國立臺灣大學資訊管理研究所碩士論文

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考慮能量使用效率下無線網路系統效益之最大化

Maximization of System Throughput in Wireless Networks with the Consideration of Energy Efficiency

研究生：俞瑩珍　撰

中華民國九十三年七月

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本 論 文 係 提 交 國 立 台 灣 大 學
資 訊 管 理 學 研 究 所 作 為 完 成 碩 士
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研究生：俞瑩珍　撰

中華民國九十三年七月

僅以此文獻給我的母親～

楊春鈺 女士

謝　　詞

研究所生涯，終於也在這篇論文的完稿後結束。將近二十年的求學歷程不算短，然而轉眼，即將面對的是另外一段人生旅程。首先要感謝我的母親，楊春鈺女士。感謝母親多年來給予的支持與鼓勵，遇到困境總能像是燈塔一樣的指引，給我勇氣、為我打氣；沒有您，我也就沒有今天。其次是姊姊與妹妹，你們的陪伴讓我能在驟變的環境中，仍心存希望；以及父親在經濟上的支持，讓我能完成學業。

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感謝這兩年來最重要的朋友：友群、翔騰，你們的陪伴讓我在這最艱難的求學路上不孤單，你們的鼓勵讓我在風雨中仍能屹立；感謝俊達、育先，在我課業上、生活上、專案上的協助與扶持，能向你們學習是我的榮幸；感謝好友佩璇、耿宏、坤威、大鈞、明立、柏鈞、閔元在學業上的互相切磋、互相砥礪。感謝實驗室的學弟妹在口試期間的諸多幫忙，讓我能全心準備口試。

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俞瑩珍 謹識

于台大資訊管理研究所

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論文摘要

論文題目：考慮能量使用效率下無線網路系統效益之最大化

作　　者：俞瑩珍　　　　　　　　　　　　　　　　　九十三年七月

指導教授：林永松　博士

無線網路環境下，最有潛力的莫過於資訊服務。許多現有的定點式服務，未來可能出現在無線環境中，而其他新式的應用也將為移動中的人們賦予新價值與新服務。

在無線環境中，能量與品質是提供應用與服務的兩大考量，是故，有限的能量資源與對延遲敏感的網路服務將會是傳輸策略的兩大議題。若能巧妙的掌握運用傳輸的資料型態、頻道品質、網路狀態，便能規劃出延長使用時間，並兼顧服務品質的傳輸策略。

本論文中，我們結合了「延遲引入」[15]的觀念與「臨界值」[7]的想法，試圖找到最大化系統效能的傳輸方案。即：在不同數量的待傳輸封包下，系統將提供不同的傳輸速率。我們根據排隊理論將系統狀態表示成數學規劃問題，在符合服務品質與傳輸功率的條件下，試圖找到一組最佳的傳輸速率與臨界值以最大化整體系統效能。

關鍵詞：無線網路、服務品質、能源使用效率、排隊理論、最佳化、數學規劃

THESIS ABSTRACT

GRADUATE INSTITUTE OF INFORMATION MANAGEMENT

NATIONAL TAIWAN UNIVERSITY

NAME：YING-CHEN YU **MONTH/YEAR：Jul, 2004**

ADVISER：YEONG-SUNG LIN

Maximization of System Throughput in Wireless Networks with the Consideration of Energy Efficiency

It seems clear that information services have an almost unlimited potential in a wireless environment. Many of today's "fixed" applications will continue to be useful in a mobile environment, and a variety of new services are certain to evolve for people on the move.

Since the energy conservation and the QoS guarantees are the major concerns in supporting heterogeneous data applications in mobile devices, the limited portable battery energy and the delay sensitivity of data services will also play important roles in the design of such transmission strategies. Therefore, intelligently using the knowledge about the traffic, channel, and network, we can design transmission strategies which are not only capable of extending the battery lifetime as much as possible, but also maintaining the agreed QoS.

In this thesis we combine the idea of smartly introducing communication delay from[15] and the threshold concept of [7], and try to find energy efficient transmission schemes that maximize system throughput, in which given different packet volume waiting to be transmitted, the system provides different service rates. According to the Queueing Theory, we preliminary model the system behavior into nonlinear mathematical programming problems. By maximizing the system throughput under the constraints of QoS requirements and the power limitation, we try to find the best transmission rate for different packet volumes.

Keys words: Wireless Network, Quality of Service, Power Efficiency, Projection Method, Queueing Theory, Optimization, Mathematical Programming, Nonlinear Programming.

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Chapter 1. Introduction

1.1 Background

The past quarter century has seen the rollout of three generations of wireless cellular systems, attracting end users by providing efficient mobile communications. Their unique capability of maintaining the same contact number, even if the user moves from one location to another, has made them increasingly popular. Over the last century, advances in wireless technologies have led to radio, television, mobile telephones, and communication satellites.

The market for wireless networks has evolved in four different segments that can be logically divided into two classes: *voice-oriented market* and *data-oriented market*. The voice-oriented market has evolved around wireless connections to the public switched telephone network (PSTN). These services further evolved into local and wide area markets. The local voice-oriented market is based on low-power, low-mobility devices with higher quality of voice, including cordless telephone, personal communication services (PCS), wireless PBX, and wireless telepoint. Meanwhile, the wide area voice-oriented market has evolved around cellular mobile telephone services that use terminals with a higher power consumption, comprehensive coverage, and lower quality of voice. The wireless data-oriented market, on the other hand, evolved around the Internet and computer communication network infrastructure. The data-oriented services are divided into broadband local and ad hoc, and wide area mobile data markets. The wide area wireless data market provides for Internet access for mobile users. Local broadband and ad hoc networks include wireless LANs (WLANs) and wireless personal area networks (WPAN), which provide high-speed internet access, as well as evolving ad hoc wireless consumer products. [13]

These wireless systems with different QoS requirements, however, are facing the challenge of the efficient use of energy. Unlike other enabling technologies for mobile information systems, the specific energy of commercially available rechargeable batteries has improved by only about 2% per year over the past half century. Thus, providing the desired QoS service within a limited energy budget in different wireless systems is a critical issue.

1.2 Motivation

Almost every wireless network provides more than one transfer rate. As expected, a higher transfer rate gives better QoS, but on the other hand, consumes more energy. However, the increasing demand for data rate and QoS in wireless communication has to cope with an energy budget that is severely constrained by ubiquity requirements. The trade off between performance and energy consumption deserves urgent attention in order to meet the “*anything, anywhere, anytime*” paradigm.

In mobile computing, energy conservation is one of most important areas of research. Energy efficient solutions are essential for reducing the size and weight of mobile devices, and methods for conserving energy have become a critical issue. Due to the scarcity of radio resources, the noisy nature of mobile channels, and the low weight requirement of mobile handsets, any optimization effort should be part of a total resource management plan. It is important to achieve the desired QoS level within a limited energy budget.

In this thesis, we introduce two thresholds that divide service rates into four strategies. If the packets in a buffer are within the first threshold, the mobile device transmits packets with a lower transmission rate to save the power. If the packets in the buffer are over the second threshold, the mobile transmits packets with a higher transmission rate in order to achieve the desired QoS. If the packets in buffer are between two thresholds, on the other hand, the mobile transmits packets by determining whether the number of packets is increasing or decreasing.

1.3 Proposed Approach

As mention in previous section, there is a tradeoff between QoS and transmission power. Since frequent recharging is not a practical option and low weight is crucial in wireless equipment, wireless systems will have to be optimized for low energy consumption subject to a desired QoS.

Extending the ideas of smartly introducing communication delay from [15] and the threshold concept of [7], the relationship between energy consumption and QoS level is modeled as a mathematical problem. By maximizing the system throughput under the constraints of QoS requirements and the power limitation, we try to find the best transmission rate for different packet volumes. The system behavior is modeled as a nonlinear mathematical programming problem, according to the steady-state and transition diagram. We also develop heuristics procedure to solve the problem.

1.4 Thesis Organization

The remainder of the thesis is organized as follows. Chapter 2 presents the wireless technology and low power design issues; Chapter 3 describes the problem, the transaction strategies, and the assumptions; Chapter 4 is the proposed method, and Chapter 5 is the computational results and discussion. Finally, Chapter 6 concludes this thesis.

Chapter 2. Literature Survey

2.1 Wireless Communication Technology

In the past few years, wireless networks have come to occupy a significant niche in the network market. Increasingly, organizations are finding that wireless networks are an indispensable adjunct to traditional wired networks, because they satisfy the requirements for mobility, relocation, ad hoc networking, and coverage that are difficult with wired networks. Recently, a great deal of attention has been focused on satellite communications, wireless networking, and cellular technology. Some of the main wireless systems are described below.

2.1.1 Satellites Communication

Satellite communications are comparable in importance to optical fiber in the evolution of telecommunications and data communications.[14] The heart of a satellite communication system is a satellite-based antenna in a stable orbit above the earth. In such a system, two or more stations on Earth communicate via one or more satellites that serve as relay stations in space. The information transmitted from a mobile user (MS) must be correctly received by a satellite and forwarded to one of the earth stations (ESs) from the satellite. Thus only

LOS (line of sight) communication between the mobile user and the satellite should be possible. Satellites have been put in space for various purposes, and their placement in space and their orbits have been determined as per their specific requirements. Four different types of satellite orbits have been identified[5]:

(i) **GEO** (geostationary earth orbit) at about 36,000 km above the earth's surface

(ii) ***LEO*** (low earth orbit) at about 500-1500 km above the earth's surface

(iii) ***MEO*** (medium earth orbit) or ICO (intermediate circular orbit) at about 6000-20,000 km above the earth's surface

(iv) ***HEO*** (highly elliptical orbit)

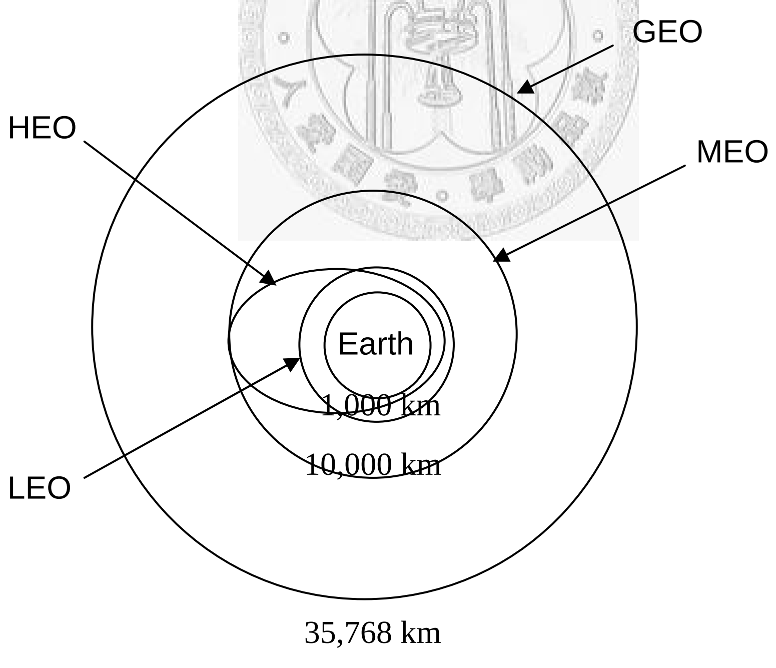

Figure 2.1 Orbits of Different Satellites. [5]

Figure 2.1 illustrates the satellite orbiting paths and distances from the surface of the earth. The orbits can be elliptical or circular, and the complete rotation time depends on the distance between the satellite and the earth.

2.1.2 Wireless PANs

Wireless PAN (wireless personal area networks, WPAN) is a special class of wireless network that covers smaller areas with low power transmission and has become increasing important for both the office and home. As the name indicates, WPANs are short to very short range (from a couple of centimeters to few meters) wireless networks that can be used to exchange information between devices in the reach of a person. WPANs can be used to replace cables between computers and their peripherals, help people do their everyday chores, or establish location aware services. The best example representing WPANs is the recent industry standard Bluetooth, other examples include Spike, and in the broad sense HomeRF.

(i) Bluetooth[1]

Bluetooth is named after the King of Denmark, who unified different factions in Christianity throughout Denmark.

Bluetooth has simplified low-bandwidth wireless connections so that they seamlessly integrate into daily life. Companies like Ericsson, Intel, IBM, Nokia, and Toshiba started this in 1998 by establishing a Bluetooth special interest group, focusing on the elimination of the short wires connecting computer peripherals. Bluetooth utilizes the unlicensed ISM band at 2.4 GHz. A typical Bluetooth device has a range of about 10 meters, supporting data (asynchronous) and voice (synchronous) with a total bandwidth of 1Mb/s.

Bluetooth is specifically designed to provide a low-cost, robust, efficient, high-capacity, ad hoc voice and data networking with the following characteristics:

- Fast frequency hopping to minimize interference
- Adaptive output power to minimize interference
- Short data packets to maximize capacity
- Fast acknowledgements, allowing low coding overhead for links
- CVSD (continuous variable slope delta) modulation voice coding, which can withstand high bit-error rates
- Flexible packet types that support a wide range of applications
- Transmission/reception interfaces tailored to minimize power consumption.

(ii) HomeRF[12]

HomeRF is a new technology that enables people to simultaneously share a single Internet connection with all electronic devices in the house. It provides a foundation for a broad range of inter-operable consumer devices for wireless digital communication between PCs and consumer electronic devices anywhere in, and around, the home. The HomeRF working group includes Compaq Computer Crop., Ericsson Enterprise Networks, Hewlett-Packard Co., IBM, Intel Crop., Microsoft Crop., Motorola Crop., and others.

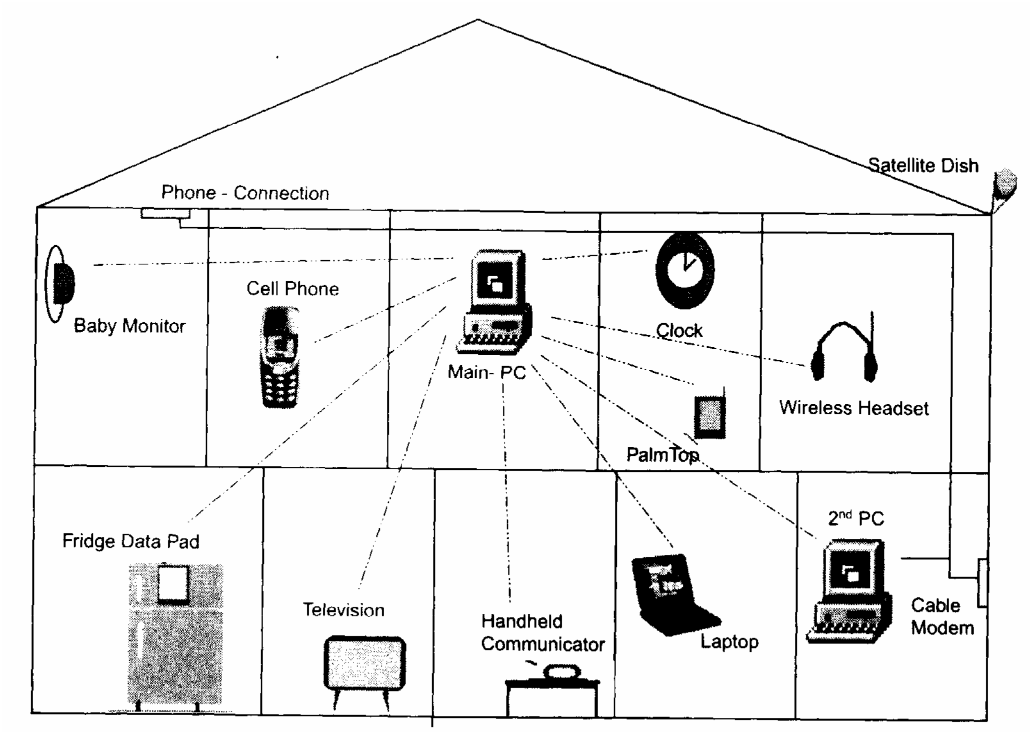

Figure 2.2 Architecture of HomeRF System[5]

HomeRF visualizes a home network, shown in Figure 2.2. A network consists of resource providers, which are gateways to different resources like phone lines, cable modems, and satellite dishes, and the devices connected to them, like cordless phone, printers, fileservers, and TV. The goal of HomeRF is to integrate all of these into a single network suitable for all applications and remove all wires and utilize RF links in the network suitable for all applications.

2.1.3 Wireless LANs

Wireless LANs (WLANs), which provide a larger transmission range and are capable of setting up an ad hoc network, save the cost of installing LAN cabling and ease the task of relocation and other modifications to the network's structure. The most well-known WLANs are based on the standards IEEE

802.11, HiperLAN, and their variants.

(i) IEEE 802.11 series.

In IEEE 802.11 series, there are IEEE 802.11, IEEE 802.11a, and IEEE802.11b. IEEE 802.11 and IEEE 802.11b standards, operating on the 2.4GHz ISM band and providing a basic rate of 1 and 11 Mbps. They can be used to provide communication between a number of terminals as an ad hoc network, using peer-to-peer mode (Figure 2.3), or as a client/server wireless configuration (Figure 2.4), or a fairly complicated distributed network. 802.11a, on the other hand, operates on the 5.2 GHz band, utilizing Orthogonal Frequency Division Multiplexing (OFDM) to provide data rates up to 54 Mbps. The keys behind all these networks are the wireless cards (also known as PCMCIA- Personal Computer Memory Card International Association) and wireless LAN access point (AP for short). The IEEE standards allow two types of transmission, frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS). FHSS is primarily used for low-power, low-range applications, and DSSS is popular in providing Ethernet-like data rates.

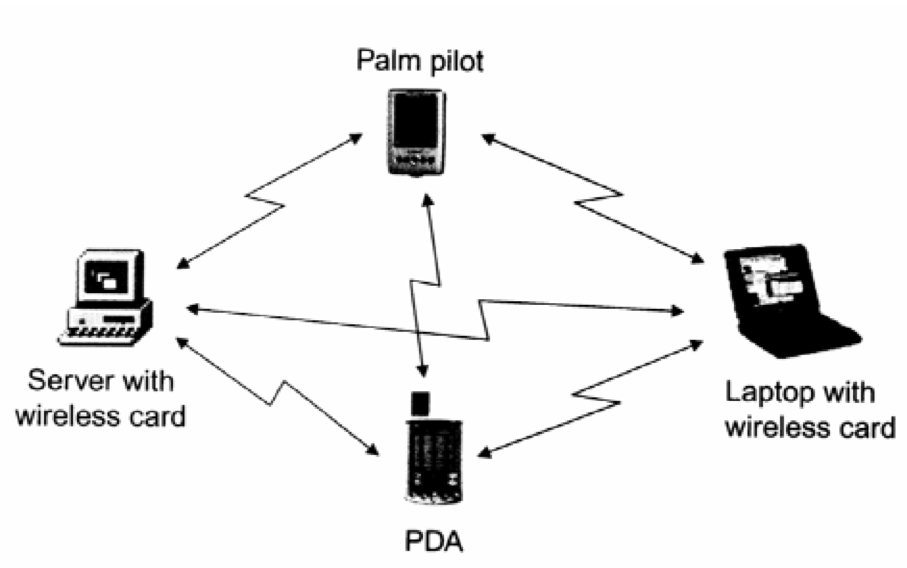

Figure 2.3　Peer-to-peer Wireless Mode. [5]

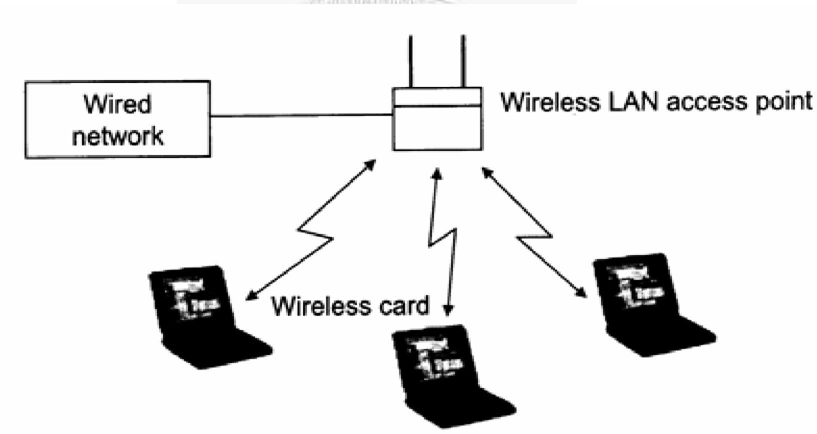

Figure 2.4　Client/Server Wireless Configuration. [5]

In an ad hoc network mode, as there is no central controller, the wireless access cards use the CSMA/CA protocol to arrange shared access of the channel. In the client/server configuration, many PCs and laptops, physically close to each other (20 to 500 meters), can be linked to a central hub (known as the access point) that serves as a bridge between them and the wired network. The wireless access cards provide the interface between the PCs and the antenna, while the access point serves as the wireless LAN hub. The access point is usually placed at the ceiling or high on the wall and supports a number of (115 to 250) users receiving, buffering, and transmitting data between the WLAN and the wired network.

(ii) HiperLAN

HiperLAN [4] stands for high-performance LAN, is derived from traditional LAN environments ad can support multimedia data and asynchronous data effectively at high rates (23.5 Mbps). HiperLAN started in 1992, and standards were published in 1995. It employs 5.15 GHz and 17.1 GHz frequency bands and has a data rate of 23.5 Mbps with coverage of 50m and mobility < 10m/s.

HiperLAN/1 is specifically designed to support ad hoc computing for multimedia systems, where there is no requirement to deploy centralized infrastructure. It effectively supports MPEG or other state-of-the-are real-time digital audio and video standards. HiperLAN/2 has been specifically developed to have a wired infrastructure, providing short-range wireless access to wired networks like IP and ATM. The goal of HiperLAN are: QoS, strong security, handoff when moving between local area and wide areas, increased throughput, ease of use, deployment, and maintenance, affordability, and scalability. Figure 2.5 shows the HiperLAN system.

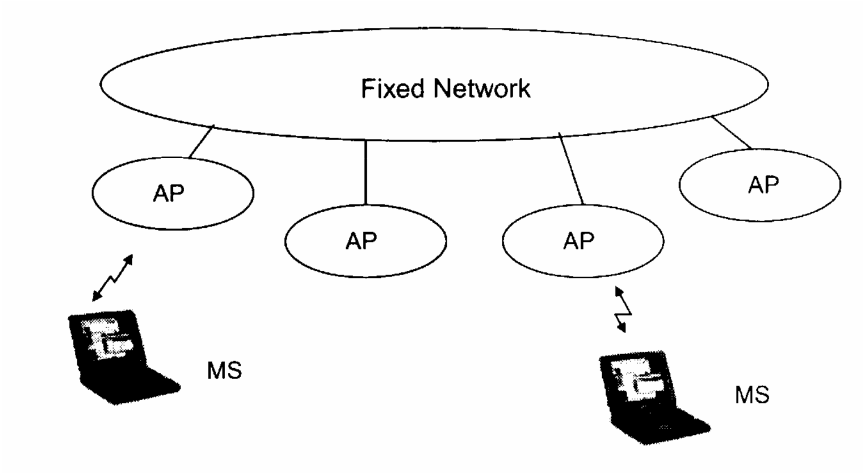

Figure 2.5 A Simple HiperLAN System.[5]

2.1.4 Cellular WANs

Cellular technology is the foundation of mobile wireless communications and supports users in locations that are now easily served by wired networks. Cellular technology is the underlying technology for mobile telephones, personal communications systems, wireless Internet and wireless Web applications, and is a technique that was developed to increase the capacity available for mobile radio telephone service. Following are some existing cellular WANs.

(i) Advanced Mobile Phone Systems (AMPS)

AMPS is the first-generation cellular system used in the United States, and is the cellular phone technology created by AT&T Bell labs with the idea of dividing the entire service area into logical divisions called cells. Each cell is allocated one specific band in the frequency spectrum. AMPS was initially only set up to cater for a limited number of users, however has expanded in recent years to accommodate the growth that has been experienced in the mobile telephone market.

AMPS is capable of supporting about 100,000 customers per city, and the system is aimed to reduce blocking probability to about 2% during busy hours. As expected, the analogue network uses analogue technology to transmit data over the radio channel. Some of the characteristics of this system are listed below:

- Three frequencies used, separated by 45 MHz: ***uplink frequency***, ***downlink frequency***, ***control channel***
- Usually only one control channel per cell.
- Frequencies used from 825 to 890 MHz.
- Receivers allocated 666 channel frequencies between 825 and 845 MHz
- Transmitters take up 666 channels between 870 and 890 MHz

(ii) Global System for Mobile Communications (GSM)

Global System for Mobile communications, or Groupe Speciale Mobile (GSM) communications, is the wireless standard chosen by some 170 countries around the world as the system of choice for digital wireless communications. It is initiated by the European Commission, is the second-generation mobile cellular system aimed at developing a Europe-wide digital cellular system. GSM was created in 1982 to have a common European mobile telephone standard that would formulate specifications for a pan-European mobile cellular radio system operation at 900 MHz. The main objective of GSM is to remove any incompatibility among the system by allowing the roaming phenomenon for any cell phone.

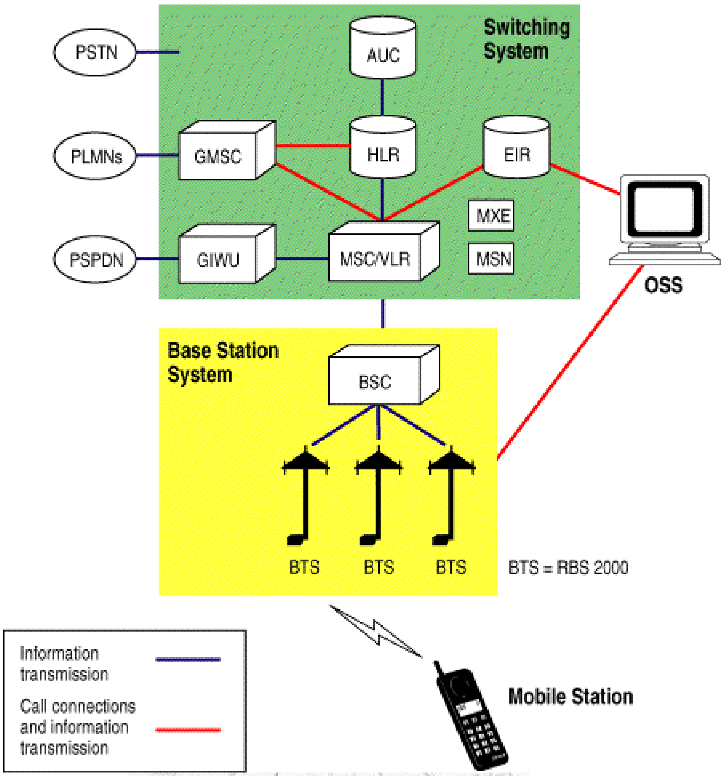

Figure 2.6 GSM Infrastructure.

Figure 2.6 illustrates the GSM infrastructure. The GSM specifications define the functions and interface requirements in detail but do not address the hardware. The reason for this is to limit the designers as little as possible but still to make it possible for the operators to buy equipment from different suppliers. The GSM network is divided into three major systems: the switching system (SS), which is responsible for performing call processing and subscriber-related functions, the base station system (BSS), which consists of base station controllers (BSCs) and the base transceiver stations (BTSs)., and the operation and support system (OSS), the functional entity from which the network operator monitors and controls the system.

GSM has been allocated an operational frequency from 890 MHz to 960 MHz. To reduce possible interference, MS and the BS use different frequency ranges (i.e., MSs employ 890 MHz to 915 MHz and BS operates in 935 MHz to 960 MHz). GSM follows FDMA and allows up to 124 MSs to be serviced at the same time. The frequency band of 25 MHz is divided into 124 frequency division multiplexing (FDM) channels, each of 200 kHz.

(iii) Universal Mobile Telecommunications System (UMTS)

Universal Mobile Telecommunications System (UMTS) is the third generation mobile communication system developed by ETSI, the European Telecommunications Standard Institute [2], which use a new frequency spectrum and extend the GSM service to include multimedia.

UMTS is based on the direct sequence (DS) spread spectrum (CDMA) technology using a chip rate of 3.84 Mcps within a 5 MHz frequency band. The spectrum assigned to UMTS is 60MHz for uplink (from 1920 to 1980 MHz), and 60MHz for downlink (from 2110 to 2170 MHz). Because of the adoption of DS-CDMA technique, UMTS provides a universal reuse factor that each user shares the same radio frequency at the same time. The spreading process is based on two codes, the spreading code and scrambling code, which separates the physical channels.

UMTS system uses the same core network as the GPRS. The new radio network in UMTS is called UTRAN (UMTS Terrestrial Radio Access Network), which is connected to the core network (CN) of GPRS via *Iu* interface, which is the UTRAN interface between the Radio network controller (RNC) and CN. The mobile terminal in UMTS is called User Equipment (UE). The UE is connected to Base Station (BS) over high speed *Uu* Interface. The BSs are the equivalent of BTS in GSM and typically serve a cell site. Several BSs are controlled by a single RNC over the *Iub* interface. Throughout the standardization process, extra effort has been mode so that most of the 2G core elements can smoothly support both generations, and any potential changes are kept to a minimum. The UMTS network architecture is showed in Figure 2.7.

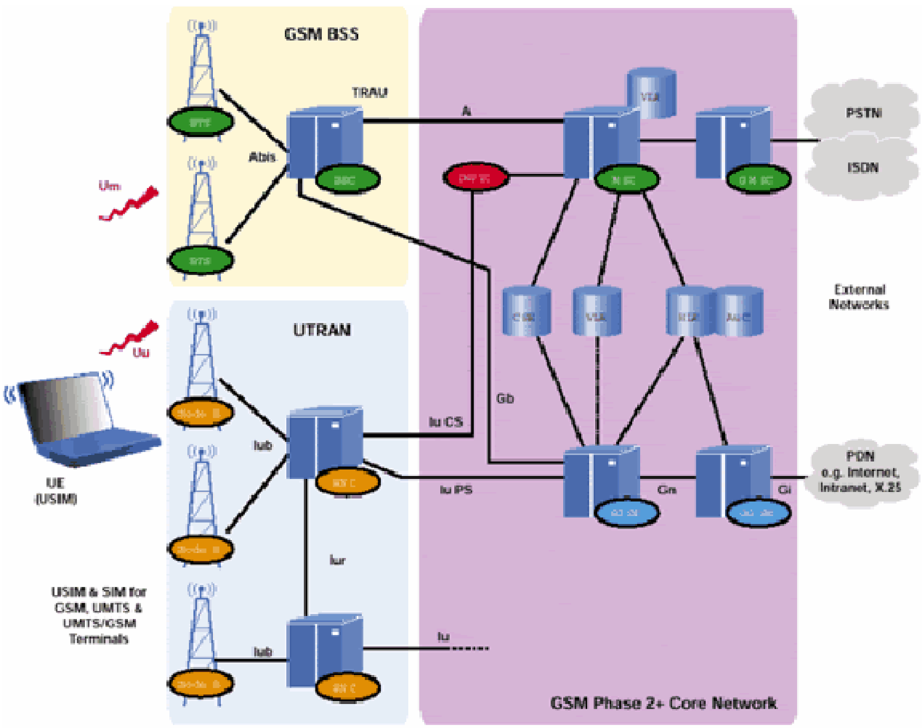

Figure 2.7　The UMTS Architecture. (Source: www.iec.org)

2.2 Low Power Design Issues

Wireless services have played an increasingly important role in society. It is anticipated that worldwide cellular services will continue to grow exponentially in the future. However, one of the main challenges in providing anyone, anywhere, anytime wireless services is the operating time of portable handsets. Mobile communication and computation platforms must rely on batteries for their operations. Unlike other enabling technologies for mobile information systems, the specific energy of commercially available rechargeable batteries has improved by only about 2% per year over the past half century. [10]

Low power design issues have been addressed by many researchers in the following four areas: [10]

2.2.1 Device Level Optimization

Low power Very Large Scale Integrated circuits (VLSI) design and low power RF circuitry optimization are the main technologies for energy saving approaches. Dramatic reduction in power dissipation requires architectural, algorithmic, and circuit design optimization, which are limited by semiconductor and device technologies.

2.2.2 Medium Access Control (MAC) Protocol Design

In [16], present an overall energy-efficient MAC protocol design principle. They present three options.

(i) Packet structure.

Due to excessively long headers (addresses, control fields, etc.) or trailers (checksums) the energy per "useful" bit relation may be negatively influenced. One solution to this problem is header compression, used for several protocols. Another idea regarding the packet structure is to split the packet in to a *low-bit-rate part* for control information (e.g., addresses) and a *high-bit-rate part* for data. The intention is to invoke costly functions only when needed. For example, the MAC evaluates first the low-bit-rate part control information such as the destination address. Receiving data, which might be costly due to high bit rates (e.g., necessary equalizer), is only performed if the packet is intended for the end terminal.

(ii) Awake/Doze mode.

In order to save energy the NIC (network interface card) may be switched off when there are no transmissions (doze mode); otherwise, the NIC is in the awake mode. Following this idea, using the doze mode has the potential to improve the power saving gain substantially.

(iii) Error Control design.

The channel quality is often improved by forward error correction (FEC) on the PHY layer. If the offered channel quality is still not satisfactory, MAC-level retransmissions may be used. Since the radio channel quality may be persistent for a while (good or impaired), retransmission of MAC packets in the impaired radio channel state is unnecessary and therefore expensive. Transmission channel probing, first proposed by Zorzi [20], can be used to overcome this problem. The idea is simple: instead of retransmitting the MAC packets again over an impaired radio channel, short low-power probe packets are sent continuously unless feedback is received for these probe packets. When an appropriate channel quality is detected, the retransmission of the data packet is scheduled.

2.2.3 Communication System Level Optimization

In [18], the author devised a communication system-level optimization approach, global interference minimization. Global interference minimization refers to the transmitter power control problem in cellular radio systems. His work has provided an optimal solution in the sense that it minimizes interference (or outage) probability. In [9] and [8], the authors have proposed a simplified distributed power control algorithm to tackle the problem of expensive computation. The distributed power control algorithm differs from the centralized power control problem in which each mobile adaptively adjusts its transmitter power according to the received interference. The distributed method releases the computational task performed by each base station.

The CDMA power control strategy also provides a simple solution to the interference minimization problem. There are two types of power control algorithms: close-loop and open-loop. Close-loop power control refers to the feed back mode from the base station to mobile stations for adjusting mobiles' transmitted power. Open-loop power control refers to the self transmission power adjustment of mobile stations by comparing the received signal strength from the base station with a reference signal level. [3]

In [11], an optimal tradeoff of Error Control Coding (ECC) and Automatic Repeat request (ARQ) in a communication system had been proposed to minimize total energy consumption. In [20], the authors proposed something similar to [11]. But their method differs from [11] by using a nonpersistent

ARQ strategy when the channel suffers from large interference.

2.2.4 Application Level Design

Engineers are developing low complexity software or hardware for multimedia processing algorithms. Usually low complexity algorithms yield low energy consumption, provided that less iterations or looping are involved in the computation.

2.3 Performance and Service Rates

Wireless networking performance is highly depends on the service rate provided by system, which have to be supported by the highly erratic radio channel in the presence of node mobility. However, the central objective in the efficient network design is to achieve the QoS support as well as the energy efficiency.

Radio resource management (RMM) forms the backbone of power-sensitive network architecture. For delay tolerable data applications, opportunistic RRM sheds some new light on the power sensitive network design. The underlying rationale of the opportunistic RRM is to reduce energy expenditure by exploiting system dynamics. Usually, there are two types of dynamics in wireless data systems: the fluctuating channel and the bursty data source. A typical approach is to capture the good opportunities for information transfer by *smartly* introducing communication *delay*. Here *delay* refers to coding/decoding delay, buffering delay, or data segmentation and reassembling

(SAR) delay; and the word *smartly* means to use intelligent management techniques to guarantee the QoS requirement. [15]

Several papers dealing with performance comparison given various service rates which lead to different QoS have appeared in the literature. In [17], the performance of a rate-adaptive CDMA system supporting homogeneous data traffic has been analyzed and compared with that of a power-adaptive system. From the analytical results, it is conjectured that data user in the rate-adaptive system may use less average power than that in the power-adaptive system to achieve the same throughput with the same E_b/N_e. With the same throughput, average packet delay in the rate-adaptive system could be less than that in the power-adaptive system. The performance gains of the rate-adaptive over the power-adaptive may translate into an increase of the overall network capacity, and prolong to battery life of mobile users.

[7] evaluates the impact of the 3GPP ARQ scheme on the QoS of traffic services. Although retransmission is one way to recover from lost packets, it places a burden on scarce battery resources of the mobile host in mobile environment, for packet transmission over a wireless medium consumes a significant amount of power. The authors introduce one threshold that separates the transmission operation into two modes: *greedy* and *saving* mode. In *greedy mode*, the transmitter is always active, regardless of the radio channel conditions. Upon the reception of a STATUS PDU notifying that some PDUs (Protocol Data Unit) was lost, it retransmits the missing data units at once and then goes on with the information transfer. On the contrary, in *saving mode* the transmitter stops transmitting and starts periodically polling the receiver to

probe the channel status. The transmitter starts retransmitting the missing data units only when good channel conditions are detected; i.e., when the transmitter receives a reply to its poll.

Chapter 3. Problem Formulation

3.1 Problem Description

In this chapter, we go into the detail of the proposed algorithm. As described in previous section, we combined the idea of smartly introducing communication delay from [15] and the threshold concept of [7]. The algorithm is as following, and is illustrated in Figure 3.1:

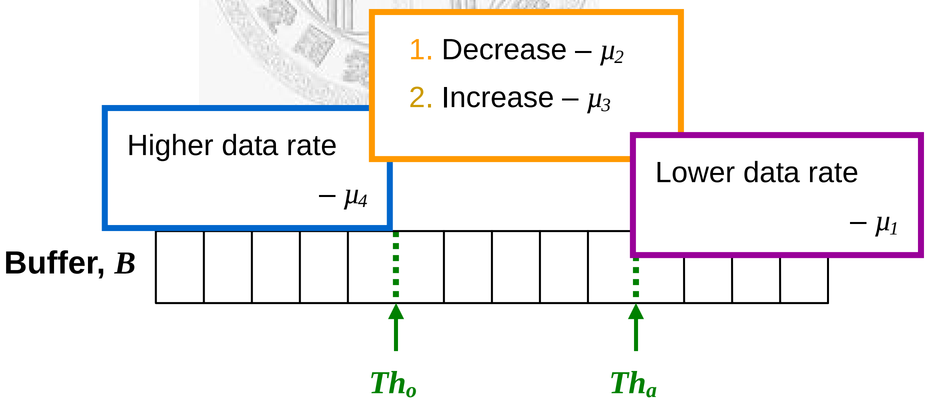

Figure 3.1 Transmission Strategy

1. If the packets in buffer are within the first threshold, the mobile transmits packet with lower transmission rate, say μ_1, in order to save limited power.

2. If the packets in buffer are over the second threshold, the mobile transmits packets with higher transmission rate, μ_4, in order to achieve the desired QoS and prevent packet lost.
3. If the packets volumes are between two thresholds, on the other hand, the mobile transmits packets by determining the packet number is increasing or decreasing. If it is increasing, transfer with μ_3 to slow down the going-up tendency, and if it is decreasing, transfer with μ_2.
4. The relationship between these service rates is :

$$\mu_4 \geq \mu_3 \geq \mu_2 \geq \mu_1$$

Table 3.1 summarizes the problem description:

Given:

- Total power of the mobile
- Buffer size of the mobile
- Packets arrival rate and available service rate
- Energy consumption at each transmission rate
- Desired quality of service

To determine :

- The best thresholds and service rates

Objective:

- To maximize the system throughput

Subject to:

- QoS constrain
- Call blocking probability constraints
- System lifetime constraint

Assumptions:
● Higher service rates consume more energy
● Mobile can switch service rates with little effort

Table 3.1 Problem description

3.2 Notation

For the convenience of the reader, a legend of the notation used in the proposed mathematical formulation is given as follows.

Given Parameters	
Notation	***Description***
E_m	Total energy of mobile
B	The queue size
λ	The arrival rate of packet
E_1	Energy consumption per bit when data rate is μ_1
E_2	Energy consumption per bit when data rate is μ_2
E_3	Energy consumption per bit when data rate is μ_3
E_4	Energy consumption per bit when data rate is μ_4
p_{loss}	Tolerable packet loss probability
D	Tolerable delay of each packet
J	Tolerable packet jitter
T_L	System lifetime requirement

Table 3.2 Notation of Given Parameters

Decision Variables	
Notation	***Descriptions***
Th_a	The threshold of abatement
Th_o	The threshold of onset
μ_1	Data rate when packet number is less than Th_a
μ_2	Data rate when queueing packet is decreasing and packet number is between Th_a and Th_o
μ_3	Data rate when queueing packet is increasing and packet number is between Th_a and Th_o
μ_4	Data rate when packet number is more than Th_o

Table 3.3 Notation of Decision Variables

3.3 Problem Formulation

According to Queueing Theory and the transmission strategy in previous section, we can sketch the system behavior as following:

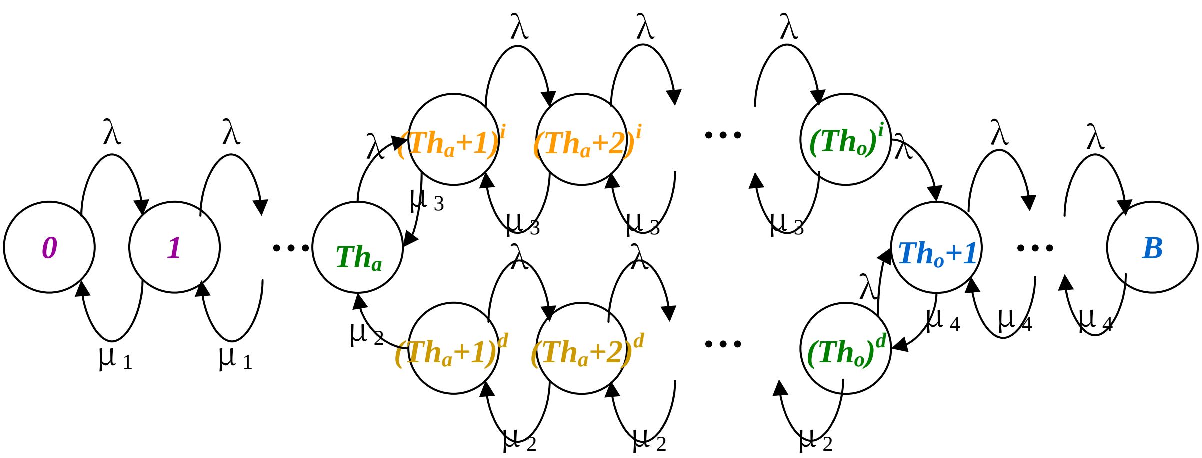

Figure 3.2 Transition Diagram of the Transmission Strategy

The queueing system is identical to the *M/M/1* system except that the service rate varies as packet number changes. And the global balance equations for the steady state probabilities p_n are:

$$
\begin{aligned}
&\lambda p_0 = \mu_1 p_1 \\
&(\lambda+\mu_1)\, p_n = \lambda p_{n-1} + \mu_1 p_{n+1} && ,n = 1 \sim (Th_a - 1) \\
&(\lambda+\mu_1)\, p_{Th_a} = \lambda p_{Th_a-1} + \mu_3 p_{(Th_a-1)^i} + \mu_2 p_{(Th_a-1)^d} \\
&(\lambda+\mu_3)\, p_n = \lambda p_{n-1} + \mu_3 p_{n+1} && ,n = (Th_a - 1)^i \sim (Th_o)^i - 1 \\
&(\lambda+\mu_3)\, p_{(Tho)^i} = \mu_3 p_{(Tho-1)^d} \\
&(\lambda+\mu_2)\, p_{(Tha+1)^d} = \mu_2 p_{(Tha+2)^d} && (3.1) \\
&(\lambda+\mu_2)\, p_n = \lambda p_{n-1} + \mu_2 p_{n+1} && ,n = (Th_a - 2)^d \sim (Th_o)^d - 1 \\
&(\lambda+\mu_2)\, p_{(Tho)^d} = \lambda p_{(Tho-1)^d} + \mu_4 p_{(Tho+1)} \\
&(\lambda+\mu_4)\, p_{(Tho+1)} = \lambda\left(p_{(Tho)^i} + p_{(Tho)^d}\right) + \mu_4 p_{(Tho+2)} \\
&(\lambda+\mu_4)\, p_n = \lambda p_{n-1} + \mu_4 p_{n+1} && ,n = (Th_o + 2) \sim B
\end{aligned}
$$

From these equations we obtain:

$$
p_n = \begin{cases}
\left(\dfrac{\lambda}{\mu_1}\right)^n p_0 & ,\ n = 0 \sim Th_a \\[2ex]
\left(\dfrac{\lambda}{\mu_1}\right)^{Th_a} \left(\dfrac{\lambda}{\mu_3}\right)^{n-Th_a} \dfrac{\lambda^{Th_o-n+1}\mu_3^{\,n-Th_a} - \mu_3^{\,Th_o-Th_a+1}}{\lambda^{Th_o-Th_a+1} - \mu_3^{\,Th_o-Th_a+1}}\, p_0 & ,n = (Th_a+1)^i \sim (Th_o)^i \\[2ex]
\left(\dfrac{\lambda}{\mu_1}\right)^{Th_a} \left(\dfrac{\lambda}{\mu_2}\right) \dfrac{\lambda^{Th_o-Th_a}(\lambda-\mu_3)}{\lambda^{Th_o-Th_a+1} - \mu_3^{\,Th_o-Th_a+1}}\, p_0 & ,n = (Th_a+1)^d \qquad (3.2) \\[2ex]
\left(\dfrac{\lambda}{\mu_1}\right)^{Th_a} \left(\dfrac{\lambda}{\mu_2}\right)^{n-Th_a} \dfrac{\lambda-\mu_3}{\lambda-\mu_2}\, \dfrac{\lambda^{Th_o-Th_a+1} - \lambda^{Th_o-n+1}\mu_2^{\,n-Th_a}}{\lambda^{Th_o-Th_a+1} - \mu_3^{\,Th_o-Th_a+1}}\, p_0 & ,n = (Th_a+2)^d \sim (Th_o)^d \\[2ex]
\left(\dfrac{\lambda}{\mu_1}\right)^{Th_a} \left(\dfrac{\lambda}{\mu_2}\right)^{Th_o-Th_a} \left(\dfrac{\lambda}{\mu_4}\right)^{n-Th_o} \dfrac{\lambda-\mu_3}{\lambda-\mu_2}\, \dfrac{\lambda^{Th_o-Th_a+1} - \mu_2^{\,Th_o-Th_a+1}}{\lambda^{Th_o-Th_a+1} - \mu_3^{\,Th_o-Th_a+1}}\, p_0 & ,\ n = (Th_o+1) \sim B
\end{cases}
$$

Using Equation (3.2) and the condition $\sum_{n=1}^{B} p_n = 1$, we obtain

$$\left(\begin{array}{l}\displaystyle\sum_{n=0}^{Th_a}\left(\frac{\lambda}{\mu_1}\right)^{n}+\sum_{n=(Th_a+1)^d}^{(Th_o)^i}\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\left(\frac{\lambda}{\mu_3}\right)^{n-Th_a}\frac{\lambda^{Th_o-n+1}{\mu_3}^{n-Th_a}-{\mu_3}^{Th_o-Th_a+1}}{\lambda^{Th_o-Th_a+1}-{\mu_3}^{Th_o-Th_a+1}}+\\ \displaystyle\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\left(\frac{\lambda}{\mu_2}\right)\frac{\lambda^{Th_o-Th_a}\left(\lambda-\mu_3\right)}{\lambda^{Th_o-Th_a+1}-{\mu_3}^{Th_o-Th_a+1}}+\\ \displaystyle\sum_{n=(Th_a+2)^d}^{(Th_o)^d}\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\left(\frac{\lambda}{\mu_2}\right)^{n-Th_a}\frac{\lambda-\mu_3}{\lambda-\mu_2}\frac{\lambda^{Th_o-Th_a+1}-\lambda^{Th_o-n+1}{\mu_2}^{n-Th_a}}{\lambda^{Th_o-Th_a+1}-{\mu_3}^{Th_o-Th_a+1}}+\\ \displaystyle\sum_{n=(Th_o+1)}^{B}\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\left(\frac{\lambda}{\mu_2}\right)^{Th_o-Th_a}\left(\frac{\lambda}{\mu_4}\right)^{n-Th_o}\frac{\lambda-\mu_3}{\lambda-\mu_2}\frac{\lambda^{Th_o-Th_a+1}-{\mu_2}^{Th_o-Th_a+1}}{\lambda^{Th_o-Th_a+1}-{\mu_3}^{Th_o-Th_a+1}}\end{array}\right)p_0=1 \qquad (3.3)$$

Rewrite Equation (3.3):

$$\left(\begin{array}{l}\displaystyle\frac{1-\left(\lambda/\mu_1\right)^{Th_a+1}}{1-\lambda/\mu_1}+\\ \displaystyle\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\frac{\left(Th_o-Th_a\right)\lambda^{Th_o-Th_a+2}-\dfrac{\lambda^{Th_o-Th_a}\mu_3+\lambda^{Th_o-Th_a+1}}{1-\lambda/\mu_3}}{\lambda^{Th_o-Th_a+1}-{\mu_3}^{Th_o-Th_a+1}}+\\ \displaystyle\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\left(\frac{\lambda}{\mu_2}\right)\frac{\lambda^{Th_o-Th_a}\left(\lambda-\mu_3\right)}{\lambda^{Th_o-Th_a+1}-{\mu_3}^{Th_o-Th_a+1}}+\\ \displaystyle\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\frac{\lambda-\mu_3}{\lambda-\mu_2}\frac{\lambda^{Th_o-Th_a+1}\left(\dfrac{\left(\lambda/\mu_2\right)^2-\left(\lambda/\mu_2\right)^{Th_o-Th_a+1}}{1-\lambda/\mu_2}-\left(Th_o-Th_a-1\right)\right)}{\lambda^{Th_o-Th_a+1}-{\mu_3}^{Th_o-Th_a+1}}+\\ \displaystyle\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\left(\frac{\lambda}{\mu_2}\right)^{Th_o-Th_a}\frac{\lambda-\mu_3}{\lambda-\mu_2}\frac{\left(\lambda/\mu_4\right)-\left(\lambda/\mu_2\right)^{B-Th_o+1}}{1-\lambda/\mu_4}\frac{\lambda^{Th_o-Th_a+1}-{\mu_2}^{Th_o-Th_a+1}}{\lambda^{Th_o-Th_a+1}-{\mu_3}^{Th_o-Th_a+1}}\end{array}\right)p_0=1 \qquad (3.4)$$

Thus, p_0 is as shown in Equation (3.5).

$$p_0 = \left(\begin{array}{l} \dfrac{1-\left(\lambda/\mu_1\right)^{Th_a+1}}{1-\lambda/\mu_1} + \\ \left(\dfrac{\lambda}{\mu_1}\right)^{Th_a} \dfrac{\left(Th_o - Th_a\right)\lambda^{Th_o-Th_a+2} - \dfrac{\lambda^{Th_o-Th_a}\mu_3 + \lambda^{Th_o-Th_a+1}}{1-\lambda/\mu_3}}{\lambda^{Th_o-Th_a+1} - {\mu_3}^{Th_o-Th_a+1}} + \\ \left(\dfrac{\lambda}{\mu_1}\right)^{Th_a} \left(\dfrac{\lambda}{\mu_2}\right) \dfrac{\lambda^{Th_o-Th_a}\left(\lambda-\mu_3\right)}{\lambda^{Th_o-Th_a+1} - {\mu_3}^{Th_o-Th_a+1}} + \\ \left(\dfrac{\lambda}{\mu_1}\right)^{Th_a} \dfrac{\lambda-\mu_3}{\lambda-\mu_2} \dfrac{\lambda^{Th_o-Th_a+1}\left(\dfrac{\left(\lambda/\mu_2\right)^2 - \left(\lambda/\mu_2\right)^{Th_o-Th_a+1}}{1-\lambda/\mu_2} - \left(Th_o - Th_a - 1\right)\right)}{\lambda^{Th_o-Th_a+1} - {\mu_3}^{Th_o-Th_a+1}} + \\ \left(\dfrac{\lambda}{\mu_1}\right)^{Th_a} \left(\dfrac{\lambda}{\mu_2}\right)^{Th_o-Th_a} \dfrac{\lambda-\mu_3}{\lambda-\mu_2} \dfrac{\left(\lambda/\mu_4\right) - \left(\lambda/\mu_2\right)^{B-Th_o+1}}{1-\lambda/\mu_4} \dfrac{\lambda^{Th_o-Th_a+1} - {\mu_2}^{Th_o-Th_a+1}}{\lambda^{Th_o-Th_a+1} - {\mu_3}^{Th_o-Th_a+1}} \end{array} \right)^{-1} \tag{3.5}$$

Now we can derive the performance matrixes from Equation (3.2) and (3.5):

p_B	Packet loss probability $p_B = \left(\frac{\lambda}{\mu_1}\right)^{Th_a} \left(\frac{\lambda}{\mu_2}\right)^{Th_o - Th_a} \left(\frac{\lambda}{\mu_4}\right)^{B - Th_o} \frac{\lambda - \mu_3}{\lambda - \mu_2} \frac{\lambda^{Th_o - Th_a + 1} - \mu_2^{Th_o - Th_a + 1}}{\lambda^{Th_o - Th_a + 1} - \mu_3^{Th_o - Th_a + 1}} p_0$
$\overline{\mu}$	Average packet service rate $\overline{\mu} = \mu_1 \sum_{n=0}^{Th_a} p_n + \mu_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + \mu_2 \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n + \mu_4 \sum_{n=Th_o+1}^{B} p_n$
$\overline{W}$	Average system time of data packet, i.e., average queueing delay $\overline{W} = \frac{1}{\mu - \lambda} = \frac{1}{\left(\mu_1 \sum_{n=0}^{Th_a} p_n + \mu_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + \mu_4 \sum_{n=Th_o+1}^{B} p_n + \mu_2 \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n\right) - \lambda}$
$\overline{E}$	Average energy consumption $\overline{E} = E_1 \sum_{n=0}^{Th_a} p_n + E_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + E_2 \left(p_{(Th_a+1)^d} + \sum_{n=(Th_a+2)^d}^{(Th_o)^d} p_n \right) + E_4 \sum_{n=Th_o+1}^{B} p_n$
$\overline{T}$	Mobile life time $\overline{T} = \frac{E_m}{\overline{E}} = \frac{W}{E_1 \sum_{n=0}^{Th_a} p_n + E_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + E_2 \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n + E_4 \sum_{n=Th_o+1}^{B} p_n}$
Var_w	The variance of packet service time $Var_w = \frac{\sqrt{\overline{W^2} - \left(\overline{W}\right)^2}}{\overline{W}}$ $= \frac{\left(\left(\sum_{n=0}^{Th_a} p_n \left(\frac{1}{\mu_1 - \lambda}\right)^2 + \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n \left(\frac{1}{\mu_3 - \lambda}\right)^2 + \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n \left(\frac{1}{\mu_2 - \lambda}\right)^2 + \sum_{n=Th_o+1}^{B} p_n \left(\frac{1}{\mu_4 - \lambda}\right)^2 \right) - \left(\overline{W}\right)^2 \right)^{1/2}}{\overline{W}}$

Table 3.4 Performance Matrixes

Therefore, the optimization problem:

Objective function:

$$Z_{(IP1)} = max\left(\frac{E_m}{\overline{E}}\overline{\mu}\right)$$

$$= max\left(E_m \frac{\mu_1 \sum_{n=0}^{Th_a} p_n + \mu_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + \mu_2 \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n + \mu_4 \sum_{n=Th_o+1}^{B} p_n}{E_1 \sum_{n=0}^{Th_a} p_n + E_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + E_2 \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n + E_4 \sum_{n=Th_o+1}^{B} p_n} \right) \qquad \text{(IP1)}$$

Subject to :

$$p_B = \left(\frac{\lambda}{\mu_1}\right)^{Th_a} \left(\frac{\lambda}{\mu_2}\right)^{Th_o - Th_a} \left(\frac{\lambda}{\mu_4}\right)^{B-Th_o} \frac{\lambda-\mu_3}{\lambda-\mu_2} \frac{\lambda^{Th_o-Th_a+1} - \mu_2^{Th_o-Th_a+1}}{\lambda^{Th_o-Th_a+1} - \mu_3^{Th_o-Th_a+1}} p_0 \le p_{loss} \qquad (3.1)$$

$$\overline{W} = \frac{1}{\mu-\lambda} = \frac{1}{\left(\mu_1 \sum_{n=0}^{Th_a} p_n + \mu_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + \mu_4 \sum_{n=Th_o+1}^{B} p_n + \mu_2 \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n\right) - \lambda} \le D \qquad (3.2)$$

$$Var_w = \frac{\sqrt{\overline{W^2} - \left(\overline{W}\right)^2}}{\overline{W}}$$

$$= \frac{\left(\left(\begin{array}{l}\sum_{n=0}^{Th_a} p_n \left(\frac{1}{\mu_1-\lambda}\right)^2 + \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n \left(\frac{1}{\mu_3-\lambda}\right)^2 + \\ \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n \left(\frac{1}{\mu_2-\lambda}\right)^2 + \sum_{n=Th_o+1}^{B} p_n \left(\frac{1}{\mu_4-\lambda}\right)^2\end{array}\right) - \left(\overline{W}\right)^2\right)^{1/2}}{\overline{W}} \le J \qquad (3.3)$$

$$\overline{T} = \frac{E_m}{\overline{E}} = \frac{E_m}{E_1 \sum_{n=0}^{Th_a} p_n + E_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + E_2 \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n + E_4 \sum_{n=Th_o+1}^{B} p_n} \ge T_L \qquad (3.4)$$

$$\mu_4 \ge \mu_1 \qquad (3.5)$$

$$\mu_4 \ge \mu_2 \qquad (3.6)$$

$$\mu_4 \geq \mu_3 \tag{3.7}$$

$$\mu_2 \geq \mu_1 \tag{3.8}$$

$$\mu_3 \geq \mu_1 \tag{3.9}$$

The objective function is to maximize the system throughput under limited energy, where $\frac{E_m}{\overline{E}}$ represents the system life time, and $\overline{\mu}$ represents the expected service rate. Constraint (3.1), (3.2), (3.3), (3.4) are the quality of service constraints sand system lifetime constraint. Constraint (3.1) represents the blocking probability can't not exceed the tolerable loss probability, p_{loss}. Constraint (3.2) defines tolerable delay, and Constraint (3.3), Constraint (3.4) represent jitter, system lifetime, respectively. Constraint (3.5), (3.6), (3.7), (3.8), (3.9) represent the relationships between the service rates, which are shown in section 3.1.

Chapter 4. Solution Approach

4.1 Pilot Tests

In this section, we first have some pilot tests to explore the picture of the problem.

It is clearly that our queueing model mention in Chapter 3 is a variation of M/M/1 queueing system which is divided into four parts by thresholds and service rates. In spite of this, we can still approximate the system behavior by M/M/1 model.

For a traditional M/M/1 model,

$$p_n = \rho^n (1-\rho), \qquad n = 0, 1, 2, ... \tag{4.1}$$

where $\rho = \frac{\lambda}{\mu}$, $\rho < 1$. And, the system time is given by:

$$W = \frac{1}{\mu(1-\rho)} \tag{4.2}$$

As ρ increases, so does W, and as $\rho \to 1$, we have $W \to \infty$. Generally speaking, in order to lower system time and maintain performance, ρ will be some value less than 0.7:

The probability sum from p_0 to p_{Th_a}, according to Eq. (4.3), is

$$\sum_{n=0}^{Th_a} p_n = \sum_{n=0}^{Th_a} \rho^n (1-\rho) = 1-\rho^{Th_a+1} \tag{4.3}$$

If $\rho = 0.7$, the first four probabilities, $p_0 + p_1 + p_2 + p_3$, contains more than half probability of all system. If $\rho = 0.5$, the sum of the first four probabilities can exceeds 90%. Thus, we can say that in our system, first service rate, μ_1, that determines ρ and first threshold, Th_a, that determines the value of $\sum_{n=0}^{Th_a} p_n$, dominate the system throughput. Based on this idea, we do some numerical experiment that focus on μ_1 and Th_a, given different power consumption.

Data Rate	Power Consumption and Power Utilization							
	E1		E2		E3		E4	
6	14	0.42857	**14**	**0.42857**	**14**	**0.42857**	14	0.42857
9	21	0.42857	22	0.40909	21.5	0.41860	**20**	**0.45**
12	28	0.42857	30	0.4	29	0.4137	27	0.44444
18	42	0.42857	48	0.375	45	0.4	42	0.42857
24	56	0.42857	66.5	0.36090	66	0.36363	61	0.39344
36	84	0.42857	102	0.35294	120	0.3	116	0.31034
48	112	0.42857	140	0.34285	200	0.24	221	0.21719
54	126	0.42857	165	0.32727	300	0.18	341	0.15835

Table 4.1 Power Consumption and Utilization with Different Service Rates

Table 4.1 is the power consumption rate with different transfer rate, each set with the most efficient one shadowed and boldface. Figure 4.1 shows the power consumption curves: E1 is a horizontal line that power consumption per bit remains unchanged as the transfer rate increases; E2 keeps linear increasing as transfer rate increases; E3 and E4 have exponential growth as transfer rate increases.

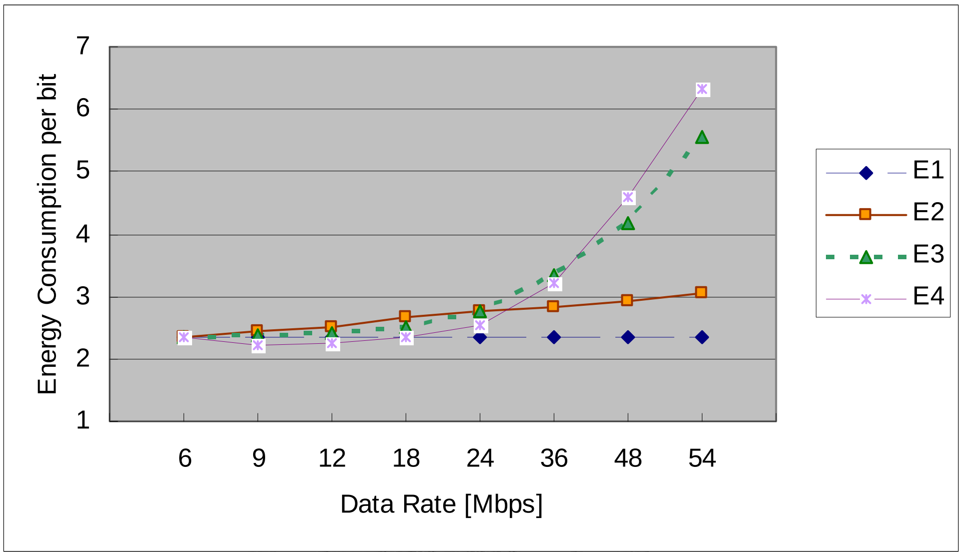

Figure 4.1 Power Consumption per Bit with Data Rates

In the following, we exploit the effect from μ_1 and Th_a. By fixed the other five decision variables, we plot the objective function values as they changes.

(i) ***Service Rate,*** μ_1

Figure 4.2 is the system throughput as service rate changes with different power consumption rate, E1, E2, E3, and E4. The summation probability from 0 to Th_a and Th_o is 0.5 and 0.7. The values of μ_2, μ_3, and μ_4 are 54 Mbps. For power- consumption set E1, the system throughput remains unchanged as the service rate changes because of the ***power utilization*** (Power consumption quantity / Data rate) is the same. For E2, the highest throughput exists on Data

Rate = 6, because of the highest power utilization it provides. For E3 and E4, the highest system throughput is closed to the highest system throughput. Figure 4.3 is the system throughput with summation probability from 0 to Th_a and Th_o, 0.3 and 0.5, respectively.

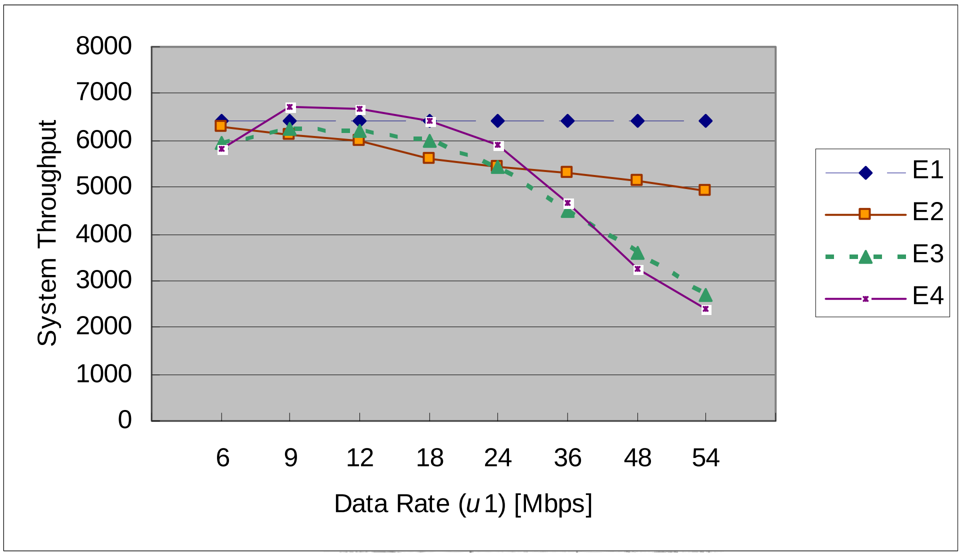

Figure 4.2 System Throughput with Data Rate of μ_1, where Summation Probabilities from 0 to Tha and Tho Are 0.5 and 0.7

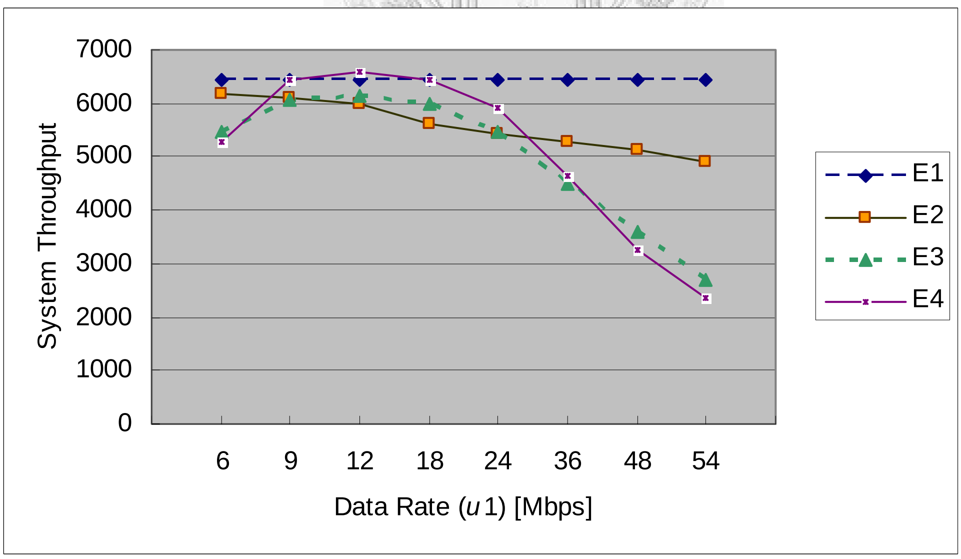

Figure 4.3 System Throughput with Data Rate of μ1, where Summation Probabilities from 0 to Tha and Tho Are 0.3 and 0.7

From above figures, it suggests that higher power utilization contributes higher system throughput. But different service rates may rearrange the probability distribution that lead to different system throughput. Thus, the main factor that governs it should be *"average power utilization"*. If μ_h is the service rate with the highest power utilization, we can say that the best service rate for μ_1 is some one *near* μ_h. The word "near" means that the best one is not always the one with the highest power utilization. If the power utilization of the service rate, say $\mu_h^{'}$, is slightly less then that of μ_h, and the data rate of $\mu_h^{'}$ is higher than μ_h, $\mu_h^{'}$ can contribute to better throughput. That's because with higher μ_1, the probability, summing from 0 to Th_a tends be greater, which then recursively leads to higher productivity.

(ii) ***Threshold, Th_a***

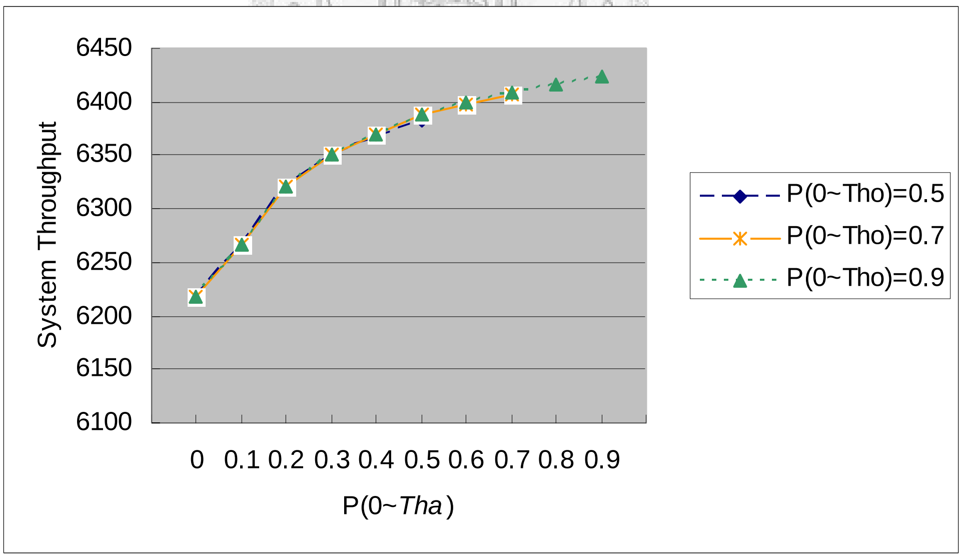

Figure 4.4 System Throughput with Different Summation Probabilities

Figure 4.4 presents the relationship between system throughput and thresholds. The service rates are 6, 9, 9, and 12, the power consumption set is E3, and power utilizations are 0.43, 0.42, 0.42, and 0.41. It's clearly that system throughput has little changes as Th_o varies. Th_a, on the other hand, will keep the service rate having higher power utilization with larger probability. In this case, the highest power utilization is μ_1, thus the system throughput increases as Th_a increases.

The service rates of Figure 4.5 are 6, 9, 9, and 12, the power consumption set is E4, and power utilizations are 0.43, 0.45, 0.45 and 0.44. The highest power utilization is that of μ_2 and μ_3, and thus the throughput decreases as Th_a increases.

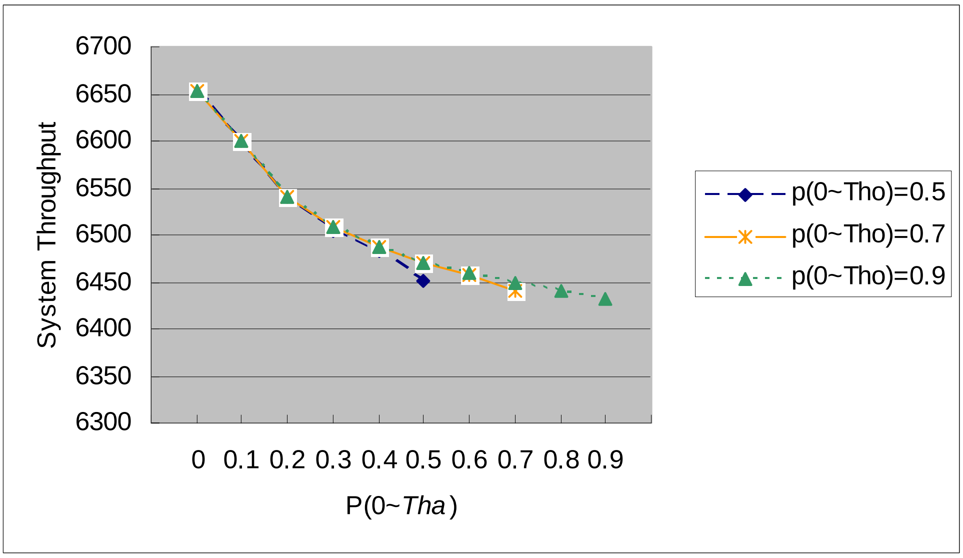

Figure 4.5 System Throughput with Different Summation Probabilities

From these pilot tests, we can conclude that

1. The best value for μ_1 is some one "*near*" that with the highest power utilization.
2. Th_a tends to enlarge the probability of the most efficient service rate.

4.2 Initial Point

For any algorithm searching iteration by iteration, initial point is critical. Good initial point can save the computational time and provide good approximation to optimal solution. Bad initial pints, on the other hand, may not only waste the computational power, but also lead to wrong direction.

According to the pilot test and the assumption that higher transfer rate consumes more power, we know that when maximizing system throughput, the value of μ_1 needs to be low, and Th_a needs to enlarge the probability of the most efficient service rate. Thus, the initial point of service rates should be the *lowest* service rate with acceptable delay, so to maximize the throughput and ensure the QoS at the same time. Take UMTS network for example, available service rates and their performance are listed in Table 4.2. If the tolerable delay is within 0.03 second, the initial value of μ_1, μ_2, μ_3, and μ_4 will be 64 Mbps.

Service Rate (Mbps)	***Arrival Rate***	***Energy Consumption***	***Delay(s)***
32	20	8	0.083333
64	20	16	0.022727
128	20	34	0.009259
256	20	75	0.004237
384	20	136	0.002747
768	20	420	0.001337

Table 4.2 Available Service Rate and Their Performance in UMTS network

On the other hand, since thresholds tend to keep the highest efficient service rate in largest probability, their initial value can be given by the summation equation:

$$\sum_{n=0}^{k} p_n = m, \quad 0 < m < 1 \tag{4.4}$$

where ***m*** is any arbitrarily value between 0 and 1. And from the perspective of M/M/1 model, the p_n in (4.3) can be approximated as

$$p_n = \left(1 - \frac{\lambda}{\mu_1}\right)\left(\frac{\lambda}{\mu_1}\right)^n \tag{4.5}$$

From preceding equations, we have

$$\begin{aligned} &\sum_{n=0}^{k} \left(1 - \frac{\lambda}{\mu_1}\right)\left(\frac{\lambda}{\mu_1}\right)^n = m, \\ &\left(1 - \frac{\lambda}{\mu_1}\right)\frac{1 - \left(\frac{\lambda}{\mu_1}\right)^{k+1}}{1 - \frac{\lambda}{\mu_1}} = m, \\ &k = \frac{\log\left(1 - m\right)}{\log\left(\frac{\lambda}{\mu_1}\right)} - 1 \end{aligned} \tag{4.6}$$

4.3 Heuristic for the Model

When solving the maximization programming problems presented in Chapter 3, we propose a heuristic algorithm to help the searching process.

First, we introduce slack variables, namely S_1, S_2, S_3, and S_4, to replace the complicated terms in Constraints (3.1), (3.2), (3.3), and (3.4). Thus, the transformed objective function and constraints are:

Transformed objective function:

$$Z_{(IP2)} = max\begin{pmatrix} \left(\frac{E_m}{\overline{E}}\overline{\mu}\right)+ \\ A_1\left(p_B+S_1-p_{loss}\right)^2+A_2\left(\overline{W}+S_2-D\right)^2+ \\ A_3\left(Var_w+S_3-J\right)^2+A_4\left(\overline{T}-S_4-T_L\right)^2 \end{pmatrix} \qquad \text{(IP2)}$$

Subject to:

$$\mu_4 \ge \mu_1 \qquad (3.1)$$

$$\mu_4 \ge \mu_2 \qquad (3.2)$$

$$\mu_4 \ge \mu_3 \qquad (3.3)$$

$$\mu_2 \ge \mu_1 \qquad (3.4)$$

$$\mu_3 \ge \mu_1 \qquad (3.5)$$

$$S_1 \ge 0 \qquad (3.6)$$

$$S_2 \ge 0 \qquad (3.7)$$

$$S_3 \ge 0 \qquad (3.8)$$

$$S_4 \ge 0 \qquad (3.9)$$

where

$$\begin{aligned} S_1 &= p_{loss}-p_B \\ &= p_{loss}-\left(\frac{\lambda}{\mu_1}\right)^{Th_a}\left(\frac{\lambda}{\mu_2}\right)^{Th_o-Th_a}\left(\frac{\lambda}{\mu_4}\right)^{B-Th_o}\frac{\lambda-\mu_3}{\lambda-\mu_2}\,\frac{\lambda^{Th_o-Th_a+1}-\mu_2^{\,Th_o-Th_a+1}}{\lambda^{Th_o-Th_a+1}-\mu_3^{\,Th_o-Th_a+1}}\,p_0 \end{aligned}$$

$$\begin{aligned} S_2 &= D-\overline{W} \\ &= D-\frac{1}{\left(\mu_1\sum_{n=0}^{Th_a}p_n+\mu_3\sum_{n=(Th_a+1)^i}^{(Th_o)^i}p_n+\mu_4\sum_{n=Th_o+1}^{B}p_n+\mu_2\sum_{n=(Th_a+1)^d}^{(Th_o)^d}p_n\right)-\lambda} \end{aligned}$$

$$S_3 = J - Var_w = \frac{\sqrt{\overline{W^2} - \left(\overline{W}\right)^2}}{\overline{W}}$$

$$= \frac{\left(\left(\begin{array}{l} \sum_{n=0}^{Th_a} p_n \left(\frac{1}{\mu_1 - \lambda} \right)^2 + \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n \left(\frac{1}{\mu_3 - \lambda} \right)^2 + \\ \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n \left(\frac{1}{\mu_2 - \lambda} \right)^2 + \sum_{n=Th_o+1}^{B} p_n \left(\frac{1}{\mu_4 - \lambda} \right)^2 \end{array} \right) - \left(\overline{W}\right)^2 \right)^{1/2}}{\overline{W}}$$

$$S_4 = \overline{T} - T_L$$

$$= \frac{E_m}{E_1 \sum_{n=0}^{Th_a} p_n + E_3 \sum_{n=(Th_a+1)^i}^{(Th_o)^i} p_n + E_2 \sum_{n=(Th_a+1)^d}^{(Th_o)^d} p_n + E_4 \sum_{n=Th_o+1}^{B} p_n} - T_L$$

Combined with the conclusion from pilot tests, the searching operation is as following:

Initial	1. The initial values of Th_a and Th_o are evaluated by $$k = \left\lceil \frac{log\left(1-m\right)}{log\left(\frac{\lambda}{\mu_1}\right)} - 1 \right\rceil, \quad 0 < m \leq 1,$$ where m is any arbitrarily value such as 0.3 or 0.5. 2. The initial values of μ_1, μ_2, μ_3 and μ_4 are given according to the acceptable delay and the performance of IEEE 802.11g and UMTS system.
Iteration	1. Given a set of decision variable values, increase and decrease two units in iteration, to see whether there is any increment in objection function. 2. Pick up the value of decision variables that maximized the

	objective function. If there are more than one set values of decision variables with same objective function, pick the better QoS one. 3. Go to step 1.
Stopping Criteria	1. If there is no any improvement for objective function or changes in decision variables, stop the searching procedure.

Table 4.3 Heuristic Operation

Chapter 5. Computational Experiments

5.1 Case 1: IEEE 802.11g, Non Real-time Service

5.1.1 Parameters and Experiment Results

Total energy of mobile, E_m	15000 unit
The queue size, B	50
The arrival rate of packet, λ	0.2 Mbps
Tolerable packet loss probability, p_{loss}	0.001
Tolerable delay of each packet, D	10 (s)
Tolerable packet jitter, J	N.A
System lifetime requirement, T_L	1000 time unit
Available service rate	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Energy consumption per time unit, E_n	14, 22, 30, 48, 68, 120, 200, 300 unit
Penalty multiplier, A_1, A_2, A_3, and A_4	100000000
Initial service rates	6, 6, 6, 6
Summation probability for Th_a	0.5
Summation probability for Th_o	0.7

Table 5.1 Parameters for IEEE 802.11g Non Real-time Services

The parameters simulated IEEE 802.11g OFDM are listed in Table 5.1, and Figure 5.1 is the power consumption curve according power consumption rate listed in Table 5.1. The consumption rate is exponential growth with data rate, as case E3 and E4 we discuss in pilot tests.

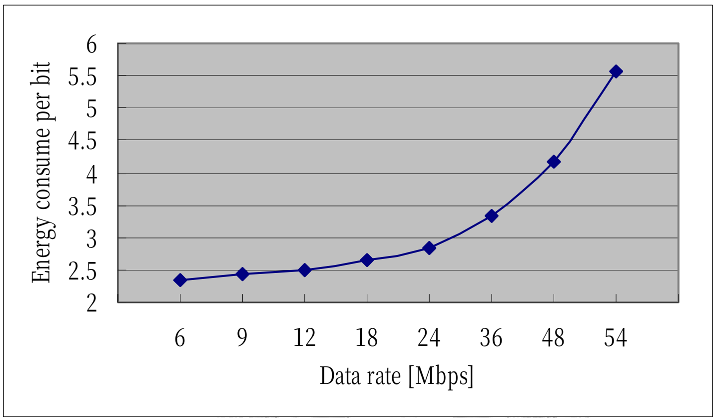

Figure 5.1 Power Consumption Curve of IEEE 802.11g

Suggested by our algorithm, the best transfer rates for μ_1, μ_2, μ_3, and μ_4 are 6, 6, 9, 36 Mbps, and the best thresholds value for Th_a and Th_o is 24. This contributes to system throughput of 6428.474597, as shown in Figure 5.2.

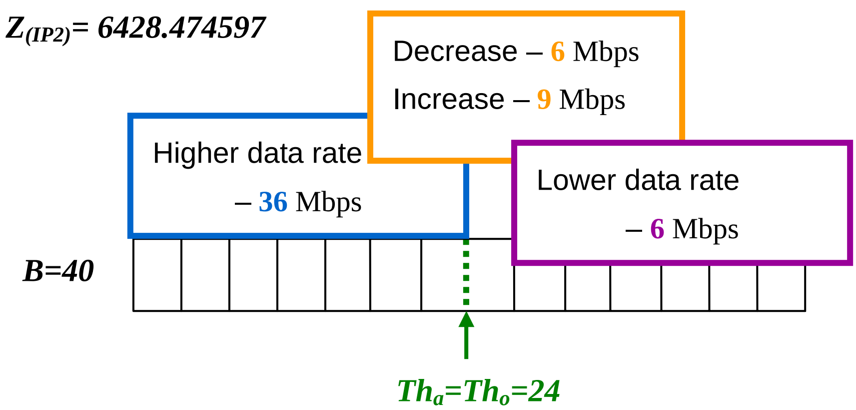

Figure 5.2 Computational Results for IEEE 802.11g Non Real-time Services

5.1.2 Result Discussion

Table 5.2 lists the throughput, system life time, and delay with single transfer rate along with proposed strategy. The transfer rates suggested by our algorithm are shown in different colors. As we mention in previous section, QoS and throughput are tradeoff with each other, higher transfer rate gives less delay, but lower throughput. It is clearly that our model has higher productivity, and meets the QoS requirement at the same time.

Service Rate	***Throughput***	***System Life Time***	***Delay (s)***
6	6428.571429	1071.428571	2.5
9	6136.363636	681.818182	0.294118
12	6000	500	0.15625
18	5625.000000	312.5	0.080645
24	5294.117647	220.588235	0.054348
36	4500	125	0.032895
48	3600	75	0.023585
54	2700	50	0.020661
6.006388	6428.474597	1071.381104	2.498902

Table 5.2 IEEE 802.11g System Performance vs. Proposed Model (Non Real-time Service)

In order to facilitate the reading, we normalize those numerical data suggested by our algorithm with its throughput, life time, and delay, as shown in Table 5.3:

Service Rate	***Throughput***	***System Life Time***	***Delay***
6	1.00002	100.00%	100.04%
9	95.46%	63.64%	11.77%
36	70.00%	11.67%	1.32%

Table 5.3 System Throughput Comparison with Service Rates that Adapted by Algorithm

For the sake of showing the efficiency of heuristic algorithm we proposed, Table 5.4 lists the computational results from heuristic algorithm and exhaustive search. The values of decision variables from heuristic algorithm have little difference in thresholds and μ_4, and thus the throughput, system lifetime, and delay. However, the heuristic takes only 9 iterations ($5^6 \times 9 = 140,625$ combinations), which is faster than exhaustive search ($50^2 \times 8^4 = 10,240,000$ combinations), and more efficient than exhaustive search.

	Heuristic	***Exhaustive Search***
$\boldsymbol{Th_a}$	23	19
$\boldsymbol{Th_o}$	23	19
μ_1	6	6
μ_2	6	6
μ_3	9	9
μ_4	36	54
Throughput	6425.057463 (99.95%)	6428.571429
System Lifetime	1069.704102	1070.728516
Delay	2.460706	2.490436

Table 5.4 Comparison of Heuristic Algorithm and Exhaustive Search

5.2 Case 2: IEEE 802.11g, Real-time Service

5.2.1 Parameters and Experiment Results

Table 5.2 lists the parameters that simulate the IEEE 802.11g system, and those necessary initial values. We assume that the power consumption rate is exponential growth with data rate, tolerable delay is 0.15 seconds (because of real-time service), and tolerable jitter is 0.2 seconds. The initial value for four service rates is both 24 Mbps, and the probabilities, summation from 0 to Th_a and Th_o, are0.5 and 0.7, respectively.

Total energy of mobile, E_m	15000 unit
The queue size, B	30
The arrival rate of packet, λ	10 Mbps
Tolerable packet loss probability, p_{loss}	0.05
Tolerable delay of each packet, D	0.15 (s)
Tolerable packet jitter, J	0.20 (s)
System lifetime requirement, T_L	200 time unit
Available service rate	12, 18, 24, 36, 48, 54 Mbps
Energy consumption per time unit, E_n	30, 48, 68, 120, 200, 300 unit
Penalty multiplier, A_1, A_2, A_3, and A_4	100000000
Initial service rates	18, 18, 18, 18
Summation probability for Th_a	0.5
Summation probability for Th_o	0.7

Table 5.5 Parameters for IEEE 802.11g Real-time Services

According to the algorithm, the best transfer rates for μ_1, μ_2, μ_3, and μ_4 are 18, 18, 36, 54, and the values for thresholds are 23 and 27. These give a throughput of 5624.999804, jitter of 0.000588 seconds.

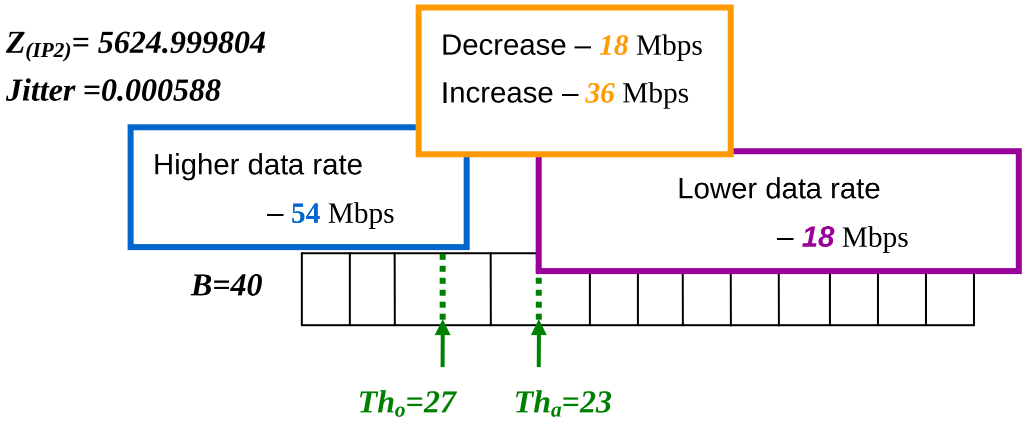

Figure 5.3 Computational Results for IEEE 802.11g Real-time Services

5.2.2 Result Discussion

Table 5.6 lists the throughput, system life time, and delay with single transfer rate with the proposed model at the last row. The transfer rates suggested by our algorithm are shown in different colors.

Service Rate	***Throughput***	***System Life Time***	***Delay (s)***
12	6000	500	0.5
18	5625	312.5	0.12
24	5294.117647	220.588235	0.071429
36	4500	125	0.038462
48	3600	75	0.026316
54	2700	50	0.022727
18.000002	5624.999804	312.5	0.125

Table 5.6 IEEE 802.11g System Performance vs. Proposed Model (Real-time Service)

Table 5.6 shows that our transfer strategies not only provide the advantages of low transfer rates, but also remove the disadvantages of high transfer rates. Table 5.7 is the numerical data normalized with the performance of our strategies.

Service Rate	***Throughput***	***Delay***	***Jitter***
18	1	96%	0
36	80%	30.77%	0
54	48%	18.18%	0

Table 5.7 System Throughput Comparison with Service Rates that Adapted by Algorithm

Table 5.8 shows the computational results from heuristic algorithm and exhaustive search. The performance of throughput, system lifetime, and delay is almost the same with each other, although with different decision-variable-values. The heuristic algorithm takes only 10 iterations (Iteration 11 to Iteration 18 provides some alternatives for decision variables.) that save much more computational power and searching time.

	Heuristic	***Exhaustive Search***
Th_a	23	24
Th_o	27	24
μ_1	18	18
μ_2	18	18
μ_3	24	24
μ_4	36	24
Throughput	5624.999804 (99.999%)	5625

System Lifetime	312.5	312.5
Delay	0.125	0.125

Table 5.8 Comparison of Heuristic Algorithm and Exhaustive Search

Figure 5.4 and Figure 5.5 present system throughput as service rate varies and system throughput with delay time. The performance of proposed algorithm is very closed to the line of single transfer rate, since the transfer strategy from the proposed algorithm is the combinations of these single transfer rates.

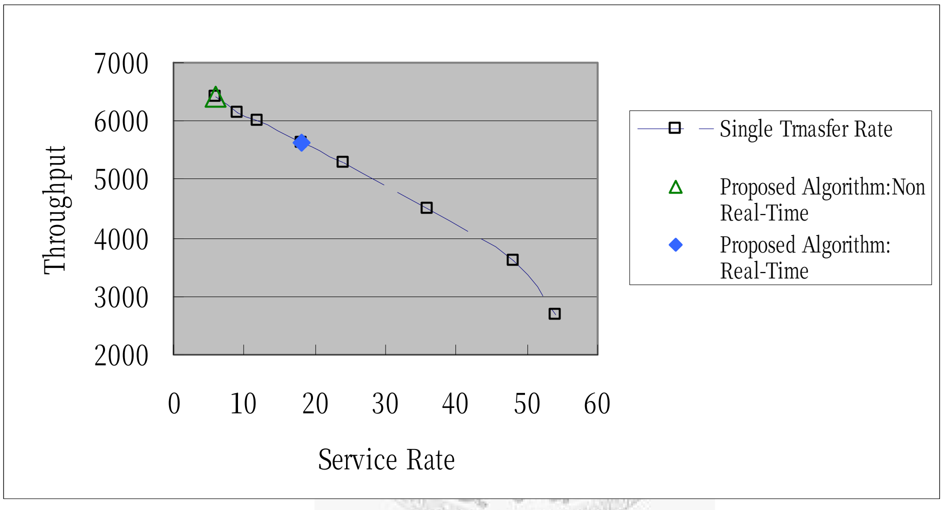

Figure 5.4 IEEE 802.11g System Throughput vs. Proposed Strategy, as Service Rate Varies

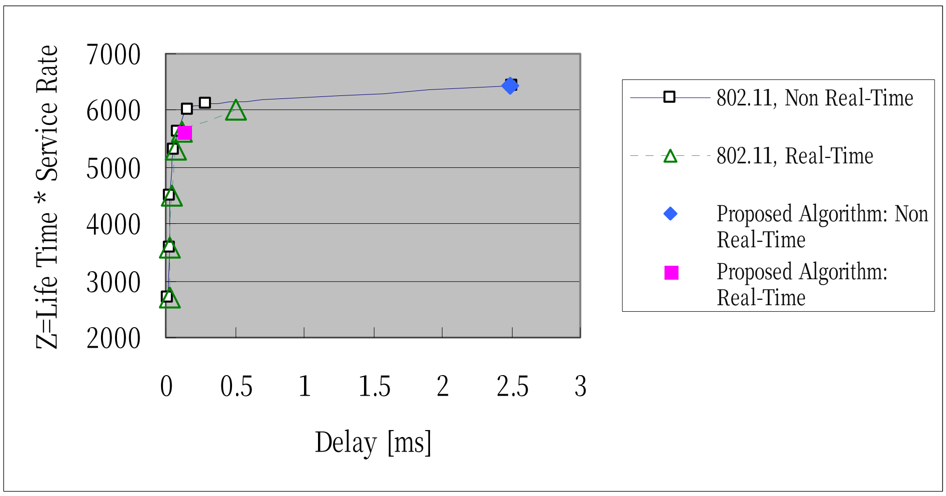

Figure 5.5 IEEE 802.11g System Throughput versus Delay Time

5.3 Case 3: UMTS Network, Non Real-time Service

5.3.1 Parameters and Experiment Results

The parameters simulate UMTS network are listed in Table 5.9, and Figure 5.6 is the power consumption curve according power consumption rate listed in Table 5.9. Packet arrival rate is 20, acceptable delay is within 10 seconds for non real-time service, and system lifetime requirement is 1200 time units. The power consumption rate is exponential growth with data rate, as the E3 and E4 discuss in pilot tests. The initial service rates are both 32 Mbps, and the summation probabilities from 0 to Th_a and Th_o are 0.5 and 0.7, respectively.

Total energy of mobile, E_m	15000 unit
The queue size, B	50
The arrival rate of packet, λ	20 Mbps
Tolerable packet loss probability, p_{loss}	0.001
Tolerable delay of each packet, D	10 (s)
Tolerable packet jitter, J	N.A
System lifetime requirement, T_L	1200 time units
Available service rate	32, 64, 128, 256, 384, 768 Mbps
Energy consumption per time unit, E_n	8, 16, 34, 75, 136, 420 unit
Penalty multiplier, A_1, A_2, A_3, and A_4	100000000
Initial service rates	32, 32, 32, 32
Summation probability for Th_a	0.5
Summation probability for Th_o	0.7

Table 5.9 Parameters for UMTS Network, Non Real-time Services

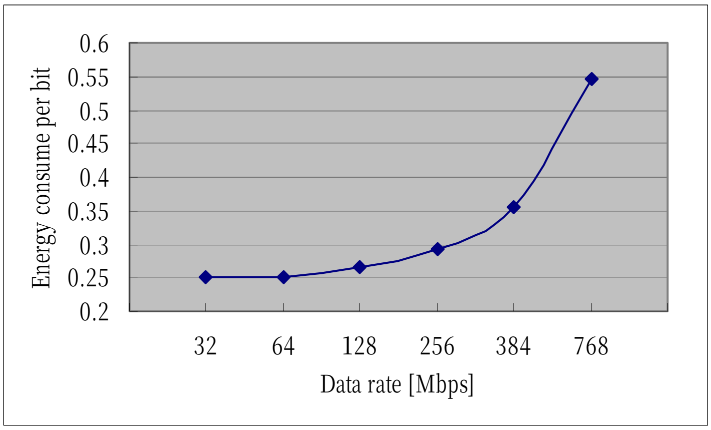

Figure 5.6 Power Consumption Curve of UMTS Networks

The algorithm tells that the thresholds should both be 0 (thus there is no μ_2 and μ_3), and the service rates all are 64 Mbps. These give a throughput of 60000.

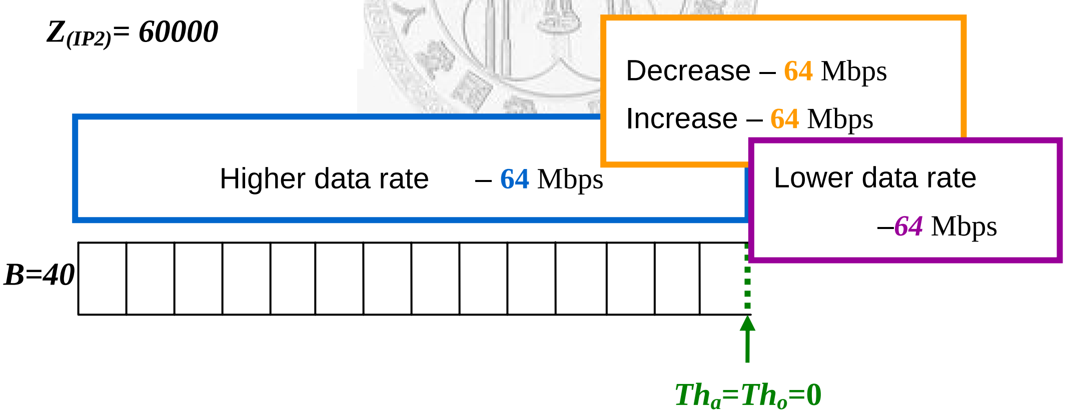

Figure 5.7 Computational Results for UMTS Non Real-time Services

5.3.2 Result Discussion

Table 5.10 is the throughput, system life time, and delay with single transfer rate along with proposed model. The transfer rates suggested by our algorithm are shown in different colors. The suggested service rates are all 64 Mbps, because the constraints of QoS are quite loose. In this case, the acceptable delay time is any one less than 10 seconds. However, all the delay time provided by avaliable service rates are far less than 1 seconds. In this way, the altorighm will pick up that with highest power utilization. Here 64 Mbps is the right one, and the transmission strategy is to transmit with 64 Mbps no matter the packet volumns to be transmitted.

Service Rate	***Throughput***	***System Life Time***	***Delay (s)***
32	60000	1875	0.083333
64	60000	937.500000	0.022727
128	56470.588235	441.176471	0.009259
256	51200	200	0.004237
384	42352.941176	110.294118	0.002747
768	27428.571429	35.714286	0.001337
64	60000	937.500000	0.022727

Table 5.10 UMTS Network System Performance vs. Proposed Model (Non Real-time Service)

The computational results shown in previous section is obtained from our heuristic that takes only 2 iterations ($5^6 \times 2 = 31,250$ combinations), and the values of decision variables are exactly the same with that from exhaustive search (needs $6^4 \times 50^2 = 3,240,000$ combinations). Thus, our heuristic is a quick powerful one.

	Heuristic	***Exhaustive Search***
$\boldsymbol{Th_a}$	0	0
$\boldsymbol{Th_o}$	0	0
μ_1	64	64
μ_2	64	64
μ_3	64	64
μ_4	64	64
Throughput	60000	60000
System Lifetime	1428.571411	1428.571411
Delay	0.045455	0.045455

Table 5.11　Comparison of Heuristic Algorithm and Exhaustive Search

5.4 Case 4: UMTS Network, Real-time Service

5.4.1Parameters and Experiment Results

Table 5.12 lists the parameters that simulate UMTS system, and those necessary initial values. We assume that the power consumption rate is exponential growth with data rate, tolerable delay is 0.012 seconds for real-time service, and tolerable jitter is 0.05 seconds. The initial value for four service rates is both 128 Mbps, and the probabilities, summation from 0 to Th_a and Th_o, are 0.5 and 0.7, respectively.

Total energy of mobile, E_m	15000 unit
The queue size, B	30
The arrival rate of packet, λ	28 Mbps
Tolerable packet loss probability, p_{loss}	0.05
Tolerable delay of each packet, D	0.012 (s)
Tolerable packet jitter, J	0.05 (s)
System lifetime requirement, T_L	400 time unit
Available service rate	32, 64, 128, 256, 384, 768 Mbps
Energy consumption per time unit, E_n	8, 16, 34, 75, 136, 420 unit
Penalty multiplier, A_1, A_2, A_3, and A_4	100000000
Initial service rates	128, 128, 128, 128
Summation probability for Th_a	0.5
Summation probability for Th_o	0.7

Table 5.12 Parameters and Initial Point for UMTS Network, Real-time Services

Figure 5.8 illustrates the computational results for UMTS real-time services. The first two service rates are both 128 Mbps, and the others are 256 Mbps. The value of thresholds, Th_a and Th_o, are 16 and 22. In this case, there are many alternative thresholds, they can be any value from 16 to 22. Here we pick up 16 and 22 for variety.

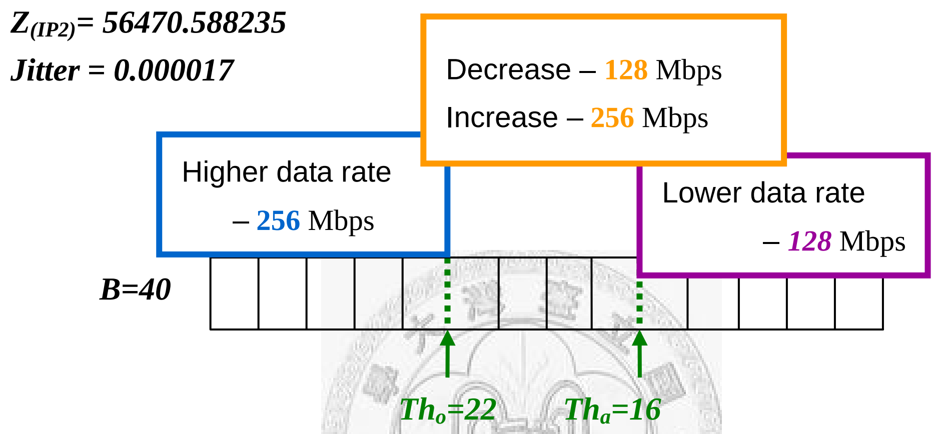

Figure 5.8 Computational Results for UMTS Real-time Services

5.4.2 Result Discussion

Table 5.13 is the performance with single transfer rates. The service rates suggested by our strategy are 128 and 256, as listed at the bottom of the table. The throughput, system life time, and delay are exactly the same with that of serving with 128 Mbps because the probability of serving with 256 Mbps in our strategy is too small. Table 5.14 lists the normalized data to provide an easy reading way.

Service Rate	***Throughput***	***System Life Time***	***Delay (s)***
32	60000	1875	0.25
64	60000	937.5	0.027778
128	56470.588235	441.176471	0.01
256	51200	200	0.004386
384	42352.941176	110.294118	0.002809
768	27428.571429	35.714286	0.001351
128	56470.588235	441.176483	0.01

Table 5.13 UMTS Network System Performance vs. Proposed Model (Real-time Service)

Service Rate	***Throughput***	***Delay***	***Jitter***
128	1	1	0
256	90.67%	43.86%	0

Table 5.14 System Throughput Comparison with Service Rates that Adapted by Algorithm

Table 5.15 presents the computational results from heuristic algorithm and exhaustive search. Except Th_a, the values suggested by heuristic algorithm are the same with that by exhaustive search. The heuristic algorithm takes only 3 iterations then meets the stopping criteria. These data shows that the heuristic algorithm is a very efficient and effective one.

	Heuristic	***Exhaustive Search***
Th_a	16	14

Th_o	22	22
μ_1	128	128
μ_2	128	128
μ_3	256	256
μ_4	256	256
Throughput	56470.588235	56470.588235
System Lifetime	441.176483	441.176483
Delay	0.01	0.01

Table 5.15 Comparison of Heuristic Algorithm and Exhaustive Search

Figure 5.9 and Figure 5.10 illustrate the relationship between throughput and service rate, and between throughput and delay. The performance of proposed algorithm is very closed to the line of single transfer rate, since the transfer strategy from the proposed algorithm is the combinations of these single transfer rates.

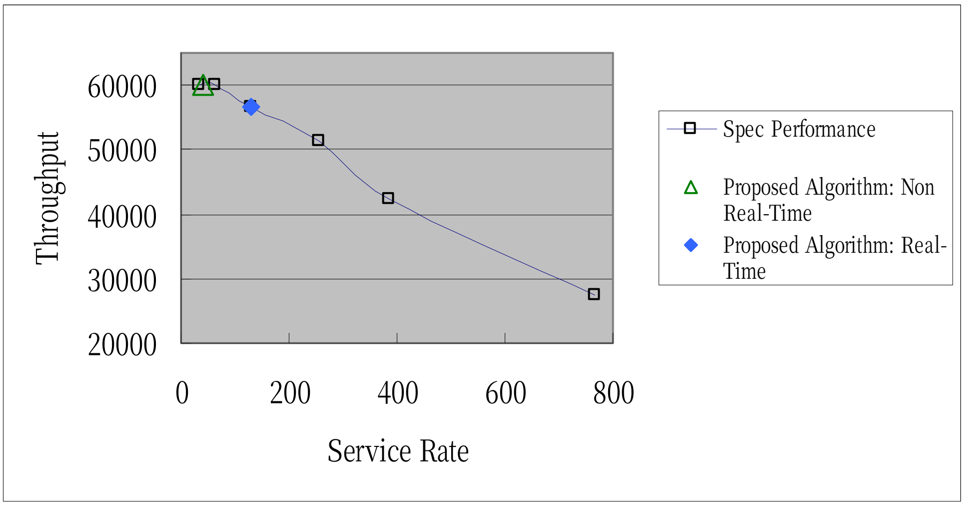

Figure 5.9 UMTS Network System Throughput vs. Proposed Strategy, as Service Rate Varies

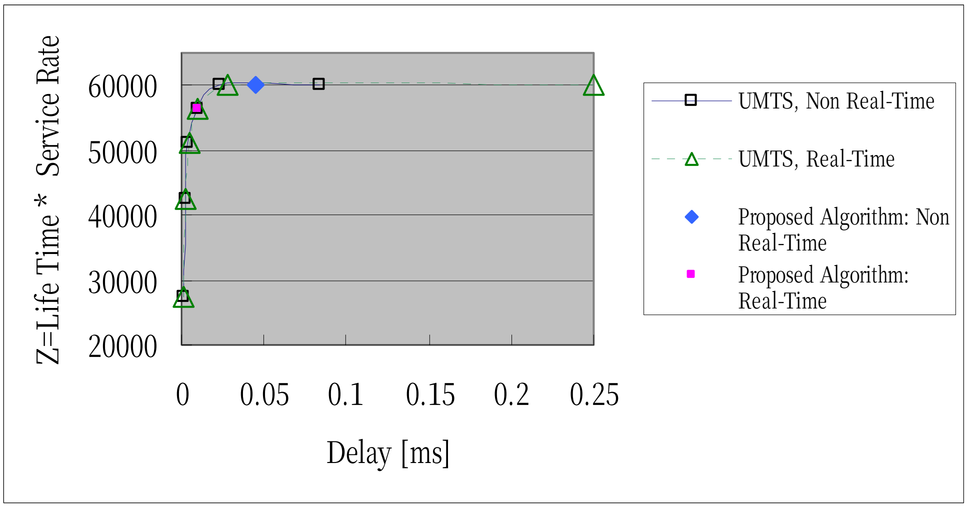

Figure 5.10 UMTS Network System Throughput versus Delay Time

Chapter 6. Summary and Future Work

6.1 Summary

In wireless networks, system throughput has been trade-off with QoS: in order to maintain the required quality. It usually transfers data with higher service rate that consume higher energy for those delay-sensitive packets. However, we have some better choices: to transfer packets by *smartly* introducing communication *delay*. Here *delay* refers to coding/decoding delay, buffering delay, or data segmentation and reassembling delay; and the word *smartly* means to use intelligent management techniques to guarantee the QoS requirement.

In this thesis, we first give some introductions of wireless networks and discussion of low power issues, then propose a transferring strategy that transmits packets depends on the packet volume buffering in queue. By introducing two thresholds, the transmission policies are separate into four parts. According to queueing theory, we developed a mathematical model to describe the system behavior and performance. Based on the pilot tests, we design a heuristic algorithm for the solution.

There are four cases for the problem are studied, which are solved by our heuristic algorithm to find the solutions. We can see that the performance of our model is much better than the original ones and meet the QoS requirements at the same time.

6.2 Future Work

There are some more work can be extended from this thesis:

1. The transferring strategy we proposed considers only one queue for each mobile device. It can be extended to more than one queue, such as one for data packets, one for streaming packets, and one for video packets. Packets belong to video or streaming classes have higher priority than that belong to data packets, and each has their own transferring strategies.

2. In most cases, mobile devices can determine the channel conditions according to the failure portion in a period of transmission. The mobile device can be much more intelligent by stopping the transmission or transmits with a probability if it detects the channel in disadvantageous condition.

3. According to queueing theory, service rate should always larger than arrival rate. Under this constraint, although there are many service rates available, the reasonable values for μ_1, μ_2, μ_3 and μ_4 are

quick limited. If this constraint can be removed, the analysis can be much more flexible.

4. In this thesis, we don’t take the strategy switching cost in to consideration. Strategy switching cost such as modulation switching consumes power, too. In power saving issues, this can’t not be neglected.

5. The experimental results show that the performance of transmission strategy with two thresholds is better than that with only one threshold. It is worthwhile to study how the performance is affected if we consider cases with more thresholds.

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