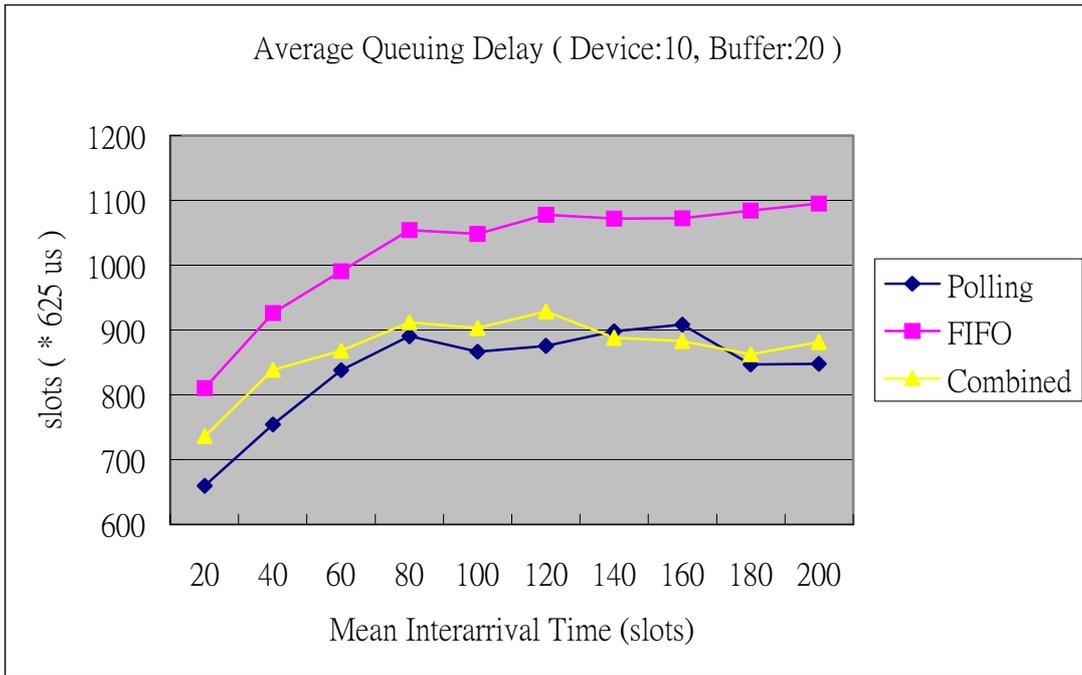


Figure 3-11: Average queuing delay of dynamic scatternet consisting of 10 devices whose buffer size is of 20 packets

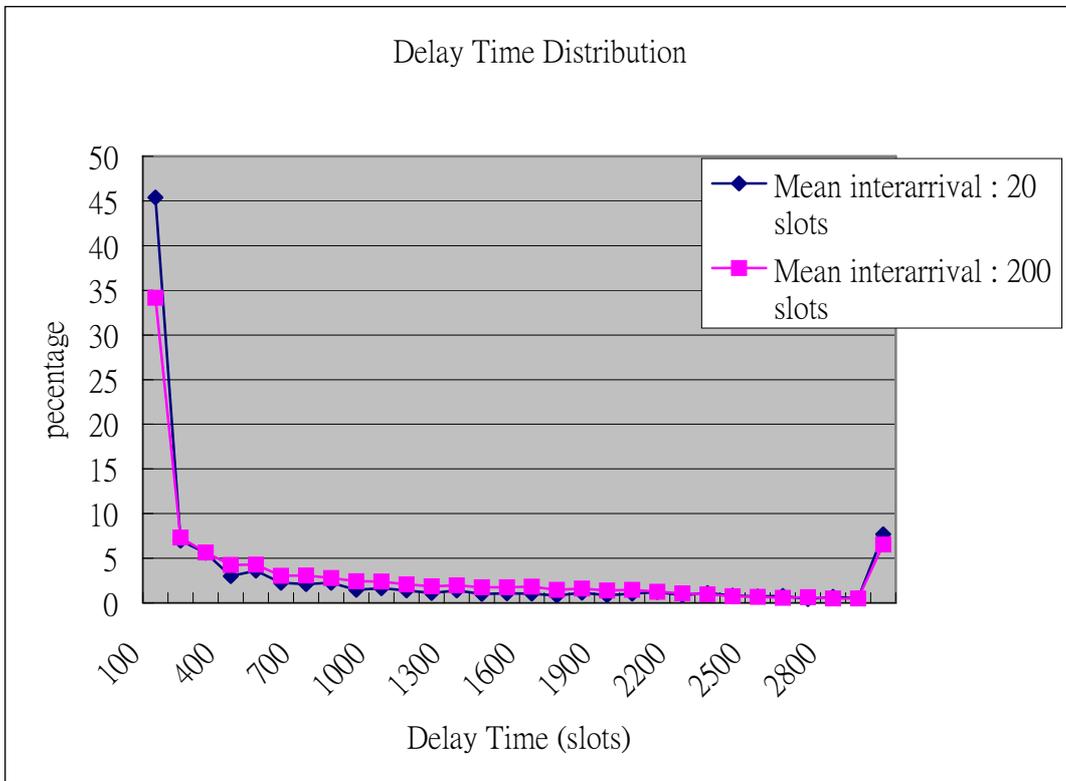


Figure 3-12: The distribution of delay time of the scatternet

consisting of 10 devices whose buffer size is of 20 packets. The bandwidth allocation scheme is Round-Robin Polling

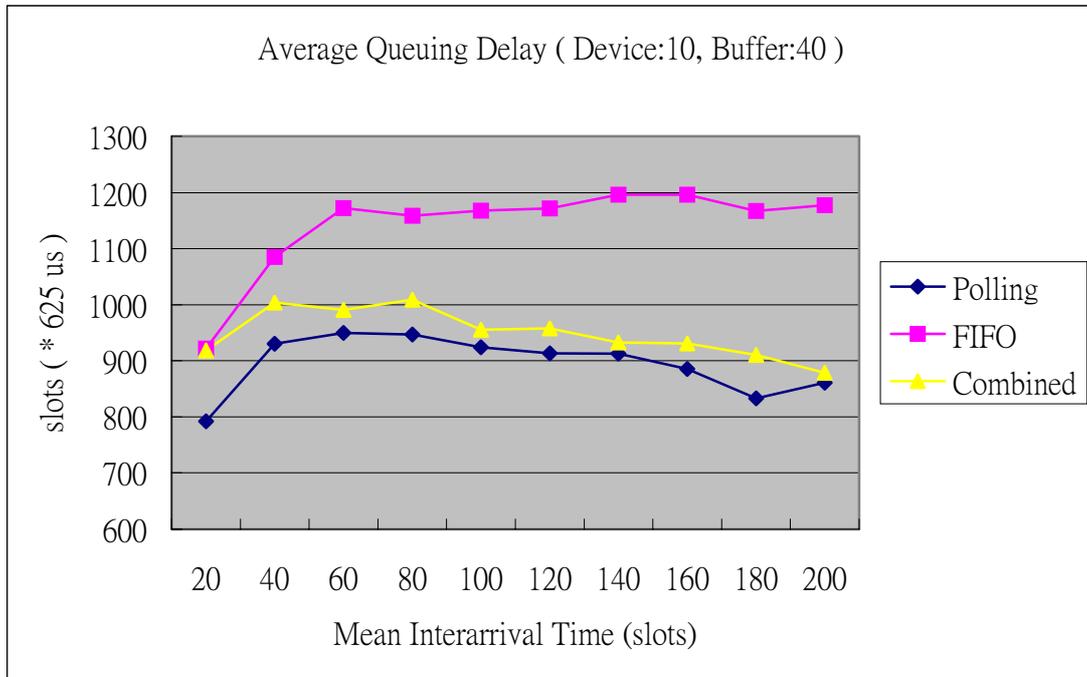


Figure 3-13: Average queuing delay of dynamic scatternet consisting of 10 devices whose buffer size is of 40 packets

Figure 3-14 and Figure 3-15 show the average queuing delays of the scatternet consisting of 20 devices, where the buffer of each device is of 20 and 40 packets, respectively. As compared to Figure 3-11, the queuing delay increases a little more rapidly.

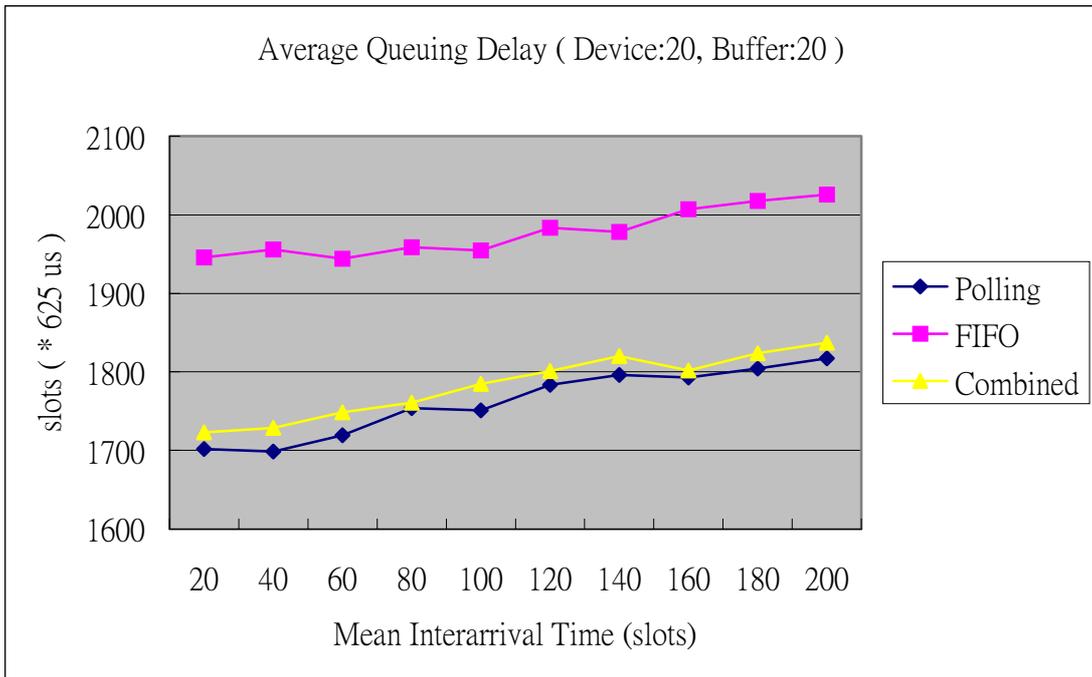


Figure 3-14: Average queuing delay of dynamic scatternet consisting of 20 devices whose buffer size is of 20 packets

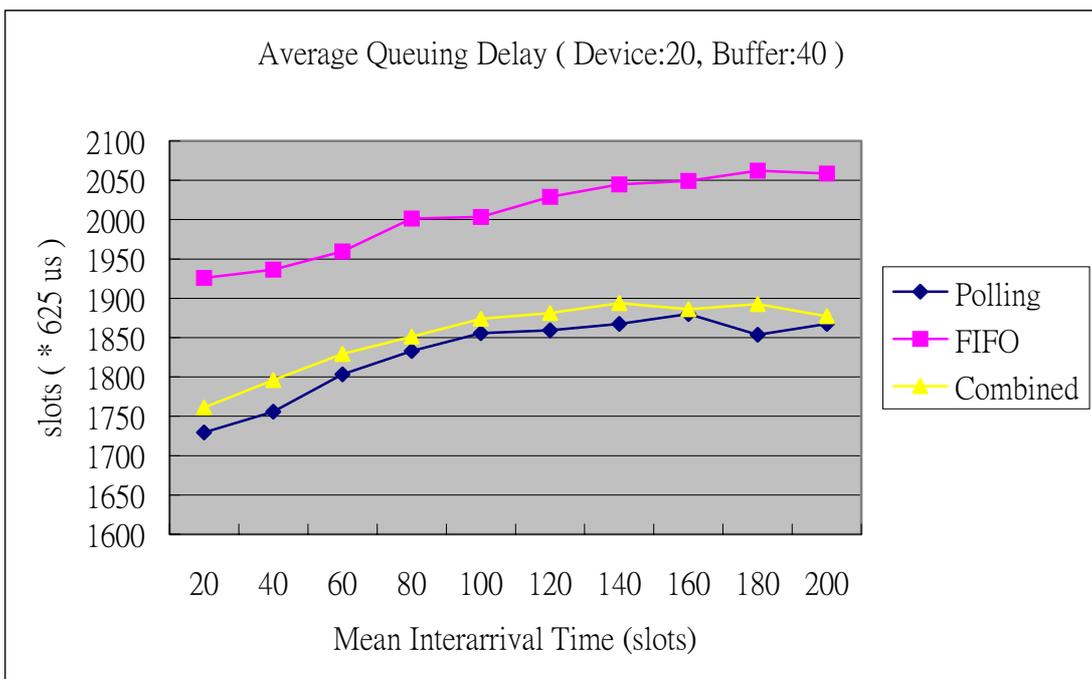


Figure 3-15: Average queuing delay of dynamic scatternet

consisting of 20 devices whose buffer size is of 40 packets

Chapter 4 Conclusions and Future Works

In this thesis, we experiment three kinds of bandwidth allocation schemes. The performance, including average system throughput and queuing delays, of two fixed and three dynamic Bluetooth network topologies with different populations are simulated. We observed that a dynamic scatternet (of large population) has significant performance degradation in throughput and delay. Also, in a dynamic scatternet, the Round Robin Polling scheme has better performance than the other two schemes. Furthermore, the FIFO scheme may cause congestions in the master's buffer, so it may not be a suitable scheme for Bluetooth with dynamic master/slave topology.

In our simulations, we have simplified the Bluetooth architecture, and also made some assumptions, such as the packet is always of single slot in duration. One may re-do the simulations for different packet sizes (multi-slot packets). Besides, different traffic distribution, such as one with long-term dependence, can be used. We also assume that all the devices are completely synchronized, which may not be true in real Bluetooth environment. The asynchronous effect to performance degradation would be an important future work to research on.

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