Adaptive Capacity Management in Bluetooth Networks

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Publication date:
2004

Document Version
Også kaldet Forlagets PDF

Link to publication from Aalborg University

Citation for published version (APA):
Son, L. T. (2004). *Adaptive Capacity Management in Bluetooth Networks*. Aalborg Universitetsforlag.

ADAPTIVE CAPACITY MANAGEMENT
in
BLUETOOTH NETWORKS

A thesis submitted in partial fulfillment of the requirements for the
degree of Doctor of Philosophy in Electronic and Electrical
Engineering

by

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ISBN 87-90664-16-7
Doc. no. D-04-4707
January 2004

This thesis was typeset using LaTeX2ε in `report` document class.

Drawings were made in XFIG.
Graphs were generated in MATLAB™ from The MathWorks Inc.

to all of you who have supported me throughout my life

Abstract

With the Internet and mobile wireless development, accelerated by high-speed and low cost VLSI device evolution, short range wireless communications have become more and more popular, especially Bluetooth. Bluetooth is a new short range radio technology that promises to be very convenient, low power, and low cost mobile ad hoc solution for the global interconnection of all mobile devices.

To implement Bluetooth network as a true mobile ad hoc wireless network operating in short radio range, highly dynamic network environment, low power, and scarce resources, many new research challenges occur, such as limited wireless bandwidth operation, routing, scheduling, network control, etc. Currently Bluetooth specification particularly does not describe in details about how to implement Quality of Service and Resource Management in Bluetooth protocol stacks. These issues become significant, when the number of Bluetooth devices is increasing, a larger-scale ad hoc network, scatternet, is formed, as well as the booming of Internet has demanded for large bandwidth and low delay mobile access. This dissertation is to address the capacity management issues in Bluetooth networks. The main goals of the network capacity management are to increase the network efficiency and throughput, reduce queueing size or delays, increase resilience, stability and fairness among users.

To achieve these objectives, several adaptive distributed approaches have been proposed for dynamic capacity management in Bluetooth networks, including capacity allocation, network traffic control, inter-piconet scheduling, and buffer management. First, after a short presentation about Bluetooth technology, and QoS issues, queueing models and a simulation-based buffer management have been constructed. Then by using analysis and simulation, it shows some issues of the current Bluetooth specification, which lead to the following research to improve Bluetooth performance: Inter-piconet predictive scheduling, adaptive distributed network traffic control and hybrid distributed capacity allocation. These approaches are proposed as heuristic solutions of the convex optimization problem of maximization of the total network flows, and minimization of total cost functions, thus increase the network utilization and efficiency, while still maintaining a certain satisfactory level of Quality of Services. Their operations are distributed, comply with scarce resource constraints in Bluetooth networks and adapt to mobility and frequent changes of the network topology, as well as to bursty traffic of Internet data applications, which are supposedly very common in Bluetooth. Some performance characteristics of these approaches are illustrated by analysis as well as simulations. The results from these research are not only applicable in Bluetooth networks, but it opens many future research on Bluetooth and next generation of mobile communications.

Acknowledgments

This Dissertation would not be possible without the great helps of many people, whom I have received their direct or indirect contributions, their helpful assistances.

First of all, I would like to express my most sincere thanks to my supervisor, Associate Professor Henrik Schiøler and my advisor, Professor Ole Brun Madsen , who have foresight, inspired and encouraged me about research issues, and when I got stuck. Their tireless support, advice, and discussions have helped me a lot in my research. I am also grateful to Associate Professor Anders Svensson and Professor Arne Nilsson at Department of Telecommunication and Signal Processing, Blekinge Institute of Technology, Sweden, for their invaluable helps and advice to this research.

I am grateful to Professor Ramjee Prasad, Research Director, Head of Wireless Networks Division, Aalborg University, and Professor Gordon L. Stüber, Director of Wireless Systems Laboratory (WSL), School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, USA, for their interesting lectures, their kind helps and suggestions during my period at WSL.

My sincere thanks go to Associate Professor Kirsten Mølgaard Nielsen, Head of Department of Control Engineering, Professor Jakob Stoustrup, Associate Professor Jan Helbo and the International Doctoral School, Aalborg University, for their management and financial supports. Thanks are due to Mrs. Karen Drescher and Mrs. Jette Damkjær for their wonderful helps and arrangements before my arrival, and during my period at Aalborg University. I would like to thank to all my colleagues at Department of Control Engineering, for their interesting discussions, and especially Dr. Brian Andersen, Assistant Professor Anders la Cour-Harbo, Michael Melholt Quottrup and Pernille Dahl for their helps on LaTex problems. I am thankful to the computer network administration group, including Henrik Larsen, Ole Jørgensen, Peter Lorenzen Petersen, Aage Nielsson, who have maintained very reliable Sun servers with good compilers and debuggers. Many my computer problems have been quickly fixed by their invaluable supports.

I thank to Associate Professor Erik Ström, Department of Signal and Systems, Chalmers University of Technology, for his helpful advice. Special thanks to my friends and colleagues at Department of Telecommunication and Signal Processing (ITS), Blekinge Institute of Technology, including Associate Professor Jan-Olof Gustavsson, for his kind helps and supports, Dr. Ajit K. Jena and Associate Professor Adrian Popescu for their kind helps and advice on my research as well as computer problems, Dr. Sven-Olof Larsson for discussion about ATM research, Associate Professor Marcus Fiedler for his courses, my colleagues Henric Johnson, Patrik Carlsson, Madeleine Jarlten, Lena Magnusson for their kind helps, and many other people at ITS.

I am grateful to my colleagues at WSL lab, Georgia Tech, who helped me a lot during my period at WSL, who worked with me through days, nights, Christmas, New Year, without breaks: Apurva Mody, Loral Iapunov, Galib Asadullah, Jun Tan, Qing Zhao, Joon Beom Kim, Wajih Abu-Al-Saud, and many others.

I thank to Professor Ulf Körner, Techn. Lic. Niklas Johansson, Department of Communication Systems, Lund Institute of Technology, for their useful document about Bluetooth. The explanations which I received from Professor Frank P. Kelly and Dr. Richard J. Gibbens of Statistics Lab are grateful appreciated.

I thank to Vietnamese friends, who are working or studying in Aalborg, Copenhagen, Denmark and many other countries. They have helped and encouraged me throughout my research.

Last but not the least, I would like to convey my special thanks to my parent and siblings, who have come a long with me through difficult moments, who always encourage me and give me advice for many issues.

October 2003, Aalborg, Denmark

Le Thanh Son

Synopsis

Med udviklingen indenfor internet og trådløs mobil kommunikation, fremskyndet af udviklingen indenfor VLSI teknologi mod højere hastighed og lavere omkostninger, er kortdistance trådløs kommunikation blevet mere og mere udbredt. Særligt Bluetooth, der er en ny kortrækkende radio teknologi, forventes at være meget praktisk anvendelig på grund af mindre kapacitet, færre trådløse omkostninger samt ad hoc løsninger til globale forbindelser endda til alle mobile apparater.

Implementation af Bluetooth netværk som egentlige mobil ad hoc trådløse datanet i et højt dynamisk netværksmiljø med lav kapacitet, kort rækkevidde og knappe ressourcer står over for en række tekniske udfordringer, såsom begrænset trådløs båndbredde, routing, schedulering, netværkskontrol ect. Endnu har - i særdeleshed - Bluetooth specifikationen ikke beskrevet detaljeret hvordan 'Quality of Service of Bluetooth Management' for Bluetooth protokol skal implementeres. Disse detaljer bliver betydningsfulde, når antallet af Bluetooth enheder er stigende, og i større målestok ad hoc netværk baseret på Bluetooth scatternet er formet. Ligeledes har internet-opsvinget krævet omfattende båndbredde og mindre forsinkelser for mobil adgang.

Denne afhandling tager fat på spørgsmålet om kapacitetsstyring i Bluetooth datanet. De vigtigste mål for netværkets kapacitetsstyring er, at forøge netværkseffektivitet og throughput, samt reducere kødannelser eller forsinkelser, forøge robusthed, stabilitet og tilfredshed blandt brugerne.

For at opnå/udføre disse mål, har adskillige fremgangsmåder om tilpasningsevne været foreslået for dynamisk kapacitetsstyring i Bluetooth netværker herunder også kapacitetstildeling, netværk trafikkontrol, inter-piconet schedulering, og buffersstyring. Først, efter en kort præsentation om Bluetooth teknologi og QoSs udfald, dannelsemønster 'queueing models' og en simulation-basserede bufferstyring har været konstrueret. Derefter ved brug af analyse og simulation, stilles det nogle spørgsmål for den aktuelle Bluetooth specifikation, som fører til efterfølgende undersøgelser for at forbedre gennemførelsen af Bluetooth: Inter-piconet, schedulering, tilpasningsevne distribueret netværk trafikkontrol og hybrid distribueret kapacitetstildeling. Disse fremgangsmåder er udført ligesom en heuristisk løsning af konveks optimering, optimering af netvær-

kets flows samt minimering af total omkostningsfunktioner. Således vil det forøge udnyttelsen af netværket, mens det stadig vedligeholder et vis tilfredsstillende niveau af ’Quality of Services’. Deres funktioner er distribueret og sjælden retter sig efter begrænsninger i Bluetooth netværker og tilpasse sig til bevægelighed og hyppige netværksforandringer topologi. Ligeledes sprænger det internet trafik applikationer, som formodentligt er meget almindeligt for Bluetooth. Nogle af de karakteristiske træk af disse fremgangsmåder er illustreret med analyser såvel som simuleringer. Resultater fra disse undersøgelser er ikke kun anvendelige for Bluetooth netværker, men åbner også muligheder for næste generation af mobile kommunikationer.

Contents

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List of Abbreviations

2G	Second Generation of Mobile Communication
3G	Third Generation of Mobile Communication
ACK	Acknowledgement
ACL	Asynchronous Connectionless Link
AFP	Adaptive Flow based Polling
AM_ADDR	Active Member Address
AMPS	Advanced Mobile Phone System
AODV	Ad hoc On-demand Distance Vector Routing
ARQ	Automatic Repeat reQuest
AVQ	Adaptive Virtual Queue
BD_ADDR	Bluetooth Device Address
BNEP	Bluetooth Network Encapsulation Protocol
BSC	Base Station Controller
BTCP	Bluetooth Topology Construction Protocol
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
DICA	Distributed Iterative Capacity Allocation
DiffServ	Differentiate Service

DSR	Dynamic Source Routing
DSSA	Distributed Scatternet Scheduling Algorithm
ECN	Explicit Congestion Notification
EDGE	Enhanced Data Rate for Global Evolution
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FEP	Fair Exhaustive Polling
FHSS	Frequency Hopping Spread Spectrum
GFSK	Gaussian Frequency Shift Keying
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
HCI	Host Controller Interface
HDICA	Hybrid Distributed Iterative Capacity Allocation
HLR	Home Location Register
HSCSD	High Speed Circuit Switched Data
IBP	Interrupted Bernoulli Process
IP	Internet Protocol
ISM	Industrial - Scientific - Medicine
L2CAP	Logical Link Control and Adaptation Protocol
LAP	Lower Address Part
LB	Leaky Bucket
LMP	Link Management Protocol
LWRR	Limited and Weighted Round Robin
MAC	Media Access Control
MBAC	Measurement Based Admission Control

MDRP	Maximum Distance Rendezvous Point
MP	Maximum Priority
MPR	Multipoint Relay
MSC	Mobile Switching Center
NAP	Non-significant Address Part
OLSR	Optimized Link State Routing Protocol
PAN	Personal Area Network
PCSS	Pseudo Random Coordinated Scheduling Algorithm
PFP	Predictive Fair Polling
PPP	Point to Point Protocol
QoS	Quality of Service
RED	Random Early Discard
SCAB	Scatternet Capacity Assignment Algorithm for Bipartite Graph
SCO	Synchronous Connection Oriented Link
SDP	Service Discovery Protocol
SIG	Special Industry Group
StickyAFP	Sticky Adaptive Flow based polling
TCP	Transport Control Protocol
TD-CDMA	Time Division - Code Division Multiple Access
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TSF	Tree Scatternet Formation
UAP	Upper Address Part
UMTS	Universal Mobile Telephone System
VQ	Virtual Queue

WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

Chapter 1

Introduction

1.1 Evolution of Wireless communications

The ability to access of information and data from anywhere and at anytime has been historically ultimate desire of mankind civilization. The recent years have seen a rapid development of wireless mobile communications. Advances in high speed micro-electronics, which have helped to reduce the sizes and costs of mobile devices and progress in radio communications multiple access schemes, and coding algorithms brought the practical meaning of mobile communications for personal users. They also opened the new era of personal mobile communication. Mobile communication has enjoyed a huge popularity and mobile devices have become to available to a large segment of the population, with a wide range of applications. Wireless communications have evolved from the early 1980s strongly with the large scale deployment of analog cellular telephone systems, e.g AMPS (Advanced Mobile Phone System) [77] by US mobile operators.

The second generation ($2G$) [21] [100] of mobile communications, which began in about mid 1980s, is the first digital mobile communication. Both rather reliable voice and data services are supported in 2G mobile communication. The most common systems of 2G are GSM (Global System for Mobile Communications), which is based on TDMA for radio access (Time Division Multiple Access) and cdmaOne, which is based on narrowband CDMA radio access (Code Division Multiple Access).

The GSM allows up to 8 users to share a single 200 kHz channel by using TDMA based time slot allocation. The system operates in 900 and 1800 MHz frequency bands, and its architecture is an open architecture, which is very advantageous for both mobile manufacturers and operators. The interfaces are used for communicating between network elements such as Base Station Controller (BSC), Mobile Switching Center (MSC), or Home Location Register (HLR), etc. Although having been extremely successful, the GSM contains some limitations, especially constrained 9.6 kbps data transmission speed.

A spread spectrum technology, Direct Sequence Code Division Multiple Access (DS-CDMA), has been employed in the cdmaOne. In CDMA, many users share the same channel. Each user has its own pseudo random code, which is used to separate the user traffic at the receiver. Like the GSM, the initial cdmaOne (IS-95A) offers throughput limited data traffic.

The booming of the Internet demands data services with higher data communication bandwidths in Mobile Networks. Some improvements of the current 2G mobile services have been carried out. These led to the standardizations of 2.5G mobile communications: High Speed Circuit Switched Data (HSCSD), General Packet Radio Service (GPRS) with its enhanced version Enhanced Data Rate for Global Evolution (EDGE), and IS-95B CDMA.

The popularity of mobile Internet is followed by the needs of large bandwidths, higher bit rate, new frequency spectrum, and new multimedia services. These requirements force the development of the successive generation of mobile communication, which is called $3G$, including the state-of-the-art Universal Mobile Telephone System (UMTS) and the cdma2000 [97].

The UMTS includes two variances: Wideband CDMA (WCDMA), and TD-CDMA (Time Division CDMA). The WCDMA uses frequency division duplex mode (FDD) with 5 MHz channel bandwidth. The TD-CDMA employs time division duplex mode (TDD) with 1.6 MHz carrier spacing. The initial deployment of UMTS can support data rate up to 2 Mbps. Several versions of cdma2000 can provide currently up to 2.4 Mbps downlink.

In parallel to the development of the cellular mobile services, the Wireless Personal Area Network (WPAN) and Wireless Local Area Network (WLAN) have been extensively developed to provide high speed wireless Internet access services to hot spots, such as at conference rooms, or at airports. Although both of these technologies have the same target, which is to serve the users with lower mobility compared to the cellular mobile services, the WPAN (such as Bluetooth) is distinguished from the WLAN by its smaller coverage area or network capacity, as can be seen in figure 1.1 [14], lower power levels, control mechanisms, and its ad hoc styled topology. Because of this ad hoc mode, it does not require base stations for spontaneous communication between devices as cellular mobile systems, it means a connection made through a WPAN involves little or no infrastructure or direct connectivity to networks outside the link. However, the combination of cellular network and WPAN can increase the stability of radio transmission, the mobility and the radio coverage [61].

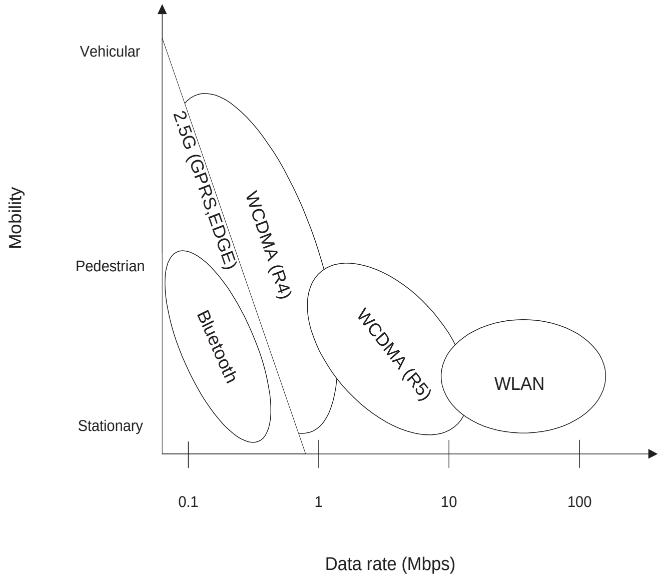


Figure 1.1: Data rate vs. mobility [14]

1.2 Wireless Personal Area Network and Bluetooth

WPAN is a new concept for wireless short range communication, which uses RF technologies close to those of WLAN. WPAN, which is characterized by innovative ideas of simple, low cost, low power, flexible mobile communication, is becoming very popular in providing mobile Internet data access from cell-phones, PDA, notebooks, which have very limited power resources. Because of its multimode ad hoc styled operation, it can enable many kinds of devices to be connected without prior configuration processes as required in WLAN. It is supposed to coexist with WLAN. The main advantages of WPAN are self-creation, self-organization and self-administration. There is no need of infrastructure, because it allows users to dynamically form a private network. Only the interactions among the wireless devices are used to provide the necessary control and administration functions supporting the network. Each node in WPAN acts both as host and routers for other nodes in the network. This ad hoc mode can increase coverage, and lower power consumption compared to WLAN. The communication of mobile devices within a WPAN or between WPANs are seamless with many possible applications, such as sensors, PDAs, handheld computers, home devices, etc. Because these systems use unlicensed radio spectrum and less expensive hardware devices, they can offer mobile communication at very low cost and low power.

The current research within WPAN is extensively related to Bluetooth [73][17]. Bluetooth is a new low cost and lower power wireless short range communication, which enables users to connect to a wide range of computing and telecommunication devices easily and simply, without having a cable. It operates in the 2.4 GHz Industrial-Scientific-Medicine (ISM) band. Its radio link uses fast acknowledgment and frequency hopping scheme to reduce the impacts of interferences from other noise sources, which use the same frequency band. The topology of Bluetooth is a true mobile ad hoc network. Thus it has self-reconfiguration capability to adapt to constantly changing users and resources.

The devices in Bluetooth networks are organized into piconets. In each piconet one device will act as master for the control and synchronization purposes, and the others as slaves. Two or more piconets can communicate with each other to create a true mobile ad hoc network, scatternet. Both voice and data services are supported in Bluetooth.

1.3 Research Objectives

Since Bluetooth offers unique benefits and versatility for certain applications in certain environments, there are rapidly increasing interests of Bluetooth, both in research and application aspects. The growing importance of Bluetooth based wireless short range communication and of the Internet makes higher demands for mobile data services over Bluetooth networks. Numerous research challenges must be overcome to exploit the full potential of Bluetooth networks. These include capacity management issues. From the fact that the Bluetooth networks, especially scatternet, is true mobile ad hoc network with various constraints, for example scarce resources and capacity, mobility, etc., the capacity management over Bluetooth networks is quite complicated and related to many aspects, such as Quality of Services (QoSs), resource management, and protocols [10].

Thus in this dissertation, I try to address some research challenges of the capacity management issues in the Bluetooth data network environment, which cover from capacity allocations, network traffic control, inter-piconet scheduling to buffer management. Although there are still many works requested for further research, the research from this thesis could be understood as an initial step to the future research on the fourth-generation, $4G$, of mobile communications [5], which supposedly allows high speed ultra wideband wireless access.

To provide some background knowledge about Bluetooth, the thesis begins with some brief descriptions about Bluetooth Technology in **CHAPTER** 2. The basics on radio, baseband, protocol stack and some advancements of Bluetooth Technology also are presented.

In **CHAPTER** 3, which is re-edited from the paper [89]:

- Le Thanh Son and Anders Svensson, "Buffer Dimensioning in Bluetooth Networks", in Proceedings of the Nordic Radio Symposium 2001 Conference on Towards 4G and Future Mobile Internet, Nynashamn, Sweden, April 2001

In this paper, queueing models of Bluetooth networks are considered with some scenarios, following by descriptions of QoSs in Bluetooth. The Bluetooth application model is presented. A buffer dimensioning method, which uses the application model, is proposed. The performance of the method is studied by simulations with bursty traffic.

CHAPTER 4 is the extended version of the paper [57]:

- Le Thanh Son, Henrik Schiøler and Ole Brun Madsen "Predictive scheduling approach in Inter-piconet Communications", in Proceedings of the 4th international symposium on Wireless Personal Multimedia Communications, Aalborg, Denmark, Sep 2001

features the inter-piconet communication issues in Bluetooth scatternet. Some backgrounds of the inter-piconet scheduling are mentioned. The inter-piconet scheduling optimization problem is formulated. A predictive inter-piconet scheduling approach is proposed as a heuristic solution of the inter-piconet scheduling optimization problem, which uses low power mode operation of Bluetooth and information on predicted inter-piconet traffic, the QoS requirements to increase efficiency of the network capacity. The performance of the proposed predictive inter-piconet scheduling is evaluated by simulations.

CHAPTER 5, which is rewritten from the papers [85, 86, 84]:

- Le Thanh Son, Henrik Schiøler, Ole Brun Madsen and Du Dinh Vien "A Network Traffic Control Enhancement Approach over Bluetooth Networks", in Proceedings of the 3rd IASTED International Conference on Wireless and Optical Communications (WOC2003), Banff, Alberta, Canada, July 2003
- Le Thanh Son, Henrik Schiøler and Ole Brun Madsen " A Distributed Admission Approach based on Marking Mechanism over Bluetooth Best-effort Network", in Proceedings of the Radio Communications Science and Technology, RVK2002, Stockholm, Sweden, June 2002
- Le Thanh Son, Henrik Schiøler and Ole Brun Madsen "An adaptive distributed admission approach in Bluetooth networks with QoS provisions", in Proceedings of the CATA 2002 international conference, San Francisco, California, USA, April 2002

The chapter considers the network traffic control issues in Bluetooth. Some problems concerning QoSs and the network traffic controls in current Bluetooth specification are highlighted. A Bluetooth network model and a modified distributed marking scheme based on virtual queue are analyzed. A capacity optimization problem of maximization of network utilization and minimization of price expressed in mark packets is formulated. An adaptive distributed traffic control approach provisioning QoS in Bluetooth networks is proposed as an heuristic solution of the formulated optimization problem. The approach uses the modified distributed marking scheme to increase the total network flows and to provide a certain level of QoSs and satisfy the Bluetooth network constraints. The simulations are carried out to illustrate its performance. Some approaches are discussed to improve the network performance.

CHAPTER 6, which is rewritten from the papers [87, 88]:

- Le Thanh Son, Henrik Schiøler and Ole Brun Madsen "An Efficient Approach to Enhance Capacity Allocation over Bluetooth Networks", in Proceedings of the IASTED International Conference on Communications and Computer Networks (CCN2002), Cambridge , USA, November 2002
- Le Thanh Son, Henrik Schiøler and Ole Brun Madsen "Hybrid Distributed Iterative Capacity Allocation over Bluetooth Networks", in Proceedings of the 8th IEEE International Conference on Communication Systems (ICCS2002), Singapore, November 2002

presents the capacity allocation issue of the Bluetooth networks. The capacity allocation problem is formulated as a convex optimization problem of maximizing network flows and minimizing cost functions representing for QoSs requirements, and it should satisfy the constraints of Bluetooth network. A hybrid distributed iterative capacity allocation approach is proposed as its approximated solution. The evaluation and simulations illustrate the working ability of the approach. Some improvements of the approaches are suggested, and some open issues are discussed.

CHAPTER 7 is devoted to conclusions and future developments. It includes a short summary and extent comments of the studies in this thesis. Some directions for research and developments in future are also described.

The significant contributions of this work to are summarized as follows:

- The study on capacity management issues in Bluetooth networks
- Formulate capacity allocation problem in Bluetooth networks as a convex optimization problem
- Develop a hybrid distributed iterative capacity allocation approach in Bluetooth networks, and some suggestions for improving the proposed approach
- Study on network traffic control issues and formulate the optimization problem of the network traffic control in Bluetooth
- Develop an adaptive distributed network traffic control approach in Bluetooth as a heuristic solution of the optimization problem, which uses the modified distributed

marking scheme, information on real-time network traffic status and prediction to adaptively improve the network performance

- Study on inter-piconet communication issues, inter-piconet scheduling optimization problem and feasible schedule solution of bridge node in Bluetooth scatternet
- Develop a predictive inter-piconet scheduling approach to increase the network capacity efficiency
- Study on issues of queueing and QoSs in Bluetooth networks
- Develop a method for transient buffer dimensioning in Bluetooth networks and construct the Bluetooth application model
- Study on the effect of bursty data traffic, which is similar to the internet traffic, on Bluetooth network performance.
- Discuss some open issues in Bluetooth networks, and suggest directions for applying the mobile ad hoc routing algorithms, dynamic network formations and resource managements
- Analysis on priority queuing in Bluetooth
- Study on inter-piconet scheduler and the requirements of the scheduling

Chapter 2

Bluetooth Technology

2.1 Bluetooth History

The Bluetooth wireless technology is designed as a wireless short-range connectivity solution for personal, portable, and handheld electronic devices. Unlike Wireless LAN, it enables to users to connect a wide range of computing and mobile devices easily and simply, without having additional cables or prior setting up network parameters. Bluetooth does not require the light-of-sight connection as in the infrared solution. Bluetooth history began when a Swedish telecommunication company, LM Ericsson, who realized the potential of global short-range wireless communications, initiated Bluetooth wireless technology. In 1994, the project had been begun with feasible study of low cost and low power radio interface to connect mobile phones and their accessories. In winter 1998, leading companies in computing and telecommunication industries formed Bluetooth Special Industry Group (SIG) [28] to develop and promote a global solution for short-range wireless communication operating in the unlicensed 2.4 GHz ISM (Industrial, Scientific, Medical) band. The founding companies of SIG are Ericsson, Intel, IBM, Nokia and Toshiba. These companies formed the original core group of the Bluetooth SIG.

The name Bluetooth comes from the Danish king Harald Blåtand (Bluetooth) who ruled from approximately A.D. 940 to 985. During his reign King Harald is reported to have united Denmark and Norway and to have brought Christianity to Scandinavia. For a technology with its origin in Scandinavia, it seemed appropriate to the SIG founders to name the organization that was intended to unify multinational companies after a Scandinavian king who united countries [67].

To facilitate the wide acceptance of this new technology, the SIG decided to offer all intellectual property explicitly included in the Bluetooth specification royalty-free to adopter members of the technology when it is used to introduce Bluetooth products in the market. This fundamental objective of Bluetooth SIG is to sell more the members' and adopted members' products, and the users can choose wide range of Bluetooth products from many suppliers. Although open standard can be quite advantageous, for example inter-operable, cross-platform hardware and software implementation for all kind of devices, the Bluetooth SIG founders understood that one potential disadvantage of standards bodies, special interest groups and similar organizations is that they tend toward inherent inefficiencies as compared to single company effort. To overcome some of these potential drawbacks and to avoid incompatible issues of products from various manufacturers, which occurred at initial development stage of WLAN, the Bluetooth SIG intentionally was created with small number of companies committed to the rapid development of specification, who were willing to expend the resource necessary to accomplish this [7]. The SIG is dependent on contributions from its members, and organized itself into working groups such as the air interface working groups, the software working group, the interoperability working group, the compliance working group, etc..

The Bluetooth SIG announced its existence and intentions to the public in May 1998. As the specification evolved and awareness of technology and the Bluetooth SIG increased, many other companies joined the Bluetooth SIG as adopters. Today there are more than 3000 adopter members. In summer of 1999, the Bluetooth specification version 1.0A became publicly available.

In March 1999, the IEEE 802.15 was created to develop a family of communication standards for wireless personal area networks (WPAN) and Bluetooth was accepted as candidate for IEEE 802.15.1. The Bluetooth proposal was chosen to serve as the baseline of the 802.15.1 standard [96].

2.2 Bluetooth protocol stack

The dominant innovation concept of Bluetooth technology defined by Bluetooth founding members is to provide a universal communication to mobile devices, which connect to data networks, peripheral devices as well as small ad hoc networks in simple fashion and without prior setting up process. To solve these problems and requirements, the SIG has developed the Bluetooth specification [28] that allows for developing interactive services and applications over inter-operable radio modules and data communication protocols. The Bluetooth specification consists of two different parts: core and profiles. These will be briefly described below:

2.2.1 Core Specification

The core specification defines the different layers in the Bluetooth protocol stack, which is shown in figure 2.1 [7]. The protocol stack has been grouped in two categories: the

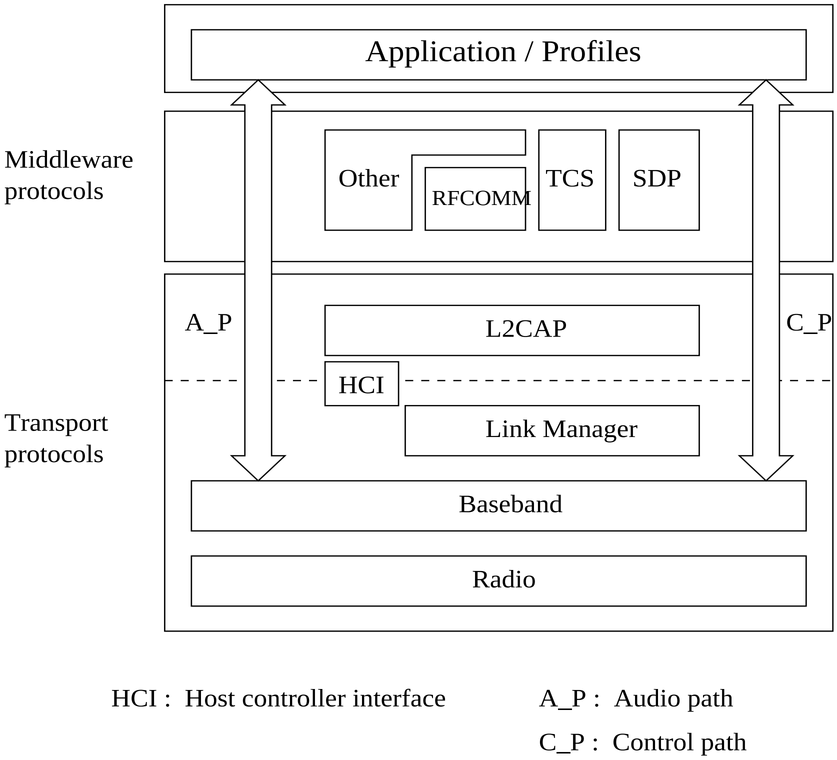


Figure 2.1: The Bluetooth protocol stack [7]

transport and the ***middleware*** protocols. The transport protocols comprise protocols developed exclusively for the Bluetooth wireless technology. The function of the protocols in this group is to allow Bluetooth devices to locate and connect to each other. These protocols are involved in all data communications as well as carrying audio traffic between two Bluetooth devices. The protocols are also responsible to create, configure and control the physical and logical links between devices so that the layers above can pass data through the connections. These protocols consist of the radio, baseband, link manager, logical link and adaptation, and the host controller interface. The middleware protocols comprise both Bluetooth specific protocols and other adopted protocols, which are used to enable different applications to exchange data using Bluetooth wireless technology.

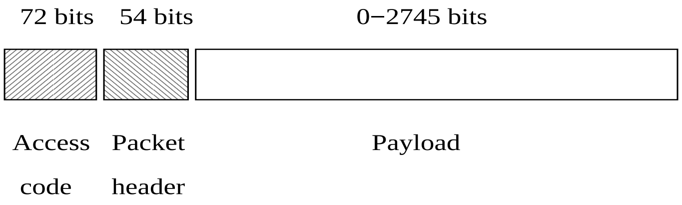


Figure 2.2: The format of Bluetooth packets [28]

2.2.1.1 The transport protocols

THE RADIO - Bluetooth devices operate in globally available, unlicensed ISM band situated at 2.4 GHz. This band is reserved for general use by Industrial, Scientific, and Medical applications. Since ISM radio band is free to be accessed by any radio transmitter as long as it satisfies the regulations and since high-power transmitters like microwave ovens and lighting coexist in this band, interference immunity is an important issue. As to achieve the interference avoidance objective, Bluetooth employs a fast (1600 hops/sec), frequency hopping, spread-spectrum (FHSS) technique. The radio hops in a pseudo-random fashion on 79 channels, 1 MHz bandwidth each (23 channels in some countries, such as Spain or France). The pseudo-random sequence is based on each piconet's identity/access code. The use of frequency hopping gives Bluetooth secure and robust communications. Co-user interference can be experienced as short interruptions in communications, which can be overcome with measures at high-layer protocols.

The modulation technique is GFSK (Gaussian Frequency Shift Keying) with a modulation index between 0.28 and 0.35. The raw transmission speed is 1 Mbps. Symbol timing accuracy is ±20 ppm. Three power classes are defined in the Bluetooth specification with maximum range up to 100m.

THE BASEBAND - The baseband layer determines and instantiates the Bluetooth air-interface. It defines the process by which devices search for other devices and how they connect to each other. The baseband layer defines the master and slave roles. The device that initiates a connection process becomes the master of the link, while the other device becomes a slave. The baseband also defines how the frequency hopping sequence used by communicating devices is formed. It defines the rules for sharing the air-interface among several devices, which are based on time division duplex (TDD), packet-based polling. All transmitting or receiving Bluetooth connections are in 1, 3, or 5 slots (a packet), with a slot of 625 μs duration (figures 2.2 and 2.3). It further defines how synchronous and asynchronous traffic can share air interface. The baseband defines various packet types supported for synchronous and asynchronous traffic, as well as various packet processing procedures including error detection and correction, encryption, packet transmission and re-transmissions.

BLUETOOTH DEVICE ADDRESS AND CLOCK - Each Bluetooth device has a 48 bit

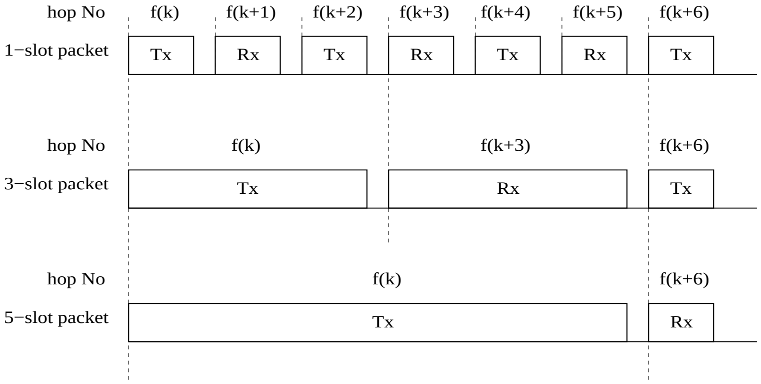


Figure 2.3: Slot timing for multi-slot packets

IEEE MAC address known as the Bluetooth Device Address (BD_ADDR). The MAC address is splitted into Non-significant Address Part (NAP), Upper Address Part (UAP) and Lower Address Part (LAP). It also uses a free-running 28-bit clocks that ticks once every $312.5\ \mu s$. Bluetooth devices communicate with each other by acquiring each other's Bluetooth addresses and clocks.

PICONET AND SCATTERNET - A Bluetooth piconet is a collection of Bluetooth-enabled devices which are physically close enough to be able to communicate and exchange information in a regular way. A piconet contains one device identified as a master and up to seven other devices identified as slaves. The master regulates and controls its slaves. A Bluetooth device can be a master or a slave at different times.

To identify each slave, the master of a piconet assigns a locally unique active member address (AM_ADDR) to the slaves participating in active communications in the piconet. While up to seven slaves can be $active$ at one time, additional devices in $parked$ mode may be registered with the master and be invited to become active members at any time. Other devices not associated with any piconet are in $standby$ mode.

Figure 2.4 shows two piconets, each piconet has a master, active slaves and a number of slaves in parked mode. It also has some devices in standby mode. There is one slave belong to both piconets. This is so-called $scatternet$ and this slave is named the $bridge$ node.

If a device is operating as a master, it uses its own native clock, $CLKN$, as its internal reference timing. If a device is operating as a slave, then its timing must be exactly synchronized to that of its master. There is another clock value defined in Bluetooth : $CLKE$, which is derived from $CLKN$ by adding an offset value and is used by the master to get CLK of a slave device.

Figure 2.5 [67] shows the operational states for a Bluetooth device. In the connected

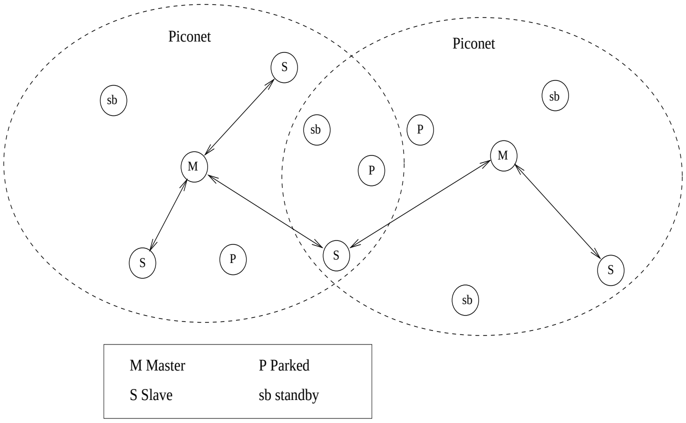


Figure 2.4: Bluetooth piconets and scatternet

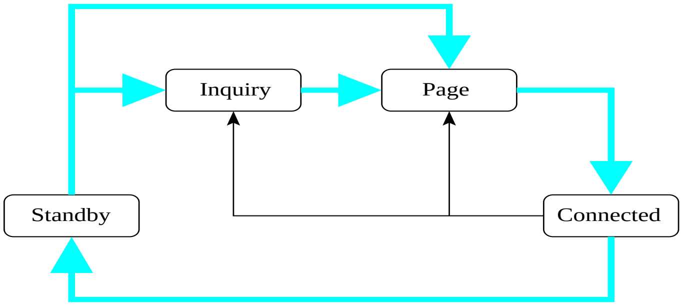


Figure 2.5: Operation states of a Bluetooth device [67]

state, the device is a member of a piconet. Before any connection in a piconet is created, all devices are in $standby$ state. To move to the connected state, a device goes through the $inquiry$ and $page$ states. The connection procedure is initiated by any one of devices, which later becomes the master. In the $inquiry$ state, a device learns about the identity of other devices and these device must be in an $inquiry\ scan$ state to listen and subsequently respond to inquiries. In the $page$ state, the device invites another device to join the piconet whose master is the inquiring device and the other device must be in the $page\ scan$ state to listen for and subsequently response to pages.

To become a member of a piconet, a Bluetooth device needs to know how to recreate the frequency hopping sequence that defines that piconet and which frequencies from this sequence will be visited and when. Also, to participate in communications over the piconet, the device needs to know how to formulate, read and write information packets on the piconet. So it needs following information:

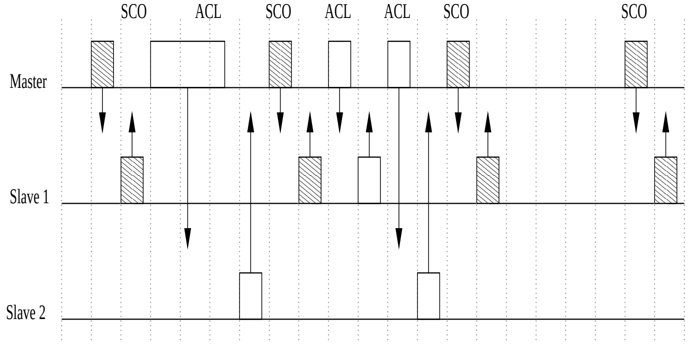


Figure 2.6: An example of mixing a synchronous SCO link and an asynchronous ACL link on a single piconet channel [30]

- Bluetooth device address (BD_ADDR)
- Bluetooth device (native) clock of the master

PHYSICAL LINKS AND BASEBAND PACKETS - Bluetooth link supports both synchronous services such as voice traffic, and asynchronous services, such as bursty data traffic. Two types of physical links have been defined: the synchronous connection-oriented (SCO) link and the asynchronous connectionless (ACL) link. The SCO link is a point-to-point link between the master and a slave. This link is established by reservation of duplex slots at regular intervals. The SCO link supports a user rate of 64 kbps in both directions.

The ACL link is a point-to-(multi)point, packet-oriented link between the master and all slaves in the piconet. The ACL link can use all the remaining slots on the channel not used by SCO links. The maximum rate that can be obtained over the ACL link is 723.2 kbps. In that case a return link of 57.6 kbps can still be supported. Alternatively a symmetric link with a maximum user rate of 433.9 kbps in both directions can be set up.

Figure 2.6 [30] depicts an example of mixing a synchronous SCO links and an asynchronous links on a single piconet channel based on TDD scheme.

ERROR CORRECTION AND CONTROL Bluetooth includes both Forward Error Correction (FEC) and packet retransmission schemes. For FEC, $\frac{1}{3}$ rate and $\frac{2}{3}$ rate FEC codes are supported. The $\frac{1}{3}$ rate code uses a 3-bit repeat coding with majority decision (voting) at the recipient. The $\frac{1}{3}$ rate code is used for the packet header and can additionally be applied on the payload of packets on SCO link. For the $\frac{2}{3}$ rate FEC codes, a Hamming code is used and is applied on payload on both the SCO and the ACL links.

On the ACL link, an Automatic Repeat Request (ARQ) scheme can be applied. In

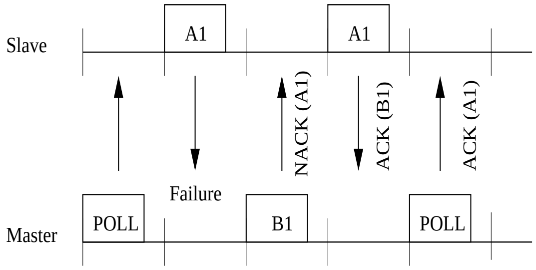


Figure 2.7: An example of retransmission operation in Bluetooth [30]

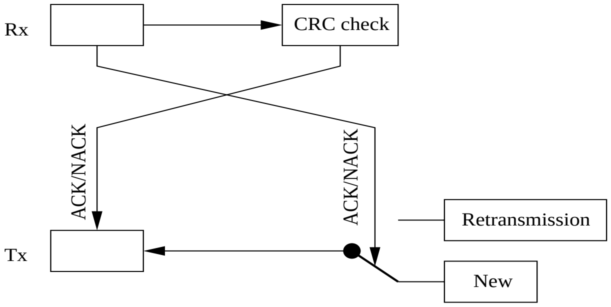


Figure 2.8: The ARQ mechanisms in Bluetooth [30]

this scheme, a packet retransmission is carried out if the reception of the packet is not acknowledged. Each payload contains a Cyclic Redundancy Check (CRC) to check for errors. A fast-ARQ scheme is implemented where the sender is notified of the packet reception in Rx slot directly following the Tx slots in which the packet was sent (see figure 2.7 [30]). The ACK/NACK information is piggybacked in the packet header of the return packet.

Figure 2.8 [30] depicts the ARQ mechanism where the received ACK/NACK information decides on retransmission and the received payload determines transmitted ACK/NACK information.

LINK MANAGER PROTOCOL - Link managers in communicating devices exchange messages to control the Bluetooth link between those devices. They carry out the following operations:

- Attaching slaves to a piconet and allocating their active member addresses
- Breaking connections to detach slaves from piconet
- Configuring the link including controlling the master/slave switches
- Establishing and releasing ACL and SCO links

- Power management tasks by using low-power modes: Hold, Sniff or Park
- Traffic scheduling
- Controlling test modes

A Bluetooth Link Manager communicates with Link Manager on other Bluetooth devices using Link Management Protocol (LMP)

LOW-POWER MODES - A piconet can include up to seven active slaves and more than 200 parked slaves. Active slaves can be in three different modes, namely $Active$ mode, which has been described, $Sniff$ mode and $Hold$ mode, where the modes apply to the communication links. In Active mode a slave always listens for transmissions from the master. Hold, Sniff and Park modes constitute low-power modes with the purpose of reducing power consumption by letting slaves sleep most of the time and wake up at pre-defined time interval or periodically.

Hold mode is used when a device should be put to sleep for a specified amount of time.

Sniff mode is used to put a slave in a low-duty cycle mode, whereby it wakes up periodically to communicate with master, thus reducing its duty cycle.

Park mode is similar to Sniff mode, but it is used to stay synchronized with the master without being an active member of the piconet. The devices in Park mode give up their MAC address and occasionally listen to the traffic of the master to re-synchronize and check on broadcast messages.

HIGHER LAYERS IN TRANSPORT PROTOCOLS:

- **Host Controller Interface (HCI)** is the interface between higher and lower layers in a Bluetooth device. Through HCI, a host device passes and receives data destinating to or coming from another Bluetooth device. Also many messages are transfered through HCI. The HCI packets, including command packets, even packets and data packets, are carried on the HCI transport layer.
- **Logical Link Control & Adaptation Protocol (L2CAP)** is layered over the Baseband protocol and also resides in the transport group. All data traffic is passed through this layer. L2CAP supports higher-layer protocol multiplexing, segmentation and re-assembly of larger-size, higher-layer packets to and from the smaller baseband packets. It also provides the exchange of Quality of Service (QoS) information, such as peak bandwidth, latency and delay variation. The L2CAP layer is responsible for admission control based on the requested level of QoS and maintains this level. The L2CAP is only capable of handling ACL communication.

2.2.1.2 Middleware Group

On the top of the L2CAP layer, the Service Discovery Protocol (SDP), RFCOMM, Point to Point Protocol (PPP) and more are situated. This enables legacy applications that normally would interface with those protocols to operate seamlessly over Bluetooth protocol.

2.2.2 Profile Specification

The profiles specify which protocol elements are mandatory in certain applications, i.e. devices with limited resources only need to implement a fraction of the full protocol. It also ensures interoperability between the many implementations of the protocol stack. The profile specification is dynamic in the sense that for a new applications, new profiles can be added [30]. Examples of already defined profiles are: FAX, LAN access point and headset.

The Bluetooth SIG has recently published a profile called the Bluetooth Personal Area Networking (PAN) profile, which defines a means of enabling Bluetooth devices to participate in a personal area network. The PAN profile provides networking capabilities for Bluetooth devices for network protocols such as IPv4 and IPv6.

To achieve this, the Bluetooth Network Encapsulation Protocol (BNEP) has been specified and published together with the PAN profile. The BNEP is located in the Bluetooth protocol stack between the IP layer and L2CAP layer and provides an Ethernet-like interface for the IP layer. Completely unmodified Ethernet payload can be transmitted using BNEP to exchange packets between Bluetooth devices. BNEP emulates a multiple access link on top of the point-to-(multi)point link of a piconet. The master acts as an Ethernet bridge, forwarding packets that are not destined for itself.

For many IP applications BNEP will replace the point-to-point approach which is currently the only supported IP stack within Bluetooth, that is, via the Point-to-Point Protocol (PPP) over RFCOMM.

2.3 Bluetooth ad hoc personal area networking

One of major goals of Bluetooth wireless technology is to allow Bluetooth devices to communicate directly in an ad-hoc fashion, which is often referred to as a personal area network (PAN). By connecting a number of piconets into larger network, scatternet, the communications between the Bluetooth devices could be carried out beyond radio range, and the total network capacity could be increased. The ad hoc Bluetooth PAN would be expected to work in higher mobility environment and larger radio coverage comparing to the simple single piconet. There are some requirements that should be addressed for connectivity and traffic delivery in the Bluetooth PAN [38]:

- Distributed operation: a device in PAN cannot rely on a network in the background to support security and routing functions. These functions should be designed to operate in a distributed manner.

- Dynamic network topology: due to high mobility of Bluetooth devices, network topology of Bluetooth PAN will vary frequently. The design of routing function, traffic control, etc., should respond to network topology variations.
- Fluctuation link capacity: In Bluetooth PAN, packets are transfered in a multi-hop environment. During an end-to-end transmission session, there is very high possibility that packets would be blocked, dropped out or lost. This occurs the buffer overflows, the connection is lost, or the network suffers from bottleneck. Moreover, the end-to-end path could be broken, due to the mobility of Bluetooth devices, which can disrupt packet transmissions. As a result, it may require buffer optimization, special admission or congestion control, appropriate capacity allocation scheme.
- Scarce resources and lower power devices: Bluetooth PAN has limited capacity, which is dependent on the number of hopping frequencies, of the devices and on the network topology. In most cases, the Bluetooth nodes will be battery-driven, which will make the power budget tight for all the power consuming components in a device. This will affect the CPU processing, memory size, signal processing, and transceiver output/input power.
- Quality of service support for Bluetooth: Supporting QoS in Bluetooth based personal ad hoc network is great challenge, as it has not wired backbone network, and to support end-to-end QoS, it requires that all Bluetooth nodes in route paths should support the same QoS demands. Several performance parameters can be used as QoS criteria, such as bandwidth, delay, packet loss. Thus control mechanisms should be built to support QoS requirements.

In order to implement the Bluetooth PAN, much research is underway to enhance the current Bluetooth functionality to provide an improved networking support. These works may include improving inter-piconet scheduling, network formation, a robust capacity allocation or network congestion control.

2.4 Summary

This chapter has provided an overview of Bluetooth wireless technology, the brief story of its evolution, the general protocol stack description, the most important features and problems, which are backgrounds for further investigations in the following sections, and finally, a look toward the future development and research of Bluetooth Personal Area Network. To be concluded, Bluetooth wireless technology will change the way we handle and access information in the near future.

Chapter 3

Dynamic Buffer Optimization in Bluetooth Networks

3.1 Introduction

Wireless ad-hoc networks, or mobile distributed multihop wireless networks, have gained a lot of attention during the last couple of years [102] [64]. The mobile nodes may rapidly move around and all communication is carried over the wireless channel. The main difference between ad-hoc networks and conventional cellular technology is the lack of any centralized entity within ad-hoc networks. Ad-hoc networks can be deployed quickly since no fixed infrastructure is needed. These networks are fault tolerant because the networks can operate in wireless ad hoc style environment, with dynamic distributed network topology, and no central entity required.

Bluetooth is a wireless communication technology using the unlicensed Industrial-Scientific-Medical (ISM) frequency band, supporting both voice traffic and data traffic. Bluetooth is a de facto standard, and a specification for low cost short range radio link between electronic devices, such as cordless phones, laptop and wireless headsets. The communication is organized in piconets with a master and a number of slaves. Each piconet uses a unique frequency hopping sequence, and several piconets can be created with overlapping coverage areas to form a scatternet.

The end-to-end quality-of-services (QoS) delivered to users in Bluetooth networks depend on a large number of parameters at different levels. A network consists of limited resources of different types, e.g. capacity, buffer space and power, which are requested in certain patterns and controlled by various algorithms. Furthermore, the algorithms on different levels may interact in a complex and unpredictable way. One may view the problem of providing QoS to users as a complex non-linear time varying optimization, which includes buffer optimization.

In Bluetooth, packet buffering is needed in a number of the protocols used in Bluetooth protocol stacks, e.g. baseband, L2CAP, IP and TCP. The available memory in many "thin" nodes is limited, which makes buffer management (dimensioning and control) an important issue to study. It is important that each protocol has sufficient buffer space, but not too much, to satisfy the specified delay and throughput constraints. These QoS constraints are demanded by users in corresponding applications, such as voice, video, or data services, in which Bluetooth devices are deployed. For reason of simplicity, only the same size Bluetooth data packets are considered in this thesis.

This chapter is organized as follows. In section 3.2, traffic queueing model in Bluetooth is constructed and QoS issues are discussed. Some simple queueing scenarios are presented. Although analysis from queueing model can give the most general view of the Bluetooth network behaviors, the transient model that captures event at all time scale is not always tractable. The combination with the simulation method could bring great advantages, such as reduce the computation complexity, and getting acceptable accuracy by dictating the appropriate level of abstraction. Thus a Bluetooth application model is described in section 3.3. Section 3.4 presents the buffer dimensioning method for Bluetooth devices in the network. Section 3.5 features the Bluetooth network model and the integrated arrival traffic. The buffer optimization method performance is illustrated by simulations in section 3.6. The last sections are devoted to some open issues and conclusions.

3.2 Queueing model for Bluetooth networks

3.2.1 Quality of service issues in Bluetooth

The objective of providing quality of services poses a variety of research challenges. The overriding goal of providing quality of services is to develop highly dependable systems with correct behavior, high reliability and availability, and predictably good performance, even under stress conditions. Thus service quality must comprise both qualitative and quantitative properties.

In Bluetooth, quality of services can be defined by the following parameters: bandwidth, delay, delay variance, throughput, and packet loss [99].

- **Bandwidth**: In order to allow applications to run sufficiently and smoothly over a Bluetooth wireless link, there should exist a certain amount of bandwidth. Bandwidth requirement varies depending on the specific application. For example, the telephone voice traffic from a headset can require 9.6 kbps real-time, while the video traffic may need 128 kbps real-time to get acceptable quality. Basically, the air-interface bandwidth in Bluetooth is determined by the polling algorithm executed by the master in the piconet, and the baseband packet type, selected by the Link Manager for transmission. The maximum data rate for Bluetooth, in theory, is 721 kbps. However it suffers from interference and adverse propagation conditions, thus the actual bandwidth will be much more lower.

- **Delay**: Delay sensitive applications such as interactive real-time and streaming audio/video application may have strict delay requirements. The primary cause of delay is the amount bandwidth available at the time of transmission. Retransmission can cause additional delay. Lower power modes, or switching between piconets also increase packet delay. Message exchange between layers can reduce data transmission.
- **Delay variation**: Delay variation comes along with delay of system. In most practical cases, it is the difference between the minimum and maximum delays within the system.
- **Throughput**: Throughput is amount of data received at the end system. Throughput depends on available bandwidth. The packet delay also affects throughput. For a specific system, an increase of traffic load can cause higher packet delay. The network throughput can be seriously downgraded when it suffers the bottleneck phenomenon, which is caused by congestion of the ACL buffer or physical layer buffer at sensitive Bluetooth devices in the network, such as bridge nodes.
- **Packet loss**: Packet loss is related to available bandwidth. When a packet arrives at a fully loaded node, it could be blocked or dropped. Furthermore, when the transmission delay exceeds time-out, the packet is considered to be lost. Once there is a loss of packets, re-transmissions of these packets may be required to fulfill the service. As a result, other QoSs, for example throughput, can be affected.

3.2.2 Simple case: piconet with Round-Robin polling

In [31], the authors give an analysis of a very simple case: Bluetooth piconet which uses a Round-Robin polling scheme. When a master operates in the piconet with Round-Robin polling and if the traffic arrivals are assumed to be exponentially distributed, the piconet can be analyzed as TDMA system and the queueing model can be considered as an $M/D/1$ system. Thus the expected packet delay, for example for 1 slot packet from a slave depicted in figure 3.1, can be calculated as :

$$D_i = 1 + \frac{n}{1 - 2n\lambda_i} \tag{3.1}$$

where n is number of slaves in the piconet and λ_i is the arrival rate from the source to slave i.

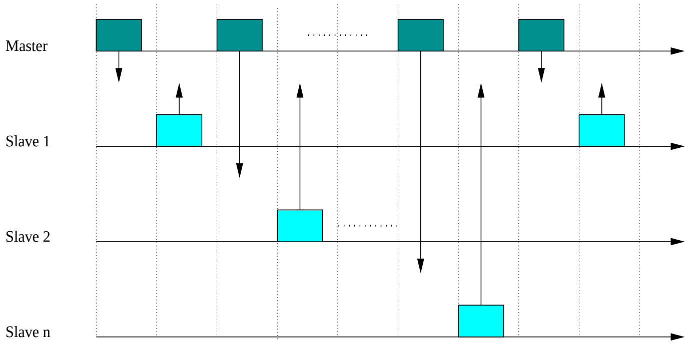


Figure 3.1: Pure Round Robin Polling scheme

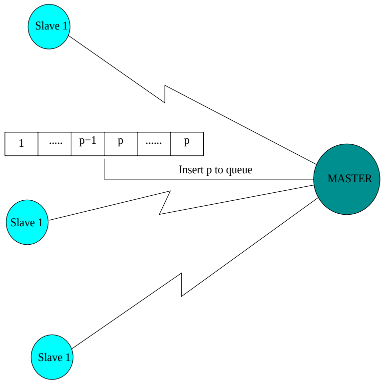


Figure 3.2: Bluetooth priority based queueing model [83]

In [46] and [83], with priority based scheduling policy, the queueing model as shown in figure 3.2 is analyzed as an $M/G/1$ queue. The average delay within the system can be calculated:

$$D = \sum_{p=1}^{P} \frac{\lambda_p \overline{\chi}_p}{2} \tag{3.2}$$

where $\overline{\chi}_i$ denotes the mean service time for each job in priority class p and P is number of priority classes.

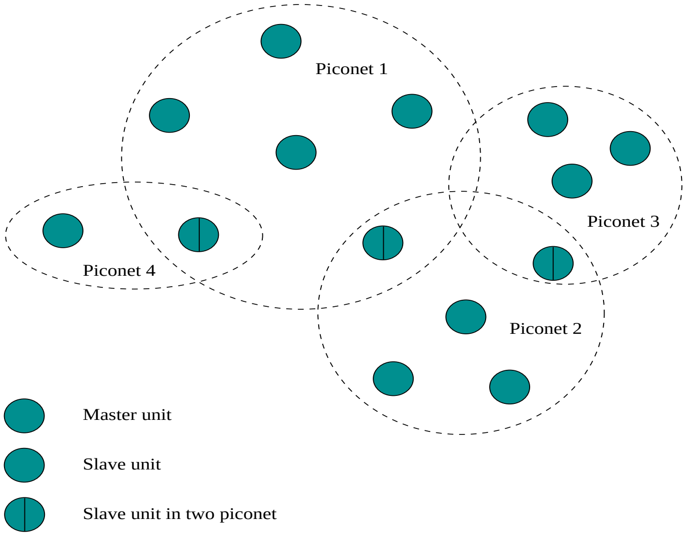


Figure 3.3: Bluetooth scatternet model

3.2.3 Queueing model of Bluetooth networks

The Bluetooth network consists of J nodes, indexing by $j = 1, \ldots, J$, as depicted in figure 3.3. Each node has an infinite buffer space. Packets arrive at the node j with a renewal process rate α_j, where $\alpha_j \geq 0$. It is assumed that the packets are served at a first-in-first-out (FIFO) discipline with service rate μ_j, $\mu_j > 0$. Furthermore, it is also assumed that a packet comes to the network and eventually departs from the network.

Next, to construct the queue length and traffic equation, let $Q_j(0)$ a non-negative integer random variable, represent the number of packets at node j at time $t = 0$. Let $A_j = \{A_j(t), t \geq 0\}$ be the renewal process with A_j indicating the number of jobs that have arrived at node j exogenously during $(0, t]$. For convenience, define the renewal process $S_j = \{S_j(t), t \geq 0\}$ as service process. Let $R_j = \{R_j(t), t \geq 0\}$ be the routing sequence. From these data, it is possible to construct the queueing length process $Q = \{Q(t), t \geq 0\}$ [52]:

$$Q_j(t) = Q_j(0) + A_j(t) + \sum_{k=1}^{J} R_j^k(S_k(B_k(t))) - S_j(B_j(t)) \tag{3.3}$$

for all $t \geq 0$ and $j = 1, ..., J$. $B = \{B(t), t \geq 0\}$ is the busy time process. If a workconserving rule is in force, we have:

$$B_j(t) = \int_0^t 1\{Q_j(s) > 0\} ds \tag{3.4}$$

It should be noted that $S_j(B_j(t))$ indicates the number of jobs that have completed service at node j during the time interval $(0, t]$, and that $R_i^j(S_j(B_j(t)))$ indicates the number of jobs that enter node i from node j during the time interval $(0, t]$.

From the theory of the strong law of large number [27], we have :

$$\lim_{t \to \infty} \frac{A_j(t)}{t} = \alpha_j \tag{3.5}$$

$$\lim_{t \to \infty} \frac{S_j(t)}{t} = \mu_j \tag{3.6}$$

$$\lim_{t \to \infty} \frac{R_i^j(t)}{t} = r_{ji} \tag{3.7}$$

where r_{ji} is the probability that a packet is routed from the node j to the node i.

If the effective flow rate λ_j is defined as the sum of exogenous and endogenous inflow rates to the node j . We must have the traffic equation:

$$\lambda_j = \alpha_j + \sum_{k=1}^{J} (\lambda_k \wedge \mu_k)\, r_{kj} \tag{3.8}$$

Let :

$$\Lambda_j = \frac{\lambda_j}{\mu_j} \tag{3.9}$$

and call it traffic intensity of the node j, $j = 1, ..., J$. It is clearly that the buffer of the node j is bottleneck if $\Lambda_j \geq 1$ and stable condition (non-bottleneck) if $\Lambda_j < 1$.

In next section, we will use these conditions to buffer optimization for nodes in Bluetooth network.

3.3 Bluetooth Application Model

The main part of the Bluetooth application model is a Bluetooth ad hoc network model, which could be just a simple piconet or more complex network, scatternet. The overall

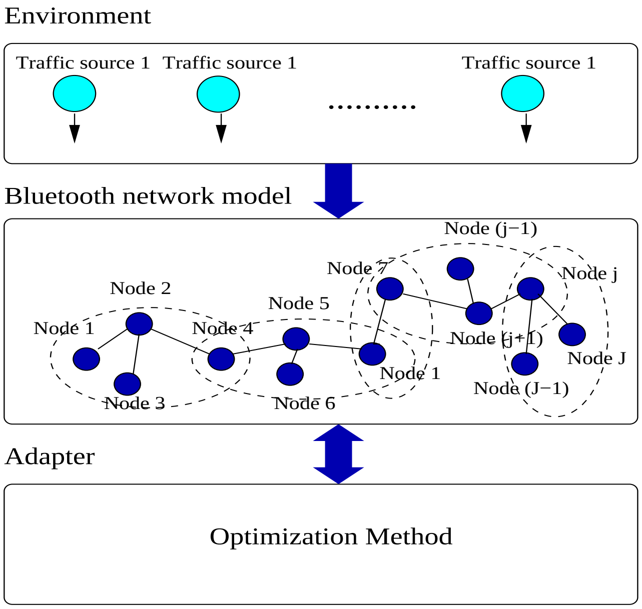


Figure 3.4: Block scheme: Environment, Bluetooth Network and Adapter

structure of the Bluetooth network application, which arises from the novel ideas presented in [93], is shown in figure 3.4. The structure is organized into blocks. Each block consists of variables and activities. Inter-block communication is handled by procedures and external variables.

- **ENVIRONMENT BLOCK**: The environment block represents the Bluetooth network users. Associated with each user is a traffic source. Depending on the usage classification, the associated traffic sources can have different models. For voice traffic, it is possible to characterize it as Poisson traffic. For bursty data traffic, the question of 'what is the distribution of the inter-arrival time of Bluetooth packets from traffic source to the Bluetooth node' occurs. There are many attempts to model this, including the approaches that employ the correlation between the arrivals. One way to achieve is to use a model with ON and OFF periods. The Interrupted Bernoulli Process (IBP) can be a possible candidate. The duration of these periods in IBP has a geometrical distribution and these two periods alternate during the time of operation.
- **BLUETOOTH SYSTEM**: The simulated system includes the Bluetooth nodes, forming piconet or scatternet. It is assumed that the simulated network has knowledge about network topology and routing algorithms. The network topology is set

up by the Bluetooth network formation algorithm and by INQUIRY/PAGE procedures with the objective to increase network capacity and to satisfy the QoS requirements. A packet comes from a traffic source and is represented by a pair of the originating node and the destination node. The packet is transfered through the network according to the routing algorithm. The performance criteria are defined based on the quality of service requirements in Bluetooth network, as mentioned in section 3.1.

- **THE ADAPTER**: The optimization method resides in the adapter. The adapter continuously exchanges data with the Bluetooth system block. The performance data of the system affected by the environment is fedbacked to the adapter and by using optimization method, the current best parameters of buffers could be determined.

In the next section, the optimization method for buffer dimensioning in Bluetooth networks is described. The method is based on queueing model of Bluetooth networks highlighted in section 3.2.3.

3.4 Optimization method

The buffer optimization method for Bluetooth networks is based on the transient behaviors of the network and is developed from the tabu search method for buffer dimensioning of Bluetooth nodes in the network. The method is inspired by the Adaptive Cross Validation method [92], which was applied to the dimensioning of circuit switched networks [91]. The tabu search optimization technique is the generalization of the local search method to explore the search space of all feasible solutions by moving from one solution to another, which is the best available, hoping that this will eventually lead to a better local optimum [2, 60]. The optimization method uses simulation as an effective approach to optimize buffer spaces for the nodes in the network. No assumptions are needed regarding the arrival and service times. Neither are any assumptions about the internal details of the simulation model. By investigating the performance of a number of simulation models, it finds the current best model and then the best model and a number of alternative models are investigated next. As a result, the method selects the best model from a list of the best solutions with the longest simulation period, and satisfying QoS demands. If Bluetooth network satisfies conditions about the network stabilities in the queueing model equations (3.5, 3.6, 3.7 and 3.8), then it is possible to apply conservation law [78] to optimize the buffer spaces for the Bluetooth nodes. Let $f(x)$ be the objective function of the parameter to be optimized, $x = \{x_1, x_2, ...x_J\}$ be the buffer space of the nodes in the network. Let $g_j(x)$ be the constraints, which also is a function of parameter x. The constraints represent the performance of the network, in terms of quality of services, such as queueing length, time delays, etc. Both the objective function $f(x)$ and the constraints $g_j(x)$ are stochastic functions.

$$\begin{aligned} \min \quad & f(x) \\ & g_j(x) \leq c_j \\ & x = \{x_1, x_2, ..., x_J\} \quad \text{discrete} \end{aligned} \tag{3.10}$$

where c_j is Quality of Service criterion of node j in the modeled network.

The objective function $f(x)$ represents the performance of Bluetooth network with parameter x in a stochastic environment. It may be estimated by a simulation.

The optimization method is iterated in the simulation and with the set of best values for buffer space x selected from each simulation iteration. Some initializations are needed in the simulation: the initial values of buffer space x for Bluetooth nodes in the network, the initial state z of the modeled network and some time related parameters. The simulation period τ is the simulation duration used in an iteration, measured by the number of time slots. To obtain a short execution time, the initial value of the simulation period τ should be as small as possible. During the optimization process, the simulation period may be increased according to the current best value x^* selection. It means that during the period, if the optimization method has selected the set of the best values of buffer space for the Bluetooth nodes, the simulation period should have an increment, $\Delta\tau$ time slots, to select the better values for whole optimization process. Two limits, τ_1 and τ_2, where $\tau_1 \ll \tau_2$, are used as stopping conditions of the optimization process. In addition, the simulated time t, an iteration counter n and the current best value x^* are also initiated.

In first phase of an iteration, the modeled Bluetooth network is simulated with the initiated buffer size parameter $x = \{x_1, x_2, ..., x_J\}$. The simulation period τ in time slots and the initial model state z are also used as inputs to the simulation. The simulation results, such as buffer sizes x, the number of packet losses due to buffer overflow, mean packet delays for each node, etc., are used for the estimations of the objective function $\widetilde{f}(x)$ and the constraints $\widetilde{g}_i(x)$. The final model state is assigned to z and is used as an initial state for next iteration.

In the second phase, the results are stored in memory using two data structures: a circular buffer, which keeps the simulation results from one iteration in one entry and a size-limited table, which stores the accumulated simulation results. The buffer entry is used as the initial data for next simulation, if the parameter x is not in the table. The table contains only the most recent simulation results.

In the third phase, the current best parameter in memory $\widehat{x}$ is selected. The selection is based on the principle that the parameter which has minimum objective function $f(x)$ should be chosen as the current best parameter. In case that there are more than one candidates, the most recent parameter will be selected.

In the last phase, the simulation period τ may be updated. It is possible to find better solutions by increasing a $\Delta\tau$ time slots to the simulation period τ. In general, τ should be

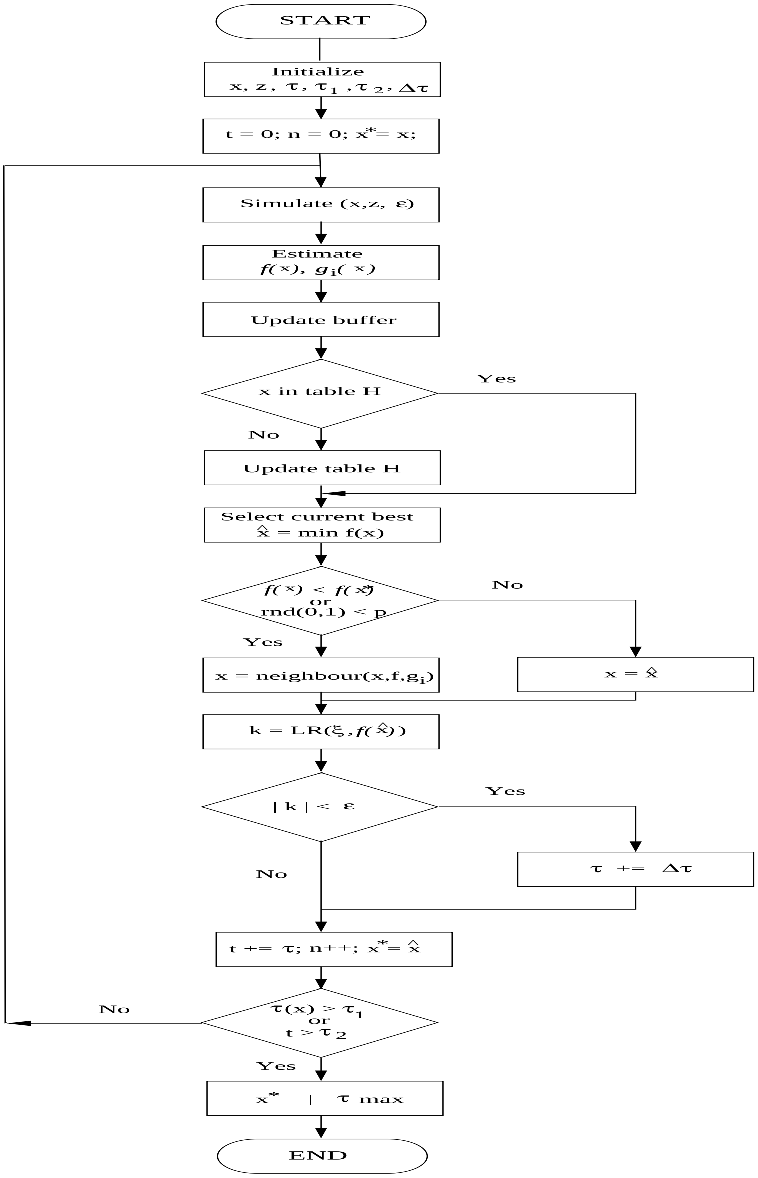


Figure 3.5: Buffer optimization method

Symbol	Description
$x = \{x_1, ..., x_J\}$	Set of parameters to be optimized, i.e. buffer sizes of Bluetooth nodes
$f(x)$	The objective function, represents the performance of the system
$g_i(x)$	Constraint function for a Bluetooth node
c_i	Quality of Service criterion for a Bluetooth node
τ	Simulation period
t	Simulation time
τ_1, τ_2	Lower and Upper limits of simulation, to stop simulation
$\Delta\tau$	Increase step of simulation period
k	Slope of linear function
n	Iteration count of simulation
z	Model state of the network
x^*	Current best value of x

Table 3.1: Some parameters used optimization

increased when no significantly better solution is found and this is detected by approximating the latest ξ $(= 6)$ values of the objective function $f(\widehat{x})$. The linear regression method is used for the approximation. Here the simulation period τ is increased when the absolute value of the slope k resulting from the linear regression is less than a certain level ε (ε= 0.01).

The optimization is terminated when the simulation period τ exceeds the lower threshold τ_1 or the total simulation time t is larger than the upper threshold τ_2. At this time, the optimized parameter of buffer sizes $x = \{x_1, x_2, ..., x_J\}$ is selected as the parameter in table with the longest simulation time τ.

3.5 System modeling and traffic characteristics

3.5.1 Bluetooth system modeling

The system under consideration is a Bluetooth piconet, which consists of one master and $J - 1$ slaves as depicted in figure 3.6. The modeled piconet provides full-duplex transmission using time slots, where each slot is 0.625 ms long. For intra-piconet scheduling, it uses just simple strict Round-Robin scheduling as described in section 3.2.2. The communication in the investigated Bluetooth piconet is followed the polling scheme, in which the master polls each slave according to the strict Round-Robin scheme with uniform distribution. A slave is only allowed to transmit after having been polled by the

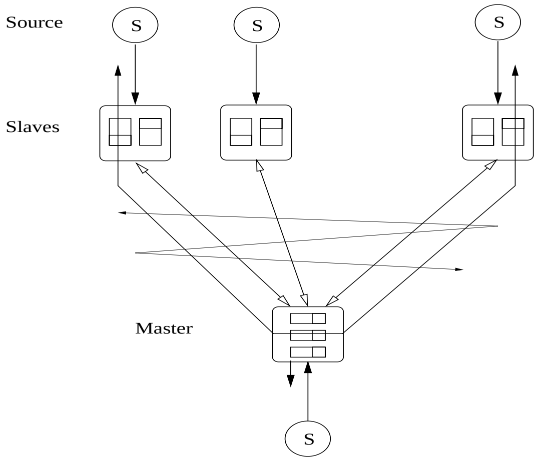
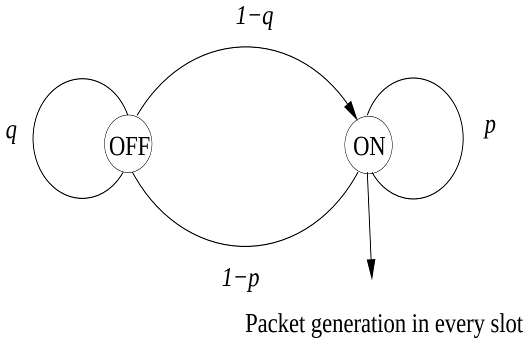


Figure 3.6: Bluetooth piconet simulation model

master. Other polling schemes, such as Fair Exhaustive Polling (FEP) [35] may also be used. These schemes have a number of advantages, e.g. lower time delays, more robust to traffic loads, etc. For simplicity, the strict Round-Robin is applied to the modeled piconet, in order to illustrate performance of the buffer optimization method.

The number of slaves in the Bluetooth piconet can be up to 7. The Bluetooth modeled piconet can operate at synchronous SCO or asynchronous ACL link modes. The synchronous link mode is used for voice traffic and the data traffic mostly is carried in the asynchronous link mode. However, we just concentrate on data traffic and the Bluetooth piconet runs in the asynchronous link mode. Packets transfered between nodes in the piconet can have different packet sizes, i.e. they could be 1, 3 or 5 slots long. To simplify, this study considers only single slot data packet transmitted between the nodes in the modeled piconet.

The radio links between Bluetooth nodes are affected by the operation environment. The radio signals can be lost due to many reasons, such as path losses, noise interference which reduce signal-to-noise ratio (SNR). Furthermore unlicensed 2.4 GHz ISM radio band is also used by other applications, e.g. Wireless LAN IEEE 802.11b and home appliances. These can cause packet losses or errors during transmission. Bluetooth supplies several schemes to protect packet transmissions, including re-transmissions of packets or error correction control. However, as we study the buffer optimization method and the Bluetooth performance of packet losses due to buffer overflow, it may be assumed that there is no packet loss due to transmission errors.



$$\begin{array}{c|cc} & \text{On} & \text{Off} \\ \hline \text{On} & p & 1-p \\ \text{Off} & 1-q & q \end{array}$$

Figure 3.7: The Markov chain for the arrival IBP

3.5.2 Integrated arrival traffic in the modeled Bluetooth network

Since the arrivals to a node in the Bluetooth modeled piconet are assumed to come from data services, which presumably are bursty by nature. The most common services are file transfers, internet traffic or possibly video transfer and the network is expected to carry these different traffic types in an integrated fashion. Hence, the Poisson arrival assumptions, although having been used extensively in studying the performances of circuit-switched voice telephony and packet-switched networks, are no longer valid. The problem is that the Poisson process doesn't always work, particularly when dealing with stream-type, continuous bit rate traffic. To be able to make arrival traffic close to real data traffic, some other models may be applied that reflect these bursty arrivals. Among these models, the Interrupted Bernoulli Process (IBP) is applied as the traffic source model in our Bluetooth network.

The Interrupted Bernoulli Process source as depicted in figure 3.7 is a two state Markov chain and uses a model with both arrival period (ON state) and silence period (OFF state). The duration of these periods has a geometrical distribution and the two periods alternate continuously. The probability that a given process is in the ON state and remains in that state is p. So $(1-p)$ is the probability of changing to the OFF state. If the process is in the OFF state, it will remain in that state with probability q, or will change to the ON state with probability $(1-q)$. If the process in the ON state, it will generate a packet with probability υ.

Let ξ_A be the time interval from a slot in the ON state to the time of the next arrival of a packet, then the mean inter-arrival time $E(\xi_A)$ is:

$$E(\xi_A) = \frac{(2-p-q)}{\upsilon(1-q)} \tag{3.11}$$

And the squared coefficient of variation of the inter-arrival time is C^2:

$$C^2 = 1 + \upsilon \left[\frac{(1-p)(p+q)}{(2-p-q)^2} - 1 \right] \tag{3.12}$$

The probability ρ that any slot is busy (i.e. it carries a packet) is equal to the mean number of packets transmitted during the ON period (which is equal to the mean length of the ON state) over the mean length of the OFF and ON periods. This is equal to:

$$\rho = \frac{\upsilon(1-q)}{2-p-q} \tag{3.13}$$

In our Bluetooth model, when the source is in the ON state, it will generate a one slot length packet. Thus, $\upsilon = 1$ which gives us:

$$\rho = \frac{1-q}{2-p-q} \tag{3.14}$$

$$C^2 = \frac{(p+q)(1-p)}{(2-p-q)^2} \tag{3.15}$$

For the homogeneous traffic load scenario, the incoming and outgoing traffics between nodes (master and slaves in the modeled piconet) are equally distributed and the traffic matrix can be written as:

$$M = \begin{bmatrix} 0 & \rho_A & \cdots & \rho_A \\ \rho_A & 0 & \rho_A & \cdots \\ \cdots & \rho_A & 0 & \rho_A \\ \rho_A & \cdots & \rho_A & 0 \end{bmatrix} \tag{3.16}$$

where ρ_A is the offered traffic intensity from the IBP traffic source to a destination. In case of heterogeneous traffic load scenario, the offered traffic intensity would not be equal to all destinations.

3.6 Simulations

3.6.1 Parameter setup of the simulation

To illustrate the working ability and the performance of the buffer optimization method applied to Bluetooth networks, a simulation, which is based on the Bluetooth system modeling as described in section 3.5.1, is carried out.

The simulated network is a Bluetooth piconet, which consists of a master and 7 slaves, i.e. $J - 1 = 7$. At the initialization stage, to reduce the running time, the simulation period τ is small and the lower simulation limit is much smaller than the upper simulation limit. The simulation period τ is set to 5000 time slots. During operation, the simulation period will increase with the incremental value $\Delta\tau = 5000$ time slots. The simulation will be stopped if the simulation period τ reaches the lower limit $\tau_1 = 5 \cdot 10^5$ time slots, or the total simulation time t reaches the upper limit $\tau_2 = 2 \cdot 10^7$ time slots.

The constraints $g_i(x)$ and the objective function $\widehat{f}(x)$ depend on the QoS requirements. For example, the constraints can be time delays and the objective function can be the sum of buffer sizes, so that the buffer optimization method will try to minimize the sum of buffer sizes, while it keeps the packet delays less than a certain level. In this simulation, however the constraints $g_i(x)$ represent the packet loss probability due to buffer overflow and the objective function is to minimize total buffer requirements for the nodes in the Bluetooth modeled network, while trying to satisfy QoS (packet loss probability) criteria. Hence, the equation 3.10 can be rewritten as:

$$\begin{aligned} \min \quad & f(x) = \sum_{i=1}^{J} x_i \\ & g_j(x) \le c_j \\ & x = \{x_1, x_2, ..., x_J\} \quad \text{discrete} \end{aligned} \tag{3.17}$$

3.6.2 Numerical results

Figure 3.8 shows the mean queueing lengths at the output buffers for bursty homogeneous traffic intensity ρ. The mean queueing length is a function of traffic intensity, which itself depends on the probabilities of being in the ON state p and in the OFF state q in the IBP Markov chain. It is assumed that the output buffer sizes are infinite. As can be seen, the mean queueing lengths increase dramatically when the traffic intensity ρ increases, for both master and slaves. However, the queueing size at the master was significantly higher than the queueing sizes of the slaves. It means the buffer size at master should be higher than buffer sizes of slaves to reach the same amount of packet loss criteria.

Figures 3.9 and 3.10 show the transient behaviors of the Bluetooth modeled piconet,

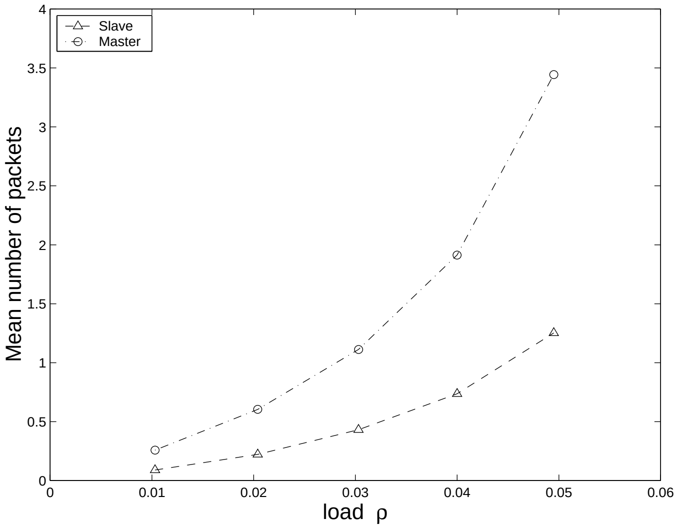


Figure 3.8: Mean number of data packets queueing at master and slave output buffers, for homogeneous traffic load

when the buffer optimization method was applied. As can be seen, when the buffer sizes increased, the packet loss probabilities decreased considerably. In the investigated case, the buffer sizes went up to 6 for the slaves' output buffers and to 15 for the master's output buffer. The probability of packet loss for each node reached 10^{-2} for the simulation time $t \geq 1 \cdot 10^6$ time slots. As the optimization proceeded, it got more and more difficult to reduce the probability of packet loss and also the output buffer sizes of the master and slaves just fluctuated between certain values. The optimization stopped when the simulation period exceeded the lower limit, $\tau_1 = 5 \cdot 10^5$ time slots, which occurred after $2 \cdot 10^7$ time slots.

The output buffer requirement at the master was higher than at the slaves. This was due to the fact that the traffic intensities were assumed to be homogeneous and the slaves sent traffic through the master.

Furthermore, from the figures, it is clear that when the packet loss probability criteria decreased from 1% to 0.01%, the buffer size requirements would increase for both master and slaves.

To verify the buffer optimization results, the modeled system was simulated, in which the output buffer sizes were pre-selected. When the output buffers were 20 for master and 9 for slaves, the simulation results indicated that the packet loss probabilities were approximately 10^{-3} after 10^6 time slot simulation. When decreasing the output buffer sizes (19 packets and 8 packet at master and slaves, respectively), the packet loss proba-

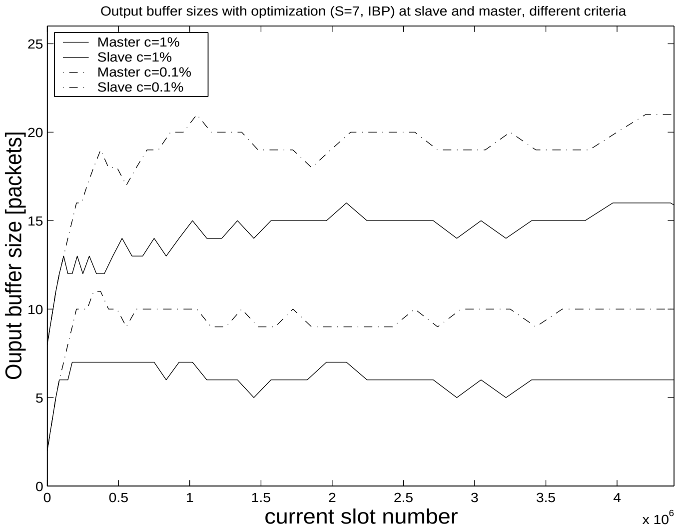


Figure 3.9: Transient behavior of output buffer sizes at master and slaves, homogeneous traffic load $\rho = 0.05$, modular step size $\Delta = 1$, for different constraints

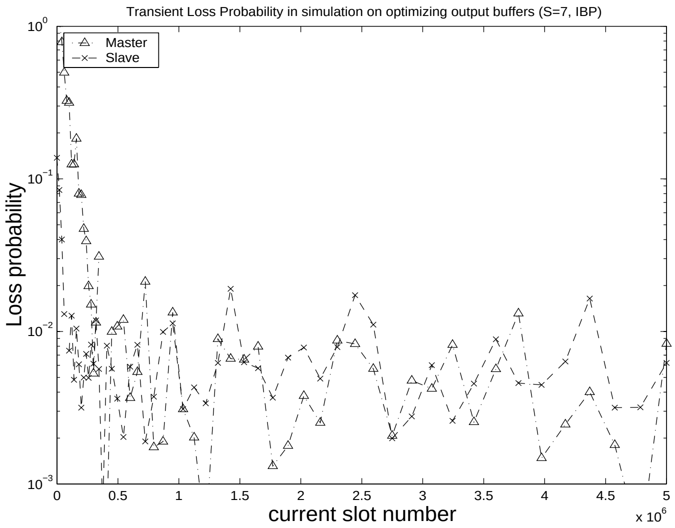


Figure 3.10: Transient behavior of packet losses at master and slaves, homogeneous traffic load $\rho = 0.05$, modular step size $\Delta = 1$, for the constraint $c_i = 10^{-2}$

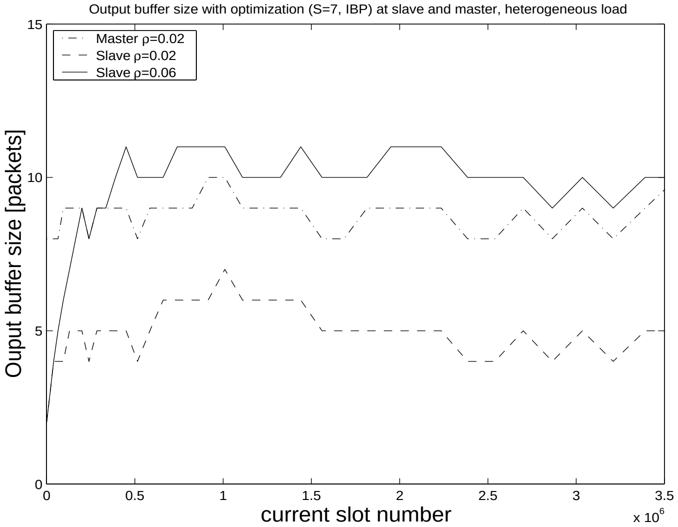


Figure 3.11: Transient behavior of output buffer sizes at master and slaves in heterogeneous traffic load scenario, modular step size $\Delta = 1$, for the constraint $C = 10^{-3}$

bility at each node increased to about $2 \cdot 10^{-3}$. This was expected, since the constraints were 10^{-3}.

In a heterogeneous traffic load scenario, the bursty sources are divided into two groups: high and low traffic intensities. For the case of the high traffic intensity group, which consists of two slaves, the probability that a job arrives from one source, ρ_H, is set to 0.06 and in the other group, the probability that a job arrives from one source, ρ_L , is set to 0.02.

Figure 3.11 shows the output buffer sizes for the master and the slaves with low and high traffic loads. As can be seen, although the output buffer sizes also approached to optimal values after $5 \cdot 10^5$ time slots of simulation time, the output buffer sizes for the nodes were different between the high traffic load and low traffic load groups.

3.7 Open issues

This chapter studied QoS issues and queueing model in Bluetooth, and proposed a method for buffer dimensioning for the nodes in Bluetooth networks by using simulation based approximated solution. A Bluetooth application model has been constructed and a simulation of a simple Bluetooth piconet was implemented, in which the near optimized values of buffer sizes that satisfying certain QoS requirements for Bluetooth nodes were found by applying the buffer optimization method.

However, through analyses of queueing model in Bluetooth networks as well as simulation, there are some open issues that need to be solved:

- The optimization method's analysis and simulation show that queueing sizes at some certain nodes are much higher than at other nodes. This is because for a certain traffic model and routing algorithm, the bottleneck phenomenon can happen at these nodes, due to the packet arrival rates exceeding the process abilities of these nodes. It indicates that for the nodes, such as master or bridge nodes, the bottleneck problem is significant and should be addressed in other network designs or control algorithms.

- The bottleneck problem deeply affects the QoS issues. It can cause packet loss due to buffer overflow, exceeded round trip time or seriously downgraded bandwidth of links in the Bluetooth network. There are several approaches to address this issue, including both intra and inter piconet scheduling, admission control, routing algorithm, network formation or network capacity allocation, etc.

- In Bluetooth networks, it can happen that the network topology can quickly change, from one topology to another topology. This scenario can occur when a Bluetooth device moves around and simultaneously joins several piconets at different time intervals. When traffic directions are changed, it could also result in creating new topology, with new masters or bridge nodes. Furthermore, traffic patterns can be robust and difficult to predict. As a result, the buffer optimization method should address to these issues.

- Some problems of Round-Robin polling are revealed. Because the Round-Robin scheme polls slaves in a fixed order, so when there are some variations of packet arrivals, it would not respond to these traffic variations. Several alternatives of Round-Robin polling have been proposed and these schemes are robust to traffic changes. Additionally, Differentiate Service (DiffServ) styled traffic priority based procedures have been proven for the integrated working environment of Bluetooth.

- Although this chapter has used the simple IBP traffic model to characterize bursty nature of data traffic, it also shows the need of investigating performance of the simulation-based buffer optimization method, when other traffic models, such as video streaming traffic, internet traffic, are independently multiplexed and transfered through the network. This type of traffic is characterized by alternating, randomly varying periods of inactivity and activity, and maybe it makes longer packet delays or requires larger buffer sizes. The generation of Bluetooth packets by a source, which can be voice or video, in the active state can be approximated as a Poisson process producing packet exponentially-distributed in length, i.e. the

Markov-modulated Poisson Process (MMPP). Internet traffic can be characterized by self-similar heavy-tail traffic.

3.8 Conclusions and future developments

In this chapter, the quality of services in Bluetooth networks were highlighted, a queueing model for Bluetooth networks has been developed and analyzed. It gave a simple case where a Bluetooth piconet using the strict Round-Robin polling and Poisson traffic arrivals could be analyzed as an $M/D/1$ queueing model.

A simulation-based optimization method has been used to determine the output buffer sizes for the master and slaves in Bluetooth networks. The application model of Bluetooth networks has been constructed and the buffer optimization method has been applied to this application model.

To understand the working abilities of the buffer optimization method in Bluetooth networks, a simulation of a simple piconet was carried out. The objective was to minimize the total cost function, while still satisfying the QoS criteria (the packet loss probabilities for the nodes in the simulated network). The traffic sources have been modeled by Interrupted Bernoulli Process (IBP), which gives behavior characteristics similar to data traffic: active and idle periods, bursty traffic, etc.

An advantage of this simulation-based approach is that no assumptions need to be made regarding the involving arrival and service distribution processes involved. Neither are any assumptions needed about the internal details of simulation model. In practical meaning, by using this simulation based buffer optimization method, Bluetooth device producer can predict performance and determine buffer requirements to satisfy QoS demands of the Bluetooth devices according to a specific network scenario and application.

The simulation results show that the performance of the piconet, in terms of queueing lengths and delays, is significantly affected by traffic intensities. During the optimization, the output buffer sizes approach to the optimal value and then fluctuate in a small region.

By using differently designed QoS criteria (e.g. packet loss probability), different expected buffer sizes according to these QoS criteria can be obtained. The optimization results have been verified by running simulations with preset buffer sizes to obtained satisfaction results.

This chapter also discussed some open issues concerning scheduling, bottleneck and capacity distribution. From the analysis and simulation model, some enhancements of inter-piconet scheduling, admission control and capacity allocation will be discussed in the next chapters.

Future works include using the simulation-based optimization method to dimension scatternet and to study different optimization patterns and control algorithms for Bluetooth networks. The performance of the method, when applying to various network topologies, and other traffic models, e.g. heavy-tail traffic, MMPP traffic, should be investigated.

Chapter 4

Predictive Scheduling of Inter-piconet Communication

4.1 Introduction

While the market for fixed, wired personal computers shows stagnating tendencies, mobile computing receives more and more attention. The number of mobile devices, which are used for many purposes, are steadily increasing. The main advantage of mobile devices is that users can travel all over global and they can access the Internet without the need of light of sight or access point knowledge. Mobile terminals for UMTS network can be used for watching movies downloaded from Internet or video conferences from different locations with a data rate, for example WCDMA, of up to 2 Mbps or 10 Mbps for its enhanced version.

To complement wireless cellular communications, which although have large radio coverage require infrastructure such as base stations, wireless short range communications and mobile ad hoc networks such as Bluetooth have gained special interests, in both research and applications.

The Bluetooth radio transmission uses a slotted protocol with a Frequency Hopping Spread Spectrum (FHSS) technique. The hopping rate is up to 1600 hops per second, for one slot packets. The radio spectrum is divided into 79 channels of 1 MHz bandwidth each. The frequency hopping scheme is combined with fast ARQ (Automatic Repeat Request), CRC (Cyclic Redundancy Check) and FEC (Forward Error Correction) to achieve the appropriate reliability of a wireless link. Communication in Bluetooth follows strict master-slave scheme. Every Bluetooth device has a unique Bluetooth device address. All slaves use the the master's clock and address to synchronize to the master frequency hopping sequence. The master allows slaves to transmit by allocating slots for voice and data traffic.

A collection of slave devices operating together with one common master is referred to as a $piconet$. A piconet can have up to 7 active slaves, with each slave only communicating with the shared master. A packet can be exchanged between master and slave device in each slot.

Even though all data is transmitted in packets, the Bluetooth packet can be carried in both synchronous data on Synchronous Connection Oriented (SCO) links, mainly intended for voice traffic, and asynchronous data on Asynchronous Connectionless (ACL) links. The master can allocate capacity for SCO links be reserving slots and for ACL links by using, for example, a polling scheme.

Since Bluetooth has been designed as short-range radio interfacing, normally a range of 10 m, and a maximum of eight active devices can be attached to a piconet. For the time being, a demand for a network with larger coverage than just 10 m and more than eight active devices leads the Bluetooth SIG to define a true mobile ad hoc network, $scatternet$, which is frequently referred as a Bluetooth Personal Area Network (PAN).

Although Bluetooth PAN, which comprises a number of inter-connected piconets, significantly increases network capacity and flexibility, this leads to numerous problems in terms of communication, such as synchronization issues between piconets. To overcome these drawbacks, some enhancements of the current network supports in Bluetooth are needed. These enhancements are to improve quality of services like packet delays, link bandwidths or to make use and flexibility of Bluetooth devices easier. Furthermore, the new concepts introduced in Bluetooth systems, e.g. piconet and scatternet scheduling, need to be understood to exploit efficiently the ability of the new technology. Concerning to Bluetooth scatternet, the issues of Inter-piconet Communication and Inter-piconet Scheduling have special roles and become hot topics for discussion in the SIG as well as in research.

Inter-piconet scheduling, which is to be described in more details in sections 4.4 and 4.5, is to allocate durations of the shared device, which is called the bridge node, to be active in the interconnected between piconets. As bridge node can be master or slave that operates in time division manner on two or more inter-connected piconets, which have different frequency hopping sequence, clock, and Bluetooth is supposed to support both voice and data services with different QoS demands, the inter-piconet scheduling should address to these requirements.

This chapter formulates the inter-piconet scheduling optimization problem and presents an approach as an approximate solution to facilitate inter-connection between piconets, which use ACL links to transmit Bluetooth data packets. The main idea is to re-distribute the capacity of Bluetooth networks based on inter-piconet scheduling and prediction of inter-connected traffic. The purpose of the optimization problem of the inter-piconet scheduling is to answer the question of 'how to schedule the bridge node, which has very limited resource, to be active in the inter-connected piconets and to satisfy the QoS demands, such as time delays, packet losses, required by data applications'. This inter-piconet scheduler should give the best resource utilization, and support QoSs. To simplify the optimization process, a heuristic predictive inter-piconet scheduling is proposed, which takes bridge node available resource, QoS demands into account, and increases the utilization, e.g throughput, of bridge node. The chapter is structured as follows: section 4.2 takes in to account some related works, section 4.3 describes some simple features of the Bluetooth scatternet, section 4.4 presents the inter-piconet communication and some inter-connected issues, a inter-piconet scheduler is described in section 4.5, background for the inter-piconet predictive scheduling is mentioned in section 4.6, section 4.7 formulates the inter-piconet scheduling optimization problem, section 4.8 describes the inter-piconet scheduling approach and its performance is illustrated in section 4.9 through simulations, some extension issues are discussed in section 4.10, and the last section is devoted to conclusions and some future developments.

4.2 Related works

The emergence of Bluetooth Technology has opened many exciting research areas. These research topics spread in a large range, from radio links, MAC layer to QoS issues or application scenario of Bluetooth. Although some researches have been done, still a large number of open issues need to be carried out. These should be done in close collaboration with industry.

Research on the Bluetooth inter-piconet communication and scheduling is quite hot topic. In [42], the author proposed a rendezvous point based inter-piconet scheduling. The proposed algorithm calculates the possible forward throughput between the visiting piconet and all piconets it connects to, as if the inter-connected link had already been established. For each possible rendezvous slot it looks at the minimum among forward throughput, then keeps the point that results in the maximum of the minimum forward throughput.

A credit based scatternet scheduling has been proposed in [16]. The authors have defined presence points for each inter-piconet link at which communication may start. The SNIFF mode provides the basis mechanism to implement the presence point concept and the scheduling is to decide when to abort an ongoing SNIFF event in order to use an upcoming SNIFF slot and this decision is based on link credits. The link credit represents the use of one slot of the corresponding link. An ongoing SNIFF event is aborted in order to use another link's upcoming SNIFF slot, if the latter has a higher number of credits, indicating a lower relative allocation of airtime for the corresponding link. An enhancement of adaptive presence point density can be implemented.

In [75], the authors proposed the Pseudo Random Coordinated Scatternet Scheduling algorithm to perform scheduling of both intra and inter piconet communications. In this algorithm, Bluetooth nodes assign meeting points with their peer nodes such that the sequence of meeting points follows a pseudo random process that is different for each pair of nodes. The uniqueness of the pseudo random sequence gives occasionally collision of different peer nodes.

In [36], the authors have shown that constructing an optimal inter-piconet schedule is an NP hard problem, and propose a scheduling algorithm referred to as Distributed Scatternet Scheduling Algorithm. Although the algorithm provides a solution for scheduling communication in the scatternet, some of its idealized properties and its high complexity make it difficult to apply in a real environment.

4.3 Bluetooth scatternet

In a Bluetooth PAN context the scatternet functionality is important to allow forming of ad hoc PANs. Although Bluetooth PAN originally focused on piconet, the possibility of a node that can participate in multiple piconets will open many new usage scenarios of Bluetooth devices. The node participating in multiple piconets, called the inter-connected bridge node, will allow creation of a bigger PAN network than a single piconet. This bridge node will forward traffic between piconets. To give an example, a Bluetooth PAN comprises a number of devices, such as printers, notebooks, mobile phones, or LAN access points. The traffic can be between devices, like notebooks and printers or Internet access through LAN access point. The Bluetooth PAN can have a master at LAN access point, another master at a notebook computer and a notebook computer as a bridge node to transfer inter-piconet traffic. Thus the bridge node will switch between piconets. Figure 4.1 shows a case of a scatternet.

Even though current Bluetooth specification describes rather in detail about piconet, from radio, baseband layers to Bluetooth PAN profile, it gives very little information about scatternet. The methods for scatternet formation, inter-piconet communication and controlling services have not been clearly considered. Especially inter-piconet scheduling with a controlled delay and throughput has not been addressed in Bluetooth specification.

The formation of scatternet will extend the rather limited capacity of Bluetooth piconet. It permits the creation of a mobile ad hoc multihop network, which allows traffic to be transfered through a number of hops. As a result, the communication distance can reach beyond the 10 m radio link limit of normal Bluetooth nodes.

The scatternet may enhance traffic of certain applications. For example, the LAN access point can be a master and one of the slaves can be become the bridge node, so that traffic from distant devices can be transfered or Internet webpages can be downloaded through the Bluetooth access point.

By dividing a large, single piconet into a scatternet, which consists of some small pi-

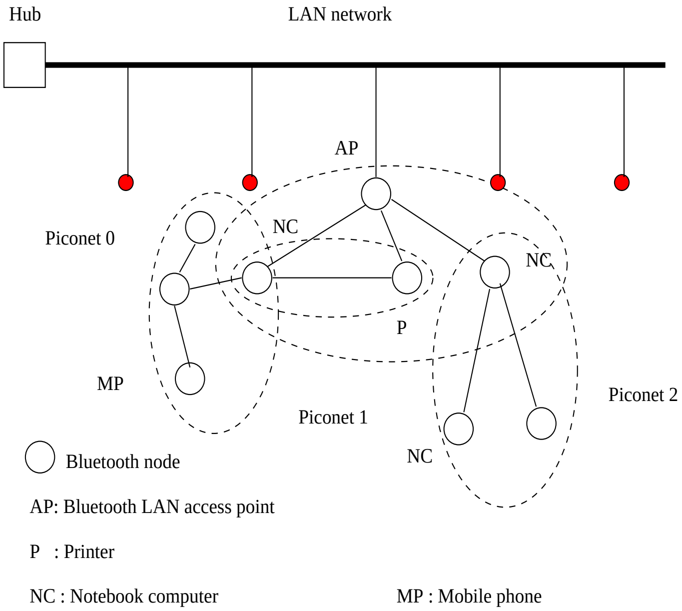


Figure 4.1: A Bluetooth PAN with an LAN Acess Point

conets, the overall capacity of Bluetooth PAN may be increased. We use the figure from the previous example. From the topology, it can be seen that for printing applications, there is no point of sending data through the access point, which is a master. A small piconet can be setup between the printer and the notebook, so that the network capacity will be efficiently exploited.

From these points, scatternet formation might have significant impacts on overall network capacity of Bluetooth PAN. The formation of piconets and scatternet should be able to adapt to the changes of connections, traffic characteristics and node mobility. Setting up new piconet or deleting a piconet might be done to achieve the optimal topology, in which the network throughput can be maximized, packet delays are minimized, etc. This formation will use the Bluetooth connection establishment commands, such as INQUIRY and PAGE.

4.4 Inter-piconet communication

Because Bluetooth is based on master-slave, where traffic flows between master and slaves in a piconet using TDD scheme, a node can participate in multiple piconets. Although a Bluetooth node can be in more than a single piconet, it can be a master in

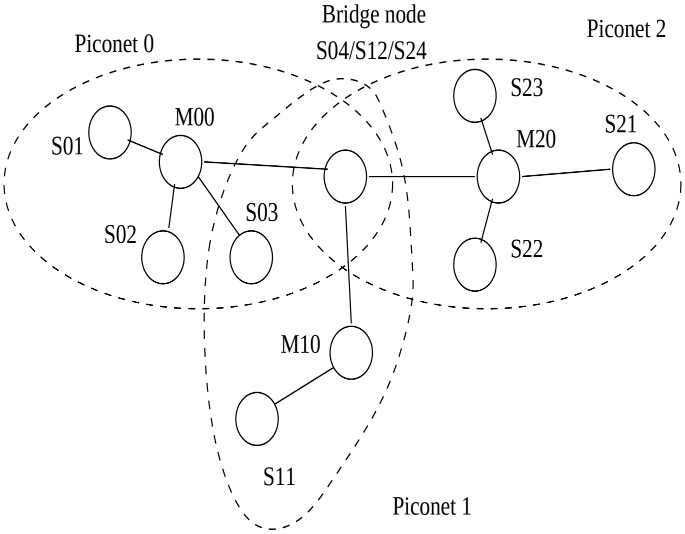


Figure 4.2: A scatternet with a bridge node connected by three piconets

only one piconet. The node participating in multiple piconets will serve as a bridge thus allowing formation of a larger network, scatternet. When a node from a piconet wants to join another piconet, it will use INQUIRY and PAGE commands. The bridge node switches between piconets using time divisions.

Bluetooth specification creates low power modes, where a slave can be in SNIFF, PARK or HOLD modes, and these modes can be applied to the bridge node. A slave can be polled by master in a piconet and change to SNIFF, for example, to be in ACTIVE state in another piconet. Figure 4.2 shows an example of scatternet, where the bridge node is connected by three piconets, $P0$, $P1$, and $P2$.

Because the master clock controls piconet timing and slaves set to be synchronized with the master clock, it needs to synchronize from one piconet to another piconet. Furthermore, when a slave device returns from low power mode, it has not been accessed by the master for a while, its clock will have drifted with the master clock. Normally the slave predicts the start of the next transmission from master and scans to synchronize for a period of 10 μs. The worst case allowed by the Bluetooth specification is a clock with a jitter of ± 10 μs and drift of 250 ppm (part per million). Thus when a bridge node switches between piconets, it may take some time and this also affects the performance of scatternet.

In [66], the authors have showed that the total number of Bluetooth links and the number of bridge nodes have a large impact on the scatternet performance, such as throughput. When increasing the number of bridge nodes, there are more links created and as a result, the network carries a higher the amount of traffic. However due to effect of bridging overhead, the overall capacity of network will not increase but begin to decrease.

Another factor that also has a large impact on performance of scatternet is inter-piconet scheduling. When the bridge node presents in its connected piconets, an algorithm to schedule the time of be active in a piconet is necessary. The inter-piconet scheduling should be distributed and adapt to inter-connected traffic.

The bridge node can only exchange data about traffic, delays, etc. with the master when it is active in that piconet, so the inter-piconet scheduling should coordinate between master and bridge slaves.

Clock drift will affect the bridge overhead, which reduces the network capacity. When the bridge node is switched between piconets, it has to synchronize in phase and frequency with the master time slot clock of the piconet that it is active. A design of the inter-piconet scheduling should take into account of clock drift.

In addition, a combination of polling scheme within piconets and inter-piconet scheduling can also increase efficiency of the network. For example, when there is high load between piconets, the bridge node should be polled more frequently so that it can serve more traffic flows and reduce delays.

4.5 Inter-piconet scheduler

The current version of Bluetooth Specification (v1.1) does not give detailed information about scatternet and does not describe how to implement inter-piconet communication. In [15], the authors proposed a scatternet scheduler. The overview block diagram of the scheduler for a node is described in figure 4.3. The scatternet scheduler consists of two parts: Master-Slave scheduler and Inter-piconet scheduler. The Master-Slave scheduler residing in the Master uses a polling scheme to control traffic flows within piconet. Several polling schemes have been proposed, such as Fair Exhaustive Polling (FEP) or Predictive Fair Polling (PFP), which provide an efficient and fair bandwidth distribution to the Bluetooth devices inside the piconet.

The inter-piconet scheduling uses a time-sharing basis to schedule ACTIVE intervals of the bridge node in a piconet. During the time that the bridge node is not ACTIVE in that piconet (to move to the ACTIVE state in the other connected piconet), it will switch to the lower power save mode, i.e. to SNIFF or HOLD modes. The duration and time to be ACTIVE in a piconet and to change to another state are determined by the inter-piconet scheduling algorithm residing in the scheduler. Updating ACTIVE, SNIFF or HOLD intervals can be done through messages exchanging between Link Manager Protocol (LMP) layers, when the bridge node is in ACTIVE state in the piconet.

Information about traffic, delays or network status, etc., are messaged between nodes. Whenever the bridge node is active in a piconet, the master starts to exchange packets

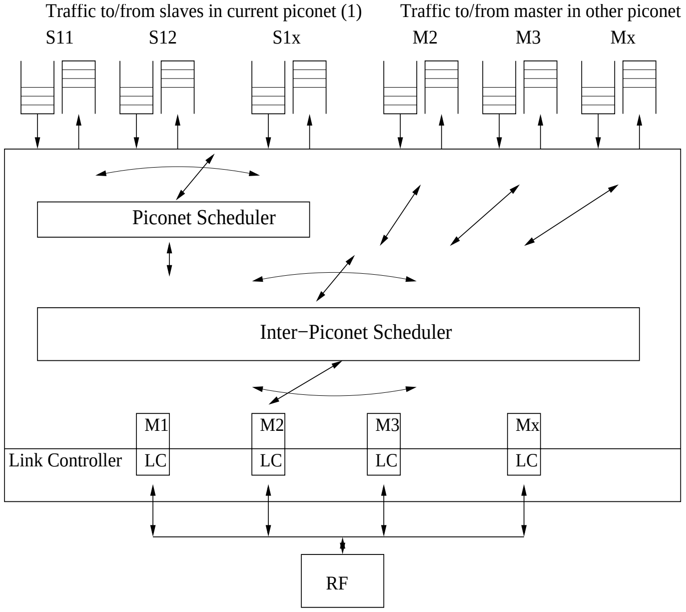


Figure 4.3: Scatternet scheduler sub-layer in master node [15]

with it, and stops when the active duration in the piconet is finished. The inter-piconet scheduler in each node will use this information and coordinate with the peer inter-piconet scheduler in the other nodes. The results of the coordination are the time and duration of the ACTIVE, SNIFF or HOLD states for the bridge nodes.

Some applications can strictly require on bandwidth, time delays, etc. These QoS requirements are given to the inter-piconet scheduler. By changing the time and the duration of ACTIVE state of the bridge node, these requirements can be satisfied in a certain level.

The coordination between inter-piconet scheduling and polling schemes of the connected piconets should be optimized. When the bridge node is not in ACTIVE state of a piconet, to increase efficiency of the network, it should not be polled by the master of that piconet. Messages for the coordination are exchanged between the inter-piconet scheduler and masters, which control polling schemes of piconets.

To implement these functions of the inter-piconet scheduler, some modifications of LMP defined in the current version of Bluetooth Specification are needed. It could be new types of messages, or extensions of current messages, etc.

4.6 Background of the predictive inter-piconet scheduling

We assume that a number of piconets have been formed and maybe two or more piconets will be inter-connected together to create a larger network, scatternet. The topology of the new network is set by the network formation algorithm and there are several criteria that would affect the decisions of the network formation algorithm, as mentioned in section 4.3. To set up an inter-connection, a node in a piconet will use INQUIRY and PAGE to join another piconet within its radio range. When this node becomes member of the other piconet, it will have a role as a bridge to carry inter-piconet traffic between the connected piconets.

Because the bridge node is in the ACTIVE state in each connected piconet at different slot timing, the inter-piconet scheduling will determine the time point to switch between the piconets. When the bridge node is not active in a piconet, it will be shifted to low power mode, e.g. SNIFF mode or HOLD mode.

In SNIFF mode, the time interval is periodic and the bridge node will change to ACTIVE state or return to SNIFF state simultaneously. In HOLD mode, after the HOLD time interval, it is necessary to identify a new time point. Thus for a not too much dynamic environment, perhaps the SNIFF mode is more suitable, because fewer messages are needed, comparing to that of the HOLD mode. It means the bridge overhead can be reduced.

For each bridge node, the inter-piconet scheduler maintains an inter-piconet scheduling window, in times slots. The scheduling window defines which piconet is active or idle (sniff) and for how long. The ACTIVE and SNIFF states cycle in the scheduling window. The size of the window T_{SW} in time slots is varied, depending on traffic load passing through the bridge node. In the scheduling window, the bridge node is only active in one piconet at a time and the active duration of the bridge node in the piconet depends on the inter-connected traffic through the bridge node between the piconet and others.

Figure 4.4 illustrates an example of a scheduling window for a bridge node inter-connected to three piconets in the scatternet in figure 4.2. The effect of clock drift is eliminated and the ACTIVE state of the bridge node in each piconet occurs in cycles. First, the bridge node is active in piconet p_0, and is idle (sniff) in other piconets. After a duration of $T^A_{p_0}$, it changes to idle (sniff) state in piconet p_0 and becomes active in piconet p_1. While active in piconet p_0, Bluetooth packets between the piconet and the others are routed through the bridge node, and also between other nodes in the piconet and the bridge node. Thus, a coordination between polling and scheduling of intra-piconet and inter-piconet, respectively, is necessary. The active state is shifted from one piconet to another piconet in cycles defined by the scheduling window, and the process continues until the inter-piconet communication through the bridge node is no longer necessary or an inter-connected pattern is established, e.g. the bridge node joins in new

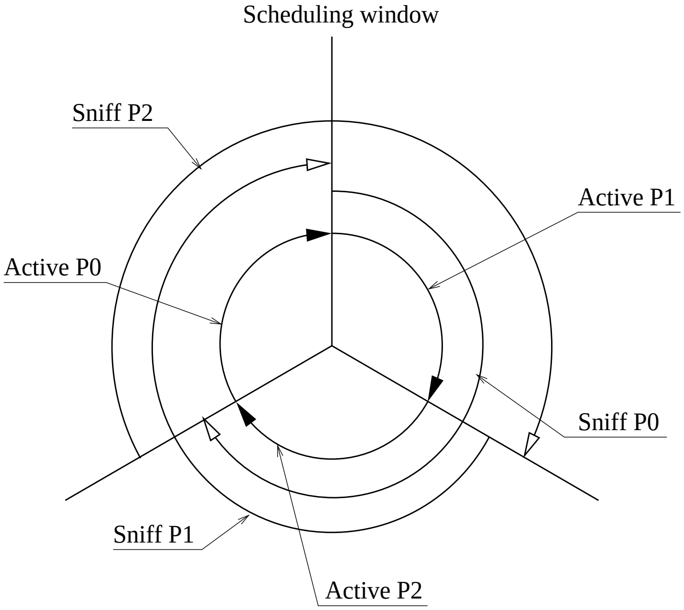


Figure 4.4: Scheduling window for a bridge node connecting to three piconets

piconet or leaves a currently connected piconet. In that case, a new scheduling window should be determined.

To further illustrate the timing of the scheduling window set up through SNIFF mode, the scheduling active frames for the bridge node connecting to the masters in piconets p_0, p_1 and p_2 are depicted in figure 4.5. During the operation, the scheduling window and active frames may be adjusted according to the traffic pattern or the network topology. As indicated in figure 4.6 a larger scheduling window will make longer packet queueing and increase packet delays at bridge node, and inversely a smaller scheduling window will create inter-piconet overheads to the network, which reduce network flows or increase packet delays. The inter-piconet scheduling algorithm handles these scheduling and activation changes and the messages between the connected nodes, where the inter-piconet scheduler resides in, are exchanged through LMP layers.

4.7 Inter-piconet scheduling problem formulation

We consider a Bluetooth scatternet model with nodes $J = \{1, .., J\}$. The scatternet consists of $N = \{0, .., N-1\}$ piconets which inter-connect through bridge nodes. Let $B = \{1, .., B\}$, where $B < J$, be a set of bridge nodes. The links between the nodes are

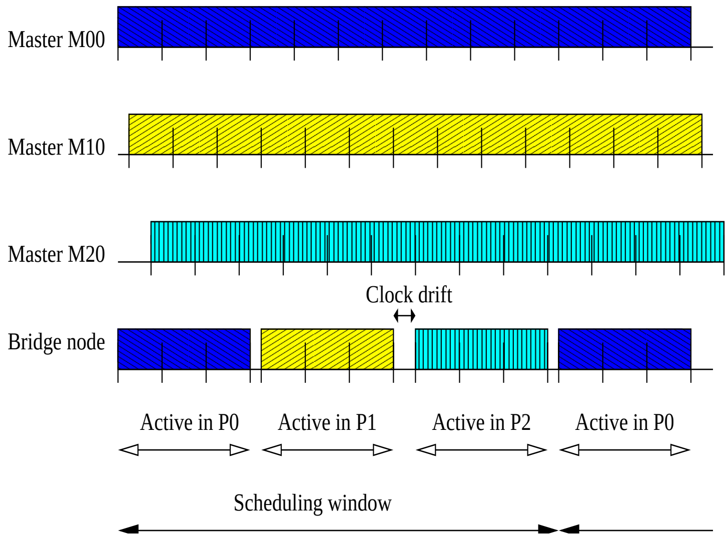


Figure 4.5: Scheduling frames for a bridge node connecting to three piconets

given by $L \subset J \times J$, where $L_{ij} \in L$ is a directional link that connects node i to node j, $i, j \in J$. $Z(i)$ is a collection of node i's neighbors. Assume that each link is assigned to a capacity c_{ij} and the bridge node has capacity C_b, $b \in B$.

The objective is to find the schedule $S_b = \left(\{\alpha_{ij}c_{ij}\}, \{t^{sd}\}, \{f_{ij}^{sd}\}\right)$ for inter-piconet traffic from the sources to the destinations at the bridge nodes that maximizes the flows and minimizes the total costs, which represent the price to obtain the QoS requirements, which can be packet loss probabilities for sources. t^{sd} is total traffic carried from source s to destination d, f_{ij}^{sd} is an amount of traffic from source s to destination d transfered through link L_{ij} connecting to bridge node b, where one of nodes on the link is bridge node, $\langle i \parallel j \rangle \equiv b$. Let $\alpha_{ij}c_{ij}$ be fraction of time that link L_{ij} connecting to bridge node b active.

In order that the inter-piconet links are in equilibrium state, the capacity of each link must not be exceeded, which itself is limited by the capacity of the bridge node:

$$\sum_{s}\sum_{d} f_{ij}^{sd} \leq \alpha_{ij}c_{ij} \tag{4.1}$$

$$\sum_{\langle i \| j \rangle \equiv b} \alpha_{ij}c_{ij} = C_b \tag{4.2}$$

If these conditions (eq. 4.1 and 4.2) are satisfied for all bridge nodes and all variables are non-negative (i.e. $0 \leq t^{sd}$, and $0 \leq f_{ij}^{sd}$), then from [74] we can find feasible schedules

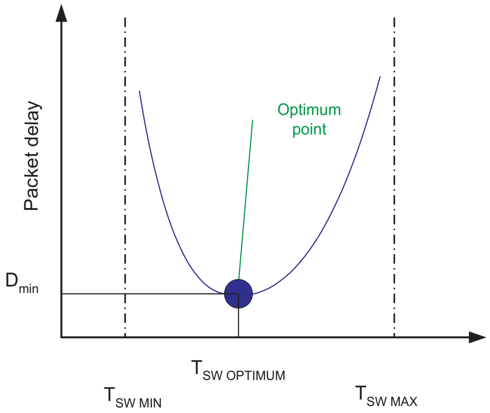


Figure 4.6: Relationship between scheduling window and packet delay

$S = \{S_b\}, \forall b \in B$, which is stable point of the inter-piconet system that maximizes the total flows and minimizes the cost functions:

$$\max_{S=\{S_b;\ \langle i \| j\rangle \equiv b\}} \sum_s \sum_d \left\{ \Delta_b U_b(f_{ij}^{sd}) - \beta_b \Phi_b(f_{ij}^{sd}) \right\} \tag{4.3}$$

where Δ_b and β_b are the weight constants, $\Phi_b(f_{ij}^{sd})$ is cost function, and $\langle i \parallel j\rangle \equiv b$. Since our goal is to build a scheduler that maximizes network flows, the cost function can be the loss rates of transmitting Bluetooth packets from sources to destinations in the network and we assume that it is non-negative, continuous, increasing function. The result of solving the optimization problem of inter-piconet scheduling is the optimum point, in which the inter-piconet scheduler transfers maximum throughout at lowest packet delay level for traffic between the connected piconets, as indicated in figure 4.6.

Due to the fact that solving this formulated equation to find the optimal solution is quite complicated, which can be NP hard problem, a predictive inter-piconet scheduling is proposed as an approximated solution in the next section.

4.8 Predictive inter-piconet scheduling approach

The predictive scheduling approach for inter-piconet communication is based on estimation and prediction of traffic between piconets handled by the bridge node, which is controlled by the inter-piconet scheduler. The scheduling approach is distributed, which is necessary in mobile ad hoc environment of scatternet, and there is no central entity or prior assumption about the network. It will try to allocate adaptively just enough capacity of the bridge node to each piconet, which it is connected to, by changing the scheduling window and active frames, in order to satisfy QoS requirements. The QoSs can be buffer sizes, packet delay, number of packets queueing, throughput, etc. On the other hand, it will try to reduce the bridge overheads, which exist in the inter-piconet communication. The reduction can be through using SNIFF mode or minimizing the messages exchanged between the inter-connected nodes.

In the predictive scheduling approach, after the inter-connected communication is established, the bridge node sets up pre-determined ACTIVE and SNIFF intervals for each connected piconet. The traffic information is periodically updated by the inter-piconet scheduler. The information can be the current traffic loads, utilization or measured traffic flows through the bridge node between piconets. The offered traffic is estimated from a record of the collected information. It is also possible to be fed the traffic demands from the piconets. These update and estimation of the traffic give the scheduler real-time information about transient behaviors of current traffic in the network. Thus the scheduler can adjust its allocations to adapt to QoS demands.

There are several approaches to obtain information about traffic information and prediction, among these, the mechanism proposed by R.A. Yahiz and G. Heijenk in [1], which uses fractional-model based predictor, gives both efficiency and fairness. Some other predictors, which are based on the Linear Minimum Mean Square Error (LMMSE) estimation, can perform approximately accurate as the fraction-model based predictor, and yet can be practically implemented [20].

The predicted traffic is compared with the allocated capacity, accompanied by a specific scheduling window, and the inter-piconet scheduler will decide whether the allocated capacity can satisfy the demand traffic with QoS criteria and changes the allocated capacity to meet the requirements. These decisions are done when there is a certain traffic change or by periodic intervals. The allocated traffic accompanied by the scheduling window of the bridge node is then divided to each piconet connected to the bridge node. The division is based on the predicted inter-connected traffic on each piconet routed through the bridge node, and the active intervals of the bridge node in each connected piconet will be identified from the its allocated fraction in the scheduling window.

Figure 4.7 illustrates the steps for the predictive inter-piconet scheduling approach. In very first step, the traffic information about inter-piconet communication is measured and updated to the inter-piconet scheduler. Depending on QoS requirements, the inter-connected traffic information can be traffic intensities between piconets, delay or throughput, etc. The updating interval is T_u and can vary in accordance with each specific traffic model. Longer updating and measurement intervals can give better information for prediction, however it also gives a certain delay to respond to fast fluctuation of traffic, thus creates errors of the allocation process. The following process is to estimate and predict the offer traffic based on history records of the updated traffic information.

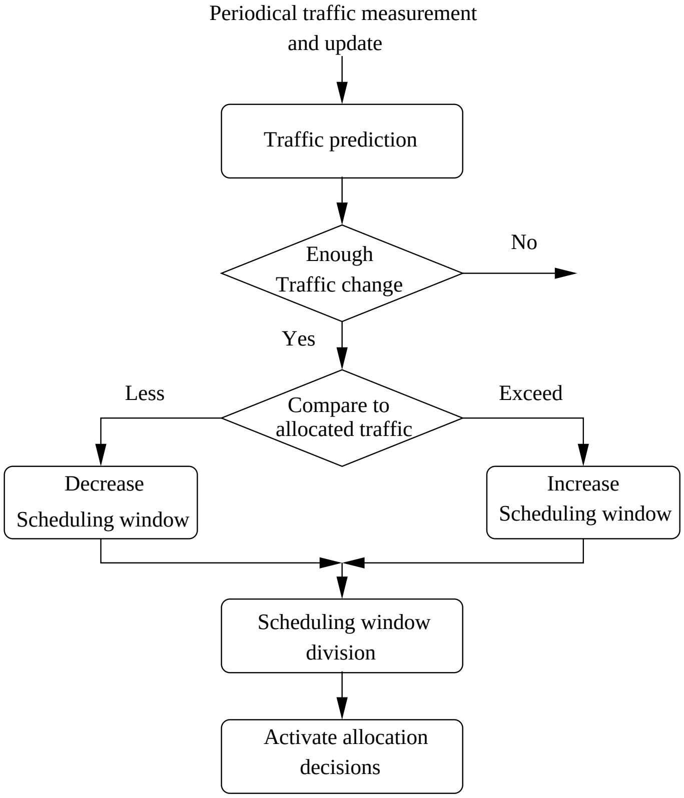


Figure 4.7: Predictive Inter-piconet scheduling approach

Some further information about packet arrivals can assist to the prediction.

The next step is to change the allocated capacity according to the predicted traffic. To reduce the bridge overhead, the process of allocating capacity is only initiated when the scheduler measures a significant change in the predicted traffic. After initialization, the scheduler will compare the predicted offer traffic with the current allocated traffic to find whether the offer traffic will be excessive or not. If it occurs, an increase of the scheduling window is needed. Inversely, the scheduling window is reduced in the case where the offer traffic is less than the current allocated traffic. Thus, by changing the scheduling window size T_{SW} a correction amount of ΔT_{SW}, a certain QoS criteria, such as delay, queueing size, for inter-piconet packets can be reached. The calculations of how much the scheduling window size should be is quite complicated and depends on the traffic pattern. An adaptive approach with fixed steps or with varying steps, which are based on the complex inter-piconet traffic analysis, may be applied. Another approach to simplify calculations is based on a look-up table. The look-up table contains the pre-calculated scheduling window according to specific traffic.

In the next step, the scheduler assigns the results of the inter-piconet scheduling process to each piconet connected to the bridge node. To make the decision, the scheduler will use the analysis of the predicted traffic. It calculates the predicted traffic on each of the connected piconet's directions that supposes to route through the bridge node. The active interval of the bridge node in piconet k in the scheduling window depends on its fraction in the total inter-piconet traffic through the bridge node:

$$T_A(k) = \gamma(k) \frac{F(k)}{\sum_{i=0}^{n-1} F(i)} T_{SW} \tag{4.4}$$

where $T_A(i)$ and $F(i)$ are the active intervals of the bridge node in piconet i and the predicted inter-piconet traffic to this piconet, respectively. n is the number of piconets connected to the bridge node and $\gamma(k)$, where $\gamma(k) \geq 0$ and upper bounded by $\sum_{k=0}^{n-1} T_A(k) = T_{SW}$, is relative proportion constant of piconet k.

In the last stage, the scheduler will activate the new scheduling window and the active intervals of the bridge node in the piconets. The on-going scheduling window is depleted to change to the new allocation. As a result, the fair share capacity allocation of the bridge node to each connected piconet is done based on the total inter-piconet traffic demand and the predicted traffic to each piconet.

Figure 4.8 describes the process that the scheduler changes the bridge node to active or idle (sniff) state in its connected piconets. After initialization, the scheduler sets the bridge node to operate with a pre-defined scheduling window and active intervals in each piconet. It also sets the active cycle of these piconets. The current active state of the bridge node in a piconet will be continued if the measured amount of time that the bridge node is active in this piconet is still less than the active interval of the bridge node for the piconet in the scheduling window or there is still traffic exchanged between the bridge node and its connected master. The scheduler will only change the bridge node to active in the next piconet defined in its scheduling window and set the sniff state of the bridge node in the current piconet if the duration of active state in the current piconet is expired or if it senses the POLL or NULL packet exchanges with the master in the current active piconet. In this case, the bridge node has nothing to send to the corresponding master or inversely, the master has nothing to send to the bridge node. During its operation, the scheduler will update the new scheduling window as well as the active intervals of the bridge node in the connected piconets.

Thus the active intervals of the bridge node in the connected piconets are varied, depending on the predicted inter-piconet traffic and QoS criteria, and these variations of the active intervals are transient as long as the bridge node is still connected to these piconets or the current network topology is still valid. The capacity allocation results of

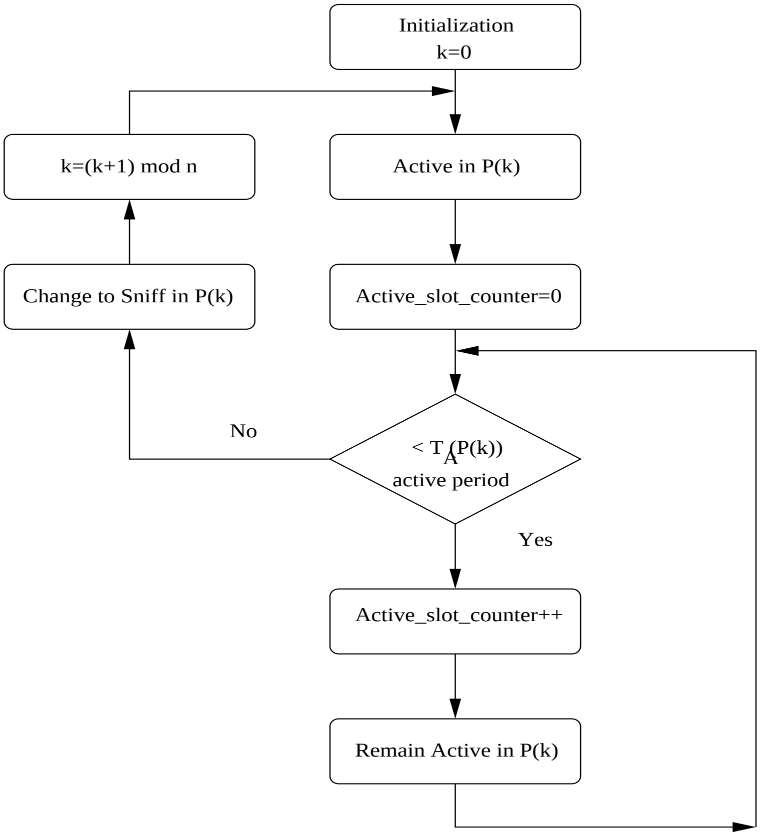


Figure 4.8: The process that the bridge node is scheduled in its connected piconets

this predictive scheduling are approaching to optimal allocation that minimizes the cost to obtain QoSs and maximizes efficiency of the bridge nodes [74] [68].

4.9 Simulation

4.9.1 Simulation model

The simulated system in consideration is a simple Bluetooth scatternet as depicted in figure 4.9, which consists of two inter-connected piconets. Each piconet provides full-duplex transmission using time slots, where each slot is 0.625 ms long. Polling in Bluetooth piconets can be done in many different ways. The difference between the polling

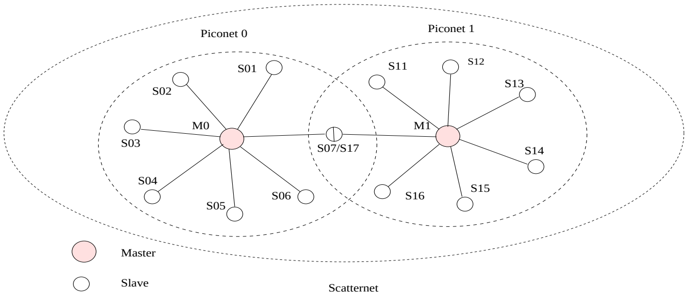


Figure 4.9: The scatternet model with two inter-connected piconets

schemes is related to the order in which slaves are polled and the service disciplines are used to serve a slave. In this simulation, we use the Fair Exhaustive Polling (FEP) [35]. One of main advantages of the FEP scheme is that it gives a high bandwidth efficiency with fair allocation while still being simplistic.

Each piconet has a master and N_S slaves, $0 \leq N_S \leq 7$. We assume that each piconet has maximum number of slaves, i.e. 7 slaves. Two piconets are inter-connected by a bridge node (the slave $S07/S17$) and its traffic can be modeled as in [81]. Although Bluetooth can support both synchronous services such as voice traffic, and asynchronous services, such as data traffic, however in this simulation, we just consider bursty data traffic and Asynchronous Connectionless links (ACL) between nodes in the modeled scatternet. Data traffic is transfered between the Bluetooth nodes and the inter-piconet data packets are passed through the bridge node (node $S07/S17$ in the modeled scatternet as depicted in figure 4.9). It is possible to send Bluetooth packets with multiple slot packet length, which may be either 3 or 5 slots long. To simplify, in this simulation we consider only single slot data packets transmitted between nodes in the modeled network. As we study Bluetooth scatternet performance in terms of queueing, it may be assumed that there is no packet loss due to transmission errors and buffer sizes of the devices are infinite. Moreover, as mentioned in [89], the piconets are assumed to be synchronized, which means that the effects of the clock drifts are neglected and there are no guard frames between nodes, when the bridge node switches to be active in the piconets.

For homogeneous traffic scenario, the packet arrivals can be modeled by an Interrupted Bernoulli Process (IBP) [82]. The IBP traffic reflects the bursty nature of data traffic, which is very common in Bluetooth data services, such as file transfer services, internet traffic or multimedia applications. Incoming and outgoing traffic between nodes in the scatternet are equally distributed. The probabilities of an IBP source being in an ON state and an OFF state are p and q, respectively, as depicted in figure 4.10. The probability to change from an ON state to an OFF state is $(1-p)$ and to change from an OFF state to an ON state is $(1-q)$. The probability for a packet arrival in one slot is v and it is set to zero in the OFF state and one in the ON state. The packet arrival is set to be aligned

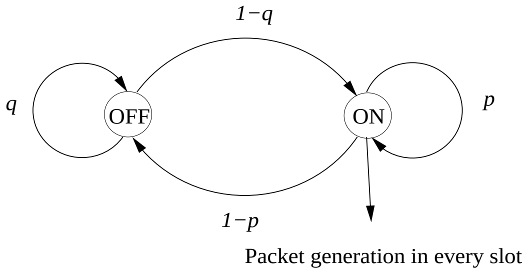


Figure 4.10: Markov transition model of IBP source

with time slots for the modeled piconets.

In equations 4.5 and 4.6, the probability that a job arrives from a IBP source, ρ and the squared coefficient of variation, C^2 for packet arrival time are used to express the burstiness of the traffic source[89]:

$$\rho = \frac{1-q}{2-p-q} \tag{4.5}$$

$$C^2 = \frac{(p+q)(1-p)}{(2-p-q)^2} \tag{4.6}$$

From the queueing analysis described in chapter 3 and in [69], to simplify the inter-piconet traffic prediction process, information on queueing size status of Bluetooth packets at the masters and the bridge node is used for the traffic prediction at the scheduler.

At the initialization, the scheduling window T_{SW} of the bridge node for inter-piconet communication is set to 400 time slots and is fairly allocated to each piconet, piconets p_0 and p_1. The simulation length is 10^6 time slots for all simulations. When applying the inter-piconet predictive scheduling approach, the scheduling window T_{SW} is updated and changed adaptively in accordance with the predicted traffic and queueing packets at the output buffers of the Bluetooth nodes. The active intervals of the bridge node in each connected piconet are dynamically varied, depending on the inter-piconet traffic, which comes through the bridge node.

4.9.2 Numeric results

The simulations were carried out for both imbalance and balance arrival traffics. In the balance mode, the traffic to and from a Bluetooth node in the modeled network is assumed to be symmetric and packets outbound from a node are equally destinated to the other nodes. Figures 4.11, 4.12 and 4.13 show the mean queueing lengths for homogeneous balance traffic loads for three output buffers: master, the bridge node and a slave.

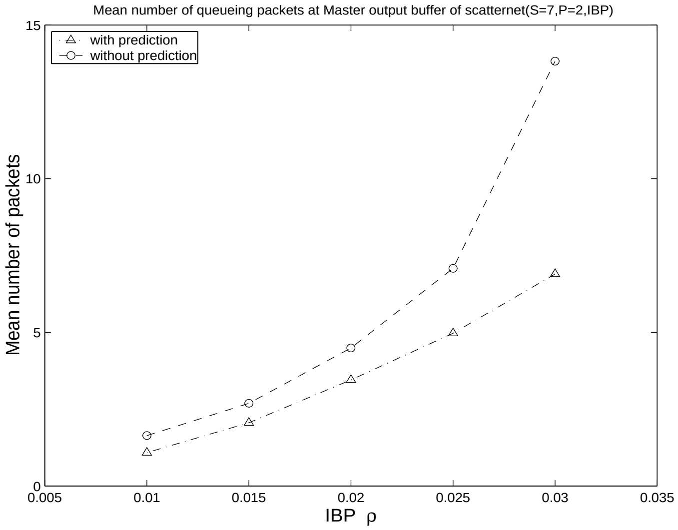


Figure 4.11: Mean number of data packets in master output buffer, with and without the predictive inter-piconet scheduling for piconets using FEP polling scheme, homogeneous balance traffic loads

As can be seen, the mean queueing lengths increased, when the traffic load increased. The traffic load depends on the probabilities of being in the ON states and in the OFF states of the IBP traffic sources that were connected to the nodes in the scatternet. Higher traffic load means higher queueing length. However, the mean queueing lengths were significantly reduced, when the predictive inter-piconet scheduling was applied. The mean queueing length at the bridge node was much higher than the queueing length at the other nodes, especially at the slaves. This was because of the homogeneous balance traffic. Furthermore, the inter-piconet packets were transfered through the bridge node, which made the bridge node become sensitive to congestion. The mean queueing lengths more severely increased when the predictive scheduling was not used, compared to the case when it was.

In the imbalance traffic load scenario, the traffic sources connected to piconet 0 generated packets which were destined less to the nodes within the piconet than to nodes outside that piconet. This scenario is designated to determine the working ability of the predictive scheduling, when traffics are highly imbalanced. The imbalance rate R_0, which was defined as the probability that a generated packet was destined to a node within the piconet, was set for 0.35 to piconet 0. This meant that there were very high rates of packets from the nodes in piconet 0, which were addressed to the nodes in piconet 1. The destinations for the packets generated from the nodes in piconet 1 were still kept symmetric as in the previous experiments. The simulation results of a master

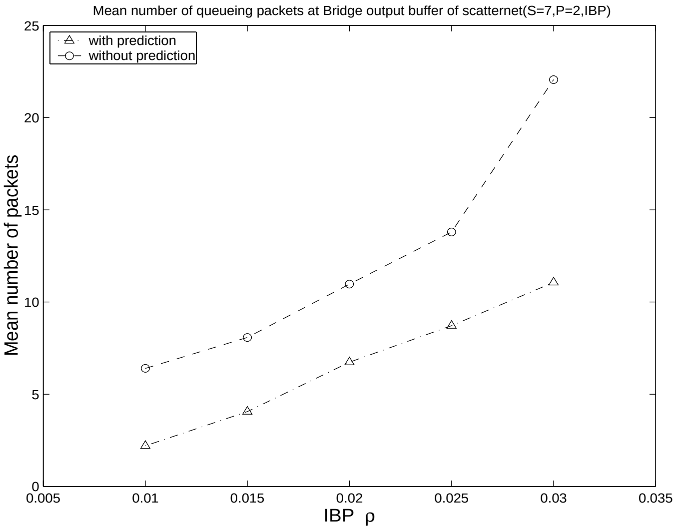


Figure 4.12: Mean number of data packets in the bridge node's output buffer, with and without the predictive inter-piconet scheduling, for piconet using FEP polling scheme, homogeneous balance traffic loads

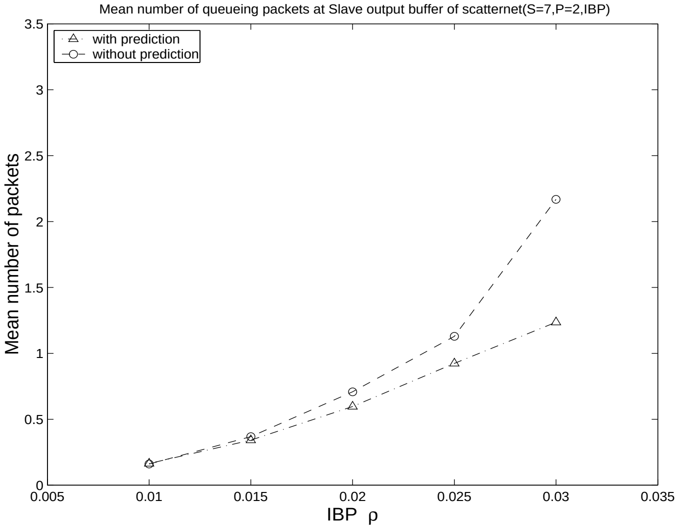


Figure 4.13: Mean number of data packets in a slave node's output buffer, with and without the predictive inter-piconet scheduling, for piconet using FEP polling scheme, homogeneous balance traffic loads

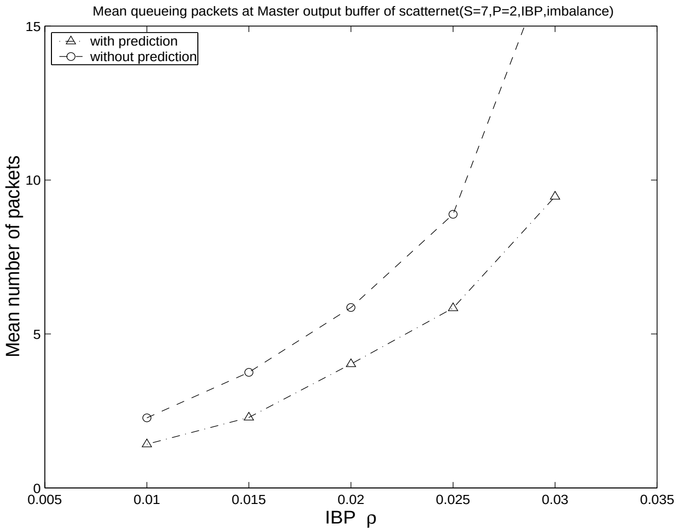


Figure 4.14: Mean number of data packets in a master node's output buffer, with and without the predictive inter-piconet scheduling, for piconet using FEP polling scheme, imbalance traffic loads, imbalance rate $R_0 = 0.35$

and the bridge node for the imbalance traffic load scenario are shown in figures 4.14 and 4.15. Similar to the balance traffic scenario, the mean queueing lengths at the output buffers of the heavy traffic nodes, which are the master and the bridge node in the simulations, were lower than when the predictive scheduling was not applied.

When the imbalance rates R_0 were set equally for both piconet 0 and piconet 1, the performance of the bridge node, which is highly sensitive to high external traffic, is shown on figure 4.16 for different traffic loads and with the predictive scheduling application. Note that when the imbalance rate R_0 is small, it means high inter-piconet traffic.

4.10 Extended discussions

As shown in the simulations, the inter-piconet predictive scheduling could have some improvements over Bluetooth scatternet performance. The sensitive nodes, such as the bridge node, could highly be subjected to the congestion or bottleneck problem, which severely downgrades the entire network performance. There are several approaches to alleviate this problem, including traffic classification or priority, dynamic alternative routing, forming a new network topology, etc.

In traffic classification or priority approach, the arrival traffic is attached with priority

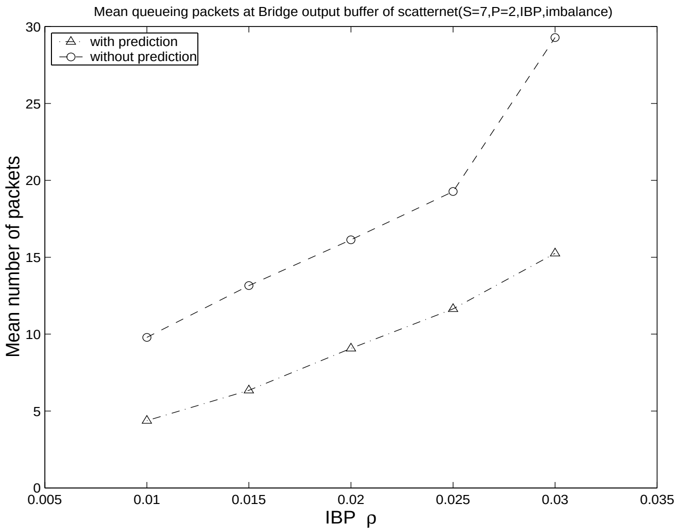


Figure 4.15: Mean number of data packets in the bridge node's output buffer, with and without the predictive inter-piconet scheduling, for piconet using FEP polling scheme, imbalance traffic loads, imbalance rate $R_0 = 0.35$

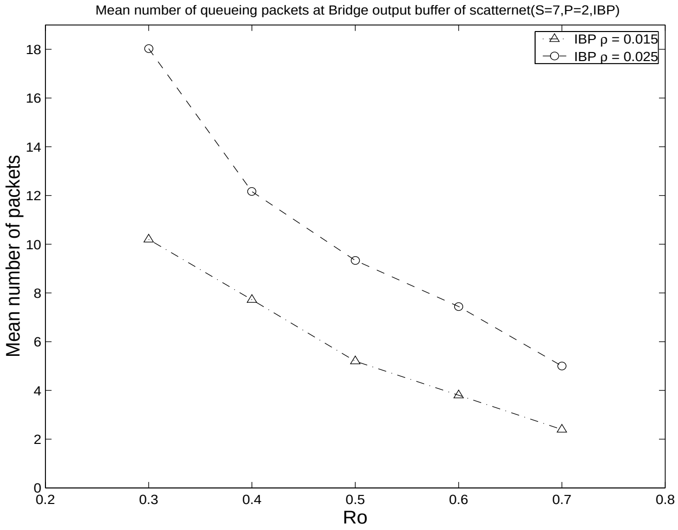


Figure 4.16: Mean number of data packets in the bridge node's output buffer, with the same imbalance rate R_0 for both piconets, and with the predictive inter-piconet scheduling, for piconet using FEP polling scheme

level. The packets with the highest priority level will be scheduled first and the lowest last. This approach is quite similar to DiffServ, which is very common on the Internet. Some modifications of the inter-piconet predictive scheduling may be necessary. These modifications include priority queue set up, priority queue based scheduling, etc. The results of this approach are some QoS improvements, and QoS requirements could be satisfied at a certain level for the highest priority traffic.

For the dynamic alternative routing approach, the routing algorithm sets up a set of favorable routes and a set of several optional routes. When inter-piconet traffic passes through the bridge node on the favorable route, and is still under a certain level, the Bluetooth packets are transfered on the favorable route through this bridge node. When the traffic exceeds a certain level, some part of the packets will be routed on the optional routes through other bridge nodes. Thus traffic load at the bridge node is leveraged, and will increase QoSs in the network.

Another approach is to set up a new network topology. This can be implemented in several ways, which can result in a capacity increase. For example, when the traffic between a group of nodes is high, it may create a new piconet between nodes in the group. Thus the inter-piconet traffic in the Bluetooth network could be significantly reduced. Or when traffic through a bridge node is high, maybe a new bridge node could be set up to take some parts of the inter-piconet traffic. However, as analyzed by [66], the capacity only increases to a certain level. After that, it begins to reduce because of the bridge overhead created by the inter-piconet scheduling above at the new bridge node. At a certain level, the bridge overhead will exceed the capacity profit from the new bridge, and overall network capacity will be reduced. The Master/Slave role switching approach could be efficient in some application scenarios. However, this might request complex algorithms for routing, scheduling, synchronization, etc.

The inter-piconet scheduling approach uses low power mode, i.e. SNIFF or HOLD mode, to switch between the connected piconets. The native clock may be disabled or operate in less accuracy, when it is in the low power mode. The specified accuracy of ± 250 ppm can result in slippage of 1 slot every 2.5 s. Because of this clock drift effect, the active frames of bridge node can overlap each others, i.e. two master can poll a bridge node at the same time, message overheads will be increased, and the total network flows will be reduced. Thus a regular synchronization is very important for the performance of inter-piconet scheduling. Maximum duration for re-synchronization is $40.9s$, which is equal to 65440 time slots and requires an uncertainty window of ± 17 time slots [8].

4.11 Conclusions and future developments

The Bluetooth technology will enable many new applications and services, and will bring a wide range of interesting research areas. To enable flexible and efficient Bluetooth networks, and to increase the coverage, the small network groups, the piconets, should be inter-connected together to create larger and higher capacity network, which is called scatternet. This chapter described the inter-communication between piconets in the scatternet. These piconets are inter-connected through the bridge node. The bridge node uses lower power modes, such as SNIFF or HOLD modes, to be in active and idle states in different piconets. A inter-piconet scheduler was mentioned. The inter-piconet scheduler was used to schedule the bridge node to be active and idle in the connected piconets. Some issues of the inter-piconet communication and the scheduling were also explained, such as message exchanges, clock drift, network formation, efficiency, etc. The inter-piconet scheduling optimization problem is formulated.

Considered as a heuristic approach to control inter-piconet communication and to solve the optimization problem, the inter-piconet predictive scheduling approach, was proposed. The approach uses knowledge the the predicted inter-piconet traffic to allocate the scheduling window and to schedule the time intervals of ACTIVE and SNIFF periods for the bridge node in the connected piconets. The predictive scheduling approach is fair and efficient. It may require some modifications of current message exchange procedures or some new messages in the LMP layer. The performance of the inter-piconet predictive scheduling for a simple scatternet was illustrated through the simulations. The traffic sources were modeled as bursty traffic (IBP) sources while considering the cases of balance and high imbalance traffics.

The simulation results show that the inter-connected traffics have significantly affected the working ability of the Bluetooth network and it is necessary to control the bridge node in the inter-connected environment. It also indicates that by applying the inter-piconet predictive scheduling approach, the performance of the Bluetooth network could have improved QoSs, such as throughput, queueing sizes of packet delays, etc.

By defining QoS criteria and constructing the appropriate QoS based predictive scheduler, the working ability of Bluetooth network could be improved in terms of QoSs.

Some extended issues were also discussed, including traffic classification or priority, dynamic alternative routing, and new network topology, which require some changes on priority based scheduler, routing algorithms or QoS based network formation algorithms.

Although this scheduling approach is designated to Bluetooth best effort network, i.e. asynchronous data network, some further work should be carried out in the future to implement for Bluetooth synchronous networks, which use SCO link. Furthermore, the working ability of the predictive scheduling depends on the precision of the traffic predictor, thus more work should be done to design better methods for estimating inter-piconet arrival traffic, especially Internet traffic. The method should take in account different dynamic traffic patterns.

Chapter 5

Adaptive Distributed Network Traffic Control over Bluetooth Networks

5.1 Introduction

As the number of mobile devices around us are increasing, cellular phones, PDA, digital camera, laptop computer and their peripheries have become necessary tools not only for business but also for the general public. The rapid adoption of the Internet and mobile wireless technologies is paving the way for high bandwidth to mobile terminals. Local and personal area networks are also increasingly becoming wireless, incorporating seamlessly all IP wireless and mobile networks. Communication between devices in the network can be in single or multiple hops. The ad hoc style networking offers infrastructure independence, flexible topology, high bandwidth, global adaption and user friendliness with various services.

In order to provide a true global mobile network, many efforts of research and developments contribute to short range wireless communication, including Bluetooth technology. Bluetooth [28] is a short range, low power wireless technology to provide communication between various devices, such as cellular phones, PDA, laptop, etc. The basic Bluetooth network topology, piconet, is a collection of slave devices operating together with one master device. All slaves use the master's clock and address to synchronize with the master's frequency hopping sequence. The master allows the slaves to transmit by allocating slots for voice and data traffics.

A collection of multiple piconets can be connected together to create larger ad hoc net-

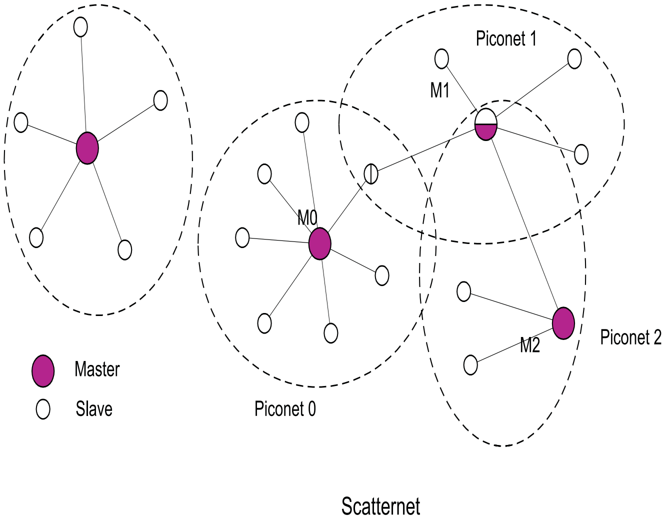


Figure 5.1: Bluetooth piconet and scatternet

work with higher capacity, which is called scatternet. In scatternet, some devices can be members of more than one piconet and are called bridge nodes. Figure 5.1 illustrates an example of a piconet and a scatternet, which includes three piconets. The bridge node can have a role as master in a piconet and slave in another or slave in both piconets. It requires careful packet scheduling for the node participating in the multiple piconets. Bluetooth can support power saving techniques. A slave in a piconet can be in ACTIVE, PARK, HOLD or SNIFF modes. To participate in multiple piconets, the bridge nodes can use the low power modes. Chapter 2 gives more information about Bluetooth technology, including protocol stacks, working modes.

Although the initial primary focus with Bluetooth is as a cable replacement, the future uses as mobile ad hoc network, scatternet, are awaited and supported by the Bluetooth SIG's specifications. To implement Bluetooth network as true mobile ad hoc network, it brings many new challenges, such as network formation, scheduling, and especially QoS issues.

The end-to-end QoSs delivered to end users in Bluetooth networks depend on a large number of parameters at different levels. When Bluetooth master polling its slaves, it divides resource to these slaves, and these divisions should be based on the application demands. The switching of bridge node between its connected piconets also affects to QoSs in scatternet. The mobility of "thin" Bluetooth nodes, scarce resources, and limited power availability make it even more difficult to be more efficient than fixed networks. Although the current Bluetooth specification defines some simple flow specifications, such as token rate, peak bandwidth or packet delay, it does not give details how to implement QoS guarantees and in [38], the issues of QoSs are mentioned including packet delays, packet losses, throughput or congestion. There are several approaches to address the QoS issues, among which using admission control gives a promising solution. Some methods for admission control are currently available, such as Random Early Discard (RED) [19], Traffic shaper, Leaky Bucket or Measurement based admission control (MBAC) [59]. A problem that nevertheless remains with these methods is how decisions should be made on an end-to-end basis. There is another approach, where the connection will decide whether or not it would accept a Bluetooth packet entering to the network. The Explicit Congestion Notification (ECN) [18] provides an mechanism to convey information on network state back to source node through an ECN marking bit. Recent research [25, 43] shows how virtual queue marking scheme allows a broad QoS framework for flows. However, one of main drawbacks of these methods is about its working ability under conditions of scarce resources and frequently topology variations of the Bluetooth networks. Furthermore, it is rather difficult to determine the appropriate sending rate parameters for bursty arrival traffic sources attached to the Bluetooth nodes in the network.

Inspired by these research, this chapter makes an attempt of applying the advanced traffic controls to Bluetooth data networks which uses Asynchronous Connectionless Link (ACL). The traffic control tries to increase the network utilization, e.g. throughput, and to support the QoS demands, e.g. packet loss, time delays, etc. An approach of the distributed traffic control provisioning the end-to-end QoSs for real time and non real time traffic applied to Bluetooth data networks is proposed. This approach controls the network traffic based on real-time measurement and prediction of network status, while complying resource constraints of Bluetooth networks, and reducing the message overheads. The key idea is to consider the acceptance of a new Bluetooth packet, and this depends on the transient behavior of the network. The method takes both advantages of virtual queue based marking scheme and measurement based admission control to get traffic information and to satisfy a certain level QoS requirements and network constraints, while maximizing network efficiency. Some mathematical backgrounds of the method are analyzed and the optimization problem is formulated and an adaptive network traffic control approach for Bluetooth data networks is proposed as an approximated solution to the optimization problem formulation. A simulation with bursty traffic sources, Interrupted Bernoulli Process (IBP), is carried out to illustrate the proposed approach, which shows that the performance of Bluetooth networks could be improved when applying the adaptive distributed traffic provisioning QoSs approach. In addition, some issues concerning the distributed traffic control approach applied in Bluetooth are also discussed, which require further intensive research.

The chapter is organized as follows: section 5.2 gives some related works to this research, section 5.3 reviews QoS issues and traffic control in Bluetooth, section 5.4 describes the Bluetooth network model and formulates the optimization problem, section 5.5 presents a distributed marking scheme for Bluetooth networks, an adaptive distributed network traffic control scheme provisioning QoSs is proposed in section 5.6, the performance of the scheme is evaluated by simulations in section 5.7, section 5.8 discusses some issues for improving the scheme, and the last section is devoted to conclusions and future developments.

5.2 Related works

In the modern day of wireless communication, there has been strong demand for QoS and fairness among flows, particularly Internet and multimedia applications. As a results, many methods for admission control and congestion avoidance have been proposed. The concept of the Leaky Bucket algorithm [95] is very simple. The Leaky Bucket consists of a finite queue. When a packet arrives, if there is a room on the queue, it is appended to the queue; otherwise, it is discarded. At every clock tick, one packet is transmitted, if the queue is not empty. One of its variants is the token bucket algorithm, which the leaky bucket holds tokens, generated by a clock. This allows the output speed to increase somewhat when a large burst arrives.

The Random Early Discard (RED) [19] was originally proposed to achieve fairness among sources with different burstiness and to control queue length. RED allows for dropping packets before buffer overflow. This method forces the links to play a more active role in congestion control and avoidance.

The Measurement Based Admission Control (MBAC) [59] approach uses information from on-line measurement to assure QoS. The MBAC offers an attractive solution in ATM networks [45, 23] by providing multiplexing gains with minimal assumptions.

Many works have recently been on decentralized end-to-end congestion control. These are based on Explicit Control Notification (ECN) [18] marking with the goal of building a low loss, low queue delay network. The control algorithm is designed on the premise that each user has a utility function, which the user is trying to maximize, while the network is simultaneously trying to maintain some sort of fairness among various users. The network tries to achieve its goal by marking packets during congestion. The notion of fairness, from the network's point of view, is a weighted proportional fairness. Through the appropriate choice of the weights, other fairness criteria such as minimum potential delay fairness can be realized. This ECN method has been proposed to Internet in IETF RFC 3168 [76], in which it suggests using an ECN marking bit to feedback the congestion in the network.

In [25, 26], the authors have described an admission control algorithm, in which a virtual queue marking is proposed. Some approaches for packet marking and some virtual queue marking properties were also discussed. However, it is not feasible to calculate the path price, because there is only one bit mark and no complex method for price determination is applied. The Single Bit Resource Marking (SBRM) is proposed in

[106], which uses two queues: one for low latency traffic with a target queue size zero, and one with a threshold to increase link utilization. Although it is less complicated, because it uses only one bit mark, its working efficiency is questionable, due to it marks leaving packet instead of entering packets.

The admission control using the virtual queue is quite an attractive approach for many wireless networks, and it inspires the research work in this chapter to study the possibility of applying the approach to the Bluetooth network. Although the proposal in this chapter complies with scarce resource requirement in Bluetooth networks, and its working principle is derived from the Virtual Marking Scheme and Measurement Based Admission Control, combining prediction, it provides powerful early warning of congestion of the network, and produces robust system behavior in response to both slowly-varying and sudden changes in demand of real-time data traffic, especially multimedia traffic.

5.3 Quality of service issues and traffic control in Bluetooth specification

Bluetooth specification [28] has defined two types of links: Synchronous Connection Oriented (SCO) and Asynchronous Connectionless Link (ACL), which provide a circuit switched type of service and a packet switched type of service, respectively. This chapter only concentrates on the ACL Bluetooth network, which is used for data transmission.

The ACL link can be configured to provide QoS by means of the HCI QoS setup command. The service type, traffic and QoS parameters, negotiated with the L2CAP configuration parameters (see table 5.1, [28]), are notified to the Baseband layer. Currently only the guaranteed service is defined, similar to the guaranteed service defined in the Integrated service architecture. However current baseband implementations do not support this type of service. Thus at the moment, Bluetooth operated in ACL link mode can support only Best Effort traffic. Furthermore, from section 5.2, we can see that current traffic control only performs at the end node, which can not give the end-to-end QoSs demanded by many applications. Some modifications on network control and resource management should be studied, in which the approaches to get the end-to-end QoS should be emphasized.

The traffic control functions ensure that the traffic entering the network satisfies a service level, which comprises both the offered traffic and the associated QoS requirements. The traffic control measures traffic, packet marks feedback from the network and can drop packets that do not meet criteria agreed in the service level. The traffic control ensures that the network resources are not overloaded and QoS requirements can be met.

Some general directions for implementing QoS and QoS frameworks for Bluetooth networks were discussed in [99]. As depicted in figure 5.2, the resource manager and re-

Configuration parameter	**Unit**	**Parameter Description**
Flags	-	Reserved for future use
Service type	No traffic, Best Effort (default), Guaranteed	The service type identifies the service level. Default service type is best effort
Token rate	Bytes/second	Represent average traffic load
Token bucket size	Bytes	Represent maximum burst size
Peak bandwidth	Bytes/second	Represent the maximum transmission rate of the source
Latency	Microseconds	Maximum delay between packet generation and start of packet transmission on the air-interface. The precise interpretation depends on the service type
Delay variation	Microseconds	Difference between maximum and minimum delays. Can be use to determine the buffer size of the receiver

Table 5.1: QoS configuration parameters [28]

source requester enable the control of traffic flows with QoS requirements in Bluetooth networks. When receiving information on traffic and QoS requirements, the resource requester makes requests for resources with QoS requirements to the resource manager. In turn, the resource manager evaluates the network resources and makes a decision whether to accept or reject the request from the flow. The traffic and QoS requirements are set by higher layers. After the request is accepted, the resource request will configure the resource allocation. The resource allocation will allocate capacity to the flows.

5.4 Bluetooth network model and optimization problem formulation

Consider an ACL link based Bluetooth data network, which consists of N nodes, each node has capacity C_i and maintains a virtual queue whose capacity is $\widetilde{C}_i$, $\widetilde{C}_i \leq C_i$, as common definition in virtual queue based approaches. The network is bipartite topology, which can be a piconet or a scatternet and the capacity of each node is limited by the

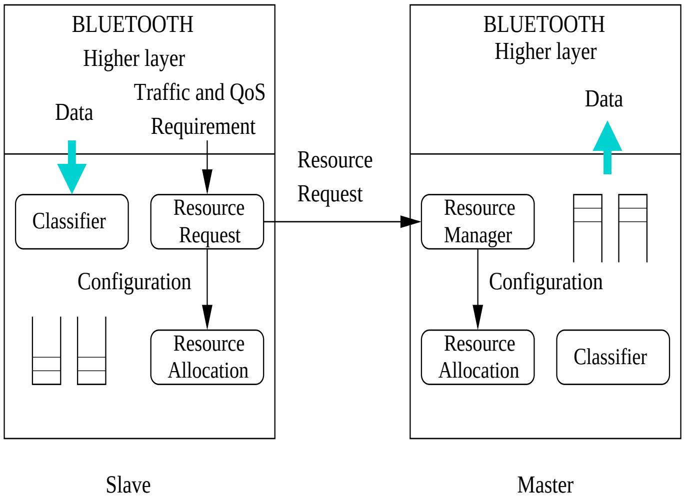


Figure 5.2: General QoS framework [99]

number of frequency channels available to the network and the topology of the network. Capacity per node of a randomly located ad hoc network with N identical nodes, in which each node has capable of transmitting C bps, is $\Theta(C/\sqrt{N \log N})$ in interference-free condition [29]. It is further considered in [62], which studied the effects of different traffic patterns on scalability for node capacity. In the case of a Bluetooth scatternet, which itself is a special form of ad hoc network, the authors in [15] described the capacity limits for nodes in the network.

Each link l_{ij} in set of directional links L, which connects node i to node j in the network, has capacity c_{ij}. Accompanied is set of traffic sources R that transmit packets into the network. Each traffic source $r \in R$ is associated with a route path, which is also denoted by r. The traffic source generates Bluetooth packets with a rate x_r, $0 \leq x_r$. x_r^i is traffic from source r and is routed at node i.

There are several key factors which can represent Bluetooth QoSs, as mentioned in section 3.2 of chapter 3, such as throughput, bandwidth, delays, etc. To simplify, only QoS performance in terms of packet losses is considered in this chapter. The approach uses packet mark information as a cost function to get the QoS requirements. After arrival of a Bluetooth packet, the packet is enqueued to the virtual queue if the virtual queue is not overflowed, otherwise it will be marked and discarded from the virtual queue. However, instead of the process that creates bit marked and sends back to the source node as in [44] and [24], the proposed approach only increases marked counter for the source. This marking information and other parameters, such as time stamp, Node ID, etc, which are used for marking prediction of the source node, are periodically piggyback to the source node. Thus, the prediction process can reduce message overhead to the network, which has very limited resources, and feedback delay, which is important in traffic control.

The Bluetooth packets are transfered through routing nodes in the network and received at the destinated nodes, at which the received rate is equal or less than the transmitted rate. These differences are caused by network congestion and many other factors, such as transmission errors (which are significant in the real network), etc. The packet loss rate for a traffic source r at a node i on the route path, assuming there is no feedback from the network, is given by:

$$PL_i^r = x_r p_i(C_i, \sum_{s:s\in R} x_s^i) \tag{5.1}$$

where p_i is the total packet loss probability at node i, which depends on the capacity of the node and the total traffic arrivals to the node, $\sum\limits_{s:s\in R} x_s^i$. It could be assumed that the total packet loss is distributed over the traffic sources in proportion to the packet rates generated from the traffic sources, and the nodes in the modeled network transmit Bluetooth packets with no transmission errors. Thus the packet loss probability p_i only depends on the node capacity, which causes the congestion, and the total arrival rate into the node.

The total packet loss rate, due to congestion, for a traffic source by the nodes along its route path is dependent on the packet loss of each node on the route path, i.e. depends on capacity and total traffic arrivals of these nodes:

$$PL_r = \sum_{i:i\in r} x_r p_i(C_i, \sum_{s:s\in R} x_s^i) \tag{5.2}$$

When applying the congestion control using a virtual queue and marking scheme, as similar derivation, the total packet mark for one traffic source is also the function of virtual capacity and traffic generated from other sources:

$$PM_r = \sum_{i:i\in r} x_r p_i^m(\widetilde{C}_i, \sum_{s:s\in R} x_s^i) \tag{5.3}$$

It is assumed that each traffic source has an utilization function $U_r(x_r)$, which is a continuously differentiable, strictly concave, increasing un-bounded function, and p_i^m is also continuously differentiable, strictly non-negative increasing. The utilization functions can be utilization factors of resources, as we try to maximize the total network flows, or functions of packet delays, as we try to minimize the end-to-end packet delays. Since our purpose is to increase the network efficiency at minimum packet losses by using packet mark information feedback from the congestion nodes along its route paths and with the assumptions mentioned above on utilization function $U_r(x_r)$ and packet mark probability p_i^m, then the optimal rate of maximizing total network flows and minimizing total of packet marks can be found by solving the following convex formulation [51]:

$$\max_{x_r} \sum_r \left\{ \Delta_r U_r(x_r) - \beta \sum_{i:i\in r} x_r p_i^m(\widetilde{C}_i, \sum_{s:s\in R} x_s^i) \right\} \tag{5.4}$$

subject to: $\forall i \in N, \forall r \in R$

$$\sum_{r\in R} x_r^i \leq C_i \tag{5.5}$$

where Δ_r and β are simply non negative constants, and $\sum\limits_{r\in R} x_r^i$ is used to express the traffics outbound from node i. The rate of convergence to the optimum value can be found by differentiating the formulation 5.4. To reduce the complexity of solving this maximization problem and to adapt to resource constraints of Bluetooth, in the following sections, we proposed the modified distributed marking scheme and the adaptive distributed network traffic control provisioning QoS as a heuristic solution to the stated maximization problem.

5.5 Distributed marking mechanism proposal

The modified distributed marking mechanism for Bluetooth networks described here has a bufferless model, which is based on virtual queue marking information. The working principle of the distributed marking mechanism is inspired from virtual queue marking in [26] and virtual capacity marking in [49], which are rather simple and efficient. However, due to the fact that Bluetooth networks have very limited resources, which can cause, for example, long delay or congestion of packet transmissions, the R. Gibbens' and F. Kelly's Virtual Queue Scheme, which is rate-based approach and uses a limited probe packets, seems badly affected by arrival traffic, especially bursty and high arrival traffic load. This process is worsened by capacity variations, which may result from frequent changes of the Bluetooth network topology, and by difficulty in determining the appropriate parameters of the sending rate. Thus, some modifications and enhancements are made in our virtual queue based distributed marking mechanism proposal to comply with the strict resource requirements of Bluetooth. Some knowledge of Measurement Based Admission Control (MBAC) method is also employed to achieve real-time traffic control and increase congestion avoidance by combining with marking prediction . The distributed marking scheme tries to give transient information on network traffic to the source node by using the updated marking measurement, while minimizing the required network resource and overhead. No probing packet generation sequence is needed.

Figure 5.3 features our proposed Virtual Queue Marking processes. At initialization, the updating clock counter, and Marking counters for traffic sources passing through Bluetooth nodes are reset. At each node i on the route r, as similar to virtual queue marking scheme, Bluetooth packets are marked when the arrival rate from a traffic source coming to the node goes beyond the limit set by its virtual capacity level, $\widetilde{C_i} = kC_i$, with $0 \leq k \leq 1$, and C_i is the real capacity of the node (see figure 5.4). Other performance parameters, such as queueing length, are interchangeable to the capacity expression, as indicated from traffic queueing analysis in chapter 3. However, instead of changing the mark bit as in ECN, it just simply increases the mark counter for the traffic source. When the updating clock reaches the T_m, the duration to update marking measurement status, the node will send back marking information to the source nodes. In order that the source node can estimate the number of marks on its route paths, the periodically updated marking information should contain the Node ID number i, the time stamp and the number of packets marked for this source node C_i^j. This reduces the overhead to the Bluetooth network, which has very limited resources, while it still gives source nodes information about congestion in the network. If some advance estimation methods are applied, the overhead can be further reduced by, for example, setting up mark levels for the source nodes. The buffer occupancy for node i on the route path r is a function of the arrival rates to the node $\sum\limits_{s:s\in R} x_s^i$, $i \in r$, and the service capacity of the node C_i. The virtual occupancy X_i of the node is also function of the arrival rate from other sources and virtual capacity, $\widetilde{C}_i$:

$$X_i = \Phi(\sum_{s:s\in R} x_s^i, \widetilde{C}_i) \tag{5.6}$$

If a_i is the acceptance probability for node i on the route path r, then the acceptance probability depends on the virtual occupancy of the node, X_i. When entering a Bluetooth node in the network, the Bluetooth packet requests a route. The node will check the virtual occupancies of the nodes on its route path to determine the acceptance probabilities of these nodes to the source. The acceptance probability for the entering packet is [43]:

$$\overline{A}_r = \prod_{i:i\in r} a_i(X_i) \tag{5.7}$$

The product-form acceptance probability for each traffic source corresponds to the assumption of independence of the packet level variations at the nodes. Based on the current traffic load, the packet must be accepted by each node along its route path, i.e. it depends on probability that the virtual occupancy does not exceed the virtual level of the node:

$$a_i = P(X_i \leq \widetilde{C}_i) \tag{5.8}$$

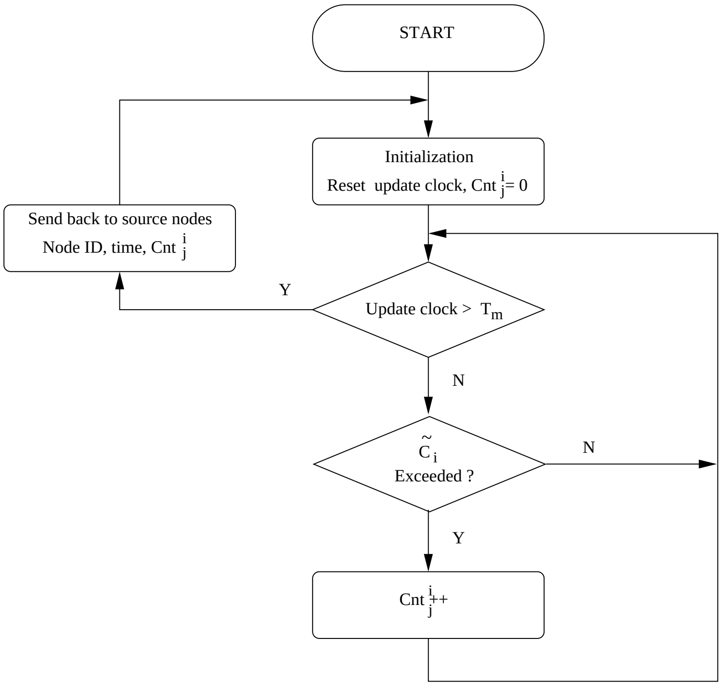


Figure 5.3: Modified Virtual Queue Marking Scheme

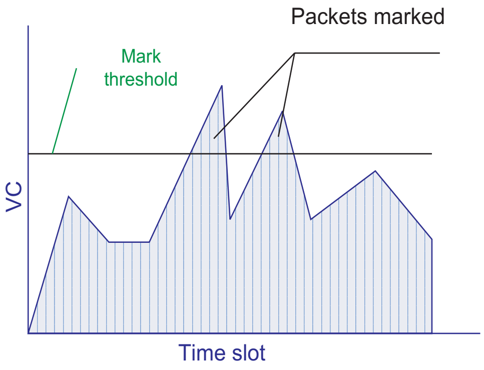


Figure 5.4: An example of packets marked when traffic exceeds virtual level

To achieve the heuristic solution of the maximization problem stated in equation 5.4, the network traffic control will use the acceptance probability of each traffic source, which depends on virtual occupancy $\widetilde{C}_i$ as indicated in equations 5.7 and 5.8. The virtual occupancy of Bluetooth nodes in the network is expressed in packet mark probability of these nodes, which is estimated from the feedback marking information described above. If queue delays are negligible, and the deterministic fluid flow approximation is applied, then by employing analysis from [39], the convergence of the accepted rate $x_r(t)$ for a source when using the network traffic control can be found by solving numerically the differential equation:

$$\frac{d}{dt}x_r(t) = k_r \left(M_r - x_r(t) \sum_{i:i\in r} p_i^m(\sum_{s:s\in R} x_s^i(t), \widetilde{C}_i) \right) \tag{5.9}$$

where $p_i^m(\sum_{s:s\in R} x_s^i(t), \widetilde{C}_i)$ is the probability the packet at node i to be marked at time t, M_r is the target number of marks per unit time and k_r is the gain constant. If assuming that marking is independent between nodes, then the probability that a packet on route r is marked at time t is $1 - \prod\limits_{i:i\in r}(1 - p_i^m(\sum\limits_{s:s\in R} x_s^i(t), \widetilde{C}_i))$.

The messages containing marking information, such as the Node ID, the number of packet marks for the source nodes, the time stamp, etc., of the nodes on the routes are periodically sent back to the source nodes. Depending on specific traffic pattern, the updating period can be optimized to give a good measure of the congestion, which are expressed in the number of packet marks, at the nodes in the Bluetooth network. In the next section, the adaptive distributed network traffic control is proposed as an implementation of the highlighted approximate solution by using this estimated marking information.

5.6 Adaptive distributed traffic control provisioning QoS in Bluetooth networks

In an attempt to solve the optimization problem of maximizing total network flows and minimizing total cost functions formulated in equations 5.4 and 5.5, the adaptive distributed traffic control approach provisioning QoSs for Bluetooth data networks is proposed as a heuristic solution. The adaptive distributed traffic control approach tries to alleviate the effects of congestion, which seriously decreases the capacity of the Bluetooth network, and to provide a certain level of end-to-end QoS, such as delays, packet losses, etc. This approach is inspired from research on end-to-end admission control, including the works in [26, 25, 43], and applied to Bluetooth network. It also complies strictly with requirements on network resources, which are very scarce in Bluetooth, 'thin' nodes, while still being simple and efficient.

The adaptive distributed traffic control approach provisioning QoSs is based on the virtual queue marking scheme described in section 5.5. The real-time network congestion status, which is expressed in the number of packet marks, is periodically measured and reported to the source nodes. This marking measurement is quite similar to the measurement process in MBAC. The source node uses this information to allocate its capacity to traffic sources by changing the acceptance probabilities.

Figure 5.5 describes the adaptive distributed traffic control approach provisioning QoSs. In first step, as mentioned in section 5.5, marking information is regularly updated to the source node. This marking information should include several parameters, such as the number of packet marks, node ID and time of measurements. The source node i uses this information to estimate and predict the number of packet marks to be received from the node j during updating period, $\widehat{W}^m_{ij,u}$. These estimation and prediction can be based on previous collected data on this node and on traffic model. In next step, the source node will calculate the probability that a packet generated from the source node to be marked by a node along its route path, during an updating period T_u:

$$p^m_{ij,u} = \gamma_j \frac{\widehat{W}^m_{ij,u}}{\sum\limits_{v \in i} \widehat{S}^j_{v,u}} \tag{5.10}$$

where $p^m_{ij,u}$ is the weighted probability that a packet from source node i, routes through node j and is marked during the updating period T_u, $T_u = \sum_{T_m(i) \in T_u} T_m(i)$, γ_j is the weight value, and $\sum\limits_{v \in i} \widehat{S}^j_{v,u}$ is the predicted number of packets to be transmitted from the source node and to be routed at the intermediate node j during period T_u. The probability that a packet transmitted from the source r attached to the node i is not marked by the nodes on its route path can be determined by:

$$P_{r,u} = \prod_{j \in r} \left(1 - p^m_{ij,u}\right) \tag{5.11}$$

In the following step, the source node will compare with mark thresholds for the traffic sources attached to it and decide if there are significant changes in the route packet mark probability. In this case, the source node will adaptively change its allocations to the traffic sources according to equation 5.9, by increasing its allocated capacity to the source, if the probability is less than the threshold, or vice versa, decreasing, if the probability is more than the threshold.

To obtain the required QoSs, and the best use of the network capacity, the increment and decrement steps of capacity allocations should be appropriately determined. However, the calculations of these amounts are quite complicated, and depend on the traffic pattern, QoS or available capacity. A pre-calculated table may give simplicity and efficiency.

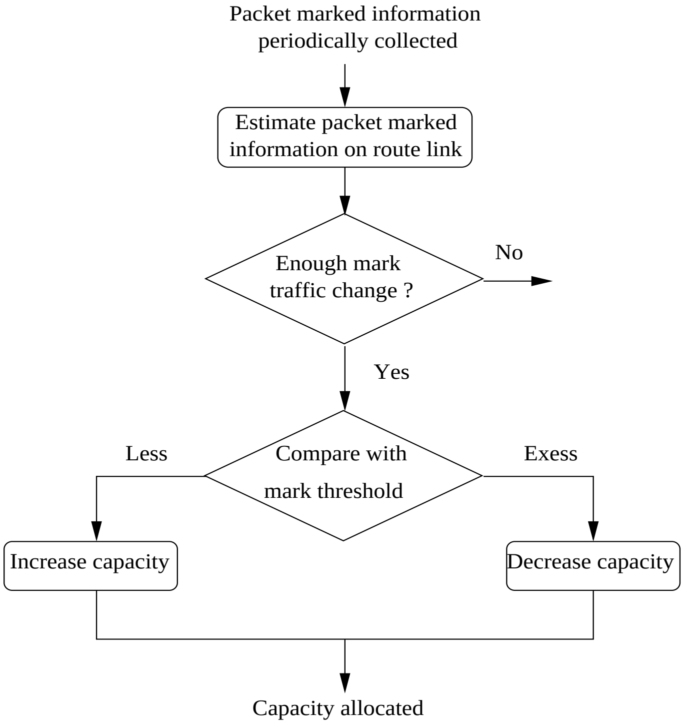


Figure 5.5: Adaptive virtual queue based distributed network traffic control provisioning QoS approach in Bluetooth networks

In order to reduce overhead due to message exchanges, marking information can be fedback to the source nodes by using piggyback method to route messages. There are several QoS routing algorithms for ad hoc networks, such as Dynamic Source Routing (DSR) [40, 65] or Ad hoc On-demand Distance Vector routing (AODV) [71, 72, 63]. The propagation of these methods can be distance vector based, link state based, or on demand. The QoS routing protocol for mobile ad hoc networks proposed in [105] can establish QoS routes with reserved end-to-end bandwidth on per flow basis and it is claimed to produce higher throughput and lower delays than the best-effort approaches.

In the last step, the allocated capacity will be assigned to the traffic sources, by changing to new acceptance probabilities for these sources. However, the current assignment is continued until its valid duration is finished, and the new one is started. Thus, the adaptive distributed network traffic control will try to avoid or reduce the effects of the congestion, and support a certain satisfactory level of QoS.

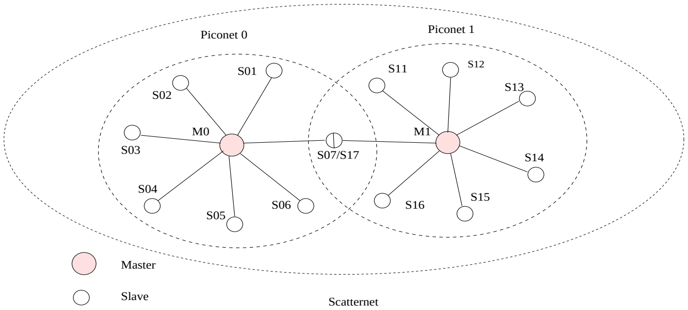


Figure 5.6: The modeled Bluetooth scatternet with two inter-connected piconets

5.7 Simulations

5.7.1 Simulation model

The Bluetooth network in consideration is a simple scatternet, as depicted in figure 5.6, which consists of two inter-connected piconets. The piconet provides full-duplex transmission using time slots. Each time slot is 0.625 ms long. Within the piconet many polling methods can be applied. Some of them are based on arrival traffic predictions to give the best QoS performance, such as throughput, delays, etc., for example the Predictive Fair Polling [1]. One of the main differences between polling mechanisms is related to the order in which slaves are polled and the service disciplines used to serve a slave. In this simulation, the Fair Exhaustive Polling (FEP) [35] is applied. As mentioned in [34], the FEP scheme gives high bandwidth efficiency with fair allocation while still being simplistic. There are a master and N_S slaves in each piconet, where $0 \leq N_S \leq 7$. In this simulation, the number of slaves in each piconet is the maximum of seven slaves. Although Bluetooth can support both synchronous and asynchronous link services, in this simulation, only Asynchronous Connectionless Link (ACL) is applied. Two piconets are inter-connected through a bridge node ($S07/S17$, see figure 5.6). It is possible to send packets in a multiple slots packet length, which may be either 3 or 5 slots long. In this study, for the reason of simplicity, we consider only single slot data packets transmitted between Bluetooth nodes in the modeled network. As we study Bluetooth scatternet performance in terms of queueing, it may be assumed that there is no packet loss due to transmission errors, the retransmission is not necessary and packet loss only occurs when the buffers are overflowed. Moreover, as mentioned in [89], the piconets are assumed to be synchronized, which means that the effects of the clock drifts are eliminated and there are no guard frames between nodes, when the bridge node switches to be active in the piconets.

The homogeneous traffic of packet arrivals can be modeled as an Interrupted Bernoulli

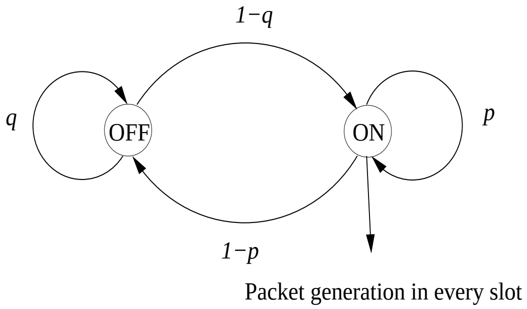


Figure 5.7: IBP traffic model

Process (IBP) [82]. The IBP traffic reflects the bursty nature of data traffic, which are supposedly very common in Bluetooth data services, such as file transfer, Internet traffic or multimedia applications. Incoming and outgoing traffic between nodes in the scatternet are equally distributed. The probabilities of IBP sources being in the ON state and in the OFF state are p and q, respectively, as depicted in figure 5.7. The probabilities to change from the ON state to the OFF state is $(1-p)$ and to change from the OFF state to the ON state is $(1-q)$. The probability for a packet arrival in one slot is v and it is set to zero in the OFF state and one in the ON state. The packet arrival is set to be aligned with time slots for the modeled piconets.

The modeled scatternet uses the predictive inter-piconet scheduling [57]. At the initialization, the scheduling window T_s of the bridge node for inter-piconet communication is set to 400 time slots and is equally allocated to each piconet, piconets $P0$ and $P1$, which the bridge node is connected to. When applying the inter-piconet predictive scheduling approach, the scheduling window T_s is adaptive updated and changed in accordance with the predicted traffic and queueing packets at the output buffers of the Bluetooth nodes. The active intervals of the bridge node in each piconet, which it is belong to, are dynamically varied, depending on the inter-piconet traffic, which is coming through the bridge node.

To verify the working ability of the adaptive virtual queue based distributed network traffic control approach provisioning QoSs in Bluetooth modeled network, the output buffer sizes on each node are set to 40 packets, the virtual queue levels of each node are set to 0.3, 0.5 and 0.8 and the marking thresholds $\theta^m_{r,u}$ are kept to 0.7 and 0.9. For the reason of simplicity, we use just a simple Levinson-Durbin algorithm, which is presented in Appendix B, to estimate the packet mark probability, with the prediction order is 4. The acceptance probability varies according to the estimated marking probability in simple additional increase and multiplicative decrease steps, which is very popular in TCP flow control. In here, the multiplicative ratio is set to 2 and the step is 0.05. The simulation length is 10^6 time slots.

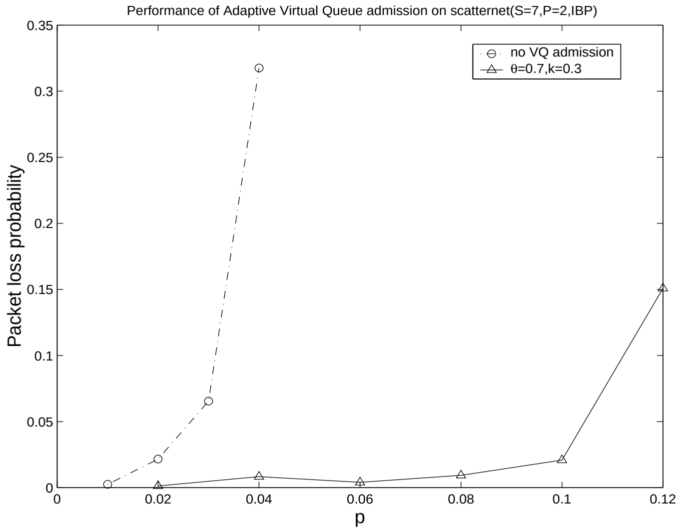


Figure 5.8: Performance of Bluetooth scatternet, with and without adaptive virtual queue based distributed network traffic control approach provisioning QoS, in terms of packet loss performance

5.7.2 Numeric results

Figure 5.8 shows comparison of the modeled scatternet, in terms of the packet loss performance, with and without the adaptive virtual queue based distributed network traffic control approach provisioning QoSs. When the approach was applied, as mentioned from section 5.7.1, the virtual queue level was set to 0.3 and the marking threshold was 0.7. A packet arriving to a node is considered to be lost if the buffer of the node is full. The packet loss probability depends on the traffic load. However, the probability of packet loss was kept very low when the adaptive virtual queue based distributed approach was applied, compared to the case when the approach was not applied, which suffered very high packet losses.

Figure 5.9 shows comparison of the modeled scatternet, in terms of the profitability, with and without the adaptive virtual queue based distributed network control with QoS provisions, with the same marking threshold and virtual queue level as the above experiment. The process gain ratio is defined by ratio of handled traffic of the packets transfered through the network from sources to destinations, without overhead, and arrival traffic. As can be seen from the figure, when the traffic load is increased, the process gain ratios in both cases are decreased. At low traffic, the process gain when not applying the adaptive virtual queue based distributed network traffic control seems higher than when the adaptive virtual queue based distributed network traffic control is applied.

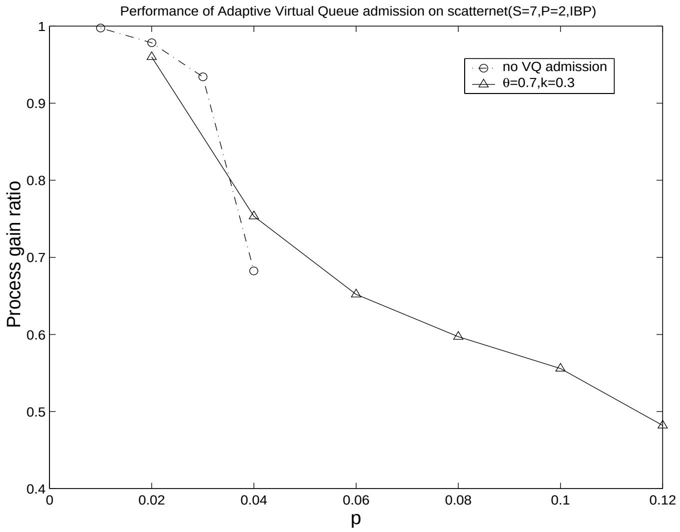


Figure 5.9: Performance of Bluetooth scatternet, with and without adaptive virtual queue based distributed network traffic control approach provisioning QoS, in terms of process gain ratio

By continuing to increment of the traffic intensity, the process gain when not applying the adaptive virtual queue based distributed network traffic control is quickly decreased to lower than when applying the distributed network traffic control. This means the throughput of the modeled network is higher when applying the adaptive virtual queue based distributed network traffic control. This is because in the case of not applying the network traffic control, the congestion and packet losses have significantly reduced the network throughput.

In figure 5.10, it shows the performance of the modeled network, when the adaptive distributed network traffic control was applied. It can be seen that when increasing traffics of nodes in the network, the probability of the marked packets is increased. Higher packet marking threshold means higher packet marked probability. In figure 5.11, it also shows the variations of the probability of packet loss corresponding to the traffic variations. It indicates when the traffic load is increased, the probability of packet loss is also increased. But it is apparent that the probability of packet loss is far lower compared to the case when not applying the adaptive virtual queue based distributed network traffic control provisioning QoS. It also indicates that when increasing the marking threshold or virtual queue level, the probability of packet loss is increased.

Figure 5.12 gives some characteristics of the relationship between packet losses and marked packets. As can be seen, a lower marking threshold or virtual queue level can

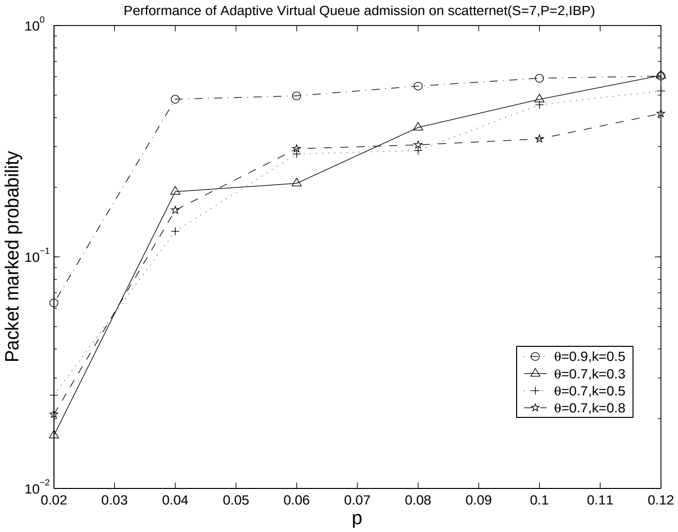


Figure 5.10: Performance of Bluetooth scatternet, with adaptive virtual queue based distributed network traffic control approach provisioning QoSs, different marking thresholds and virtual buffer sizes, in terms of packet marked probability

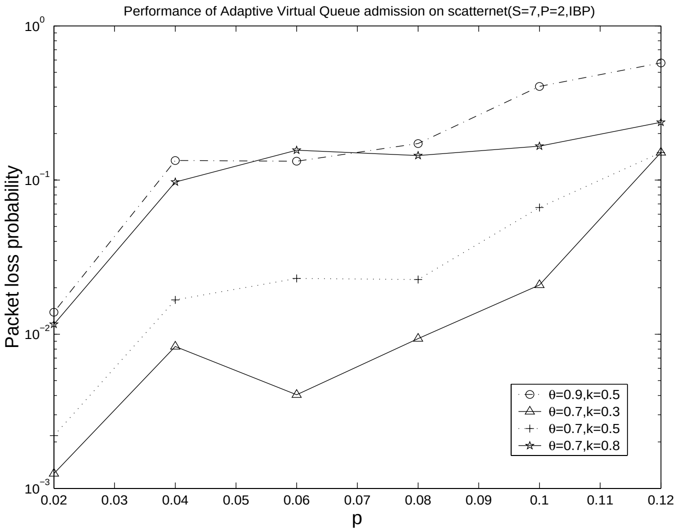


Figure 5.11: Performance of Bluetooth scatternet, with adaptive virtual queue based distributed network traffic control approach provisioning QoS, different marking thresholds and virtual buffer sizes, in terms of packet loss probability

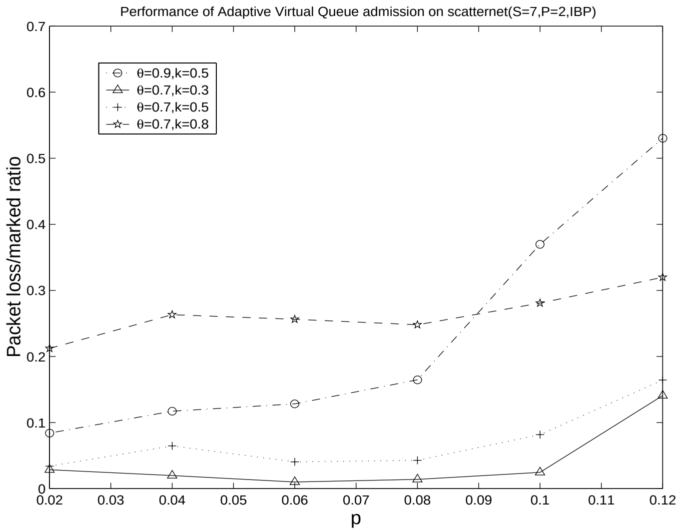


Figure 5.12: Performance of Bluetooth scatternet, with adaptive virtual queue based distributed network traffic control approach provisioning QoS, different marking thresholds and virtual buffer sizes, in terms of packet loss over packet marked ratio

reduce the packet loss over marked packet ratio. When the traffic load continues to increase, the packet loss over marked packet ratio seems highly increasing. The working capability of the network traffic control is reduced.

Figures 5.13 and 5.14 show the performance of the modeled network, in terms of the packet blocked probability and the process gain ratio. The process gain ratio, as mentioned above, is the ratio of handled traffic, without overhead, to the arrival traffic. From the figures, the increment of traffic loads of the nodes in the modeled network is followed by the increment of the packet blocked probability and the decrement of the process gain. When the packet marking threshold was increased or virtual queue level was increased approaching the real buffer size, the process gain was higher and the packet blocked rate was lower. It means there was an increment of throughput. However, from figures 5.10 and 5.11, the packet loss was also higher. When the traffic intensity continues increasing, the higher marking threshold or virtual queue level reduces the process gain.

Figure 5.15 shows a comparison of the modeled scatternet, in terms of the profitability, when applying the adaptive virtual queue based distributed network control with QoS provisions, at different marking thresholds and virtual queue levels. The profitability is the ratio between the handled traffic without overhead and the traffic admitted to the network. As be seen, when increasing traffic intensity, the profitability is decreased.

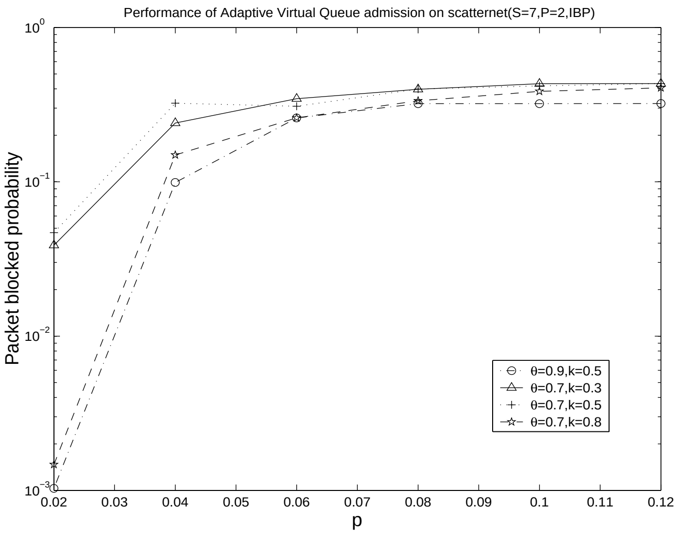


Figure 5.13: Performance of Bluetooth scatternet, with adaptive virtual queue based distributed network traffic control approach provisioning QoS, different marking thresholds and virtual buffer sizes, in terms of packet blocked probability

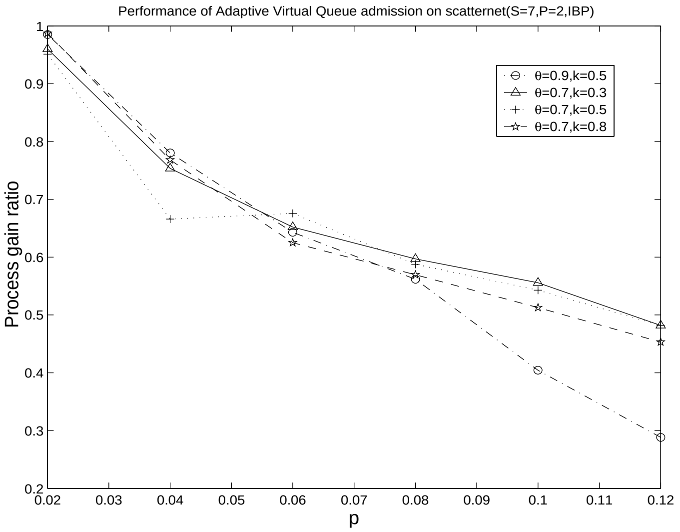


Figure 5.14: Performance of Bluetooth scatternet, with adaptive virtual queue based distributed network traffic control approach provisioning QoS, different marking thresholds and virtual buffer sizes, in terms of process gain ratio

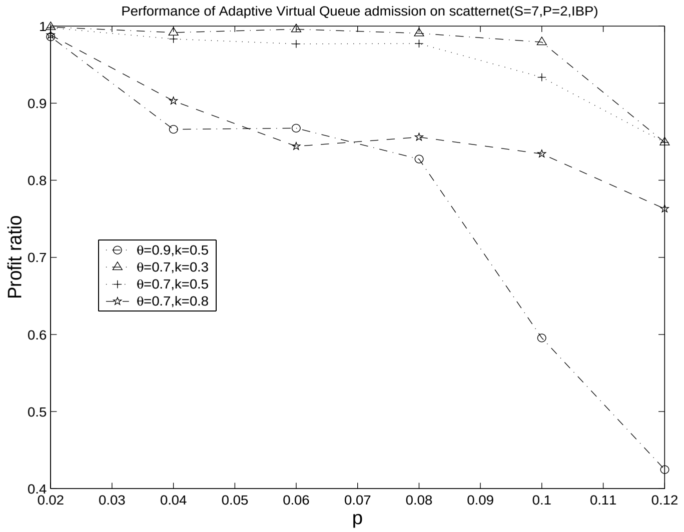


Figure 5.15: Performance of Bluetooth scatternet, with adaptive virtual queue based distributed network traffic control approach provisioning QoS, in terms of profitability ratio

However, a lower marking threshold or lower virtual queue level can maintain a high profitability ratio at a certain level.

To investigate the characteristics of the adaptive virtual queue based distributed network traffic control approach provisioning QoS, we define the mean number of hops of packets transmitted over the Bluetooth network as H:

$$H = \frac{\sum\limits_{\forall i \in N} h_i}{N} \tag{5.12}$$

where h_i is the mean number of hops of packets transmitted from the source node i and N is the number of Bluetooth nodes in the network. In case that the network is without losses, the mean number of hops for the network is calculated as the ratio of the sum of packets transmitted into the network from source nodes i, and intermediate nodes j, $\forall i, j \in N$ on their route paths and the sum of the packets transmitted from the source nodes:

$$H = \frac{\sum\limits_{\forall i \in N} \left(\sum\limits_{\substack{\forall v \in i \\ i \neq j}} S_v^j + \sum\limits_{\substack{\forall v \in i \\ j \equiv i}} S_v^j \right)}{\sum\limits_{\forall i \in N} \sum\limits_{\substack{\forall v \in i \\ j \equiv i}} S_v^j} \tag{5.13}$$

where $\sum\limits_{\forall v \in i, j \neq i} S_v^j$ is the sum of the number of the packets from source node i transmitted from the intermediate nodes and $\sum\limits_{\forall v \in i, j \equiv i} S_v^j$ is the sum of the number of the packets transmitted from source node i.

Figure 5.16 shows the approximate mean number of hops of the packets transmitted over the modeled network, when applying the adaptive virtual queue based distributed network traffic control approach provisioning QoS. As be seen, when the traffic intensity increases, the mean number of hops of the packets transmitted over the modeled network is reduced. It means the number of the packets admitted and transmitted into the network with longer hops, e.g. inter-piconet packets, is significantly decreased compared to the shorter hop packets, e.g. intra-piconet packets. This is due to the fact that when increasing homogeneous arrival traffic intensity, as the links connecting to the bridge node are approaching to the saturated maximum capacity levels and are no longer able to transfer higher data rates, then the adaptive network traffic control scheme can only increase traffic to the links that still have available capacities, i.e. local piconet traffic. Furthermore, the mean number of hops is lower when applying more restricted admission criteria: lower mark threshold and lower virtual queue level, i.e. lower packet loss probability and higher profitability.

5.8 Some extended discussions

Although the performance of the adaptive virtual queue based distributed network traffic control approach has been evaluated through the simulations of the Bluetooth modeled network, the approach is still in need of further investigation. Many other network control approaches, which are based on virtual queue marking and measurement based admission control [58], can be applied to Bluetooth networks to use efficiently network capacity, while still satisfying QoS requirements and resource constraints of Bluetooth networks.

In [49], the authors presented the Adaptive Virtual Queue (AVQ) and designed the AVQ

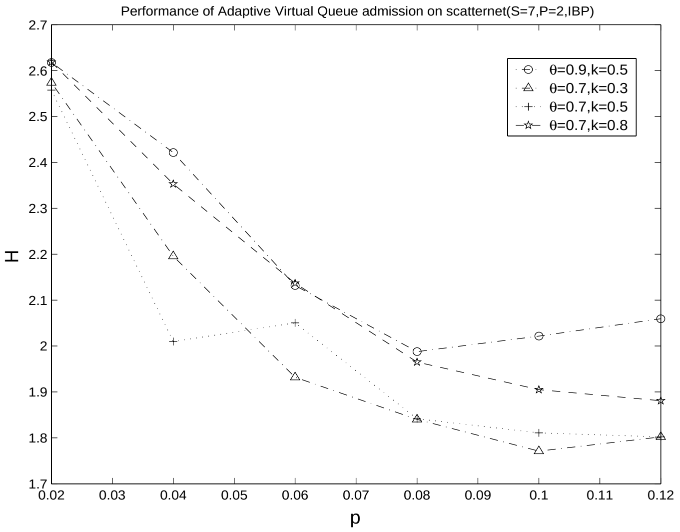


Figure 5.16: Performance of Bluetooth scatternet, with adaptive virtual queue based distributed network traffic control approach provisioning QoS, different marking thresholds and virtual buffer sizes, in terms of mean number of hops

algorithm. The AVQ maintains a virtual queue whose capacity, virtual capacity, is less than capacity of the link. Packets in the real queue are marked or dropped when virtual buffers are overflowed. The virtual capacity is then modified such that the total flow entering each link achieves a desired utilization of the link.

The authors in [70] have developed a fair end-to-end window based congestion control algorithm which balances between user fairness and resource utilization. The protocols use only information that is available to the end nodes and are designed to converge reasonably fast.

Another feasible approach is to classify the arrival traffic into guaranteed traffic and best-effort traffic, then the network traffic control will probe and allocate capacity to the guaranteed traffic if the available bandwidth can support the traffic with QoS requirements. The remaining bandwidth is allocated to the best effort traffic. However the performance of this approach can be affected by, for example, transmission errors caused by SNR deterioration.

5.9 Conclusions and future developments

This chapter has presented about the adaptive virtual queue based distributed network traffic control approach provisioning QoS for the Bluetooth best effort networks. An analysis of the modeled network was considered, in which the optimal rate of packet transmission could be found by the optimization problem of maximization of network flows and minimization of the total packet marks. Some virtual queue fundamentals were studied. The modified virtual queue distributed marking scheme and the adaptive distributed network traffic control approach for the Bluetooth best-effort network were proposed and analyzed. This network traffic control approach is a heuristic solution to the stated optimization problem and satisfies the constraints of Bluetooth networks, e.g. ’thin’ Bluetooth node, scarce resources and a limited capacity. The simulation to investigate the working ability of the modeled network, when applying the adaptive distributed network traffic control approach, was carried out for bursty traffic sources. The simulation results show the necessity of the adaptive distributed network control approach, which can offer a high capacity utilization of the Bluetooth network, while still satisfying QoS requirements. The simulation shows some characteristics of the approach and indicates a relationship to QoS requirements, such as packet delays, packet loss, and throughput.

Some extensions of the approach were discussed, which suggest for the applications of other advanced network control approaches. More advanced marking prediction algorithms should be investigated to reduce the prediction errors, which can severely affect to performance of the proposed network traffic control scheme, especially when Bluetooth network serving low arrival traffic or highly robust self-similar ON-OFF integrated traffic, e.g. video streaming, VoIP, etc.

The approach also indicates that the QoS routing algorithms should be applied in Bluetooth networks. Further investigation on the effects of dynamic network topology is needed. The working ability of Bluetooth networks, when applying the adaptive virtual queue based distributed network traffic control could be improved by constructing the traffic estimation method and optimizing the marking scheme and capacity allocation steps. Designing the message management to reduce control overheads due to the message exchanges, the adaptive marking scheme as well as the capacity estimation in various dynamic traffic patterns, for both real time and non real-time traffic, and especially Internet traffic also requires further research.

Chapter 6

Hybrid Distributed Iterative Capacity Allocation over Bluetooth Networks

6.1 Introduction

Wireless short range technologies have recently attracted much attention in the public market and in industry. There is much research on wireless short range communication, especially on Bluetooth. Bluetooth is a new radio technology that promises to be a very convenient, low cost solution for the interconnection of all kinds of mobile devices. Currently, Bluetooth Special Interest Group (SIG) has defined a simple network topology, piconet, that only supports a limited number of devices and requires all devices to be in range. However, support of the more demanding multi-hop ad hoc network, which is called scatternet, is not yet specified in detail. In this chapter, we investigate an analytical model for the analysis of the capacity allocation problem in Bluetooth networks and propose the hybrid distributed iterative capacity allocation scheme as its approximated solution. Simulations show that the performance of Bluetooth could be improved by applying the hybrid distributed iterative capacity allocation scheme.

Bluetooth, as presented in chapter 2, operates in the unlicensed ISM (Industrial-Scientific-Medical) band using a frequency hopping scheme. Bluetooth units are organized into $piconets$. There is one Bluetooth device in each piconet acting as master, which can have any number of slaves out of which up to seven can be active simultaneously. Master and slaves are allowed to send 1, 3 or 5 slot packets. Although Bluetooth can support both voice and data traffic, here we concentrate on the networks, in which only data links are used. Two or more piconets can form a $scatternet$, a true mobile ad hoc network [102], in which a unit that can participate in multiple piconets is called the bridge node.

There are many studies going on of Bluetooth scatternet, in both theoretical and practical aspects. Much attention has been given to polling and scheduling schemes for piconets and scatternet, respectively [16]. Some research concentrates on scatternet topology and on development of efficient scatternet formation algorithms [56, 4]. The issues of resource allocation however are still open. Zussman et al. [107] have studied the capacity assignment problem and proposed a heuristic algorithm, which has much lower complexity than that of the optimal algorithm and its performance is claimed to be close to that of the optimal algorithm. However the author's heuristic algorithm is centralized, which makes impractically to implement in Bluetooth networks. This is because of piconet based structure, master/slave switching and inactive low power mode operations, such as SNIFF or HOLD modes, which are extensively used in inter-piconet communication. Another backward of this method is the end to end QoS issues. The authors in [41] proposed a set of capacity problem formulations for cellular and ad hoc networks, which allocates the networks resources to optimize SNR, maximize throughput and minimize delays. This suite accommodates a variety of realistic QoS and fairness constraints.

In this chapter, the problem of resource allocations in Bluetooth data networks is studied. The resource allocated to a link can be achieved by, for instance, polling of master-slave pair, active duration of bridge node in piconet or by admission control. When increasing the allocated resource, the traffic passing through the link is increased, which can result in overload of Bluetooth node's capacity or increase congestion probability. These affects to QoSs in Bluetooth networks, such as longer time delay, higher packet dropped probability. Thus the resource allocation problem can be formulated as a convex optimization problem of maximization of total network flows and minimization of total cost of flows. The solution of the optimization problem should satisfy the constraints of the Bluetooth networks. It should be decentralized and have the ability to respond to frequent changes of topology and of capacities assigned to nodes in the network. A heuristic approach, the hybrid distributed iterative capacity allocation scheme, is proposed to address the problem requirements. The purpose of the distributed capacity allocation scheme is to maximize the network flows, while minimizing the costs of satisfying the end to end Quality of Service (QoS) requirements. There is no prior assumption about the network.

The chapter is structured as follows. Section 6.2 reviews some basic backgrounds of Bluetooth and related works. Section 6.3 gives some descriptions about Bluetooth network model, capacity constraints and traffic model. In section 6.4, we formulate the convex optimization problem of capacity allocation in Bluetooth networks. Section 6.5 features the hybrid distributed capacity allocation scheme. Section 6.6 contains some evaluations of the scheme. Section 6.7 illustrates some properties of the hybrid distributed capacity allocation scheme by presenting simulation results from basic scenarios. Some approaches are suggested in 6.8 to improve the proposed distributed capacity allocation approach. In section 6.9, some open issues are discussed. Finally, conclusions and future work are in section 6.10.

6.2 Bluetooth background and related works

Bluetooth has the capability of point-to-multipoint connections at speeds up to 1 Mbps. It uses frequency hopping to minimize the effects of signal interference caused by various devices operating the same 2.4 GHz ISM band, e.g. Wireless LAN, Home RF, microwave ovens or even other Bluetooth devices. The system supports both synchronous link (SCO), which is primarily for voice traffic, and asynchronous link (ACL), which is primarily for data traffic. The SCO link is symmetric and SCO packets are transmitted in reserved intervals. The ACL link is packet-oriented and supports both symmetric and asymmetric traffic. This chapter just concentrates on Bluetooth networks operated in asynchronous link mode for data transmission. A network of devices in point-to-point or point-to-multipoint connection forms a piconet. The Bluetooth devices from the same piconet share the same hopping sequence whereas the devices from different piconets have different hopping sequences. A collection of piconets with overlapping coverage areas is called a scatternet. A slave, which called bridge node, can participate in more than one piconet (but at any given time, it can only be active in one piconet).

Currently Bluetooth is an active research topic. A method for device discovery in Bluetooth multihop scatternet has been proposed in [3]. By exploiting the inquiry and paging procedures provided by Bluetooth technology, the authors have defined a mechanism by which each pair of neighboring nodes tries to gain knowledge of each other. The device discovery and connection establishment can be further enhanced by using Infrared Data Association (IrDA) [103].

A scatternet formation protocol, Tree Scatternet Formation (TSF), has been proposed in [94], which connects nodes in a tree structure that simplifies packet routing and scheduling. The protocol is claimed to work well with dynamic environments, where nodes arrive and leave arbitrarily. The TSF incrementally builds topology and healing partitions when they occur. However the TSF as currently implemented fails to create a single connected scatternet when either the coordinators or the roots cannot hear each other.

Bluetree is scatternet formation protocol for large scale Bluetooth networks, in which devices can be out of range of each other. The simulation results for routing properties of the scatternet were presented in [104].

The authors in [55] have presented a randomized distributed protocol for scatternet formation. The protocol achieves $O(\log n)$ time complexity and $O(n)$ message complexity and supposedly closes to be optimal. It can help prevent overloading of any single device and lead to low interference between piconets.

In [101], a new scatternet formation scheme was described. The scheme follows three basic rules: avoid forming further piconet inside a piconet, avoid setting up more than one connection to the same piconet for a bridge node, and the master tries to acquire some reasonable slaves and only maintaining the connections to the active slaves. Through simulation, the authors have shown that Bluenet has some properties better than Bluetree.

The Bluetooth Topology Construction Protocol (BTCP), a scatternet formation protocol, has been introduced in [79], which is based on three phases: a coordinator is elected with a complete knowledge of all devices, this coordinator determines and informs other masters how a scatternet should be formed, and the scatternet is formed according to the instructions. The BTCP has more flexibility in constructing the scatternet. However, if the coordinator fails, the formation protocol has to be restarted.

The research on Bluetooth piconet and scatternet scheduling is very active topic. A piconet polling scheme, Limited and Weighted Round Robin (LWRR), is introduced in [9]. It adopts a weighted round robin algorithm with weights dynamically changed according to the observed queue status. Each slave is assigned a Maximum Priority (MP) at the beginning. Each time the slave is polled and no data is exchanged, the weight is reduced by 1. Anytime there is a data exchange between slave and master, the weight of the slave increases to the MP value.

Two methods of polling in piconet, Adaptive Flow-based Polling (AFP) and Sticky Adaptive Flow-based Polling (StickyAFP), are proposed in [13] to increase link utilization and to decrease the end-to-end delays of data packets.

The authors in [75] have described the Pseudo Random Coordinated Scheduling Algorithm (PCSS) for Bluetooth scatternet to perform the scheduling of both intra and inter-piconet communications. In this scheduling, Bluetooth nodes assign meeting points with their peers such that the sequence of meeting points follows a pseudo random process that is different for each pair of nodes. The uniqueness of the random sequences ensures that the meeting points with different peers of the nodes will collide only occasionally, so it does not need for explicit information exchange between peer devices. Because of the lack of explicit signaling between Bluetooth nodes, it is more easy to deploy the PCSS algorithm in Bluetooth devices.

In [36] the authors have shown that constructing an optimal link schedule that maximizes total throughput in Bluetooth scatternet is an NP hard problem and also proposed a scheduling algorithm referred to as Distributed Scatternet Scheduling Algorithm (DSSA). Although the DSSA provides a solution for scheduling in scatternet, some of its idealized properties and its relative high complexity make it difficult to apply in a real environment.

The authors in [37] have proposed an inter-piconet scheduling algorithm based on periodic rendezvous points. The algorithm is called the Maximum Distance Rendezvous Point (MDRP) and use SNIFF periods to establish the periodic rendezvous points between gateways and their peer nodes.

Although there is much research on Bluetooth networks, for the topic on capacity assignment in Bluetooth network there is very little research available. In [107], the authors have analyzed the quasi-static capacity assignment that minimizes the average delay in scatternet. The analysis is based on a static model with stationary flows and unchanging topology. The capacity assignment problems for $bipartite$ and $nonbipartite$ scatternet graphs are formulated as the minimization of the average packet delays. The authors have also proposed a heuristic scatternet capacity assignment algorithm in bipartite graphs (SCAB). However, although it is claimed as low complexity and in theory, the results should be close to the optimal results, the method is difficult to implement in a real life environment. This is from the fact that the method is centralized with many idealized assumptions.

6.3 Bluetooth network model

Consider a Bluetooth network as depicted in figure 6.1 with a set of directional scatternet graph $G = (N, L, R)$, where N denotes the collection of Bluetooth nodes $\{1, 2, ..., n\}$, which can be masters, slaves, or bridge nodes. The authors in [29, 98, 22] have described the upper bound and lower bound of wireless ad hoc network capacity. The maximum capacity, C_i, for the node i in the network with N nodes, is limited by the network formation and hopping frequencies. In case of minimizing the number of piconets, the maximum capacity C_i is bounded approximately by the following expression [15]:

$$C_i = \frac{\left(1 - \frac{1}{n_f}\right)^{2\left(\lceil \frac{N}{8} \rceil - 1\right)}}{\frac{N}{\lceil \frac{N}{8} \rceil - 1}} \tag{6.1}$$

where n_f is the number of frequencies in the hopping scheme.

Each piconet has the maximum possible nodes, i.e. 8 nodes, which consist of a master and 7 slaves. It is assumed that only single slot packets are transferred and the piconet is fully loaded. In the case that the number of piconets is maximized, which means the network contains only point-to-point piconets, the expression can be rewritten as [15]:

$$C_i = \left(1 - \frac{1}{n_f}\right)^{2\left(\lceil \frac{N}{2} \rceil - 1\right)} \tag{6.2}$$

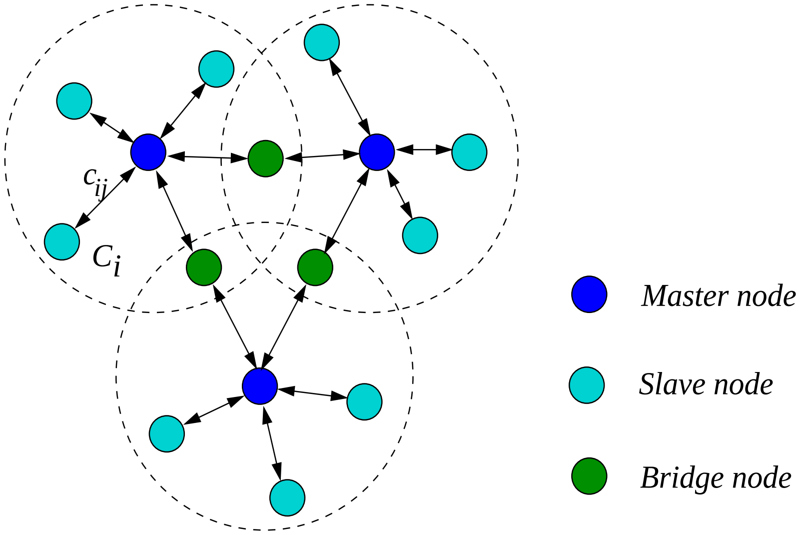


Figure 6.1: Bluetooth directional scatternet graph

The directional link connecting node i to node j is denoted by l_{ij} and the collection of directional links is denoted by L. $Z(i)$ denotes the collection of node i's neighbors. We denote by $L(U)$ $(U \subseteq N)$ the collection of links connecting to the nodes in U. Associated with each link l_{ij} is a capacity c_{ij}. Let C_{ij} denote the relative rate of c_{ij} and the maximal possibility of a link, $0 \leq C_{ij} \leq 1$. From [107], the capacity of link should satisfy the following conditions:

$$\sum_{j \in Z(i)} C_{ij} \leq 1 \; \forall i, j \in N \tag{6.3}$$

for bipartite graph, and:

$$\begin{gathered} \sum_{j \in Z(i)} C_{ij} \leq 1 \\ \sum_{l_{ij} \in L(U)} C_{ij} \leq \frac{U-1}{2} \\ \forall i, j \in N, U \subseteq N, \;\; U \text{ odd}\;, \;\; U \geq 3 \end{gathered} \tag{6.4}$$

for non-bipartite graph.

Let a route r be the non-empty subset of L and let R be the set of possible routes. We associate a traffic source with each route. Let source r generate traffic at rate x_r. The rate

x_r is assumed to have an utilization function $U_r(x_r)$ to source r . Assume that $U_r(x_r)$ is a continuously differentiable, strictly concave, increasing function in the interval $(0, \infty)$. x_r^{ij} is traffic from source r and is routed at link l_{ij}. For reason of simplicity, only the bipartite Bluetooth network is studied in this chapter. The non-bipartite network should have some modifications.

6.4 Capacity allocation problem formulation

In this section, the capacity allocation problem in Bluetooth network will be formulated as convex optimization problem of the total network flows and total costs of these flows to the network, with the network constraints. The consideration is based on the Bluetooth network modeled in section 6.3.

In a stable state, the network flows coming to the directional links should be equal or less than the link capacities, which are limited by the capacities of nodes. Thus for any moderate initial condition, if $\sum_{r \in R} x_r^{ij} \le c_{ij}$, $\forall i, j \in N$ and c_{ij} should satisfy condition expressed in inequalities 6.3 and 6.4, then the queue size, time delay, etc. will build up to an equilibrium queue length average, depends on arrival rate and service capability of the link [47]. Under a heavy traffic condition, the average queue length of n-sequences is asymptotically order of $\sqrt{n}$ and will approach a reflected Brownian motion, which provides an approximation for the original queueing network [52]. Combining with the conditions that node capacities in the Bluetooth network $G = (N, L, R)$ are constrained, and with assumptions of utilization function $U_r(x_r)$ for source r mentioned in section 6.3, the optimal rate for the network flows that can be obtained by solving the maximization problem [50, 6]:

Bluetooth network $G(N, L, R)$ **:**

$$\max_{\{x_r\}} \sum_r \Delta_r U_r(x_r) \qquad \forall r \in R \tag{6.5}$$

subject to: $\forall i, j \in N$

$$\begin{gathered} 0 \le x_r^{ij}, \quad r \in R \\ \sum_{r \in R} x_r^{ij} \le c_{ij} \\ \sum_{j \in Z(i)} c_{ij} = C_i \end{gathered} \tag{6.6}$$

where the capacity of link c_{ij} and the capacity of node C_i must satisfy the constraints in expressions 6.3, 6.4 and the maximum constraints of node capacities. This optimization problem has a strictly concave objective function and the maximization is done over a finite set, so it has a unique solution.

Let denote $x_r f_r(\sum_{s:s\in R} x_s^{ij})$ as the cost function assigned to each route $r \in R$ on the link $l_{ij} \in L$, $i,j \in N$ of the Bluetooth network G. The cost function $f_r(\sum_{s:s\in R} x_s^{ij})$ can represent for the cost to meet QoS requirements, which can be time delays, queueing sizes, etc., and we assume that it is continuous within stable limits of network. When a Bluetooth packet arrives to a Bluetooth node, it increases the probability that the node drops or blocks the packet, because it is overloaded or buffer overflow. Thus the cost function increases. It is natural to define the cost of a flow x_r in G as:

$$\Phi_r(x_r) = \sum_{l_{ij}\in r} x_r f_r(\sum_{R\ni s} x_s^{ij}) \tag{6.7}$$

As we try to increase the network capacity utilization, and the total network flows, the cost functions can represent for the number of packet losses on the flows. Furthermore only the flows satisfying the capacity constraints of Bluetooth network are considered, and if the cost function $f_r(\sum_{s:s\in R} x_s^{ij})$, $l_{ij} \in r$, is a closed proper convex and finite on c_{ij}, then:

$$\begin{gathered} \Phi_r(x_r) \leq +\infty \; \forall r \in R \\ \Leftrightarrow \sum_{s:s\in R} x_s^{ij} \leq c_{ij} \\ \forall l_{ij} \in r, r \in R, i, j \in N \end{gathered} \tag{6.8}$$

By applying the feasible distribution theorem [78, 11], it ensures the existence of at least one solution $x = (x_r, r \in R)$ that minimizes the cost $\Phi = (\Phi_r(x_r), r \in R)$ satisfying the constraints 6.3 and 6.4.

It can assume that searching the optimal rate of maximizing utilization function $U_r(x_r, r \in R)$ in (6.5, 6.6) and the minimization requirement of the cost $\Phi = (\Phi_r(x_r), r \in R)$ in (6.7) represents the convex optimization problem. So the simultaneous capacity scheduling and allocation problem can be formulated as the following convex optimization problem, which is to maximize the flows, and to minimize the cost functions with the resource capacity constraint:

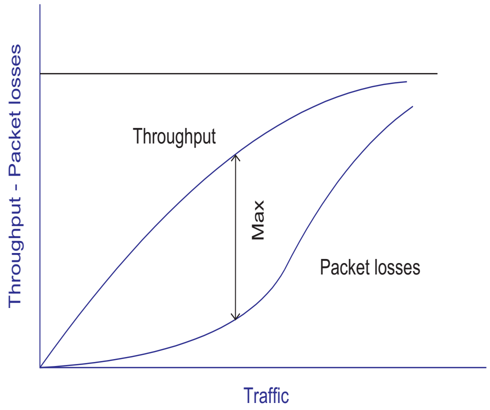


Figure 6.2: An example of the formulated optimization problem of capacity allocation

Bluetooth network $G(N, L, R)$ **:**

$$\max_{\{x_r\}} \sum_r \{\Delta_r U_r(x_r) - \beta \Phi_r(x_r)\} \tag{6.9}$$

subject to: $\forall i, j \in N, \forall r \in R, \forall l_{ij} \in L$

$$\begin{aligned} 0 &\leq x_r^{ij} \\ \sum_{r \in R} x_r^{ij} &\leq c_{ij} \\ \sum_{j \in Z(i)} c_{ij} &= C_i \end{aligned} \tag{6.10}$$

where Δ_r and β are non-negative constants that represent the trade-off of maximizing utilization function and minimizing the cost function. Figure 6.2 illustrates an example of the capacity allocation optimization problem between throughput and packet losses.

Finding the optimal solution for this convex optimization problem could be an infinite process, as the formulated optimization is an NP hard problem. Thus a heuristic solution approach is suggested to give the network performance close to the performance of the optimal solution, and to reduce the complexity of solving the formulated optimization problem. In next section, section 6.5, the hybrid distributed iterative capacity allocation scheme is introduced as an approximated solution of the convex optimization problem.

6.5 Hybrid distributed iterative capacity allocation scheme

The proposed hybrid distributed iterative capacity allocation scheme requires its own capacity partitions on each node of the Bluetooth networks and it tries to divide the network capacity to the links and to traffic sources by the principles of maximizing the network flows and satisfying the QoS requirements as formulated in the convex optimization problem in equations 6.9 and 6.10 . In the hybrid distributed iterative capacity allocation scheme, each host node informs the other nodes on the route paths about the estimated demand traffic, the estimated permitted traffic to meet QoS requirements. The capacity of Bluetooth node in the network is allocated to links controlled by the node and this allocation is based on the estimated demanded traffic outbounded from the node. Allocation processes of the link capacities are iterated on each link along the route paths. Resources of the link are allocated to the longest route paths first and the unused resources will be allocated to the shortest route paths in the last iteration. These resource partitions are combined with the estimated demand traffic, the estimated permitted traffic to meet QoS requirements and the selection is according to principles of satisfying QoS requirements and minimizing bandwidth. The process can be initiated by a Bluetooth node in the network when there is enough traffic change. It can also combine with routing discovery process, so that the capacity allocation is updated periodically.

Figure 6.3 illustrates the stages of the hybrid distributed iterative capacity allocation session with acceptance and blocking processes. The allocation process comprises three stages. In the first stage, nodes connecting to traffic sources estimate the demand traffic $\widehat{x}_r$ arriving from the sources and the permitted traffic $\widehat{x}_r^q$ that still satisfying QoS requirements. The $\widehat{x}_r$ and $\widehat{x}_r^q$ are predicted based on history records of packet arrivals from sources attached to the nodes and of QoS information updated periodically by nodes along the routes to the source nodes. The QoS information can be packet delays, packet losses, etc., for the sources. In a subsequent corrective step Δ_r^q, $\widehat{x}_r^q$ is increased or decreased according to QoS criteria being met or not, respectively. Each node will transmit the traffic estimations of the traffic sources attached to the node to other route nodes in probe messages. There are several approaches to assign link capacity [107]. However, in our scheme, the link capacity is allocated according to the outbound estimated demand traffic. Each node in the network will calculate and allocate its own capacity to the links that are under its control from the outbound estimated demand traffic and capacity of the node:

$$c_{ij} = \gamma_{ij} \frac{\sum\limits_{r:r\in R} \widehat{x}_r^{ij}}{\sum\limits_{r:r\in R, k\in Z(i)} \widehat{x}_r^{ik}} C_i \tag{6.11}$$

$$\forall i, j \in N, j \in Z(i), r \in R, l_{ij} \in L$$

where $0 \leq c_{ij}$, $\sum_{j \in Z(i)} c_{ij} \leq C_i$, and γ_{ij}, $0 \leq \gamma_{ij} \leq +\infty$, is weight value for the link. This stage can start when a node measures a significant traffic fluctuation or in a certain amount of time, and then making all nodes in network will transmit probe messages. The measurement is carried out in intervals T_m and the parameter T_u is the updating period. These parameters can be optimized for a specific traffic pattern to give the best information on the network transient behaviors. In this stage, it is assumed that each node has knowledge about the updated route paths in the links that it controls. In practice, this information can be obtained from route discovery and network state updating processes.

In the next stage, the allocated resource on each link is divided among all route paths that come through the link. This partition is based on information about the estimated demand traffic, the estimated permitted traffic to meet QoS requirements for all route paths from the previous stage and capacity fraction from fair share capacity allocation approach. An example of the fair share capacity allocation is presented in Appendix C. The modified fair share capacity allocation approach [33] is applied to get the maximum network flows and it is combined with the traffic demands, the permitted traffic to get the best use of the network capacity and to satisfy QoS requirements. In the first iteration, resources of the link are distributed to the route paths, so that the estimated Quality of Services (QoS) should not violate the QoS constraints. If any violation occurs, the link capacity will be divided according to the saturation allocation. The amount portion x_r^{ij} is the minimum value of the following three variables: the capacity limit of the route path to meet the QoS constraints, $\widehat{x}_r^q$, the estimated demand, $\widehat{x}_r$, and the divided fair share fraction, as shown in equation 6.12 below:

$$x_r^{ij} = \min \left\{ \widehat{x}_r, \widehat{x}_r^q, \xi \left(\frac{c_{ij} - \sum\limits_{s: s \in l_{ij}} x_r^s}{1 + \xi u} \right) \right\} \tag{6.12}$$

where the variable ξ expresses the ideal QoS constraints tradeoff, e.g. throughput, delay, etc., x_r^s is the allocated capacity of the saturated route paths and u is the number of route paths of the link, which are not saturated before this iteration. The results are updated to traffic information messages. The process is iterated for successive links and the amount of available capacity is stored in the traffic information messages as they traverse through the links. At the end node, the saturation portion of the capacity for the route path can be determined by the minimum value of the stored x_r^{ij}s all over the links:

$$x_r = \min_{l_{ij} \in r} \left\{ x_r^{ij} \right\} \tag{6.13}$$

The results are sent back to the original source node for assignment. The allocation

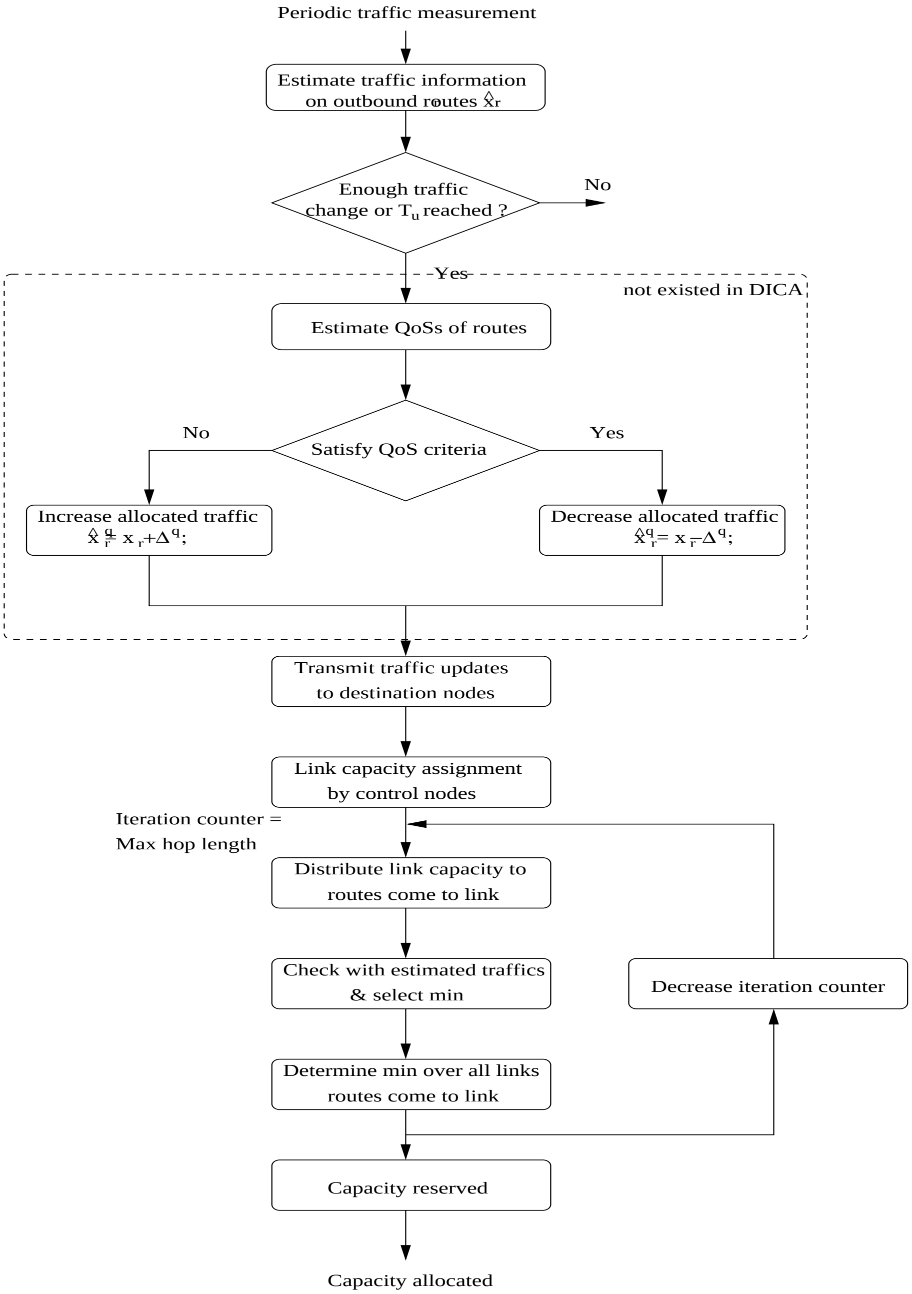


Figure 6.3: Hybrid distributed iterative capacity allocation scheme in Bluetooth network

iterating is finite, because if there are r routes, they will be allocated after no more than r iterations.

In the last stage, the final capacities are reserved. As a result of the allocation processes, the route paths with the longest hop lengths receive capacities first and the shortest route paths take all remaining available capacities. The on-going connection is normally disconnected when depleted however.

The allocated capacity results will have a tendency of adaptively approaching to the optimal solution that satisfies the QoS demands and makes the best use of the network resources highlighted in the convex optimization problem in equations 6.9 and 6.10.

6.6 Evaluation of the hybrid distributed iterative capacity allocation scheme

The performance evaluation of the proposed hybrid distributed iteration capacity allocation scheme (HDICA) addresses the following issues: the relationship between updating period and probability that a Bluetooth packet to be blocked or lost, the ability to avoid congestion and the parameters affecting the acceptance probabilities. It is also compared with the distributed iteration capacity allocation scheme (DICA), i.e. the QoS criteria are not applied, and $\widehat{x}_r^q$, which represents the permitted traffic to meet QoS criteria, does not appear in equation 6.12.

The network modeled in the section 6.2 is considered. When a Bluetooth packet from a source is supposed to arrive at a link on its route path, it would be blocked or lost if the link is overloaded. In the case that the arrival traffic is assumed to consist of a number of identical on-off sources with exponentially distributed ON and OFF periods, the probability that Bluetooth packet is blocked or lost on a link due to capacity c_{ij} of link l_{ij} exceeded can be estimated by the fluid-flow approximation for the kth interval, as:

$$p_b^{l_{ij}} = \frac{E\left[(\Lambda_{ij} - c_{ij})^+\right]}{E\left[\Lambda_{ij}\right]} \tag{6.14}$$

where $l_{ij} \in L$ and Λ_{ij} is the aggregate load of the link l_{ij} during the updated period T_u and it depends on the established traffic x_r to the link during the kth interval:

$$\Lambda_{ij} = \frac{1}{T_u} \sum_{kT_u}^{(k+1)T_u} \sum_{r \in R} x_r^{ij} \tag{6.15}$$

This probability estimation is accurate to a satisfactory degree if the sampling at the intervals of length T_u is long enough, which represents the dominant time-scale for the estimation processes. In other words, it is an asymptotic estimate of packets to be blocked or lost, which is based only on time-scale of T_u. Equation 6.14 then selects the dominant time-scale as the one giving worst packet to be blocked or lost.

The probability that a Bluetooth packet entering to the network not to be blocked or lost on the link on its route path is:

$$p_r = \prod_{l_{ij} \in r} (1 - p_b^{l_{ij}}) \tag{6.16}$$

The efficiency of the hybrid distributed iterative capacity allocation approach is heavily dependent on the estimations of the demanded traffic of outbound traffic sources, and the permitted traffic to meet QoS requirements. By adaptively changing the permitted traffic, we can ensure that it will approach to satisfy the QoS demands. These estimations can be based on the past records that are kept in the traffic histories. In the next section, the performance evaluations and the comparisons will be illustrated through simulations of a simple Bluetooth scatternet.

6.7 Simulations

6.7.1 Simulation model

The Bluetooth network in consideration is a simple scatternet, as depicted in figure 6.4, which consists of two inter-connected piconets. The piconet provides full-duplex transmission using time slots. The polling in a Bluetooth piconet can be done in many different ways. The difference between the polling schemes is related to the order in which slaves are polled and the service disciplines used to serve a slave. In this simulation, we use the Fair Exhaustive Polling (FEP) [35] scheme in the piconets. The FEP gives high bandwidth efficiency with a fair allocation, while still being simplistic. Each piconet has a master and N_p slaves, $0 \leq N_p \leq 7$, and its traffic can be modeled as in [81]. The inter-piconet traffic is transfered through a bridge node ($S07/S17$). The modeled network uses Asynchronous Connectionless Link (ACL). It is possible to send packets in multiple slots, which may be either 3 or 5 slots long. In this study, only the single slot data packet transmission between nodes in the modeled network is considered. Further, we assume that there is no transmission error and the packet losses only occur when the buffers overflow. Moreover, the piconets were assumed to be synchronized, which means there were no guard frames when the bridge node switches between the piconets and the effects of the clock drifts are eliminated.

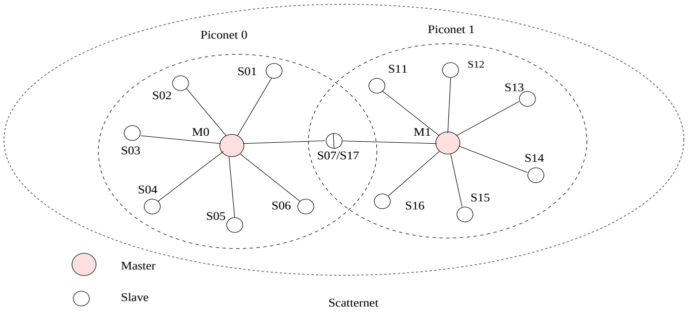


Figure 6.4: The modeled Bluetooth scatternet with two inter-connected piconets.

The homogeneous traffic of packet arrivals can be modeled as Interrupted Bernoulli Process (IBP) sources [82]. The probabilities of being in an ON state and in an OFF state could be characterized by p and q, respectively [89]. The packet arrivals are set to be aligned with the time slots in the modeled piconets.

Figure 6.4 shows the scatternet simulation model and figure 6.5 depicts its IBP traffic model.

The modeled scatternet uses the predictive inter-piconet scheduling [57], with the scheduled inter-connected window period T_s of the bridge node is set to 400 time slots and it is fairly allocated to the piconets, which the bridge node is connected to. The allocated active intervals of the bridge node on each piconet, which it belongs to, are dynamically varied depending on inter-piconet traffic and traffic to and from the bridge node.

To verify the working ability of the hybrid distributed iterative capacity allocation scheme in the Bluetooth modeled network, the output buffer sizes on each node are set to 40 packets, the capacity of each node are set to C and it is the same for the nodes in the modeled network for a update period T_u. The increase/decrease step for adaptively changing the permitted traffic to meet QoS requirement, i.e. packet losses, is set to 5 packets. The QoS parameter for each source route is γ, which can be 0.04 and 0.10. The simulation length is 10^6 time slots.

To estimate the demand traffic and the permitted traffic to meet the requirement on packet losses on routes, several methods can be used, which are possibly based on mathematical modeling of the estimated traffic. We use, however, the simple Levinson-Durbin algorithm, which is rather efficient to solve the Yule-Walker equation [32]:

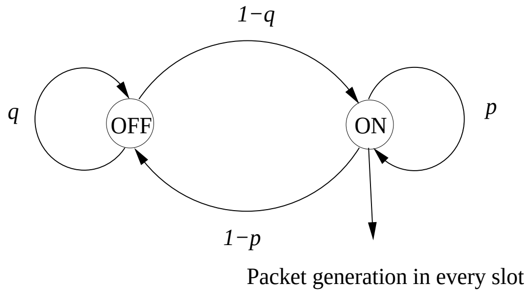


Figure 6.5: IBP traffic model

$$R_X^{(M+1)} \begin{bmatrix} 1 \\ a_1^{(M)} \\ \vdots \\ a_M^{(M)} \end{bmatrix} = \begin{bmatrix} \alpha^{(M)} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{6.17}$$

where R_x is a $(M+1) \times (M+1)$ Hermitian Toeplitz matrix, $a^{(M)}$ is prediction coefficient and $\alpha^{(M)}$ is error variance. To simplify, the prediction order M was set to 2 and the record history of 3 previous measured data was applied. Other more sophisticated estimation methods and higher prediction orders might be applied to give the better prediction results.

6.7.2 Numeric results

Figure 6.6 shows an example of capacity allocation for the links, which were controlled by the master $M0$, in the case that the hybrid distributed iterative capacity allocation scheme was applied. As mentioned in section 6.5, the capacities were allocated to links according to the demand traffic from traffic sources to the links. Higher traffic demand to a link means higher allocated capacity ratio to that link. It is natural that the capacities allocated to links that connect the node $S07/S17$, which is the bridge node, were much higher than the links that connect the other nodes in the piconets. This is because of the homogeneous traffic sources and of higher inter-piconet traffic demand.

The allocated capacity of the link was divided among the routes, which pass through the link. The partition results are illustrated in figure 6.7. It shows an example of capacity allocated to the traffic sources, which were accompanied with the routes and attached to a node in the modeled network. The capacity allocation to the traffic sources depends on the available capacity of the links that its route comes through, the estimated traffic demand and the estimated permitted traffic to meet QoS requirement (packet losses).

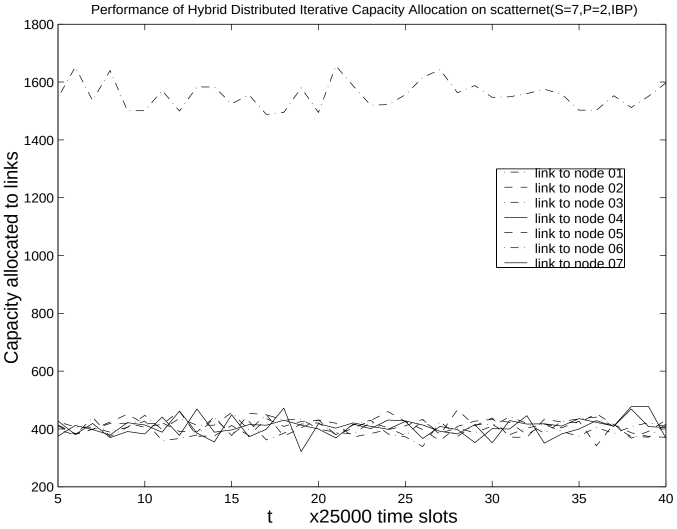


Figure 6.6: Transient behavior of Bluetooth scatternet, with hybrid distributed iterative capacity allocation: an example of link capacity allocations for links controlled by master

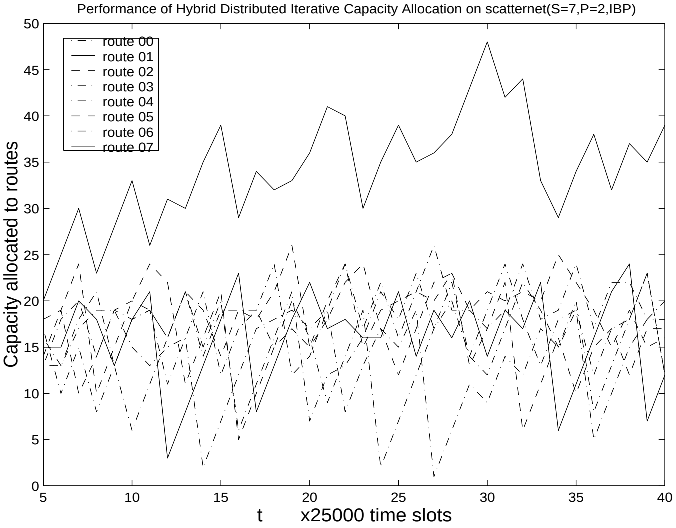


Figure 6.7: Transient behavior of Bluetooth scatternet, with hybrid distributed iterative capacity allocation: an example of capacity allocations for routes

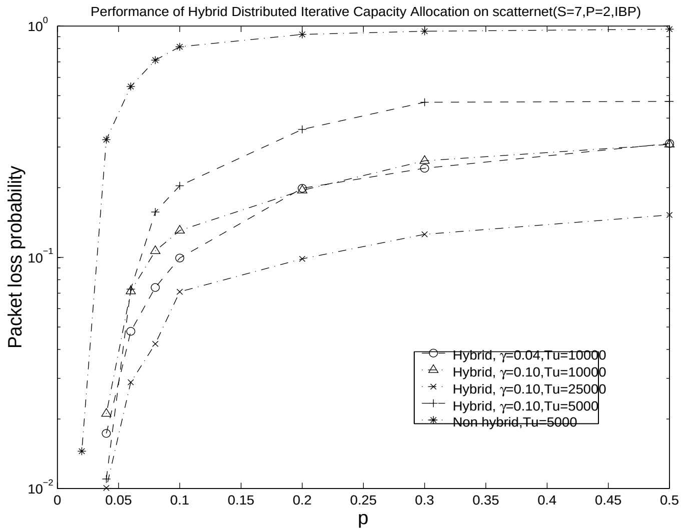


Figure 6.8: Performance of Bluetooth scatternet, comparison of hybrid and non hybrid distributed iterative capacity allocations: packet loss performance

Figure 6.8 shows the modeled network performance, when the hybrid distributed iterative capacity allocation (HDICA) and the non hybrid distributed iterative capacity allocation (DICA) were applied, when traffic intensity was increased. The latter did not use QoS oriented capacity allocation and the QoS requirement criteria, i.e. $\widehat{x}_r^q$ does not appear in the capacity selection equation 6.12. The packet loss probability with the HDICA used was much lower than when the DICA used. This indicates that the QoS oriented capacity allocation scheme reduces the packet losses. Furthermore, the figure also shows that the QoS criteria γ and the updating period T_u affect the packet loss performance. Lower γ or longer T_u means lower packet loss probability.

Figure 6.9 shows performance of the modeled network, in terms of packet blocked percentage, when increasing the network traffic intensity. From the figure, the HDICA blocked more packets entering to the network than the DICA. And similarly, the QoS criteria γ and the updating period T_u also affect the packet loss performance. When the traffic intensity was very low, the percentage of the blocked packets with the HDICA application remained high. This is due to the high prediction errors of the Levinson-Durbin recursion, which was used for traffic and QoS estimations in the HDICA. In the very low traffic, the un-correlation of the measured traffic demand and the packet loss feedback was significantly increased, the spectral flatness was inversely decreased. This means higher prediction errors.

Figures 6.10 and 6.11 compare performance of the modeled network in terms of prof-

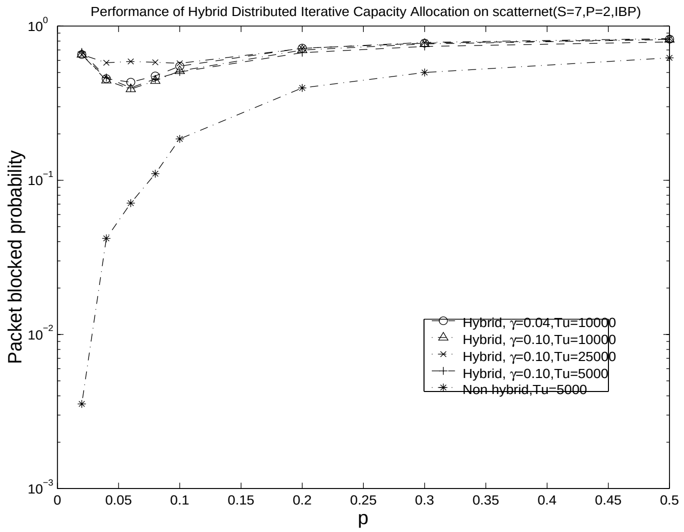


Figure 6.9: Performance of Bluetooth scatternet, comparison of hybrid and non hybrid distributed iterative capacity allocations: packet blocked performance

itability and process gain ratios, when the hybrid distributed iterative capacity allocation and the non hybrid distributed iterative capacity allocation schemes were applied. It also illustrates the modeled network performance for different QoS requirements (packet loss) γ and updating periods T_u. The profitability is the ratio between the handled traffic without overhead and the traffic admitted to the network. When increasing traffic intensity, the profitability remained higher in the case of the hybrid distributed capacity allocation. More restricted packet loss requirements or appropriate update period also helped to maintain high profitability.

Process gain comparison is depicted in figure 6.11. The process gain ratio is defined as the ratio between the handled traffic, without overhead, and the arrival traffic. The increment of traffic intensity of the nodes in the modeled network was followed by the decrement of process gain. However, at very low traffic intensity, due to high prediction errors, which were caused by low correlationess and spectral flatness, the working ability of the hybrid distributed iterative capacity allocation scheme was poor. The process gain for the hybrid distributed iterative capacity allocation scheme was higher than for the non hybrid distributed iterative capacity allocation scheme. It means higher throughput. More restricted packet loss requirements and appropriate long updating period also reduced process gain.

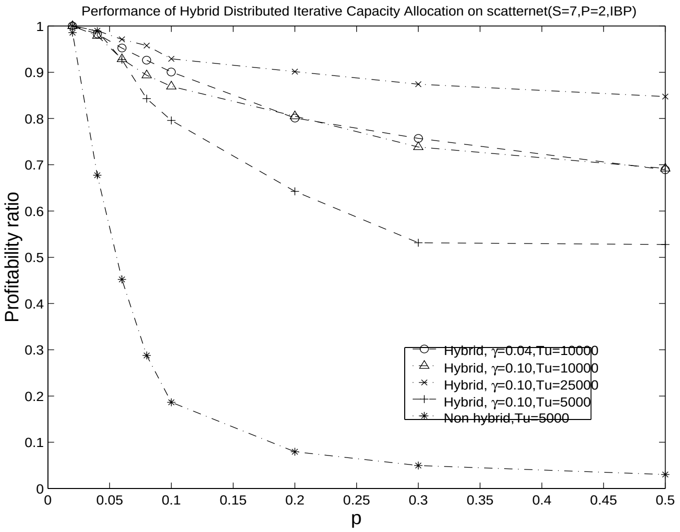


Figure 6.10: Performance of Bluetooth scatternet, comparison of hybrid and non hybrid distributed iterative capacity allocations: profit ratio performance

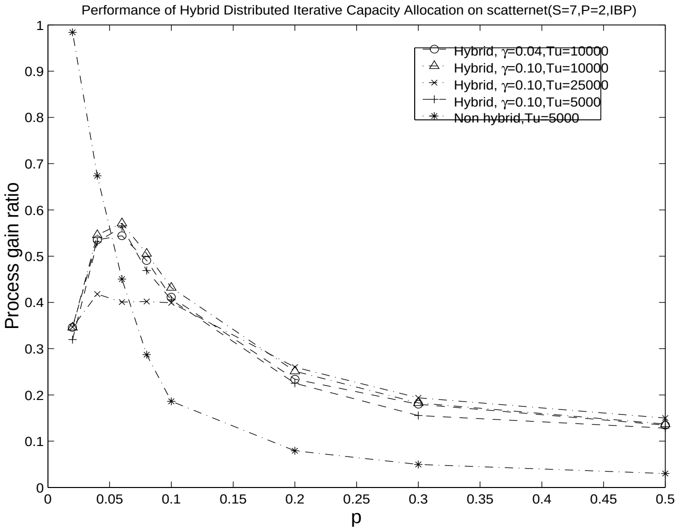


Figure 6.11: Performance of Bluetooth scatternet, comparison of hybrid and non hybrid distributed iterative capacity allocations: process gain ratio performance

6.8 Discussions

The simulations in section 6.7 have shown some behaviors of the hybrid distributed iterative capacity allocation scheme. Although it could improve QoS requirements, such as packet delays, throughput, etc., the simulations suggest some approaches to enhance capacity allocation over Bluetooth data networks.

From the simulation results, the HDICA scheme outperforms the DICA scheme in terms of QoSs, e.g. throughput, packet delays, etc. However, it also shows that the HDICA scheme blocks more packets at very low traffic, compared to the DICA scheme. As a result, the process gain is reduced, which may cause lower throughput. This is due to the fact that at very low traffic, the prediction algorithms such as Levinson-Durbin algorithm, which is employed in the simulation model, have high prediction errors. Hence, it is more difficult to estimate the arrival traffic and QoSs. These parameters are used to get the outbounded traffic demand and the traffic to meet QoS requirements. There are several ways to alleviate this effect, including the method that combines the HDICA and the DICA schemes. The combination might be based on traffic load criteria at Bluetooth nodes. At low traffic or when traffic is still below a threshold, the distributed allocation scheme uses the DICA scheme. When the traffic load is higher than the threshold, the HDICA scheme should be operated. Thus the distributed capacity allocation scheme takes advantages of both schemes, and the performance of the distributed capacity allocation over Bluetooth network could be improved. The combination scheme is carried out at local nodes, and does not require intermediate message exchanges between nodes in the network. Thus it does not make message overheads. However, determination of the thresholds is necessary, in which some factors can be useful, such as the average queue lengths, average packet delays, etc. at the nodes. An on-fly dynamic QoS configuration protocol [90] can be applied to this approach.

Another approach uses the adaptive algorithm for setting node capacity, which uses the QoS prediction parameters to assign available node capacity. The HDICA scheme is based on prior knowledge of capacity for each node in the Bluetooth scatternet. The node capacity is varied depending on the network topology, available channels, etc., which could be not feasible, in some circumstances, to determine. The adaptive algorithm for setting node capacity is applied to reduce the computation complexity of the available node capacity determination. The approach uses a certain QoS criteria, such as average queueing size, average packet delays at the node, etc. The processes of the adaptive algorithm for setting node capacity are briefly described as follows. At initialization, each node is assigned to a certain capacity, which is limited by maximum node capacity and satisfies the capacity constraints mentioned in section 6.3. The node will carry out periodic measurement of these parameters. If the criteria are not exceeded, the available node capacity is increased, and inversely, if the criteria are exceeded, the available node capacity is reduced. The amount of increment or decrement of capacity can be varied. To efficiently determine the available node capacity, a differentiated step is advised. With assumptions on arrival traffic and the cost functions as described in the capacity allocation problem formulation, the results of the setting node capacity will approach to the optimal capacity value and satisfy the criteria. The computations are implemented locally at the nodes. Thus new message exchanges can be reduced significantly. For bursty traffic with frequently traffic variations, this approach however requires appropriate measurement intervals and corrective steps of capacity allocation.

To illustrate this approach, a simulation is carried out. The same setting parameters are used as in the previous experiments and the HDICA allocation scheme is still applied, with the QoS parameter for each source route, γ, is fixed to 0.1. The QoS measurement in each node in the modeled network is expressed in packet loss probability. The packet loss criterion for each node is ε, which can be 0.001 and 0.1. The packet loss probability is predicted by using the Levinson-Durbin algorithm. When the predicted QoS of each node (the packet loss probability) exceeds the QoS criterion, then the allocated capacity of the node will be increased, and inversely, the allocated capacity of the node will be decreased if the node still has available capacity, i.e. the predicted QoS is less than the QoS criterion. The corrective step, ΔC, in the measurement period is set to 300 packets. However a more complicated QoS estimation and a differentiated corrective step for each node are recommended to adapt to traffic variations.

Figures 6.12 and 6.13 show the performance of the modeled network, when applying the enhanced hybrid distributed iterative capacity allocation approach, in terms of packet loss and profitability performance. As can be seen, the performances are quite similar to the results of previous experiments: increasing of traffic load is followed by increasing of packet losses and decreasing of profitability ratio. More restricted QoS criterion for each node (the packet loss criterion) or appropriate long T_u can help to reduce packet losses and to obtain higher profitability.

Figures 6.14 and 6.15 illustrate the performance of the modeled network in terms of the packet blocked probability and process gain ratio, when the enhanced hybrid distributed iterative capacity allocation was applied. As similar to the above experiment, the more restricted requirement, e.g. QoS criteria ε, affects these network performances. Furthermore, the network performance is improved significantly at low traffic, when applying the enhanced hybrid distributed iterative capacity allocation.

6.9 Open issues

Although there is much research on Bluetooth networks, scatternet is quite important in Bluetooth PAN, and it opens many subjects to study, including the capacity allocation issues. The hybrid distributed iterative capacity allocation scheme is an attempt to deal with capacity allocation in Bluetooth. There are still many open issues in the hybrid distributed iterative capacity allocation scheme. The main open issues are the following:

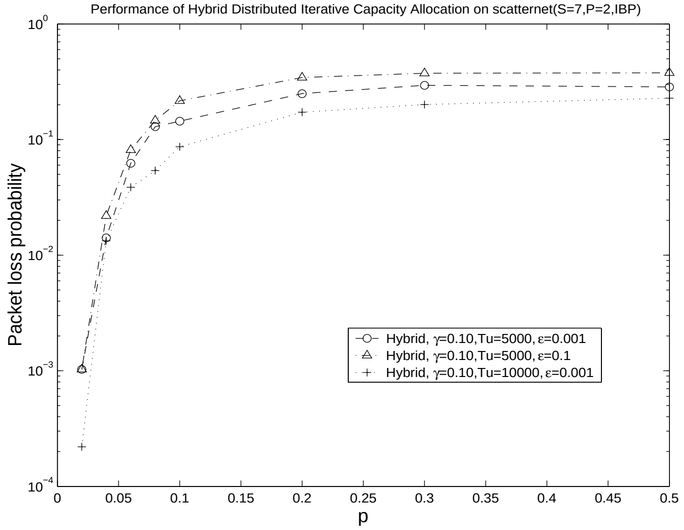


Figure 6.12: Performance of Bluetooth scatternet, adaptive hybrid distributed iterative capacity allocations: packet loss performance

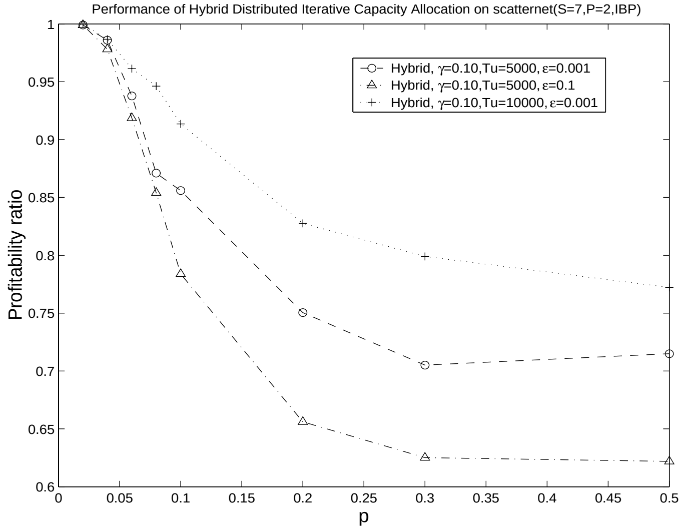


Figure 6.13: Performance of Bluetooth scatternet, adaptive hybrid distributed iterative capacity allocations: profitability ratio

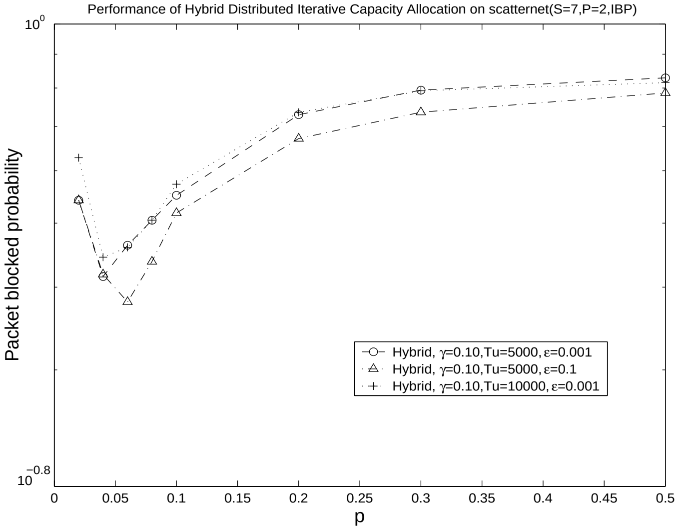


Figure 6.14: Performance of Bluetooth scatternet, adaptive hybrid distributed iterative capacity allocations: packet blocked probability

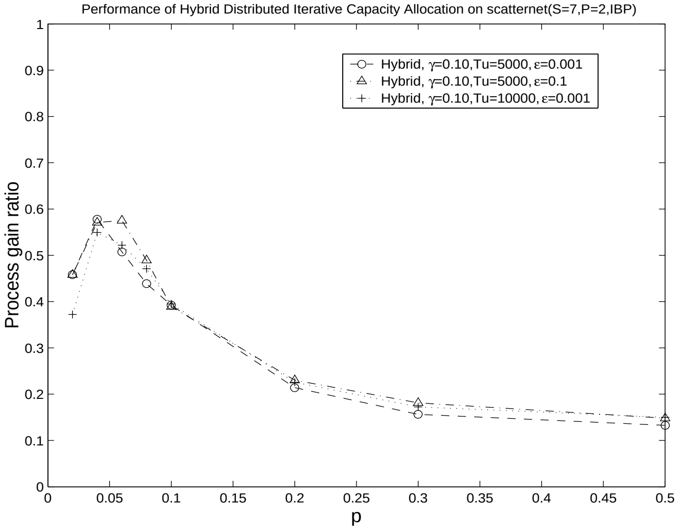


Figure 6.15: Performance of Bluetooth scatternet, adaptive hybrid distributed iterative capacity allocations: process gain ratio

- Although the hybrid distributed iterative capacity allocation scheme has tried to reduce information exchanges between nodes in the network, but the scheme still uses a significant number of messages to exchange information between nodes in the Bluetooth network. These messages could create overhead to the network and burden to the system, which has very limited resources. When the network is expanded, it can affect the working ability of the network. Thus the scheme may require complicated message handling. One of the possibilities to alleviate the problem is to use a broadcast and repetition scheme. Application of multipoint relay (MPR) technique can be the way for reducing message exchanges and overhead. Although the MPR is proved to be efficient an method for message transmission in the Optimized Link State Routing Protocol (OLSR) [12, 53], some modifications in design as well as some investigations should be carried out.

- In Bluetooth scatternet, a node can move around and participate in several piconets. The network topology can be varied according to criteria defined in the scatternet formation algorithm. The purpose of these variations is to increase network capacity and to satisfy QoS demands. The network capacity can be efficiently used by swapping master-slave roles [48]. The mobility of Bluetooth nodes, dynamic network topology can be subject to changes of routing algorithm and of capacity allocated to the nodes in the network. It may also require special message handling. Further investigation and modifications of the hybrid distributed iterative capacity allocation scheme to cope with these issues should be carried out. The adaptive algorithm for setting up node capacity could be suitable for this scenario.

- The simulations have shown the affects of prediction errors on the working ability of the distributed capacity allocation scheme. The prediction based on the Levinson-Durbin algorithm could give poor results if some conditions are not satisfied, such as the correlation condition. Thus a good predictor is needed. More efficient and sophisticated prediction algorithms should be investigated to improve the working ability of the allocation scheme. The predictions can be improved with knowledge of the mathematical model of arrival traffic, QoSs, or long enough measurement data. In this case, a model based or LMMSE based predictions can be applied.

- The applications of the QoS based dynamic alternative routing schemes and the adaptive capacity allocations, network topology could enhance the performance of Bluetooth networks. The research results on mobile ad hoc multipath QoS routing could be exploited to improve the working ability of Bluetooth networks.

6.10 Conclusions and future developments

This chapter has considered the problem of optimal resource allocation for Bluetooth networks. The network resource allocation problem is optimized through capacity constraints on the total traffic supported on individual Bluetooth nodes. It was followed by formulation of the allocation problem as a convex optimization problem, in which the total network flows and the costs of the flows to meet the QoS requirements are a concave function of the associated resource variables.

An allocation approach, the hybrid distributed iterative capacity allocation scheme, was proposed as a heuristic solution for the stated optimization problem. The hybrid distributed capacity allocation scheme tried to get maximum network flows while satisfying QoS requirements. The scheme used iteration cycles and QoS requirements to the traffic sources to reallocate the capacity. The computations needed are simple but the complexity instead moved to the management of control messages. The simulations showed the working ability of Bluetooth networks could be improved by applying the hybrid distributed capacity allocation scheme. The hybrid distributed iterative capacity allocation scheme can be improved by combining with the distributed iterative capacity allocation scheme or by applying the adaptive algorithm for setting node capacity. These improvements do not create significant overhead to the network. Some open research issues were also discussed and these request further research.

Chapter 7

Conclusions and Future Directions

7.1 Conclusions

Bluetooth Personal Area Network (BPAN), which includes Bluetooth scatternet and piconet, is a heterogeneous system. With broad ranges of applications, it opens a new era of wireless short range communications. In the meanwhile, many research topics occur, which require great efforts from both industry and academia. This thesis work studies ’adaptive capacity management’ issues of Bluetooth networks, which obviously involves a large number of topics, such as Bluetooth technology and its nature, radio links, network formation and scheduling, Bluetooth protocols, radio resource management, network performance and monitoring, etc. Furthermore, each of these topics can expand and create new frameworks for study. In the context of Bluetooth networks, these topics have a very close relationship to each other, and one topic cannot be omitted from others.

This thesis work has tried to cover many of these issues. Several approaches, including buffer management, scheduling, network traffic control and capacity allocation, have been explored in order to establish a modern and effective capacity management of Bluetooth networks, incorporating the latest achievements in the Information and Telecommunication Technologies, particularly Wireless Communications.

The first chapter gave the global view of Bluetooth technology and provided a preview to the future of Bluetooth, based on the latest developments of the Third and Fourth generations of mobile communications. The research objective and goals of this thesis were highlighted.

Chapter 2 briefly described Bluetooth Technology, which despite having a very short history, beginning with the Ericsson initiatives and the commitments of Bluetooth SIG founding members, has advanced to become the key element of future mobile communications. A short description about Bluetooth protocol stacks was presented. which includes radio link, baseband layers to middleware group. Basic features of Bluetooth were described. Lower power operation modes and advancement of Bluetooth Technology, which is represented by Bluetooth Network Encapsulation Protocol (BNEP), were specified. Current extensive efforts of Bluetooth SIG members on Bluetooth ad hoc personal area network (BPAN) were highlighted, which requires broad cooperations of both industry and academia.

In the beginning of chapter 3, a queueing model for Bluetooth networks was presented. A simple case of the queueing model for Bluetooth piconet with Poisson arrival data traffic and Pure Round-Robin polling scheme was analyzed. It can be extended to the case of the priority based scheduling. QoS issues of Bluetooth networks were discussed. Bluetooth application model was described. The model is structured into blocks, each block consists of variables and activities. The inter-block communication is handled by procedures and external variables. A buffer dimensioning approach was proposed, which uses the application model and iteratively attempts to optimize the buffer sizes of the Bluetooth nodes in the network according to its transient behavior and to QoS criteria. To illustrate working performance of the buffer dimensioning approach, a simulation model with the bursty arrival traffic, IBP traffic, was implemented. The simulation results for both homogeneous and heterogeneous traffic scenarios showed some queueing behaviors of the modeled network. Some issues from the analysis of the simulation results were discussed, which opened research issues for the following chapters.

Chapter 4 discussed about inter-piconet communication and inter-piconet scheduling. Some issues affect the network capacity and performance were discussed, such as bottleneck, scheduling, etc. It described some main structure and functions of the inter-piconet scheduler, in which the bridge node uses low power modes to switch between the piconets that it connects to. Backgrounds of the proposed predictive inter-piconet scheduling approach were described. The inter-piconet scheduling optimization problem were formulated and the predictive inter-piconet scheduling was proposed as a heuristic solution to the optimization problem. The predictive inter-piconet scheduling approach uses the predicted inter-piconet traffic to adaptively allocate the bridge node capacity to the connected piconets. The scheduling window as well as the active and sniff intervals are determined from the updated inter-piconet traffic information and the QoS requirements. Using a simple scenario of a simple scatternet, arrival bursty traffic, and IBP traffic model, the simulations showed that the predictive inter-piconet scheduling could improve performance of the modeled network. Some extended issues were discussed, which could be applied to enhance the predictive inter-piconet scheduling approach.

The QoSs and the network traffic control issues in Bluetooth networks were highlighted in chapter 5. A Bluetooth network model was mentioned and the problem of finding the optimal rate for the network flows was formulated as a maximization of total network flows and a minimization of total packet losses. A virtual marking scheme was described. An adaptive distributed network traffic control approach with QoS provisioning in Bluetooth data networks was presented. The scheme uses the virtual marking to get a certain degree of QoS requirements and efficiently exploit the network capacity, while minimizing the overheads to the Bluetooth network. The simulations of a simple Bluetooth scatternet were carried out to illustrate the working ability of the adaptive virtual queue based distributed network traffic control approach. Some extended approaches were discussed, which could be used for enhancing the adaptive virtual queue based distributed network traffic control approach.

The predictive inter-piconet scheduling scheme could improve the network performance in terms of fairness capacity allocation, network capacity utilization, and QoSs such as throughput, packet delays, which have significant impacts in Bluetooth based IP applications. It is also an important step in implementing Bluetooth Personal Area Network, in which the inter-piconet communication is used for data transfer between piconets. The scheme is robust to fluctuations of traffics and QoS requirements. However, to adapt to frequently changes of network topology and the mobility of the Bluetooth devices, some enhancements of the scheme are still needed.

Chapter 6 discussed capacity allocation issues in Bluetooth networks. A Bluetooth network model which consists of a set of directional scatternet graph was described. Some significant factors that affect the capacity of Bluetooth node followed by the capacity limitations of the directional links under its control in the network, were mentioned. The capacity limitations heavily depend on the number of Bluetooth nodes, available channels, and topology in the network. The capacity allocation problem for Bluetooth networks was formulated as a convex optimization problem of maximizing the total network flows and minimizing the total costs of flows, which represent the costs of satisfying QoS requirements. The hybrid distributed iterative capacity allocation scheme (HDICA) was proposed as an approximate solution of the formulated capacity problem. The HDICA scheme uses information on the estimated traffic demands, the estimated traffic to meet QoS requirements to allocate the network capacity to the links and to the route paths. The fair share iterative capacity allocation approach is also applied to give the best use of the network capacity, while trying to satisfy QoS requirements and to minimize bandwidths. Some aspects of the hybrid distributed iterative capacity allocation scheme were evaluated. A simple model of Bluetooth scatternet with the HDICA scheme was simulated. The simulation results showed some characteristics the HDICA scheme. Some problems were discussed and some enhancements of the HDICA scheme were suggested. The simulation also raised some open issues about capacity allocation in Bluetooth networks.

Both schemes, the adaptive virtual queue based distributed network traffic control and the hybrid distributed iterative capacity allocation, are rather simple and efficient methods. There is no central entity required. By applying these schemes, the network capacity utilization could be enhanced, and the QoSs such as throughput, packet delays, etc., could be improved compared to the current scheme described in Bluetooth specification. The hybrid distributed iterative capacity allocation scheme seems simple in calculation, but it depends heavily on the control messages exchanged between nodes in the network. Some changes such as link broken down, topology, etc. at somewhere in the network would result in whole capacity reallocation of the network. Meanwhile, although much less message handling required, the adaptive virtual queue based distributed network traffic control scheme demands more complicated computations for estimating packet marking and traffic, which could result in downgraded QoSs in the network. Some further enhancements and studies of these schemes are needed for better performance of Bluetooth networks in future mobile multimedia environment.

7.2 Future research directions

Since Bluetooth is quite new technology and at first just dedicated as cable replacement for simple applications, e.g. earphone, data connect points, it is evolving as a new technology with novel concepts for global wireless short range communications, especially Bluetooth Personal Area Network (BPAN), a true mobile ad hoc network. To overcome challenges of implementing the new technology, many novel and complicated topics occur, which require extensively researches, from radio layers to application profiles. These topics is highly inter-related to each other. The capacity management issue in Bluetooth networks is quite large and it is involving many other topics. Hence, the studies in this thesis should just be considered as initial attempts of solving capacity management in Bluetooth networks. As a result, numerous issues concerning the capacity management issue in Bluetooth networks come up which requiring many comprehensive future research work.

As Bluetooth is an implementation of the Mobile Ad hoc Network, it means a Bluetooth node can move around and be a member of several piconets. The network topology frequently changes, and capacity and routing paths are also affected. These topology variations could, on one hand, increase the network capacity and improve QoSs, but on the other hand, it has significant impacts on the capacity management approaches studied: the hybrid distributed iterative capacity allocation, the adaptive virtual queue based distributed network control, the predictive inter-piconet scheduling, etc.. Thus further research on the impact of the topology variation should be carried out and may require new designs of the proposed schemes to enhance the network performance.

There are several research on routing algorithms for Bluetooth, in which many of them suggest applications of available routing algorithms for Mobile Ad hoc Network to Bluetooth networks. The combinations of routing algorithms and the proposed schemes could reduce the overheads created by control message exchanges. The routing algorithms and their combinations with the capacity management schemes are quite interesting topics for future researches on Bluetooth. The application of multipath QoS routing should be investigated in future.

The priority based traffic classification could improve QoSs received at the end users. This approach could be incorporated into the proposed schemes. Thus a certain degree of QoS requirements for traffics with higher priority levels can be delivered to the end users.

Currently there are several scatternet formation algorithms proposed. The one of main goals of these algorithms is to use efficiently the network capacity in the dynamic environment. The results of the capacity management studies should be investigated in relation with the scatternet formation algorithms.

From the facts that these capacity management schemes have just studied for asynchronous data network operated in ACL link mode and with assumption that synchronized network, more realistic scenarios and research on SCO link mode should be done in future.

Because main applications of the Bluetooth are used for Internet applications: VoIP, web browsers, Video on demand, etc., the traffic models of these applications are quite different to each others, and the investigated IBP traffic model can be too much simple to express behaviors of these applications. Furthermore, each of these applications requires specific QoSs. Thus more studies about the Bluetooth networks with these Internet applications under the capacity management schemes should be quite interesting future research topics.

Last but not least, the research on Bluetooth could not be considered to be success if it was not to be implemented in real environment. New research challenges can be derived from practical aspects of real Bluetooth based communication environment. Thus it demands for strong research collaborations between industries and academia.

Appendix A

The Yule-Walker Equations

Here is described the Yule-Walker equation, which is based on [32]. This equation were used as basis for the traffic and QoS estimations. The transform function of a causal linear shift-invariant filter with p poles and q zeros is :

$$H(z) = \frac{B_q(z)}{A_p(z)} = \frac{\sum_{k=0}^{q} b_q(k) z^{-k}}{1 + \sum_{k=1}^{p} a_p(k) z^{-k}} \tag{A.1}$$

If input signal $x(n)$ and white noise $v(n)$ are related by the linear constant coefficient differential equation:

$$x(n) + \sum a_p(l) x(n-l) = \sum_{l=0}^{q} b_q(l) v(n-l) \tag{A.2}$$

then it follows that:

$$r_x(k) + \sum_{l=1}^{p} a_p(l) r_x(k-l) = \sum_{l=0}^{q} b_q(l) E\left\{v(n-l) x^*(n-k)\right\} \tag{A.3}$$

where $r_x(k)$ is the autocorrelation function of the input signal $x(n)$, $x^*(n-k)$ is the conjugation of $x(n)$

Since white noise $v(n)$ is the wide-sense stationary process and $r_{vx}(k)$ is the cross-correlation function, thus:

$$r_x(k) + \sum_{l=1}^{p} a_p(l) r_x(k-l) = \sum_{l=0}^{q} b_q(l) r_{vx}(k-l) \tag{A.4}$$

The Yule-Walker equations can be derived as:

$$r_x(k) + \sum_{l=1}^{p} a_p(l) r_x(k-l) = \begin{cases} \sigma_v^2 c_q(k) & \text{if } 0 \leq k \leq q \\ 0 & \text{if } k > q \end{cases} \tag{A.5}$$

where σ_v^2 is variance of noise $v(n)$, $c_q(k) = \sum_{l=k}^{q} b_q(l) h^*(l-k) = \sum_{l=0}^{q-k} b_q(l+k) h^*(l)$
Writing in matrix form of the equations gives:

$$\begin{aligned} &\begin{bmatrix} r_x(0) & r_x(-1) & \cdots & r_x(-p) \\ r_x(1) & r_x(0) & \cdots & r_x(-p+1) \\ \vdots & \vdots & \ddots & \vdots \\ r_x(q) & r_x(q-1) & \cdots & r_x(q-p) \\ r_x(q+1) & r_x(q) & \cdots & r_x(q-p+1) \\ \vdots & \vdots & \ddots & r_x(q-p+1) \\ r_x(q+p) & r_x(q+p-1) & \cdots & r_x(q) \end{bmatrix} \begin{bmatrix} 1 \\ a_p(1) \\ a_p(2) \\ \vdots \\ a_p(p) \end{bmatrix} = \\ &= \sigma_v^2 \begin{bmatrix} c_q(0) \\ c_q(1) \\ \vdots \\ c_q(q) \\ 0 \\ \vdots \\ 0 \end{bmatrix} \end{aligned} \tag{A.6}$$

Appendix B

The Levinson-Durbin Algorithm

The Levinson-Durbin algorithm [32] is one of the simple prediction methods for solving Yule-Walker equations. We can rewrite the equation A.6 as:

$$\begin{bmatrix} r_x(0) & r_x(1) & r_x(2) & \cdots & r_x(m-2) & r_x(m-1) \\ r_x(1) & r_x(0) & r_x(1) & \cdots & r_x(m-3) & r_x(m-2) \\ r_x(2) & r_x(1) & r_x(0) & \cdots & r_x(m-4) & r_x(m-3) \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ r_x(m-2) & r_x(m-3) & r_x(m-4) & \cdots & r_x(0) & r_x(1) \\ r_x(m-1) & r_x(m-2) & r_x(m-3) & \cdots & r_x(1) & r_x(0) \end{bmatrix} \begin{bmatrix} a_1^{(m-1)} \\ a_2^{(m-1)} \\ a_3^{(m-1)} \\ \vdots \\ a_{m-1}^{(m-1)} \\ 0 \end{bmatrix} = - \begin{bmatrix} r_x(1) \\ r_x(2) \\ r_x(3) \\ \vdots \\ r_x(m-1) \\ r_x(m) + k_m \alpha^{(m-1)} \end{bmatrix} \tag{B.1}$$

where $a_k^{(M)}$, $k = 1, \ldots, M$ is the set of the predictor coefficients, $\alpha^{(M)}$ is the associated error measure.

We multiply the equation B.1 by $(r_x^{(m)})^{-1}$ and obtain the following relation:

$$\begin{bmatrix} a_1^{(m-1)} \\ a_2^{(m-1)} \\ a_3^{(m-1)} \\ \vdots \\ a_{m-1}^{(m-1)} \\ 0 \end{bmatrix} = -\frac{1}{\alpha^{(m-1)}} \begin{bmatrix} 1 & a_1^{(m-1)} & a_2^{(m-1)} & \cdots & a_{m-1}^{(m-1)} \\ a_1^{(m-1)} & * & * & \cdots & a_{m-2}^{(m-1)} \\ a_2^{(m-1)} & * & * & \cdots & a_{m-3}^{(m-1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{m-2}^{(m-1)} & * & * & \cdots & a_1^{(m-1)} \\ a_{m-1}^{(m-1)} & a_{m-2}^{(m-1)} & a_{m-3}^{(m-1)} & \cdots & 1 \end{bmatrix} . \tag{B.2}$$

$$\cdot \begin{bmatrix} r_x(1) \\ r_x(2) \\ r_x(3) \\ \vdots \\ r_x(m-1) \\ r_x(m) + k_m \alpha^{(m-1)} \end{bmatrix}$$

where $k_m \equiv a_m^{(m)}$

The recursive error of the predictor is :

$$\alpha^{(m)} = \alpha^{(m-1)}(1 - k_m^2) \tag{B.3}$$

Therefore the Levinson-Durbin Algorithm, which calculates $\left\{a_j^{(M)}\right\}_{j=1}^{M}$ from $r_x(k)$, $k = 0, \ldots, M$, can be summarized as follows:

```
LEVINSON-DURBIN ALGORITHM
begin
  $\alpha^{(0)} = r_x(0)$;
  for $m = 1$ to $M$ do
      $k_m = -\frac{r_x(m) + \sum_{k=1}^{m-1} a_k^{(m-1)} r_x(m-k)}{\alpha^{(m-1)}}$;
      $a_j^{(m)} = a_j^{(m-1)} + k_m a_{m-j}^{(m-1)}$;  where $j = 1$ to $m - 1$
      $a_m^{(m)} = k_m$;
      $\alpha^{(m)} = \alpha^{(m-1)}(1 - k_m^2)$;
  end
end
```

Appendix C

An Example of Fair Share Iterative Capacity Allocation

The fair share iterative capacity allocation is based on the distributed algorithm presented on [33]. There are several variations, including the method in [54] , which could give more fair capacity allocation. However, the computing principles are almost identical to the distributed algorithm presented in [33]. Figure C.1 illustrates an example of the fair share iterative capacity allocation applied to a network. The network consists of links, called A, B, C, D, E, F, G, and H, that connect Bluetooth nodes. Associated with each link is a link capacity, in packets. The route paths which come through the links are numbered 1 to 5. When applying the fair share iterative capacity allocation, the results of the first iteration are as follows:

- Link A: route 4=400 ;
- Link B: route 5 = 200;
- Link C: route 1 = 10; route 5 = 190;
- Link D: route 1 = 20;
- Link E: route 2 = 200;
- Link F: route 1 = 30; route 2 = 60; route 3 =30;
- Link G: route 1 = $66\frac{2}{3}$; route 3 = $133\frac{1}{3}$;
- Link H: route 1 = $66\frac{2}{3}$; route 3 = $133\frac{1}{3}$;

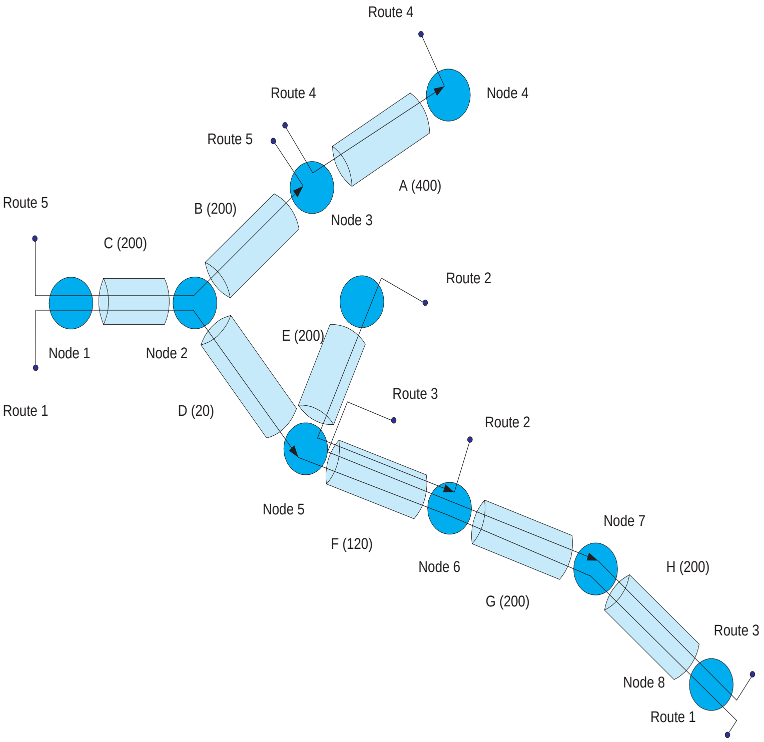


Figure C.1: An example of the fair share iterative capacity allocation

The saturated capacities allocated to route 1 and route 4 are 10 and 200 packets, respectively.

In the same way after the second iteration, the saturated capacities allocated to route 3 and route 5 are $36\frac{2}{3}$ and 190 packets, respectively (because link C allows only 190 packets on route 5).

After the third iteration, route 2 is assigned a capacity of $73\frac{1}{3}$ packets.

Appendix D

Network traffic predictability

One of main characteristics of the scheduling and capacity allocation approaches proposed in this thesis is to use information from the prediction of arrival traffic and bandwidth requirements. In this part, an analysis on the network traffic predictability is presented. This analysis is based on the study described in [80].

The primary goal of the traffic prediction is to predict the traffic with a satisfactory level of prediction error over desired prediction interval. This means that on a one hand, a large prediction interval is needed for the system to have sufficient control reaction time. On the other hand, A small prediction error is desirable to achieve high resource utilization. There are several factors affect the predictability, such as the network control time interval, resource utilization requirement, traffic measurement and statistics. It is assumed that all traffic traces used in this analysis are stationary and adequately represented by stationary model such as the auto-regressive moving average (ARMA).

The network traffic is represented by a continuous-time stochastic process $\{Y(t) = X(t) + \mu\}$, where μ is the mean rate, and $\{X(t)\}$ is pure random process with zero mean. Assume that T_m is the prediction time interval, $\widehat{Y}(t + T_m)$ the prediction results for the prediction interval T_m, η is the normalized prediction error $(\eta(T_m) \doteq (\widehat{Y}(t + T_m) - Y(t + T_m))/\widehat{Y}(t + T_m))$ and $(P_\varepsilon, \varepsilon)$ is the desired prediction confidence interval. Then the optimal prediction performance can be defined as:

$$P_{opt} \doteq \max\{T_m \mid P_\eta(T_m, \varepsilon) \leq P_\varepsilon\} \tag{D.1}$$

where $P_\eta(T_m, \varepsilon) = Pr\left[\eta(T_m) > \varepsilon\right]$. If P_{opt} accommodates enough time for measurement, prediction and network control, and the prediction meet the confident requirement, then the traffic with the time interval T_m is predictable.

If the network traffic is modeled as a Gaussian process, the an ARMA model is used to analyze the traffic predictability and the effects of traffic smoothing and aggregation.

From [80], it can express the Gaussian arrival process as linear form of stationary Gaussian property:

$$\widehat{X}(t+T_m) = \int_{T_m}^{+\infty} h_u n(t+T_m-u)du \tag{D.2}$$

$$\widehat{\sigma}^2_{T_m} = \int_0^{T_m} h_u^2 du = \sigma^2 - \int_{T_m}^{+\infty} h_u^2 du \tag{D.3}$$

where h_u is transmission function, σ^2 is variance of $X(t)$, $\widehat{\sigma}^2_{T_m}$ is the prediction variance. If assume that the arrival rate process $\{Y(t)\}$ is non-negative Gaussian, then the Gaussian P_{opt} can be obtained as:

$$P_{opt} = \max\left\{\ T_m \ \middle|\ \frac{\widehat{\sigma}^2_{T_m}}{\sigma^2} \leq O\left(P_\varepsilon, \varepsilon, \frac{\sigma}{\mu}\right)\ \right\} \tag{D.4}$$

$$O\left(P_\varepsilon, \varepsilon, \frac{\sigma}{\mu}\right) = \left[\frac{1}{\frac{\sigma^2}{\mu^2}\phi^2(1-P_\varepsilon)} - 1\right]\frac{\varepsilon^2}{1-\varepsilon^2} \tag{D.5}$$

where ϕ is inverse marginal cumulative distribution of the normalized distribution $N(0,1)$.

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