Reverse Link Scheduling and Data Rate Allocation Scheme for CDMA2000 1xEV-DV: An Alternative Approach

By

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

Master of Science

Supervisor: Attahiru Sule Alfa

Abstract

CDMA2000 1xEV-DV is designed to meet the increasing demand for high-speed packet data transmission. The previous works on 1xEV-DV reverse link scheduling were based on trying to improve reverse link throughput, thereby mainly considering the users' interests. In this thesis, we consider the system from both the service providers' and subscribers' points of view and propose an alternative reverse link resource allocation procedure for non-time sensitive data traffic based on CDMA2000 Revision D. The goal is to maximize obtained revenue for service providers and minimize loss for subscribers subject to rise-over-thermal constraint. The method is quite flexible and offers service providers the choices of either maximizing obtained revenue or minimizing loss, or balancing both of them.

The system model is formulated into a Knapsack problem which can be solved by binary integer linear programming. Branch-and-Bound as a solution is discussed, but observed to be inefficient for this problem and instead two heuristic algorithms are proposed. All the three solutions are analyzed through illustrative experiments. The results of the analysis present a trade-off between the computational time for scheduling and maximum obtained revenue. The heuristic algorithms consume much shorter computational times and are therefore more appropriate for our time constrained scheduling and resource allocation scheme. Using the heuristic algorithms we are able to make recommendations to service providers on how to schedule the transmission selecting the objective balancing parameter according to their needs.

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Table of Contents

List of Abbreviations

List of Figures

List of Tables

List of Flowcharts

Chapter 1

Introduction

1.1 CDMA2000 1xEV-DV Overview

To meet the fast increasing needs for mobile wireless packet data service, standardized Third Generation (3G) technologies are being deployed in various markets around the world. While the primary objective of the Second Generation (2G) networks was to provide mobile circuit switched voice and low rate data services, a key point that evolved into 3G networks was to have packet data networks connected to the cellular systems while at the same time increasing voice capacity. As one of the 3G technologies, Code Division Multiple Access (CDMA)2000 technology was also developed to meet this requirement. However, with the fast growing demands for increasing system capacity and packet data services, 3G technique was required to undergo an important evolutionary step so as to improve data throughput and enhance voice performance over the same Radio Frequency (RF) carrier. 1x EVolution (EV) - Data Voice (DV) is a natural evolution revision of CDMA2000 technology designed to deliver significantly higher data rates comparing to previous revisions.

The main features of 1xEV-DV are to support voice and data in the same carrier and both real-time and non real-time data services. Additionally, it can provide seamless backward compatibility with IS-95A/B and CDMA2000 1x systems. As 1xEV-DV allows voice and data traffic to share the same spectrum, it enables wireless service providers utilize their spectrum more efficiently and balance the voice and data load in their system based on their specific needs.

1xEV-DV aims to provide mixture of applications such as FTP (File Transfer Protocol), WAP (Wireless Application Protocol), HTTP (Hypertext Transfer Protocol), and near-real-time streaming applications. To efficiently utilize radio resource, 1xEV-DV adopts Time & Code Division Multiplexing (TDM/CDM) scheduling, by which the base station (BS) can allocate various number of Walsh codes to more than one Mobile Station (MS) within one or more timeslots. The system is favoring TDM when the TDM technique works best (e.g., ftp service) and allowing for CDM to efficiently serve other data services (e.g., WAP, VoIP (Voice over Internet Protocol), streaming video, etc). Because data is sent in bursts rather than on a continuous basis, TDM/CDM statistical multiplexing enables the system to maximize throughput gain. Therefore, service providers can apply this feature to balance their market demands.

While 1xEV-DV satisfies the data requirement on the Forward Link (FL), it is important to note that the Reverse Link (RL) is undergoing a complimentary evolutionary step to achieve efficiency and high speed packet data services to meet future anticipated data rates needs, such as file uploads and increasingly popular multimedia applications. The existing distributed rate control algorithm which varies the transmission power and therefore the rate in response to measured interference is well suited for low and medium rate data applications. The increasing higher rates requirements led to a growing interest in a scheduled RL.

Wireless communication requires sharing a finite natural resource: the RF spectrum. The data-rate capacity that a RF channel can support is limited. Therefore, resource allocation and scheduling policies play important roles in providing service performance guarantees. The scheduling policy decides which mobiles should transmit during a given time interval. A centralized scheduling algorithm schedules favorable mobiles to transmit at higher power. However, careful consideration has to be given to the resulting interference, which depends on the transmission power as well as the interference from other scheduled mobiles. It is therefore important to control interference through scheduling on the RL.

The enhancements of 1xEV-DV Revision D occur at the physical layer of the specification and are controlled by the upper layer [11]. There are several issues faced in designing RL air interface to support packet data transmission, such as the design of frame structure, data rate set, Automatic Repeat reQuest (ARQ) mechanism, and radio resource management. The question of interest is how to optimize system performance while maintaining the system load within acceptable limits. In this thesis, we focus on the study of RL scheduling and data rate allocation following newly published specification, 1xEV-DV Revision D.

1.2 CDMA2000 Evolution

With the rapid growth of internet applications and services, packet data services are finding their way into the mobile wireless domain such as CDMA2000. At the same time, the 3G standard needs to be evolved accordingly to respond with this requirement.

The Third Generation Partnership Project Two (3GPP2) is a collaborative 3G telecommunications specifications-setting project and provides globally applicable technical specifications for a 3G mobile system. The specification for the CDMA2000 technology and its enhancement revisions were all standardized by 3GPP2. 3GPP2 was born out of the International Telecommunication Union's (ITU). ITU has approved the CDMA2000 1x, 1xEV-DO (1x EVolution-Data Optimized), and 1xEV-DV radio access systems as members of the ITU-2000 family of standards. We will describe the evolution of CDMA2000 technique following the approval sequence of each version of standards.

CDMA2000 technology initially evolved from IS (Interim Standard)-95A/B. IS-95 networks use one or more 1.25MHz carriers. IS-95B was intended to be an enhancement to deliver high speed data by allocating the fundamental channel and one or more supplemental code channels for high speed data requests. The peak data rates are 76.8kbps.

To meet ITU-2000 technology requirement, the next revolution step for high speed data service is CDMA2000 1x. Within the CDMA2000 family, CDMA2000 1x delivers high capacity voice and 3G data in one 1.25MHz carrier, while CDMA2000 1xEV-DO devotes another 1.25 MHz channel to deliver only data traffic. We describe these two migration paths respectively. The evolution time is following the publication date of specification. The Evolution path of CDMA2000 is shown in Figure 1.1.

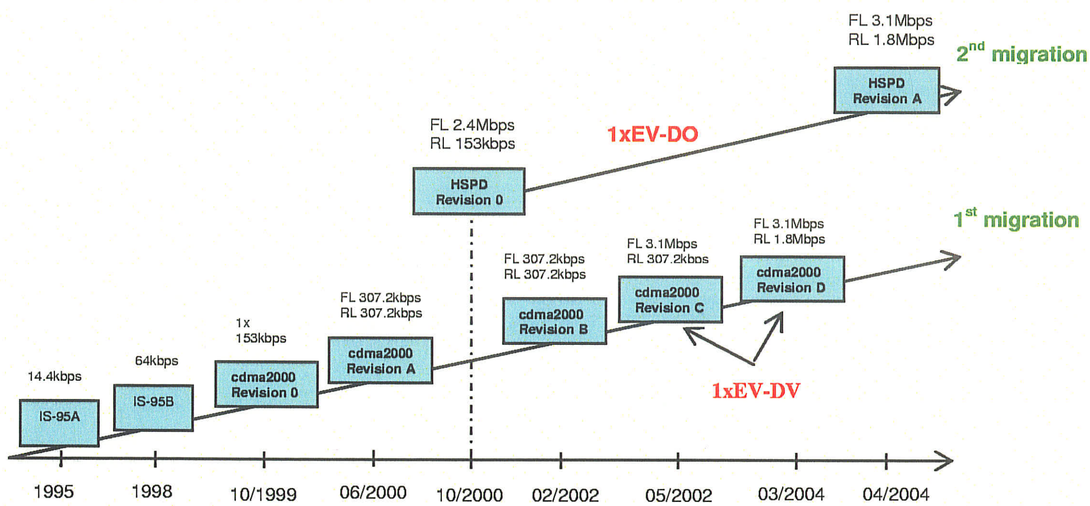


Figure 1.1: CDMA2000 Evolution Path

(a). CDMA2000 1x First Migration Path

In the first migration path of CDMA2000 1x family, so far there are total five Revisions, Revision 0, A, B, C, and D.

Revision 0 published in October 1999 provides a number of physical layer enhancements. It provides double capacity for voice and data services compare to IS-95 CDMA systems, and allows up to 153.6 kbps peak data rate. Since voice and data are allowed to transmit on the same channel, Release 0 limits the data rate. In order to improve spectrum capacity, ITU has Release 0 evolved to Release A, and then Release B. Release A and B can support peak data rate up to 307.2kbps for both FL and RL. Release A published in June 2000 introduced a new set of common channels to support high rate transmission. Especially the introduction of variable rate supplemental channels allows transmitting the data and voice with variable rates of up to 307.2 kbps. In addition, the rate adaptation mode and soft handoff mechanism are further enhanced in Release B published in February 2002.

In order to satisfy the increasing requirements of data services and support high-speed packet data transmission, CDMA2000 was made to further evolve to Release C and D which are also called 1xEV-DV. It stands for supporting voice and data transmission in one 1.25 MHz spectrum. Release C published in May 2002 specifies to achieve higher date rates in the FL which can be supported by introducing a new Forward Packet Data Channel (F-PDCH). F-PDCH is a high data rate channel and can be dynamically allocated power and Walsh code resources.

Revision D is the latest version of CDMA2000 which incorporates FL and RL enhancements to the physical layer design of Release C. It greatly increases data rates on the RL up to 1.8456 Mbps. New dedicated channel, the Reverse Packet Data Channel (R-PDCH) is introduced to support high-speed packet transmissions of up to 1.8456 Mbps on the RL by employing adaptive modulation and encoding with higher order modulation to support high-speed packet data transmission.

(b). CDMA2000 1x Second Migration Path

Another migration path for CDMA2000 1x is EV-DO which optimizes an entire 1.25MHz channel to carry data traffic. Thus, it is more spectrally efficient for data transmission than other wireless standards. There are currently two main versions of 1xEV-DO: "Release 0" and "Release A". Release 0 is the original version, and the first to be widely deployed. Release 0 offers data rates up to 2.4Mbps, averaging 300-600Kbps in the real world. Data rates provided in Release 0 are identical to those of 1xEV-DV Release C. Release A integrates most of the fast data technology from 1xEV-DV Release D, and improves latency which allows the time sensitive features such as a VoIP and video calling more possible. Although EV-DO does not include voice capability natively, Release A is fast enough to support VoIP technology at service levels equal or better to 1x Round Trip Time (RTT) voice technology. This may be a future upgrade path for CDMA carriers if EV-DV development remains stalled.

1.3 Thesis Contribution

In this thesis, we aim at developing a scheduling and rate allocation mechanism on the RL for CDMA2000 1xEV-DV. The previous works on RL scheduling mostly address on how to improve throughput with Quality of Service (QoS) concerns which consider subscribers' benefit mainly. With the intense competition of wireless communication market, the final objective of satisfying subscribers is to maximize revenue for service providers. Hence, having service providers' benefits considered in scheduling policy is a novel approach for RL scheduling. In this thesis, we consider both service providers' and subscriber's point of view, and address revenue maximization with a certain QoS consideration, such as loss minimization. The proposed method is flexible and offers service providers the choices to either maximize obtained revenue or minimize loss, or balance both of them.

As the new published Revision D of 1xEV-DV targets improvement on the RL, our system model design exactly follows the physical layer architecture of 1xEV-DV Revision D. The scheduling and rate allocation scheme is developed for non-time sensitive RL data traffic transmission.

The system model is formulated into a Knapsack problem which can be solved by binary integer Linear Programming (LP). Branch-and-Bound (BNB) as a method of solution is discussed, but observed to be inefficient for this problem and instead two heuristic algorithms are proposed. All the three solutions are analyzed through illustrative experiments. By dynamically adjusting the objective function balancing parameter, various levels of QoS guarantees to all the users are provided. The results of analysis present trade-off between the computational time for scheduling and maximum obtained revenue among three algorithms. The heuristic algorithms consume shorter computational times and are therefore more appropriate for our time limited scheduling and resource allocation scheme. Additionally, using the heuristic algorithms, we are able to recommend service providers on how to schedule the transmission using the objective balancing parameter according to their desires.

1.4 Thesis Organization

The thesis is organized as follows. In Chapter 1, we briefly overview the CDMA2000 technology and the evolution path of CDMA2000 family, and illustrate our contributions to this research. In Chapter 2, the RL features are summarized based on Revision D of 1xEV-DV. It includes RL physical layer features, resource limitation for scheduling, and the rate control schemes. Related works are reviewed in Chapter 3. In the literature, we go though most of the previous works with the contributions for reverse link scheduling and resource allocation on CDMA cellular network. Finally, we illustrate our research objective which stands for different standpoint comparing with the existing approaches. In Chapter 4, we describe the system model, model formulation and the heuristic algorithms in detail. Chapter 5 presents the results of illustrative examples and performance evaluation of proposed schemes, while Chapter 6 concludes the paper and future work.

Chapter 2

1xEV-DV Features

2.1 1xEV-DV New Features

1xEV-DV is an enhancement to CDMA2000's data carrying capability which is designed with greater spectrum usage efficiencies. It achieves higher data throughput while simultaneously providing coexisting voice services within the same spectrum. In this section, we summarize a number of key enhancements [30] of EV-DV over previous releases of CDMA2000.

TDM/CDM Multiplexing: 1xEV-DV enables both TDM and CDM scheduling which enables the system to maximize the throughput.

System Capacity Improvement: 1xEV-DV leverages a number of improvements on the capacity, such as adaptive modulation and coding schemes, the use of both TDM and CDM techniques, and a set of new channels designed to deliver high speed data.

New Channels: In order to deliver high level data rate, a number of new traffic channel and control channels are incorporated into 1xEV-DV specifications. We will describe the details for RL transmission in the next subsection.

Concurrent Voice and Data: 1xEV-DV can support voice and data services in the FL and RL. That is, voice and data users may share the same channel at the same time. Thus, it provides service providers a flexibility to utilize spectrum.

Adaptive Modulation and Coding: This feature is mainly designed for delivering higher data performance which can not be supported using the previous CDMA technology.

Multiple Traffic Types: 1xEV-DV supports multiplexing traffic over high speed packet data channels, which may benefit both the service providers and the subscribers. For subscribers, they can have more than one service at the same time. For service providers, this can be translated into revenue from multiple simultaneous applications without adding extra channels for new services.

2.2 Reverse Link Physical Layer Enhancements

As the latest Revision D of 1xEV-DV targets the improvement of RL transmission, some physical layer improvements are involved in the standard. Some of these features are taken into consideration in our system model structure design. Therefore, we summarize some key points from the Revision D specification as follows.

The goals of RL design in Revision D are to increase the RL peak rate (up to 1.84Mbps) and sector throughput (up to 600kbps), and maintain backward compatibility as well. The major improvement on the physical layer design is to introduce some new channels specific to support high speed data transmission. Three main new RL channels are added in Revision D [1].

1) Reverse Packet Data Channel (R-PDCH): A reverse traffic channel which transmits higher-level data and control information from a mobile to the base station. In R-PDCH, 10msec frame size is given with data rate sets = {19.2, 38.4, 79.2, 156, 309.6, 463.2, 616.8, 924, 1231, 1538.4, 1845.6} kbps.
2) Reverse Packet Data Control Channel (R-PDCCH): A control channel to transmit control information, such as the modulation, coding and Hybrid ARQ (HARQ) for the subpacket which is being transmitted on the R-PDCH and the mobile status indicator bit. The ARQ information allows the base station to appropriately combine subpackets, while the modulation and coding format information specifies how to demodulate and decode the signal transmit on the R-PDCH.
3) Reverse Request Channel (R-REQCH): A channel used by a mobile station to indicate its ability to the base station to transmit above the autonomous data rate on the R-PDCH. Also it updates the base station with the amount of data in the buffer, the QoS requirements, and the available power headroom.

The high speed data channel has provided high efficient radio resource management on the RL. Meanwhile, the FL enhancements are provided to support improved RL high speed transmission.

1) Forward Grant Channel (F-GCH): A control channel used by the base station to grant mobiles to transmit one or more encoder packets.
2) Forward Indicator Control Channel (F-ICCH): A control channel used by the base station to transmit rate control message to the mobiles.

According to CDMA2000 standard Revision D, a frame for R-PDCH, R-PDCCH, R-REQCH, F-GCH is 10ms long. The modulation format of R-PDCH can be Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), or 8-Phase Shift Keying (8-PSK). The modulation depends on the Encoder Packet (EP) size (EP_{size}) which is specified as 192, 408, 792, 1560, 3096, 4632, 6168, 9240, 12312, 15384, or 18456 bits. BPSK modulation is used by a mobile for encoder packet size of 192, 408, and 792 bits. QPSK modulation is used for encoder packet sizes of 1560, 3096, 4632, 6168, 9240, 12312 and 15384 bits. 8-PSK modulation is applied for an encoder packet size of 18456 bits [1]. The other parameters for R-PDCH are explained in Appendix A.

Encoder packets are transmitted as one, two, or three subpackets. Initially, the first subpacket is transmitted. Then, subsequent subpackets are transmitted if the transmitted subpacket is not the last subpacket, and a mobile station does not receive an acknowledgment from the base station. The first subpacket carries most of the information while the following subpackets are transmitted due to the requirement of retransmission. 1xEV-DV allows an encoder packet to be transmitted using from one to three 10-ms subpackets. An R-PDCH frame starts only when system time is an integral multiple of 10 ms.

2.3 Reverse Link Resource Limitation

RL is power (or interference) limited. Since the transmission on the RL can be done in TDM/CDM mode, several mobiles are allowed to transmit simultaneously. Thus, the accumulated power of the received signals represents the level of the interference at the base station. The transmission power from any other mobiles is regarded as interference for one particular mobile. In the RL, the most limiting resource is the ratio of the total received power over the thermal noise power at the base station called Rise-over-Thermal (RoT) [32]. Because thermal noise power is a constant given the bandwidth, temperature, and receiver noise figure, RoT is a direct measure of the total received power at the base station. Due to the limited capacity of a mobile's power amplifier and battery, it is important to control the RoT in order to maintain good system performance and user experience. The RL design is to ensure that the RoT at the base station does not exceed the threshold level as long as there is RL data to be transmitted [9]. Moreover, the transmission power is associated with a certain data rate. Higher data rate requires more transmission power which subsequently causes more interference. The total interference in a sector is composed of the interference caused by the target user, the interference caused by the other users and the thermal noise.

Since multiple users can be served simultaneously, it is crucial to schedule the transmission and control the power and rate of each user so as to maximize the resource utilization while keeping the interference under the maximum threshold. Two aspects are considered regarding the radio resource management of high-speed RL: rate control and scheduling [32]. Rate control works much like power control in today's CDMA system. A rate control command sent from the base station instructs a mobile to either increase or decrease its data rate. On the other hand, scheduling implies that the scheduler assigns the timeslot, duration, and data rates a mobile takes during its transmission.

2.4 Reverse Link Operation

The base station is the major power controller of mobiles. It measures the Reverse Pilot Channel (R-PICH) of each mobile and controls the received Signal-to-Interference-plus-Noise Ratio (SINR) of the R-PICH to a target level by sending power control bits to the mobiles. In Revision D, a mobile may send indications of its power limit and buffer status on the R-REQCH. Based on the data and control information received from the mobiles at the base station, the base station determines the loading on the RL. Then the base station grants the mobiles data rates via forward control channel. Once a mobile receives a grant, it transmits data on the R-PDCH and transmission format information on the R-PDCCH. A simplified RL operational indication of the 1xEV-DV system presented in [32] is shown in Figure 2.1. In this thesis, we assume that the base station behaves the same as the Base Transceiver Station (BTS) shown in Figure 2.1.

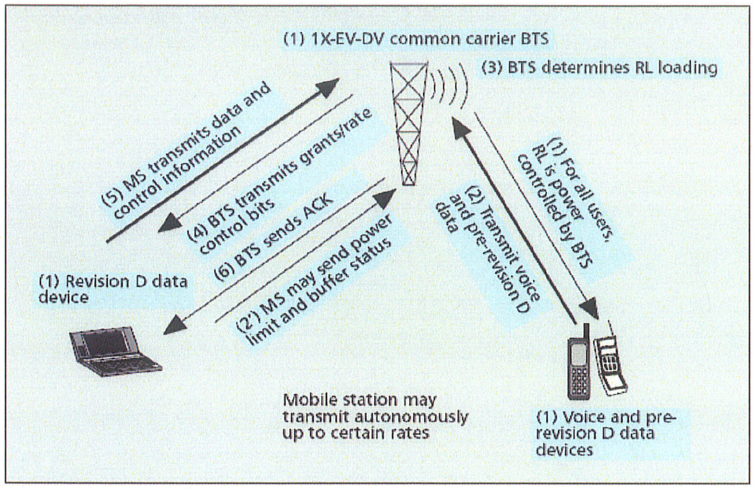


Figure 2.1: Conceptual Description of 1xEV-DV Reverse Link Operation

2.5 Reverse Link Rate Control Schemes

The allowable R-PDCH transmission rates in Revision D can be denoted by a finite rate set R = {9.2, 19.2, 40.8,......., 1845.6} kbps. Consider a cell that has *N* mobiles connected to it. Unlike the previous revision of CDMA2000, the pilot power level is not a function of the rate on the R-PDCH. Instead, RL transmission rate is associated with a nominal Transmission power to Pilot power Ratio (TPR). Therefore, Revision D is shown to provide optimal performance with low complexity [31]. TPR expresses the total power transmitted relative to the pilot transmit power, a quantity referred to as RPDCH_TPR_Table in the standard. Each mobile maintains an authorized TPR table, and updates its transmission power based on the rate control command (up/hold/down) from the base station. Table 2.1 shows the default R-PDCH Nominal Attribute Gain (TPR) [1]. The nominal TPR implies the ratio of transmission power and pilot power of R-PDCH to transmit with a certain packet size.

Table 2.1: Default R-PDCH Nominal Attribute Gain (TPR)

Rate Index	R-PDCH Rate (kbps)	Nominal TPR (1/8 dB)
1	19.2	6
2	40.8	30
3	79.2	54
4	156.0	77
5	309.6	95
6	463.2	109
7	616.8	119
8	924.0	133
9	1231.2	144
10	1538.4	153
11	1845.6	170

The calculation of R-PDCH output transmission power is described in Appendix B.

The RL Medium Access Control (MAC) in Revision D is flexible which is designed to support various rate assignment mechanisms for different environments. The rate grant mechanisms can be categorized as Autonomous Assignment, Differential Rate Assignment, and Absolute Rate Assignment shown in Figure 2.2. In Autonomous operation, the mobiles can transmit up to a pre-configured rate without authorization from the base station. In Differential Rate Assignment, the Forward Rate Control Channel (F-RCCH) carries a rate control command from the base station to the mobile stations. In Absolute Rate Assignment, a shared channel F-GCH grants an absolute rate assignment from the base station to the mobile stations.

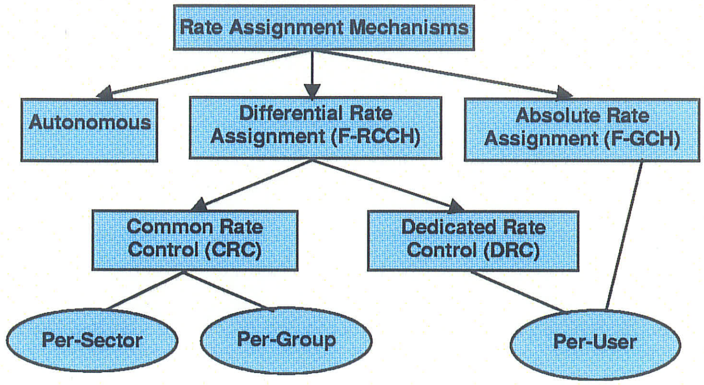


Figure 2.2: Summary of Rate Assignment Mechanism

A mobile operates in the Dedicated Rate Control (DRC) mode when a single R-PDCH is controlled by a rate control subchannel, while it works in Common Rate Control (CRC) mode when multiple R-PDCHs are controlled by one rate control subchannel [1]. A mobile's transmission rate is controlled by the rate control commands sent from the base station every timeslot.

- CRC Mode

  The mobiles in a sector or a group of mobiles are controlled by a common, one-symbol command which represents up/down/hold. This can be represented as in Figure 2.3.

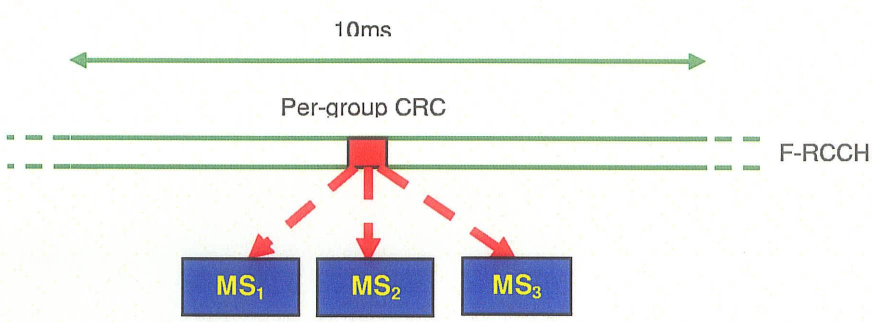


Figure 2.3: CRC Per-Group Control

- DRC Mode

Individual mobile is controlled by a dedicated one-symbol command which represents up/down/hold, which is described in Figure 2.4.

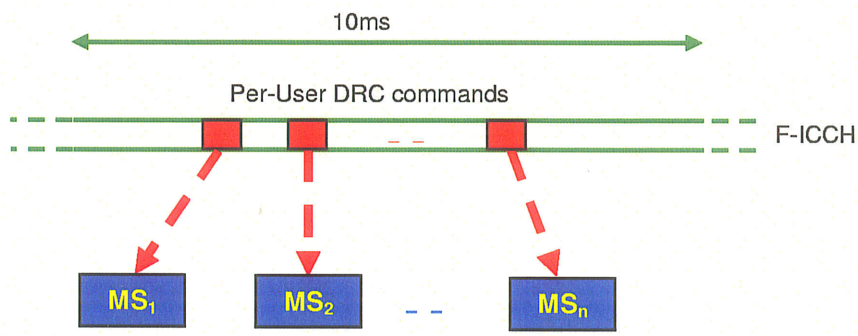


Figure 2.4: DRC Per-User Control

In this thesis, we choose DRC rate control mode as the previous studies show that DRC mode can deliver the highest packet data throughput compared to CRC mode. In DRC mode, at each packet transmission, a mobile can go up at most one rate level but may go down multiple levels. The rate transaction mode is shown in Figure 2.5.

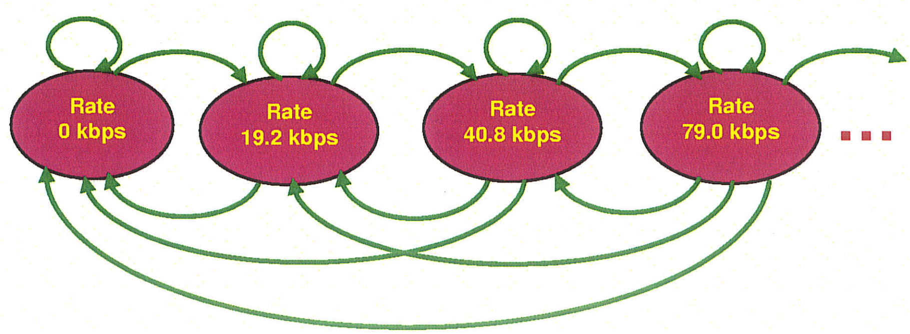


Figure 2.5: DRC Operation Mode

At each scheduling period, the mobiles are assigned to monitor DRC channel while the base station sends a dedicated tri-state-symbol (up/down/hold) to the mobiles. A mobile determines its maximum allowable rate following received command. In Revision D, the maximum allowable rate that DRC algorithm can support is 1845.6 kbps. Each mobile allows transmitting with a certain data rate which can be done by accordingly changing (increase/decrease) the transmission power shown in Table 2.2. The UP and DOWN stepsizes of transmission power signify the rate level allowed to transmit in the next timeslot.

Table 2.2: DRC TPR UP/DOWN Stepsizes Based on Default Nominal TPR Values

R-PDCH Rate (kbps)	**Nominal TPR(1/8dB)**	**UP Stepsizes (1/8dB)**	**DOWN Stepsizes (1/8 dB)**
0	-100	106	0
19.2	6	24	106
40.8	30	24	24
79.2	54	23	24
156.0	77	18	23
309.6	95	14	18
463.2	109	10	14
616.8	119	14	10
924.0	133	11	14
1231.2	144	9	11
1538.4	153	17	9
1845.6	170	0	17

Chapter 3

Literature Review

In the cellular wireless systems, resource allocation schemes and scheduling policies play important roles in providing service performance guarantees, such as throughput, capacity, delay, outage probability, interference and fairness. The base station is the major controller of the transmission process. The decision made by the base station on the RL is highly dependent on the initial request, such as data rate and QoS associated information from the mobiles. Whenever the base station performs scheduling and resource allocation, it has to consider the request and status of each mobile and the resources available at the base station. On the RL, due to near-far problem, the received power at the base station from all mobiles should all be uniform and their sum should be below a certain threshold value. There are several factors that have to be taken into consideration while making scheduling and allocation decision.

Various previous contributions, either performance evaluation for existing systems or a new approach proposition for improving system level performance has been studied for CDMA2000 cellular systems. In this chapter, we will go through previous works of RL scheduling and resource allocation for CDMA2000 wireless networks. As different Revisions of the CDMA2000 standard support various system performances, we classify the literature following the CDMA2000 technique evolution step. In each subcategory, we classify the contributions by the research objective and performance metrics.

3.1 Contributions for 1xEV-DV Revision D

As the new published Revision D of CDMA2000 targets improvements on the RL, some according works [2], [3], [4], [5], [31] and [32] which are dedicated to Revision D have been presented recently. These works emphasize on concluding the RL physical layer enhancements of Revision D and analyzing the system performance.

Derryberry, et al. [5] present a summary overview of the main enhancements over Revision D. The enhancements concluded include: summarizing the features of the new RL channels and the additional FL improvements to support RL, and illustrating the features of Broadcast and Multicast Services, Fast Call Setup, and Mobile Equipment Identifier. However, their work is based on general overview instead of giving further performance analysis.

The works in [2] and [4] present system level performance analysis according to the new RL enhancements. Wu, et al. [4] investigate the RL QoS performance of CRC and DRC rate control modes. They specify throughput and delay versus various user classes as the performance measures and study the behavior of CRC and DRC algorithms with supporting different QoS requirements through simulation. Derryberry and Pi [2] study RL scheduling and radio resource allocation over data traffic scenario. A proportional fair scheduler is used considering rate request, the allocated data rate, cell geometry, active set size, and fairness factor of each mobile. The resource allocation is done in greedy fashion by which the mobiles with the higher priority are assigned the requested rates as long as the load is below a certain threshold. The system performance is evaluated and compared with that of the predecessors in terms of throughput and delay. However, they consider subscribers' benefits only.

Three basic radio resource management mechanisms which are Rate-Control (RC) scheme, Time-Scheduled (TS) scheme and Rate Control with Quick Start (RCQS) scheme (a hybrid of RC and TS) are introduced by Kwon, et al. [3]. They evaluate and compare the performance in terms of average system throughput, packet delay and overheads over three radio resource management techniques.

Revision D RL enhancements are summarized by Chen, et al. [31]. The summary includes the major design goals, the design of a set of new channels, control mechanisms and the system operations.

Derryberry and Pi [32] present an overview of high-speed RL enhancements in Revision D together with a simple operational overview. The summarization is taken account of RL design philosophies, RL enhancements, FL enhancements to support RL high-speed packet data transmission, and RL operation.

3.2 Contributions for 1xEV-DV Revision C

In the last three years, some studies reported in [6], [7], [8], [9], and [11] are based on 1xEV-DV Revision C system. The study of RL resource allocation of improving system throughput is the common objective of the works in [6], [7], [8], and [9]. According to these works, only subscribers' advantages are considered in the proposed schemes. We classify the resource allocation studied in these works into power allocation and rate allocation.

3.2.1 Throughput Improvement---Power Allocation

Zhang, et al. [7] propose an optimal power allocation scheme considering the advantages and disadvantages of the greedy and the fair scheduling policy so as to maximize system utility subject to the constraint of peak transmit power, total received power from all the data users and minimum SINR for each user. But the study is only limited in one cell, and channel variation and mobile's buffer status are not considered either.

3.2.2 Throughput Improvement---Rate Allocation

In [6], [8] and [9], the new scheduling and rate allocation schemes are proposed. Chung, et al. [6] propose a scheme which enables dedicate rate control and group rate control considering the location of mobiles. The simulation is built for a single cell environment. It is shown that this scheme can provide high average data rate, large total amount of transmitted data and shorter delay.

Pi and Derryberry [8] build RL scheduling and rate allocation architecture. The proposed working procedure is described as follows. At each scheduling period, the priority of each mobile is calculated at the base station. The mobiles are sorted to transmit by their priorities. The priority function is defined based on rate request, the allocated data rate and the received power received from mobiles. By introducing a proper choice of the fairness factor, the scheduler can take advantage of multi-user diversity while providing certain fairness among mobiles. The procedure of resource allocation follows a greedy fashion. The mobiles with the higher priority are granted the requested rates as long as the RoT does not exceed the constraints. In addition, the scheduling algorithm always satisfies the mobiles with higher priority as much as possible and the selection stops when the RoT budget is used up. Therefore, this scheme minimizes the number of mobiles transmitting simultaneously and keeps the interference in a low level.

Chung and Cho [9] propose a transmission procedure. They describe the new operation between the mobiles and the base station, and the concept of rate control, Mobile Status Indication (MSI), and Rate Variation Indication (RVI). Scheduler controls rate of each mobile considering their location, speed and amount of data to transmit. The maximum rate is limited according to mobile's position. Thus, the RL capacity can be fully utilized using dynamic data rate control and allocation. The scheduling procedure is designed and summarized as follows. The base station receives MSI and RVI of all the mobiles. Then it allocates the lowest rate (9.6Kbps) to all new calls. If there remain allowable resources, the base station allocates resources to all calls according to their priority and RVI value. The basic priority level depends on mobile's location and speed. Afterward, the base station allocates resources and sends RC value to each request. According to the received value of RC, each call changes its data rate. The performance is evaluated in the view of average throughput, average goodput, portion of overshoot and average delay. Two types of traffic models such as Email and WAP traffic are considered. The new approach may improve average throughput and goodput. However, they do not take into account fairness among users and revenue generated for service providers.

3.2.3 System Level Performance Analysis

Additionally, Derryberry, et al. [11] describe the RL enhancements and present the analysis of system level performance such as throughput and outage under mixed voice and data traffic scenarios. The proportional fair scheduler is used considering potential achievable data rate obtained from Reverse Channel Quality Indicator Channel (R-CQICH) feedback, fairness factor, and traffic types.

3.3 Contributions for 1xEV-DO

As the TIA/EIA IS-856 standard is also known as CDMA2000 1xEV-DO, we classify approach presented in [12] into 1xEV-DO standard orientated. Yeo and Cho [12] evaluate the performance of IS-856 RL rate control by modeling it as a Markov process. The throughput and the outage probability are derived as two performance metrics.

Price and Javidi [26] construct a distributed rate assignment algorithm which address both MAC and transport layer issues. The problem is formulated as an optimization of rate assignment subject to both the interference and congestion constraints. In the formulation, a proportional fair rate assignment which represents a trade-off between total throughput and fairness is considered.

3.4 Contributions for General CDMA2000 System

The approaches reported in [13], [14], and [15] address to improve RL capacity for general CDMA2000 systems.

Sandip [13] focus on the study of capacity for voice user based on various channel conditions. The capacity is defined as the average number of users at any time in the system, and expressed as the total received power at the base station antenna for M users over a bandwidth W, and noise spectral density, summing over all the cells. The analysis results prove that CDMA2000 system presents significant capacity improvement over IS-95B system, as it is able to support more users.

Damnjanovic, et al [14] evaluate the performance of a scheduled CDMA2000 1x system RL in terms of throughput, interference and fairness through simulation.

A new RL bandwidth allocation scheme with the goal of reducing interference and increase capacity for real-time applications is studied by Heyaime-Duverge and Prabhuin [15]. Capacity in this article is described as the number of users supported while complying with the QoS requirements of the applications being served. The QoS attributes are the packet delay and probability of outage. This approach may nearly double the system capacity, but it may not be applied on 1xEV-DV system because it does not exactly follow the physical layer design of 1xEV-DV.

3.5 Contribution for CDMA Cellular System

The approaches presented in [30], [16], [27], [18]-[25] are based on the study of general CDMA cellular networks. The works of [30] and [21] address to the study of RL traffic. The contributions of [16], [27], [20] and [22] are based on the study of resource allocation with the objective of improving link throughput. The study of capacity are presented in [18], [23], and [25], while the utility study is illustrated in [19] and [24].

3.5.1 Reverse Link Traffic Analysis

Ashtiani, et al. [30] build up a traffic model for RL taking into account the interference-limitedness and soft-handoff. The model is suitable for the traffic analysis and handoff management algorithms in dynamic environment due to its flexibility.

Ishikawa and Umeda [21] propose a new traffic model expressing RL capacity with QoS guarantee, such as loss probability for communication quality and blocking rate. Two methods for call admission control are discussed. For the first method, the resources of a network are equivalent to the number of channels. In the second method which considers interference-based call admission control, the resources in the network are proportional to the level of interference. Hence, the second method appears to be more suitable for the interference-limitedness attribute of CDMA capacity.

3.5.2 Throughput Improvement

From subscribers' point of view, Krishnan and Qian [16] propose a scheduling algorithm for RL packet-data traffic in a single CDMA cell with the objective of improving throughput and providing fairness among users. The algorithm can be extended to apply in 1xEV-DO systems. However, some extra enhancements are needed if it is employed to 1xEV-DV systems.

Hossein [27] develops an optimal power allocation scheme for data users with the objective of maximizing the RL throughput. Theoretical analysis shows that more than one user transmitting at a time may be optimal with the current data traffic. Thus, Hossein derives thresholds that determine when it is optimal to serve only a signal user and optimal to simultaneously serve multiple users. Based on this derivation, a power allocation mechanism is proposed considering a certain degree of fairness.

An optimal power control strategy is derived by Sung and Wong [20], with the objective of maximizing the total effective rate. The problem is formulated as a constrained optimization problem. The proposed algorithm is suitable for two classes of problem, such as delay-tolerable and delay-sensitive. However, the model is only studied in a single cell and the intercell interference is ignored.

Ulukus and Greenstein [22] address to maximize throughput for CDMA RL. They formulate the problem as an optimization problem in terms of transmission bit rate and transmission power, and solve it using a nonlinear programming approach. But it mostly benefits users in favorable locations while ignoring the performance seen by the disadvantaged users.

3.5.3 Capacity Analysis

A power control scheme for maximizing the information capacity of the RL in single-cell multiuser communications is studied by Knopp and Humblet [18]. The main characteristics are to transmit only one user over the entire bandwidth at any timeslot. The power allocation depends on the channel conditions.

Jantti and Kim [23] propose a scheduling scheme in which users transmit data through a hybrid of CDMA and TDMA with the objective of increasing radio network capacity for non-real-time data service. The major concepts are described as follows. If the packet sizes are large and the interference plus noise power is small, then the minimum time solution can be obtained by using the TDMA transmission. If the interference plus noise power is high or the packets are very small, then the CDMA type of transmission policy is optimal. Otherwise, it is optimal to use a mixed strategy in which the transmission of the users having very small packets or being in unfavorable positions share the channel simultaneously, while the users having large packets and being in favorable positions transmit in the one-by-one fashion.

As CDMA cellular networks are well known for time-varying interference-dependent capacity, Narrainen and Takawira [25] propose an analysis for CDMA capacity that takes into account the time-varying nature. The system performance is computed in terms of the carried traffic, the queue length and the probability of blocking new and handoff calls. The admission scheme gives higher priority to handoff calls than new calls.

3.5.4 Utility Improvement

Some works have applied the microeconomic principle to the CDMA radio resource allocation, where the pricing mechanism is adopted in [19]. The pricing mechanism is a very appealing feature in the decentralized architecture. Goodman and Mandayam [19] aim at improving utilities. They propose an algorithm in which a price function is proportional to transmitter power. Pricing function represents explicitly the fact that the signal transmitted by each mobile interferes with the signals transmitted by other mobiles and can be measured as the utility function. The mobiles adjust their powers to maximize the difference between utility and price. By doing so, higher utilities are achieved than that of individual utility maximization.

A flexible traffic model for multicellular CDMA networks with multiple user classes and variable bit rates is developed by Evans and Everitt [24]. The development is based on the use of effective bandwidth concepts. Jamie and David investigate the effectiveness of bandwidth concepts utilized in the modeling of CDMA cellular mobile networks. These concepts are allowed to associate an effective bandwidth to each mobile dependent on its class and location. However, comparing with the other related works, the mobility and handoff problem are not taken into account.

3.6 Summary

From the above overview of prior works which are based on the RL transmission study of CDMA2000 cellular networks, we conclude that most of works have been targeted to increase throughput, capacity, utility and fairness, and decrease delay, outage probability and interference. They are normally concerned subscribers' benefit. In addition, only few contributions address the system level performance study following the latest Revision D of 1xEV-DV. During the fierce competition of wireless communication market, the final objective of satisfying subscribers is to maximize revenue for service provider. Therefore, it is important to have service provider's benefits considered in scheduling policy. In this thesis, we consider both service provider and subscriber's standpoint, and target on revenue maximization with certain QoS consideration based on the physical layer design of 1xEV-DV Revision D.

A novel proposed scheme is described in the next chapter. The key points that make our scheme significantly different from the existing studies in this area are the definition of the objective function and the model formulation. This alternative approach will benefit both the service providers and subscribers. The scheduling policy aims at maximizing obtained revenue for service provider and minimizing loss for subscribers. Furthermore, service providers are allowed to schedule the transmission based on their desires by dynamically adjusting objective balancing parameter. The scheduling order and rate grant mechanism highly depend on the request message from each mobile.

Chapter 4

Proposed Algorithms

4.1 System Model Description

RL operation design depends on the physical layer structure. Based on the enhancements of physical layer architecture in Revision D, we describe our system model operation as follows. In each timeslot, each mobile sends transmission rate request information which is based on authorized transmission power, together with the information of the amount of data to transmit and the buffer size to the base station through R-REQCH. The base station receives the requests from all the mobiles. The accumulated RoT value at the base station is computed. Our scheduler determines scheduling and rate allocation for each mobile using the proposed algorithms. The rate grant message is sent back to each mobile through F-ICCH. The authorized mobiles then transmit high speed data with allocated data rate through R-PDCH. The modulation, coding, HARQ information are conveyed through R-PDCCH at the same time used to help receiver decode the data delivered on R-PDCH. The transmission procedure can be briefly described in three steps shown in Figure 4.1.

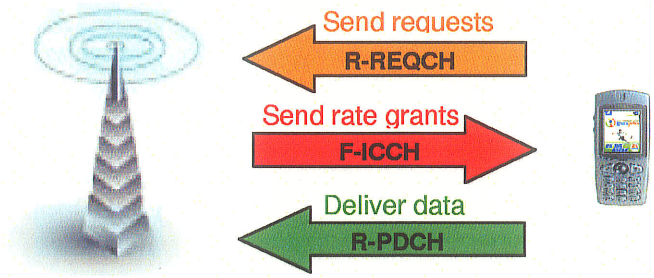


Figure 4.1: Reverse Link Transmission Procedure

1xEV-DV uses HARQ to retransmit packets at the physical layer using MAC signaling [34]. In HARQ, each data packet is subdivided into subpackets. Each subspacket is sent independently over one or more timeslots. The transmitter continues sending subpackets until it receives an acknowledgement from the receiver confirming that the packet is correctly decoded, or the maximum number of allowed transmissions has been reached. In Revision D, each packet could be transmitted through one, two or three subpackets. In this thesis, the proposed operation works based on 10ms timeslot. We describe the timing of subpacket transmission as in Figure 4.2. Note that the request frame from the mobiles to the base station and rate grant frame from the base station to the mobiles are all one timeslot long. Scheduling process takes a period of time which is ideally less than one timeslot.

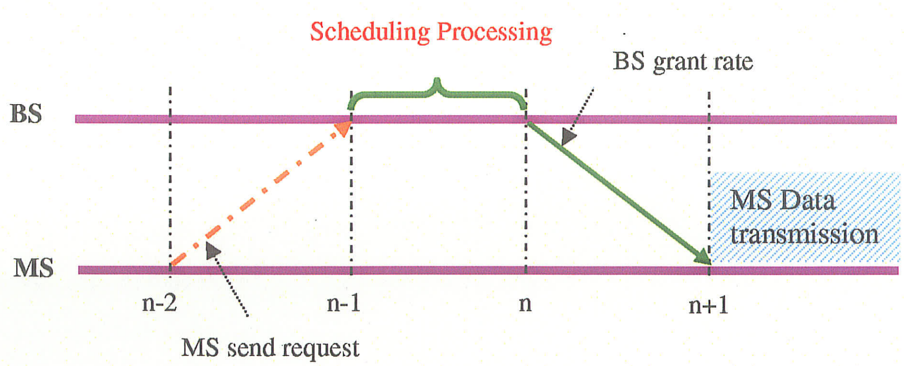


Figure 4.2: Subpackets Transmission Timing Diagram

The base station plays an important role of concentrated rate control and resource management. Hence, the scheduling scheme is implemented every timeslot at the base station.

4.2 System Model Formulation

In this thesis, the scheduling interest is to select which users are scheduled for transmission with granted rate level at each timeslot in order to maximize revenue and as well as minimize loss subject to the RoT limitation. We formulate this into a knapsack problem with multiple constraints. There are some existing solutions for the knapsack problem. The most adaptable solution to the model is a LP-based BNB algorithm for solving binary integer LP problems. We formulate the model as:

$$Max \sum_{i=1}^{N} \sum_{j=R_{min}^{i}}^{R_{max}^{i}} \left(r_{i,j}(t) + k_i(t) \frac{\alpha_i(t)}{\beta_i(t)} \right) x_{i,j}(t), \tag{4.1}$$

Subject to:

(1). $$\sum_{i=1}^{N} \sum_{j=R_{min}^{i}}^{R_{max}^{i}} w_{i,j}(t) * x_{i,j}(t) \leq RoT\ Limitation, \tag{4.2}$$

(2). $$\sum_{j} x_{i,j}(t) \leq 1 \quad \forall i, \tag{4.3}$$

At any timeslot [t, t+1], $r_{i,j}(t)$ is the obtained revenue from mobile i transmitting at data rate j; $k_i(t)$ is the objective function balancing parameter for mobile i, which can be defined by service providers based on their concerns (revenue or loss); $\alpha_i(t)$ denotes the amount of data of mobile i to be transmitted; $\beta_i(t)$ denotes the buffer size of mobile i; $w_{i,j}(t)$ is the weight (contribution to the RoT) of mobile i transmitting at data rate j; N is the total number of the mobiles in a cell; $R^{i}_{\min}$ is the minimum available data rate to transmit for mobile i; $R^{i}_{\max}$ is the maximum available data rate to transmit for mobile i; $x_{i,j}(t)$ is a decision variable, which can be represented as a binary number 0 or 1, $x_{i,j}(t)=1$ if mobile i transmitting at rate j is selected, otherwise $x_{i,j}(t)=0$.

In the objective function (Equation 4.1), $k_i(t)$ is determined based on QoS requirements. Maximizing $k_i(t)(\alpha_i(t)/\beta_i(t))$ implies minimizing loss. $k_i(t)$ is given based on service provider's expectation. Additionally, parameter $k_i(t)$ can be dynamically adjusted according to individual user's situation. For example, it can be increased when the buffer is almost full, that is $\alpha_i(t)/\beta_i(t)$ close to 1; conversely, it can be decreased when buffer is nearly empty, that is $\alpha_i(t)/\beta_i(t)$ close to 0. The greater the value of $k_i(t)$, the more the QoS concerned and the less the lost opportunities obtained. Hence larger $k_i(t)$ can improve QoS, but may loss certain revenue. Note that $k_i(t) \geq 0$.

Definition 1: The RoT is defined as

$$Z(t) = 10 * \log_{10}\left(1 + \sum_{i=1}^{N} \frac{w_{i,j}(t)}{N_0 W}\right), \tag{4.4}$$

and indicates the ratio of the total power received from all the mobiles at the base station and the thermal noise[28]. Furthermore, each mobile i is allowed to transmit with one rate level j at any timeslot [t, t+1], In the Equation 4.4, $w_{i,j}(t)$ denotes the transmission power received at the base station from mobile i with transmitting rate j at the timeslot [t, t+1]. W is the chip bandwidth, N_0 is the thermal noise density. N_0W represents the background noise power (including the intracell interference) in Watts.

Definition 2: Weight $w_{i,j}(t)$ is defined as the power contribution of mobile i with transmitting rate j to RoT value at any timeslot [t, t+1]. We assume the base station has perfect power control, that is, the pilot power $P_i^{pilot}(t)$ from each mobile i received at the base station is exactly $P^r(t)$. Thus, $w_{i,j}(t)$ can be expressed as:

$$w_{i,j}(t) = P_{i,j}^{total}(t)$$

$$= TPR_{i,j}(t) * P^r(t), \quad (4.5)$$

Where the value of $TPR_{i,j}(t)$ denotes the TPR value referring to Table 2.1 of mobile i with transmit rate j.

4.3 Proposed Solutions

4.3.1 BNB Solution Discussion

BNB method is one of the existing algorithms to solve binary integer LP problem. In BNB, the algorithm will potentially search 2^n binary integer vectors where n is the number of variables. Therefore, intuitively more variables will cause longer processing time. BNB algorithm provides two kinds of node search strategies and two kinds of branch search strategies which are described below.

Node Search Strategy:

- Depth First Search Strategy (DFSS): at each node in the search tree, if there is child node one level down in the tree that has not been explored, the algorithm will choose such child to search. Otherwise, the algorithm moves to the node one level up in the tree and chooses a child node one level down from that node.
- Best Node Search Strategy (BNSS): the algorithm chooses the node with optimal bound on the objective function

Branch Search Strategy:

- Minimum Integer Strategy (MINIS): algorithm chooses the variable with the minimum integer infeasibility. That is, the variable whose value is closest to 0 or 1 but not equal to 0 or 1.
- Maximum Integer Strategy (MAXIS): algorithm chooses the variable with the maximum integer infeasibility, that is, the variable whose value is closest to 0.5

In the experiments, we will compare the results among various search strategies. The optimal strategy which achieves best optimal objective function value will be selected as one of the solutions for the system model and is going to be used to compare with the heuristic solutions.

For BNB, we let B_i be a binary integer feasible solution of objective function at an intermediate rate of mobile i, and C_i be the first node objective relaxation value at an intermediate rate of mobile i. Then the difference between B_i and C_i can be calculated if we let BNB algorithm stop at the first node. The difference B_i and C_i is defined as objective function value gap G_i using following equation.

$$G_i = \left(\frac{C_i - B_i}{C_i} \right) * 100\% , \tag{4.6}$$

Due to the node searching strategy, BNB algorithm presents longer computational time when more users send requests. Thus, it is not efficient for the model and obviously may not meet the requirement of scheduling time. To cope with this problem, two heuristic algorithms are proposed. Meanwhile, C_i and G_i of BNB algorithm are used to compare the performance with two heuristic algorithms.

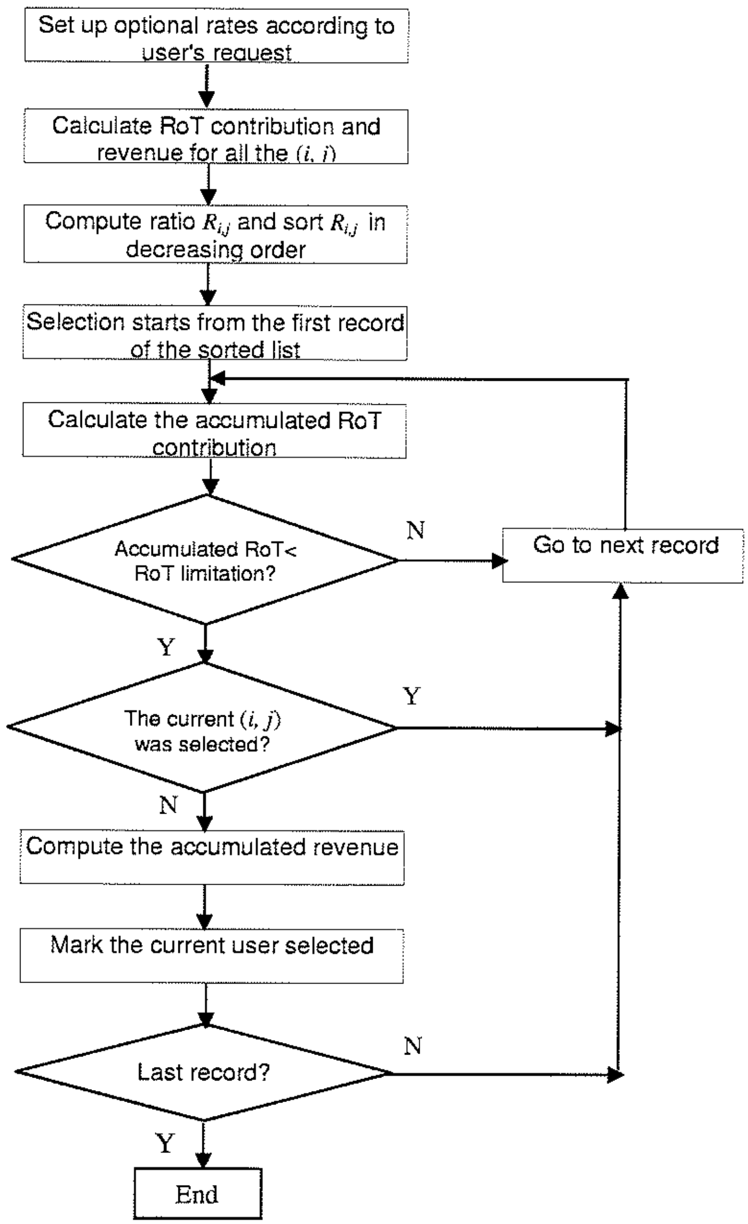
4.3.2. Heuristic Algorithm I (HAI) Description

The user with high unit price plan, low weight, and large amount of data in the buffer will have higher chance to be scheduled at any scheduling period. For each combination (i, j) which implies user i with transmission rate j, HAI calculates the value of $r_{i,j}(t)$, $w_{i,j}(t),(\alpha_i(t)/\beta_i(t))$ and ratio $R_{i,j}(t)$. The ratio function is defined as:

$$R_{i,j}(t) = \frac{r_{i,j}(t) + k_i(t)\dfrac{\alpha_i(t)}{\beta_i(t)}}{w_{i,j}(t)} , \tag{4.7}$$

Consider that the RL system works in DRC mode. In DRC mode, the base station can allocate the rate that is at most one level higher or at most two levels lower than the initial rate requested by a mobile. Hence, for each mobile, it has 4 rate options. If N is the total number of users in a cell, the possible number of combinations (i, j) available to be chosen by the base station is 4*N. HAI starts by listing all of the possible combinations of (i, j). It then sorts the list in decreasing order based on the ratio value ($R_{i,j}$). Afterward, HAI starts to choose the (i, j) from the top of the sorted list to the end and only keeps the (i, j) combinations that satisfy the two constraints given in Equation 4.2 and Equation 4.3, that is, the users are selected one at a time and the accumulated RoT value is calculated until no user can be added without exceeding the RoT budget. The algorithm is summarized in the following flowchart:

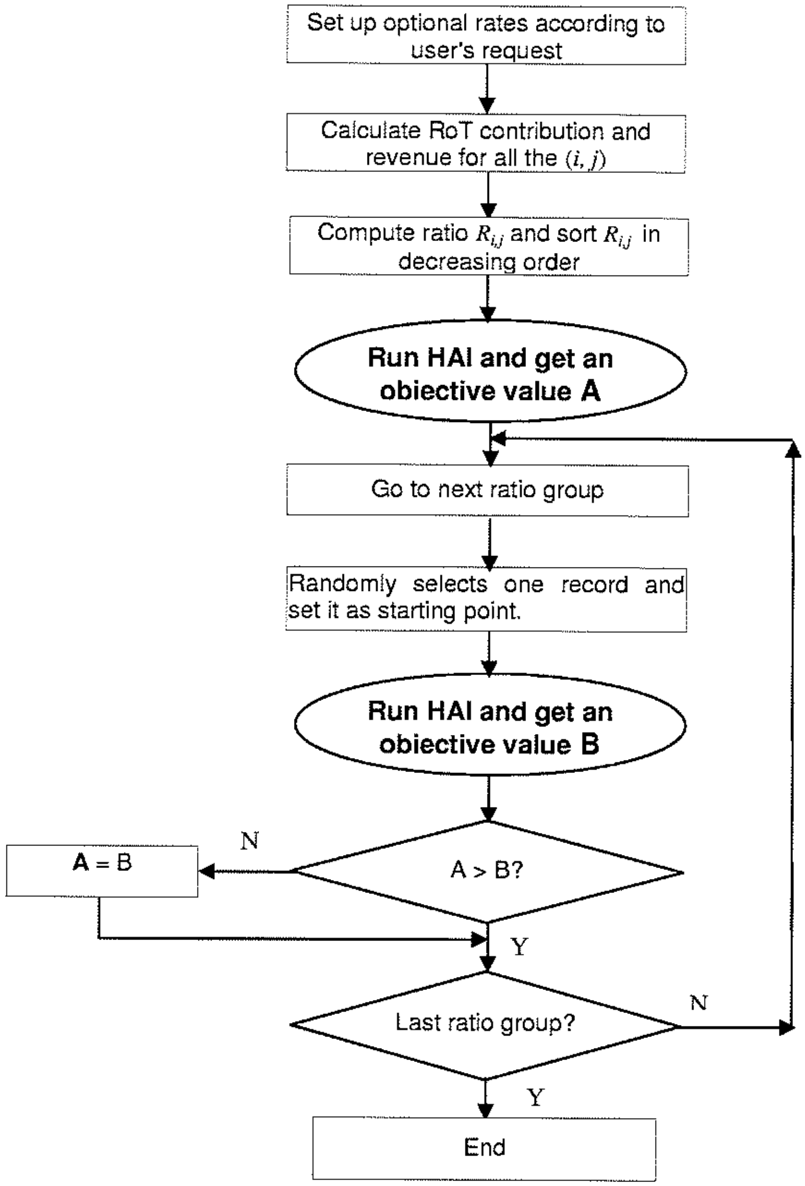
Flowchart 4.1: HAI Working Procedure



4.3.3 Heuristic Algorithm II (HAII) Description

HAII is an improved version of HAI. After running several experiments using HAI, we notice that the objective values generated by HAI are lower than those of B&B sometimes. It is due to the fact that the selection process in HAI is purely based on the ratio values. However, the ratio value is not always proportional to the objective values generated for (i, j). Note that the (i, j) combinations in the sorted list can be further classified based on their ratio values. For instance, there are X ratio groups in the list. In HAI, the algorithm always starts the selection process from the first ratio group (i.e., the group with the highest ratio value). HAII uses the same concept as HAI. However, it performs more thorough search over the combinations by using starting points from different ratio group to run HAI. Thus, HAI is run X times and in the end, HAII generates X groups of (i, j) combinations that have different objective values. The group of (i, j) combinations with the best objective value is chosen as the solution of HAII. The working procedure of HAII is shown in Flowchart 4.2:

Flowchart 4.2: HAII Working Procedure



Chapter 5

Illustrative Experiments and Discussions

5.1 Performance Metrics

In this thesis, the performance of three algorithms is evaluated in terms of average objective value gap, average RoT consumption and average processing time for scheduling. These three measurements are defined as the average value over all the experiments. The average objective value gap G_i is defined in Equation 4.6. The smaller the gap generated, the better the objective function value achieved. RoT consumption is represented by the sum of all the scheduled mobiles' RoT contributions at the base station in each timeslot. Due to the RoT resource limitation at the base station, this value should be below a certain threshold. Since we consider more than 5 users request high-speed data transmission simultaneously in the experiments, RoT resource is fully utilized most of time. Processing time implies the algorithm computational time, that is, the scheduling time. Ideally, the scheduling period should be less than one timeslot.

The balancing parameter k_i is introduced in objective function. Scheduling and objective value obtained may change given different values of k_i. The scheduling result affected by k_i is analyzed in terms of schedule opportunity which is defined as the number of times that mobile i is allowed to transmit over the total number of experiments.

5.2 Experiment Description

In this section, we describe the experiments environment and associated assumptions. We assume that all the scheduling events that we carry out in the system occurs every timeslot, and all the transmissions are successful and no retransmissions are required. To make it simple, we assume all the subpacket transmissions are successful. Thus we only consider the transmission of the first subpacket as it carries most of the information if no retransmissions are required. All the mobiles are located in one cell. According to a certain transmission rate, there are three unit price sets to be chosen: the basic class for normal users, the silver class which is 1.5 times of basic class and the gold class which is 2 times of basic class as shown in Table 5.1. In each price set, price $\lambda_j (j = 1, 2, 3,\ldots 11)$ is proportionally associated with one rate level listed in Table 2.1. In the case of service being provided with the same rate, the user who pays high unit price has high priority to be scheduled.

Table 5.1: Unit Price Value Mapping

User Class	Unit Price Plan
Normal	$\lambda=\{\lambda_1, \lambda_2,\ldots\ldots\lambda_{11}\}$
Silver	1.5λ
Gold	2λ

In the experiments, we assume the system works in DRC rate control mode. In DRC mode, the mobiles are allowed to go up at most one rate level but may go down two rate levels. Thus, there are four optional data rate selections available for each mobile.

The assumptions used in the experiments are listed below.

1) The mobiles always have enough power and enough data to transmit at their highest transmission rates.
2) The pilot power from each mobile received at the base station is exactly Pr=-80dBm.
3) The threshold of RoT=7dB, chip bandwidth W=1.23MHz, N_0= -60dBm/1.23MHz
4) 0-20 data users in a single cell.
5) Users' requests follow uniform distribution
6) Timeslot=10ms.
7) k_i is randomly selected between 1 and 50, (α_i/β_i) are randomly selected between 0 and 1.

All the experiments were implemented using MATLAB, and ran on a SunFire 480 Server with four 900MHZ, UltraSparc-III processors and 16GB of RAM.

5.3 Numerical Results and Discussion

5.3.1 BNB Algorithm Discussion

In BNB algorithm, there are two kinds of node search strategies and branch search strategies. In order to test which mode works better, we present the experimental results of each strategy in Tables 5.3 & 5.4. The output parameter explanations are listed in Table 5.2

Table 5.2: Output Parameter Explanation

Output Heading	**Description**
Explored nodes	Cumulative number of explored nodes
Obj of LP relaxation (C_i)	First node objective relaxation value
Obj of best integer point (B_i)	Objective function value of the best integer point found so far.
Iterations	Number of iterations
Exitflag	1: Function converged to a solution 0: maximum number of iterations exceed
Time	Algorithm computational time
Obj Gap between LP relaxation and integer point (G_i)	$G_i = (C_i - B_i) / C_i$

Table 5.3 compares the results of DFSS and BNSS implementing under the scenario of having 6 user sending requests. From the experimental results, we observe that two strategies present the similar behavior while BNSS works better than DFSS in terms of running time.

Table 5.4 compares the results of MINIS and MAXIS branch search strategies. It is observed that MAXIS mode takes shorter computational time than that of MINIS mode. Obviously, in our case, MAXIS mode is an optimal selection for branch search strategy.

Table 5.3: Node Search Strategy Mode Comparison

Trial	Node search strategy	Explored nodes	Obj of LP relaxation	Obj of best integer point	Iterations	Exitflag	Time(s)	Obj Gap between LP relaxation and integer point
1	BNSS	117	-4.9310E+04	-3.8110E+04	187	1	2.8125	22.71%
	DFSS	205	-4.9310E+04	-3.8110E+04	310	1	4.2969	22.71%
2	BNSS	65	-4.9310E+04	-3.8070E+04	116	1	2.0781	22.79%
	DFSS	201	-4.9310E+04	-3.8070E+04	315	1	4.1563	22.79%
3	BNSS	371	-2.6180E+04	-2.1180E+04	534	1	6.6719	19.10%
	DFSS	395	-2.6180E+04	-2.1180E+04	562	1	7.0469	19.10%

Table 5.4: Branch Search Strategy Mode Comparison

Trial	Node search strategy	Explored nodes	Obj of LP relaxation	Obj of best integer point	Iterations	Exitflag	Time(s)	Obj Gap between LP relaxation and integer point
1	MINIS	117	2.5910E+04	2.1180E+04	213	1	2.57	18.26%
	MAXIS	71	2.5910E+04	2.1180E+04	143	1	2.23	18.26%
2	MINIS	50	2.5910E+04	2.1150E+04	99	1	2.12	18.37%
	MAXIS	29	2.5910E+04	2.1150E+04	73	1	1.94	18.37%
3	MINIS	117	2.1420E+04	1.9150E+04	203	1	2.56	10.60%
	MAXIS	61	2.1420E+04	1.9150E+04	122	1	2.14	10.60%

From the above analysis, we conclude that BNSS combined with MAXIS strategy will provide an optimal BNB solution for our model. Thus, we use this combination to implement BNB algorithm. As the BNB algorithm is an exact solution to solve LP problem, it also can be used to testify the behavior of our heuristic algorithms.

5.3.2 Comparison of Results and Discussions

In this subsection, we concentrate on analyzing the performance of BNB, HAI, and HAII. To make this simple, we grant each user the same value of k_i. That is to say, we give all users equal consideration with regarding to buffer status. Later we merge QoS study (performance influenced by k_i) in the next subsection. Table 5.5 shows an example of the scheduling results with 10 users sending requests. Note that 1st node objective relaxation value is only generated by BNB solution and able to calculate G_i for HAI and HAII as well. User selection (i, l) implies that user i is scheduled to transmit with l^{th} (l =1, 2, 3, 4) rate level.

Table 5.5: Scheduling Results Example (10 users Sending Requests)

Performance Metric	BNB	HAI	HAII
1st Node Objective Relaxation Value	5.237	--	--
Scheduling time (s)	3.78	0.0146	0.0366
User selection (i, l)	(3,1), (10,2)	(3,2), (4,3), (2,4), (6,4), (8,4)	(3,1), (10,2)
Objective function value	3.9398	3.708	3.9398
RoT Consumption (dB)	6.9814	6.987	6.9814

We ran five experiments with 5, 7, 10, 15 and 20 users sending requests in one cell in one timeslot. In each scenario, twenty experimental data are collected for performance evaluation.

Figures 5.1 - 5.4 show the results in terms of processing time versus trials with variable number of users sending requests simultaneously. From the results shown in different scenarios, we observe that the processing time of BNB solution is apparently much longer than that of the other two heuristic algorithms. Increasing the number of users, processing time of BNB will be increased up to 10s which is apparently unrealistic. In the other words, BNB solution is not very suitable for large system.

Figures 5.4 - 5.8 present the results of revenue obtained in each experiment. Fluctuations occur sometimes due to the randomness users' requests generated, such as the data rate, unit price. However, from the whole trend in each scenario, the three algorithms achieve the similar behavior.

Figures 5.9 - 5.12 compare the average objective value gap obtained among three solutions. Objective value gap is another way to illustrate the revenue behavior to evaluate which algorithm achieves better performance than one another. BNB and HAII work better than HAI in most of the cases.

The comparisons of RoT utilization through different scenarios are shown in Figures 5.13 - 5.16. This measurement is used to study the utilization of RL system resource. In this thesis, we focus on high speed data traffic only. Thus, RoT resource is fully utilized when more data users are scheduled to transmit simultaneously.

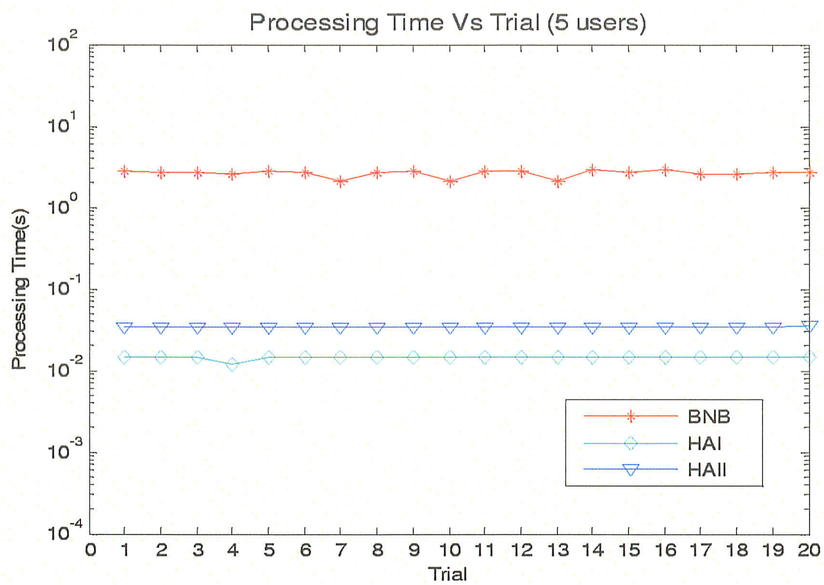


Figure 5.1: Processing Time Vs Trial (5 users sending requests)

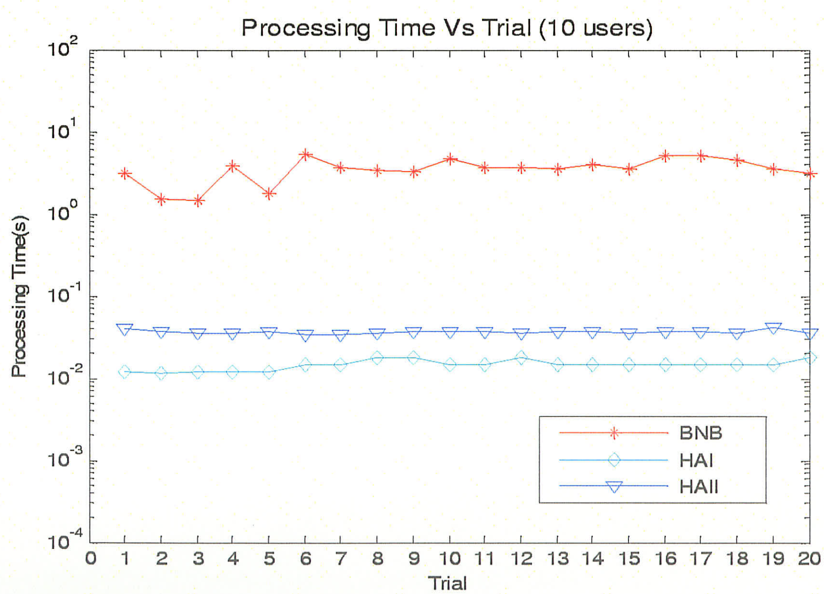


Figure 5.2: Processing Time Vs Trial (10 users sending requests)

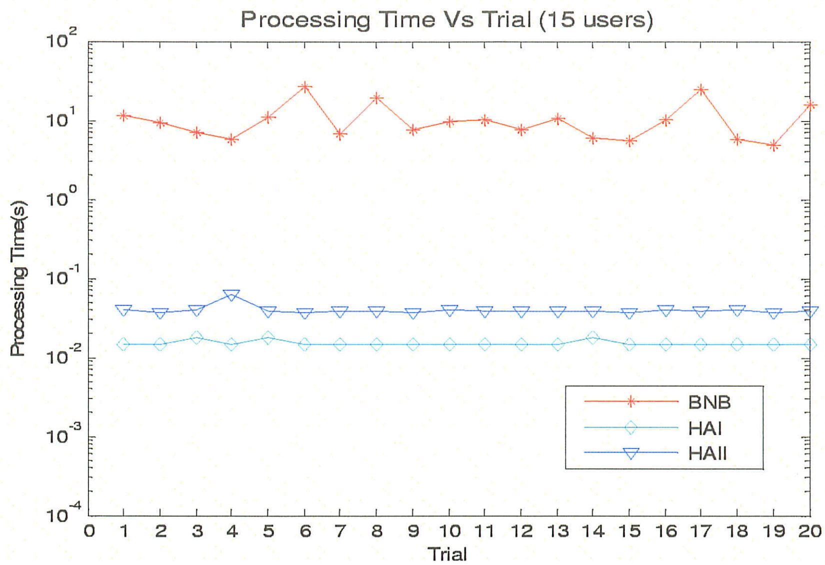


Figure 5.3: Processing Time Vs Trial (15 users sending requests)

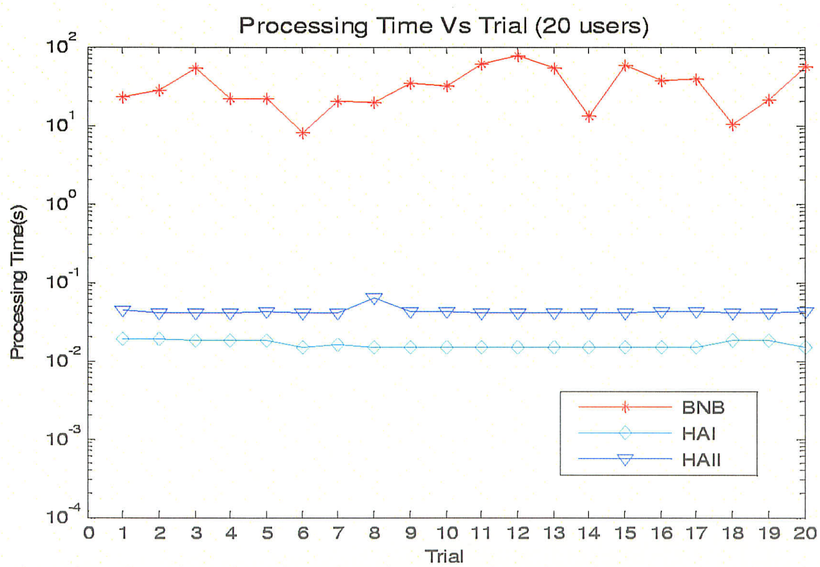


Figure 5.4: Processing Time Vs Trial (20 users sending requests)

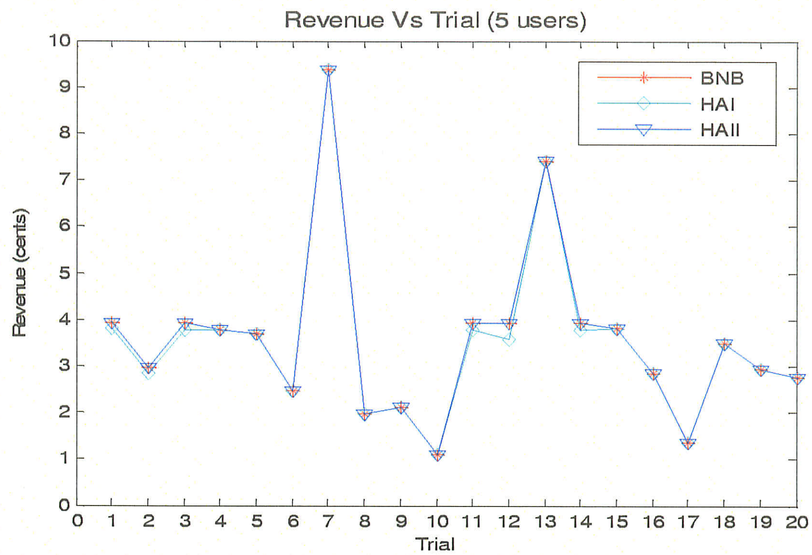


Figure 5.5: Revenue Vs Trial (5 users sending requests)

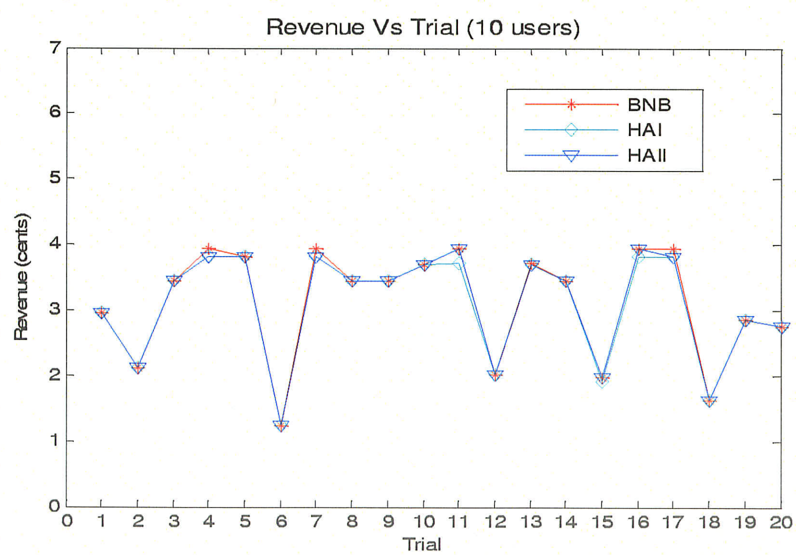


Figure 5.6: Revenue Vs Trial (10 users sending requests)

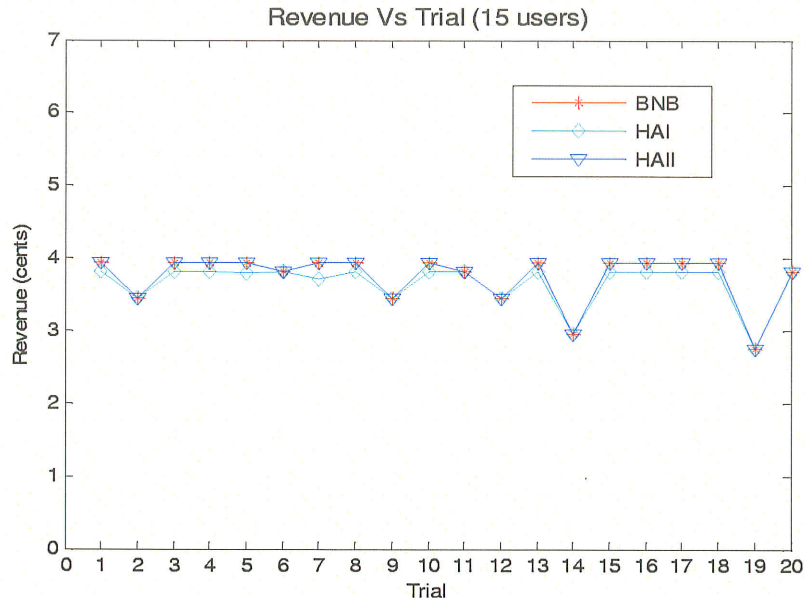


Figure 5.7: Revenue Vs Trial (15 users sending requests)

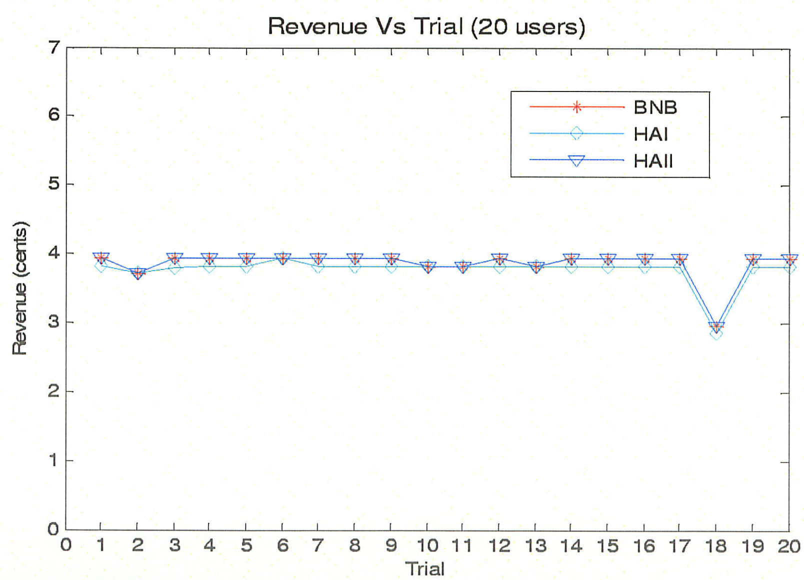


Figure 5.8: Revenue Vs Trial (20 users sending requests)

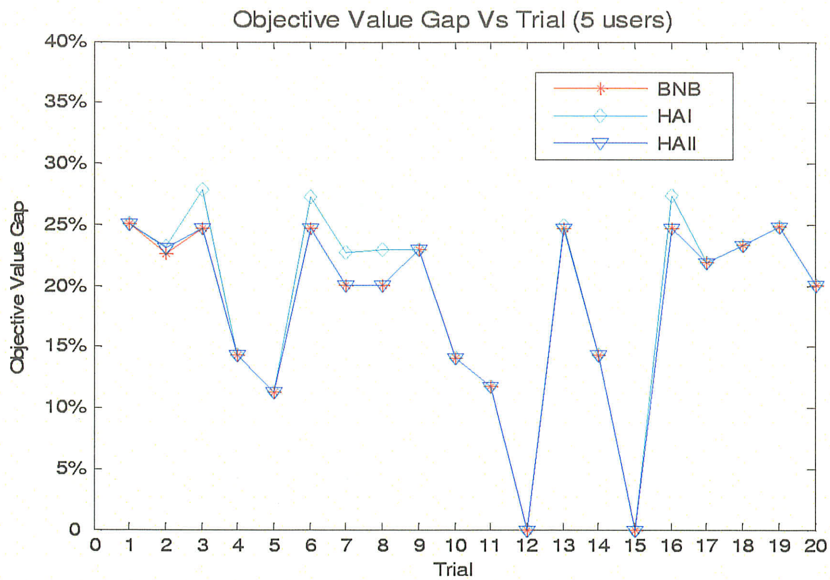


Figure 5.9: Objective Value Gap Vs Trial (5 users sending requests)

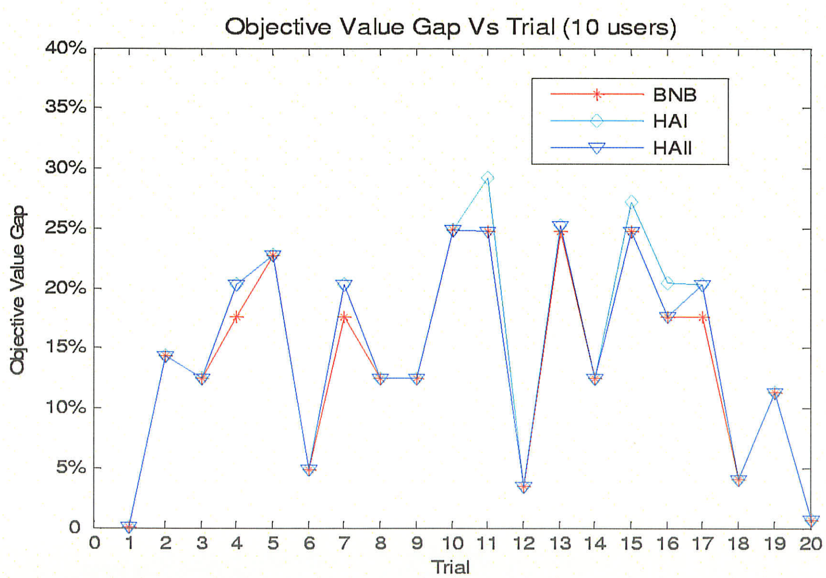


Figure 5.10: Objective Value Gap Vs Trial (10users sending requests)

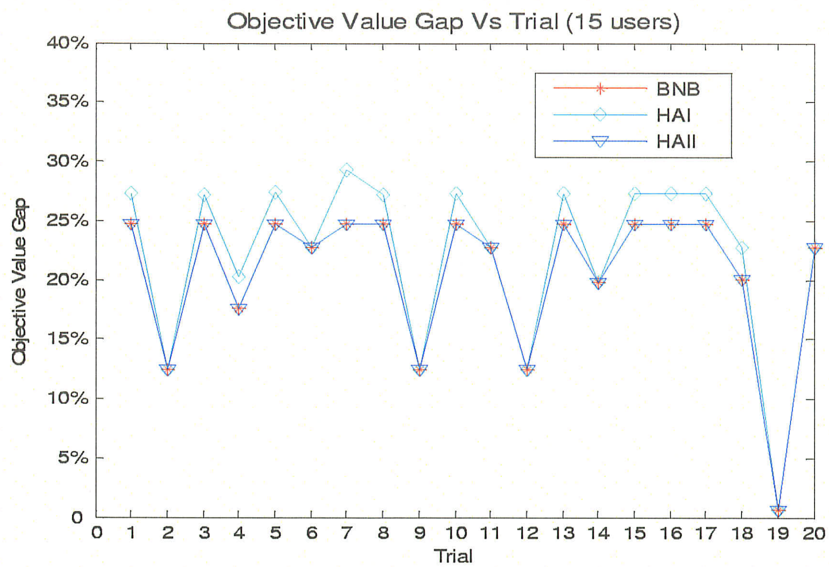


Figure 5.11: Objective Value Gap Vs Trial (15users sending requests)

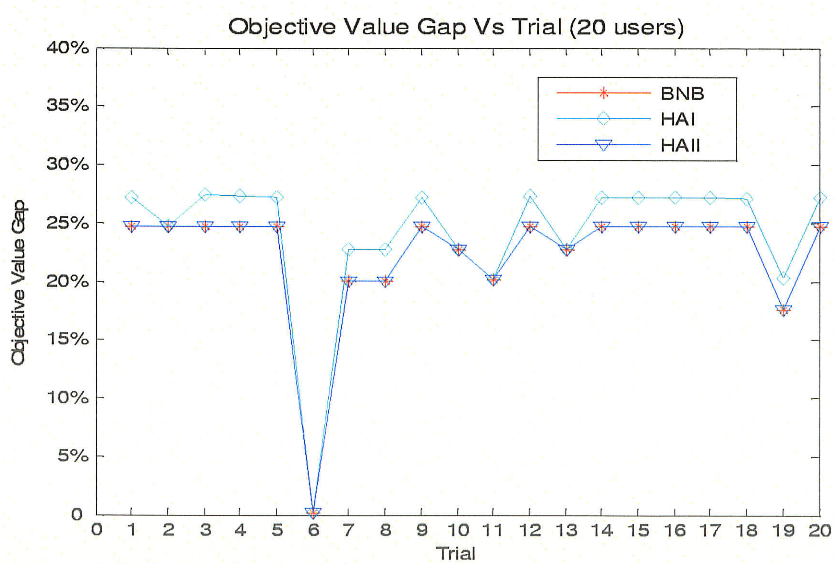


Figure 5.12: Objective Value Gap Vs Trial (20 users sending requests)

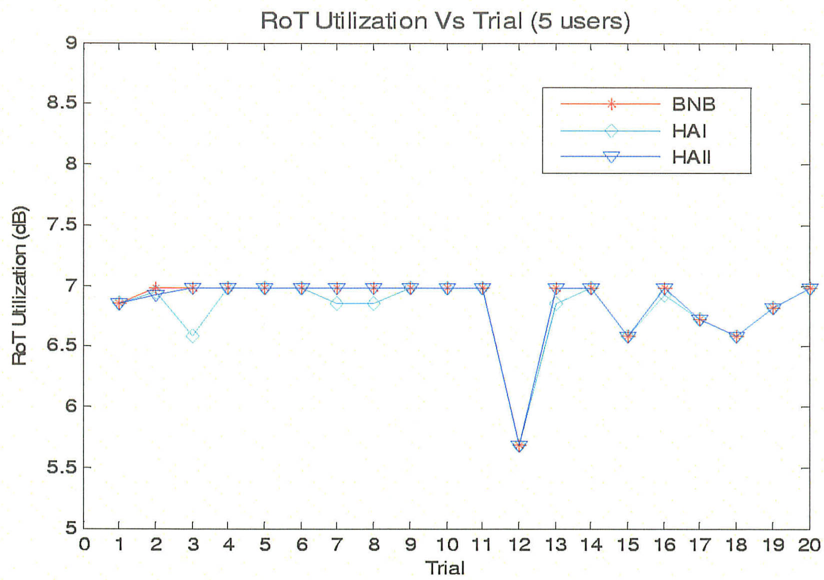


Figure 5.13: RoT Utilization Vs Trial (5 users sending requests)

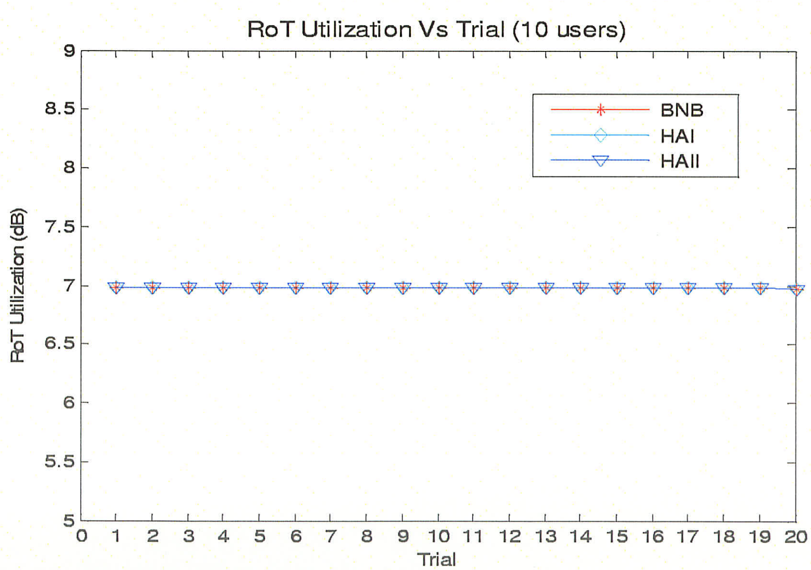


Figure 5.14: RoT Utilization Vs Trial (10 users sending requests)

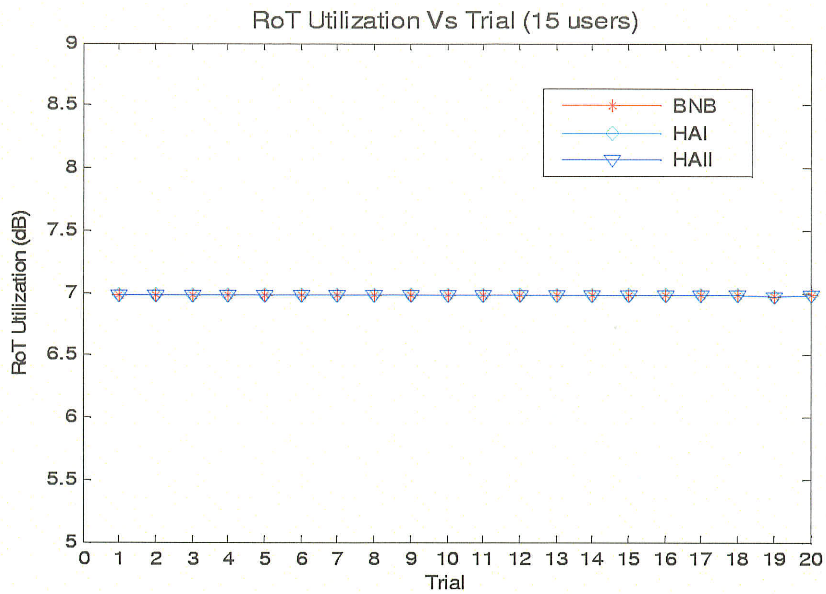


Figure 5.15: RoT Utilization Vs Trial (15 users sending requests)

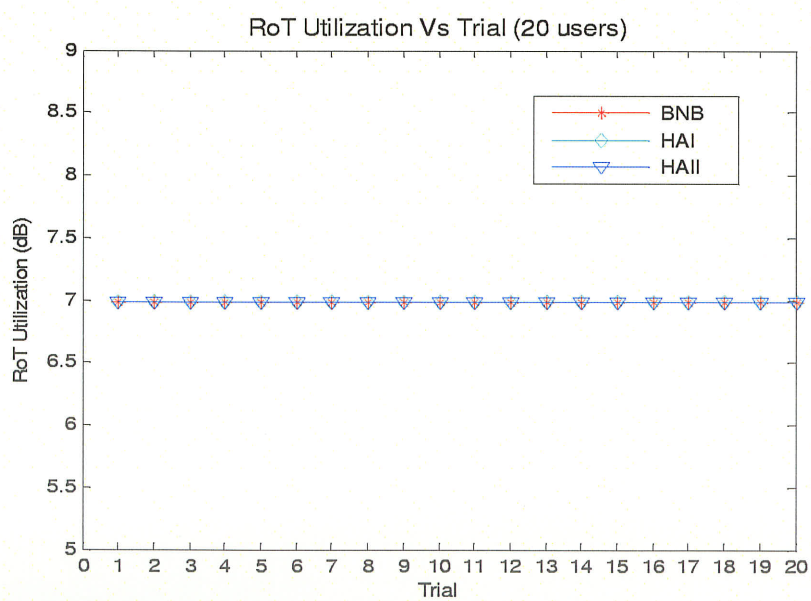


Figure 5.16: RoT Utilization Vs Trial (20 users sending requests)

As the performance behavior is highly influenced by the number of users, we study the performance based on various request scenarios. To analyze the model behaviors through diverse scenarios, we evaluate the performance using average metric value as shown below.

Figure 5.17 shows the results in terms of average processing time among three algorithms. It is observed that the average processing time of BNB increases fast as more users send requests whereas for the proposed heuristic algorithms, they appear to be insensitive to the number of users. The processing time of HAII is consistently about 2.5 times that of HAI. Due to 10ms constraint of scheduling period, BNB becomes hardly realistic when more mobiles send requests at the same time. This is to be expected. However, the proposed HAI and HAII can meet scheduling time requirement and HAI works better than HAII.

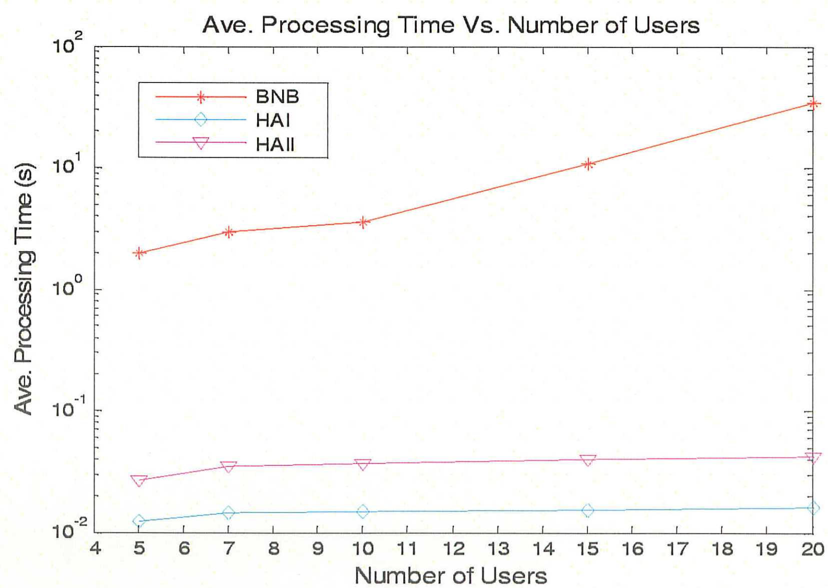


Figure 5.17: Ave. Processing Time vs. Number of Users

The average objective function value gap vs. number of users of three algorithms is shown in Figure 5.18. In this figure, BNB and HAII work better than HAI. The curves of BNB and HAII are closer in most of the scenarios, especially when the number of users is increased more than 15. Since the unit price and the request rate are generated randomly, the average Gap values of three algorithms may not follow the normal increasing trend (such as for 10 user requests). However, in this case, the Gap value may increase to catch the trend if more experiment data are collected to compute the average value.

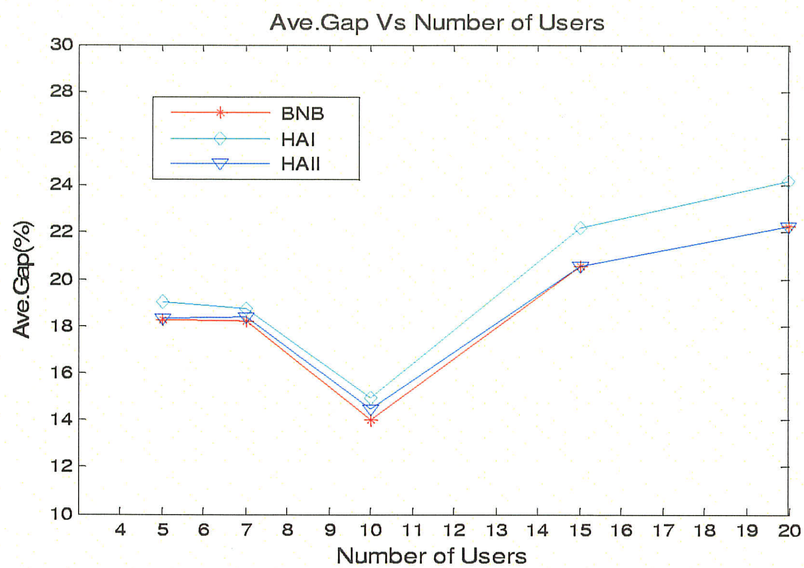


Figure 5.18: Ave Gap vs. Number of Users

Figure 5.19 shows the RoT utilization of three solutions. The more users are scheduled, the better RoT utilization performance achieve. In this case, the three algorithms are about equivalent.

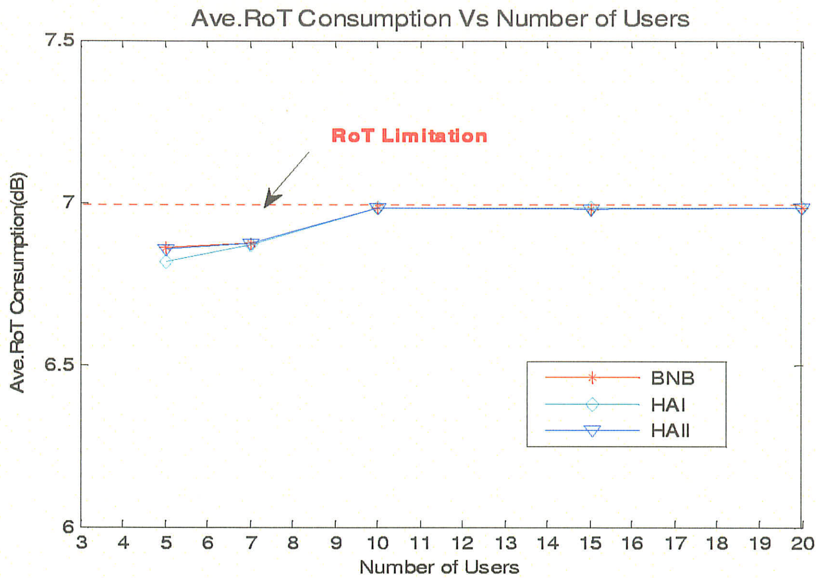


Figure 5.19: Ave RoT Consumption vs. Number of Users

The summary results for the three algorithms considering all the scenarios are presented in Table 5.6.

Table 5.6: Summary Results

	Ave. Processing Time (s)	Ave. RoT Consumption(dB)	Ave. Gap (%)
BNB	10.7685	6.9364	18.682
HAI	0.0145	6.9284	19.816
HAII	0.0361	6.9356	18.806

5.3.3 Balance of Revenue Maximization and Loss Minimization

As we mentioned in Section 5.3.2, the three solutions achieve similar performance in terms of objective value gap. Therefore, any one of them can be employed to study the scheduling influenced by objective function balancing parameter k_i. Here we choose HAI due to its fast processing. In this experiment, we assume $k_2=k_3=k_4=k_5=10$, $(\alpha_2/\beta_2)=0.3$, $(\alpha_3/\beta_3)=0.7$, $(\alpha_4/\beta_4)=0.05$, $(\alpha_5/\beta_5)=0.5$. Note that (α_i/β_i) implies the buffer status of mobile i as explained in Section 4.2. We concentrate on the study of scheduling opportunity of user 1 by granting different values of k_1 and α_1/β_1. As expect, given a fixed ratio value of α_i/β_i, larger k_i will create more schedule possibilities. Larger k_i combined with greater ratio value of α_i/β_i could create more than 90% of scheduling opportunities. However, this may be achieved by losing some revenue as shown in Figure 5.21. Figure 5.21 presents the tradeoff between revenue maximization and loss minimization of user 1 when its buffer is set close to full. The packets loss can be reduced by increasing the value of k_i from 10 to 50. However, it decreases the obtained revenue.

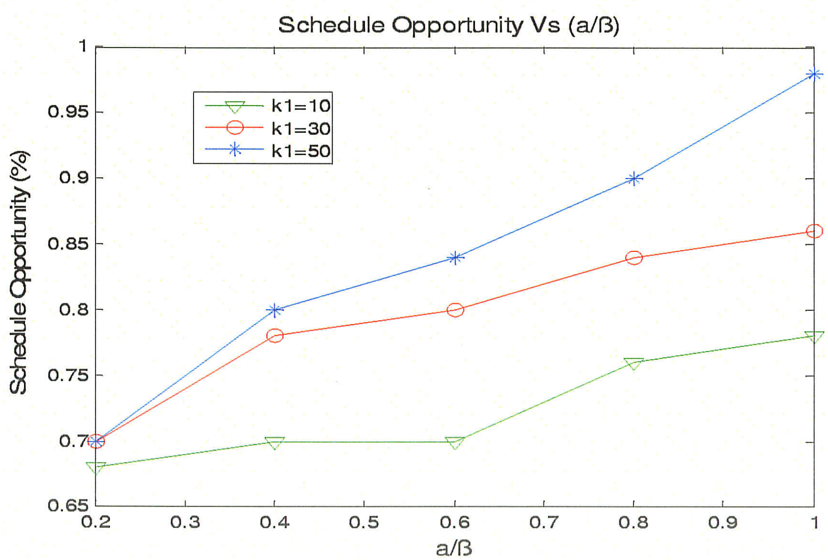


Figure 5.20: Scheduling Opportunity Vs Buffer Status (α_i/β_i)

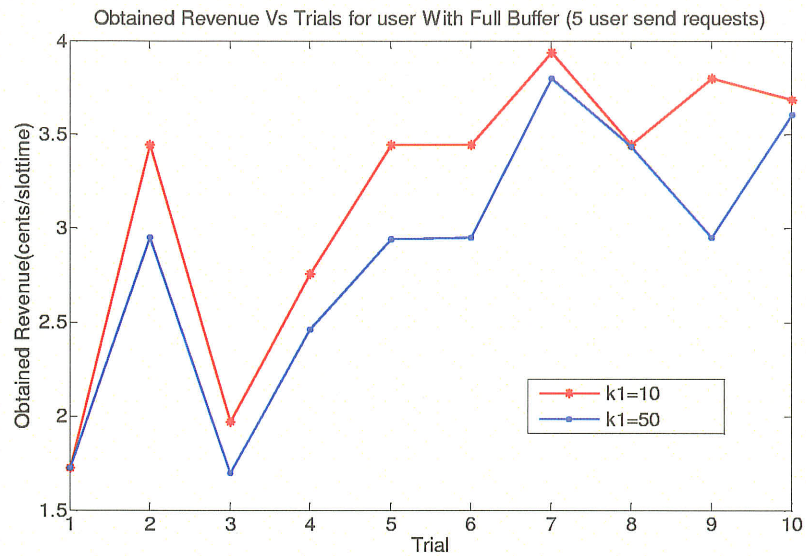


Figure 5.21: Balance between Obtained Revenue and Loss

5.4 Summary

According to the results presented above, we conclude that HAI and HAII achieve relatively shorter processing time than BNB while maintaining the same objective value with BNB in most of 95% cases. Comparing the heuristic algorithms, we find that HAII achieves smaller objective value gap than HAI by sacrificing processing time. Summarizing the trade-off between processing time and objective value gap among three solutions, we make recommendations for service providers of how to apply for each algorithm properly as follows.

- HAI is more suitable for small group of requests. In this case, the scheduling time is guaranteed with little sacrifice of maximum obtained revenue.

- HAII is expected to be applied for large group of requests. It achieves smaller objective value gap compared to HAI. Furthermore, the processing time is insensitive to the number of users.
- BNB is feasible when there are less than five users sending requests, and it also needs a fast processing server to process the scheduling algorithm.

For any of the three algorithms, HAI, HAII and BNB, options are offered to service providers to satisfy subscribers with various degrees of QoS. Moreover, a trade-off occurs between objective value and QoS satisfaction. That is, high quality of QoS could be achieved by losing certain revenue. Otherwise, to merely pursue high revenue, service providers may lose users due to lack of QoS concerns. Therefore, in order to meet the requirements in different cases, service providers are given a very flexible choice by defining the value of parameter k_i for user i based on its current status represented by α_i/β_i at any time. For example:

Let $k_i = 10$	if	$\alpha_i/\beta_i < 0.3$,	user i has little data in the buffer,
Let $k_i = 30$	if	$0.3 \le \alpha_i/\beta_i < 0.7$,	user i's buffer is around half full,
Let $k_i = 50$	if	$0.7 \le \alpha_i/\beta_i \le 1$,	user i's buffer is almost full,

In addition, the parameter k_i can be defined based on the unit price of user i. If user i chooses gold price plan, it may be granted greater value of parameter k_i comparing to those who select silver price plan in the same case (equal value of α_i/β_i). A mapping example over k_i, α_i/β_i, and price plan is shown in Table 5.7.

Table 5.7: Mapping of k_i, α_i/β_i, and Price Plan

k_i	α_i/β_i	**Unit Price Plan**
10	$\alpha_i/\beta_i < 0.3$	Common
20		Silver
30		Gold
30	$0.3 \leq \alpha_i/\beta_i < 0.7$	Common
40		Silver
50		Gold
50	$0.7 \leq \alpha_i/\beta_i \leq 1$	Common
60		Silver
70		Gold

Chapter 6

Conclusions & Future Work

In this chapter, we summarize the results obtained in this thesis. We also present some possible directions for future research on the problem of RL scheduling and resource allocation for CDMA2000 1xEV-DV networks.

6.1 Conclusions

In this thesis, a novel scheduling and rate allocation approach for CDMA2000 1xEV-DV which presents the significant different viewpoint with the existing solutions is proposed. We propose an alternative procedure for RL scheduling and rate allocation for non-time sensitive data traffic on the basis of Revision D. The goal is to maximize the revenue obtained by service providers and minimize loss for subscribers subject to RoT constraint. The method is regarded as a tool of RL resource management which offers service providers flexible option of either maximizing obtained revenue or satisfying service quality, or balancing both of them.

We formulate the problem into a Knapsack problem with multiple constraints. BNB as an existing algorithm to solve binary integer LP problem is studied for the system model.

However, it is observed that BNB becomes almost impossible for practical implementation due to its longer scheduling processing time. Instead two heuristic algorithms are proposed.

The performance of the three algorithms is evaluated through illustrative experiments. It is observed that the three algorithms can work appropriately in specific scenario considering the tradeoff between a desirable processing time – optimal objective function value (revenue maximization with a certain QoS constraint). Moreover, in the objective function, objective balancing parameter k_i for user i can be dynamically adjusted based on service providers' needs as we recommended in Section 5.4.

6.2 Future Research Work

Although the RL scheduling methods we proposed aim to solve an alternative problem compared with the other existing approaches for 1xEV-DV system, there are still some factors that are not considered in our scheduling scheme. These issues may be considered for further research and are listed below.

1) The future research in this area will extend the scheduling algorithm to more than one timeslot and study the performance of proposed solutions.
2) To achieve a long run benefit, fairness among users is encouraged to be considered in the model design.

3) Further research is required to address multi-cell systems, which may have a significant influence in RL scheduling.

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Appendix A

Parameters for R-PDCH

Table A.1 illustrates the parameters of R-PDCH.

Table A.1: Parameters for the R-PDCH with Radio Configuration 7

Number of Information Bits per Encoder Packet	Number of Frame Quality Indicator Bits per Encoder Packet	Number of Encoder Tail Allowance Bits per Encoder Packet	Number of Bits per Encoder Packet	Code Rate	Transmitted Subpacket ID	Data Rate (kbps)	Modulation per Walsh Function	Interleaver Output Sequence Starting Point for the Subpacket	Walsh Functions W_n^N	Number of Binary Code Symbols in the Transmitted Subpackets	Effective Code Rate Including Repetition
174	12	6	192	1/5	2	6.4	BPSK on I	384	+ + - -	9.216	0.0208
174	12	6	192	1/5	1	9.6	BPSK on I	192	+ + - -	6.144	0.0313
174	12	6	192	1/5	0	19.2	BPSK on I	0	+ + - -	3.072	0.0625
386	16	6	408	1/5	2	13.6	BPSK on I	24	+ + - -	9.216	0.0443
386	16	6	408	1/5	1	20.4	BPSK on I	1.032	+ + - -	6.144	0.0664
386	16	6	408	1/5	0	40.8	BPSK on I	0	+ + - -	3.072	0.1328
770	16	6	792	1/5	2	26.4	BPSK on I	2.184	+ + - -	9.216	0.0859
770	16	6	792	1/5	1	39.6	BPSK on I	3.072	+ + - -	6.144	0.1289
770	16	6	792	1/5	0	79.2	BPSK on I	0	+ + - -	3.072	0.2578
1.538	16	6	1,560	1/5	2	52.0	QPSK	4.488	+ + - -	18.432	0.0846
1.538	16	6	1,560	1/5	1	78.0	QPSK	6.144	+ + - -	12.288	0.1270
1.538	16	6	1,560	1/5	0	156.0	QPSK	0	+ + - -	6.144	0.2539
3.074	16	6	3,096	1/5	2	103.2	QPSK	9.096	+ -	36.864	0.0840
3.074	16	6	3,096	1/5	1	154.8	QPSK	12.288	+ -	24.576	0.1260
3.074	16	6	3,096	1/5	0	309.6	QPSK	0	+ -	12.288	0.2520
4.610	16	6	4,632	1/5	2	154.4	QPSK	13.704	+ + - - and + -	55.296	0.0838
4.610	16	6	4,632	1/5	1	231.6	QPSK	18.432	+ + - - and + -	36.864	0.1257
4.610	16	6	4,632	1/5	0	463.2	QPSK	0	+ + - - and + -	18.432	0.2513
6.146	16	6	6,168	1/5	2	205.6	QPSK	6.024	+ + - - and + -	55.296	0.1115
6.146	16	6	6,168	1/5	1	308.4	QPSK	18.432	+ + - - and + -	36.864	0.1673
6.146	16	6	6,168	1/5	0	616.8	QPSK	0	+ + - - and + -	18.432	0.3346
9.218	16	6	9,240	1/5	2	308.0	QPSK	36.864	+ + - - and + -	55.296	0.1671
9.218	16	6	9,240	1/5	1	462.0	QPSK	18.432	+ + - - and + -	36.864	0.2507
9.218	16	6	9,240	1/5	0	924.0	QPSK	0	+ + - - and + -	18.432	0.5013
12.290	16	6	12,312	1/5	2	410.4	QPSK	36.864	+ + - - and + -	55.296	0.2227
12.290	16	6	12,312	1/5	1	615.6	QPSK	18.432	+ + - - and + -	36.864	0.3340
12.290	16	6	12,312	1/5	0	1.231.2	QPSK	0	+ + - - and + -	18.432	0.6680
15.362	16	6	15,384	1/5	2	512.8	QPSK	36.864	+ + - - and + -	55.296	0.2782
15.362	16	6	15,384	1/5	1	769.2	QPSK	18.432	+ + - - and + -	36.864	0.4173
15.362	16	6	15,384	1/5	0	1.538.4	QPSK	0	+ + - - and + -	18.432	0.8346
18.434	16	6	18,456	1/5	2	615.2	8-PSK	55.296	+ + - - and + -	82.944	0.2225
18.434	16	6	18,456	1/5	1	922.8	8-PSK	27.648	+ + - - and + -	55.296	0.3338
18.434	16	6	18,456	1/5	0	1.845.6	8-PSK	0	+ + - - and + -	27.648	0.6675

In the above table, the data rate is the number of EP bits divided by the duration of all of the transmitted subpackets of the EP. The effective code rate is defined as the number of bits in the EP divided by the number of binary code symbols in all of the transmitted subpackets of the EPs. The "Interleaver Output Sequence Starting Point for the Subpacket" is the first symbol in the interleaver output sequence that the subpacket symbol selection operation selects for each sbupacket.

Appendix B

The Code Channel Output Power Calculation for R-PDCH

According to Revision D standard, the MS shall set the output power of the R-PDCH relative to the output power of the Reverse Pilot Channel. The MS shall transmit the data on R-PDCH at an output power given by

mean code channel output power (dBm) =

mean pilot channel output power (dBm)
0.125 × (Nominal_Reverse_Packet_Data_Channel_
Attribute_Gain[EP_SIZE, SPID, BOOST, REV_PDCH_TABLE_SELs]
+ Reverse_Packet_Data_Channel_Attribute_
Adjustment_Gain[EP_SIZE, SPID, BOOST]
+ Reverse_Packet_Data_Channel_Payload_Adjustment_Gain[EP_SIZE]
+ Reverse_Packet_Data_Channel_Subpacket_Adjustment_Gain[SPID]
+ Reverse_Packet_Data_Channel_Boost_Adjustment_Gain[BOOST]
+ Reverse_Channel_Adjustment_Gain[Channel]
– Multiple_Channel_Adjustment_Gain[Channel]
+ RLGAIN_TRAFFIC_PILOTs),

Where the values of

Nominal_Reverse_Packet_Data_Channel_Attribute_Gain[EP_SIZE, SPID, BOOST, REV_PDCH_TABLE_SELs],
Reverse_Packet_Data_Channel_Attribute_Adjustment_Gain[EP_SIZE, SPID, BOOST],
Reverse_Packet_Data_Channel_Payload_Adjustment_Gain[EP_SIZE],
Reverse_Packet_Data_Channel_Subpacket_Adjustment_Gain[SPID],
Reverse_Packet_Data_Channel_Boost_Adjustment_Gain[BOOST],
Reverse_Channel_Adjustment_Gain[Channel],
Multiple_Channel_Adjustment_Gain[Channel], and
RLGAIN_TRAFFIC_PILOTs

are integers, specified in units of 0.125 dB.

The term

$$0.125 \times (\text{Nominal\_Reverse\_Packet\_Data\_Channel\_Attribute\_Gain}[\text{EP\_SIZE, SPID, BOOST, REV\_PDCH\_TABLE\_SELs}] + \text{Reverse\_Packet\_Data\_Channel\_Attribute\_Adjustment\_Gain}[\text{EP\_SIZE, SPID, BOOST}] + \text{Reverse\_Packet\_Data\_Channel\_Payload\_Adjustment\_Gain}[\text{EP\_SIZE}] + \text{Reverse\_Packet\_Data\_Channel\_Subpacket\_Adjustment\_Gain}[\text{SPID}] + \text{Reverse\_Packet\_Data\_Channel\_Boost\_Adjustment\_Gain}[\text{BOOST}] + \text{Reverse\_Channel\_Adjustment\_Gain}[\text{Channel}] - \text{Multiple\_Channel\_Adjustment\_Gain}[\text{Channel}] + \text{RLGAIN\_TRAFFIC\_PILOTs})$$

is denoted by RPDCH_TPR_Table[EP_SIZE, SPID, BOOST].

The MS shall maintain a nominal R-PDCH attribute gain table for each value of EP_SIZE, SPID, BOOST, and REV_PDCH_TABLE_SELs. The MS shall use the values given in Table 2.1.2.3.3.8-1 through Table 2.1.2.3.3.8-4.14 which refer to Revision D standard. The MS shall maintain a R-PDCH attribute adjustment gain, denoted by Reverse_Packet_Data_Channel_Attribute_Adjustment_Gain, containing an offset relative to the Reverse Pilot Channel power for each value of EP_SIZE, SPID, and BOOST. The MS shall maintain a R-PDCH payload adjustment gain table, denoted by Reverse_Packet_Data_Channel_Payload_Adjustment_Gain, containing an offset relative to the Reverse Pilot Channel power for each value of EP_SIZE. The MS shall maintain a R-PDCH subpacket adjustment gain table, denoted by Reverse_Packet_Data_Channel_Subpacket_Adjustment_Gain, containing an offset relative to the Reverse Pilot Channel power for each value of SPID. The MS shall maintain a R-PDCH boost adjustment gain table, denoted by Reverse_Packet_Data_Channel_Boost_Adjustment_Gain, containing an offset relative to the Reverse Pilot Channel power for each value of BOOST. The MS shall initialize each entry in these four tables to 0.

Appendix C

Matlab Programming Codes

Three main subroutines of BNB, HAI, and HAII algorithms are given as follows.

1) Load data

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% According to the number of users' sending requests,
% randomly generate request rate for each user based on 11 available rates level in Revision D.
% For each user, generate possible 4 data rate levels, and randomly generate a unit price set.
% For the possible data rates of each user, get associated TPR.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Setup three unit price set based on each rate
  basic_price=[5 10 20 40 80 120 160 250 400 550 700
               7.5 15 30 60 120 180 240 375 600 825 1050
               10 20 40 80 160 240 320 500 800 1100 1400];

%Setup availabe RL data rates and associated TPR according to Revision D.

  basic_rate=[19200 40800 79200 156000 309600 463200 616800 924000 1231200 1538400 1845600];
  basic_tpr=[6 30 54 77 95 109 119 133 144 153 170];

%Could be designed for channel condition
  basic_cond=[1 1 1];             % for channel condition (1:best cond  1.2:middle 1.4 worse)

  n=input('input the number of users[50]? ');

%Randomly generate k and buffer status ratio for n users
  k=rand(1,n);
  qosratio=ceil(50*rand(1,n));

  rate=[];
  TPR=[];
  price=[];
  Pt=[];                          % defined as channel condition

%Load the data into the matix.
  for i=1:n

      c=size(basic_rate,2);
      d=floor(rand*c)+1;          % randomly selected number
```

```
        e=floor(rand*3)+1;                                        % price level
        k=size(basic_cond,2);                                     % channel condition
        k1=floor(rand*k)+1;
        Pt_tmp=[zeros(1,i-1) basic_cond(k1) zeros(1,n-i)];        % channel cond
        Pt=[Pt;Pt_tmp];

        if d==1                    % request rate=lowest rate according to availabel rate sets
            rate_tmp=[10 10 basic_rate(d) basic_rate(d+1)];
            rate=[rate; rate_tmp];
            TPR_tmp=[200 200 basic_tpr(d) basic_tpr(d+1)];    %RoT=1.0*E+11, revenue=2.0*e-5,
                                                              wi=2.0*e-16
            TPR=[TPR; TPR_tmp];
            price_tmp=[0.1 0.1 basic_price(e,d) basic_price(e,d+1)];
            price=[price; price_tmp];

        elseif d==c                % request rate=highest rate level according to availabel rate sets
            rate_tmp=[basic_rate(d-2) basic_rate(d-1) basic_rate(d) 10];
            rate=[rate;rate_tmp];
            TPR_tmp=[basic_tpr(d-2) basic_tpr(d-1) basic_tpr(d) 200];
            TPR=[TPR;TPR_tmp];
            price_tmp=[basic_price(e,d-2) basic_price(e,d-1) basic_price(e,d) 0.1];
            price=[price;price_tmp];

        elseif d==2                % request rate=second lowest rate level according to availabel rate sets
            rate_tmp=[10 basic_rate(d-1) basic_rate(d) basic_rate(d+1)];
            rate=[rate;rate_tmp];
            TPR_tmp=[200 basic_tpr(d-1) basic_tpr(d) basic_tpr(d+1)];
            TPR=[TPR;TPR_tmp];
            price_tmp=[0.1 basic_price(e,d-1) basic_price(e,d) basic_price(e,d+1)];
            price=[price;price_tmp];

        else
            rate_tmp=[basic_rate(d-2) basic_rate(d-1) basic_rate(d) basic_rate(d+1)];
            rate=[rate;rate_tmp];
            TPR_tmp=[basic_tpr(d-2) basic_tpr(d-1) basic_tpr(d) basic_tpr(d+1)];
            TPR=[TPR;TPR_tmp];
            price_tmp=[basic_price(e,d-2) basic_price(e,d-1) basic_price(e,d) basic_price(e,d+1)];
            price=[price;price_tmp];

        end

end
```

2) BNB algorithm subroutine

(a). BNB algorithm without QoS consideration

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%% BNB SOLUTION (e,g. the number of users=5)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% clear all;
% lamda=[1*ones(4,1);1*ones(4,1);1*ones(4,1);1*ones(4,1);1*ones(4,1);1*ones(20,1)];

n=input('input the number of users[10]? ');

% Calculate RoT and revenue value

RoT=10.^((Pt*TPR)./80).*10^(-10.5)*10^9;

revenue=rate*0.02.*price/1000;

f=reshape(revenue',20,1);

h=4;
t=4*n;
a1=[ones(1,4) zeros(1,t-4);];

for i=1:(t./4)-1
    a3=[zeros(1,h) ones(1,4) zeros(1,t-h-4)];
    a1=[a1;a3];
    h=h+4;
end

a2=reshape(RoT',1,20);
a=[a2;a1];
b=[4 ones(1,n)]';

% BNB calculation
options=optimset('Display','iter');
[x, fval, exitflag, output]=bintprog(-f,a,b,[],[],[],options);

% output results
y=reshape(x,4,5)';
sparse(y)
RoT_use=a2*x
fval
output
```

(b). BNB solution with QoS consideration

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% OBJECTIVE FUNCTION BALANCING PARAMETER BEHAVIOR OF BNB SOLUTION
%% (e,g. the number of users=5)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% clear all;

  n=input('input the number of users[10]? ');

% Calculate RoT and revenue value

  k=[1000;1000;1000;1000;1000];                                %added in september,2005

  qosratio=[0.1; 0.3; 0.7; 0.05; 0.5];                         %given buffer status value of each user

  qos=[k.*qosratio k.*qosratio k.*qosratio k.*qosratio];

  RoT=10.^((Pt*TPR)./80).*10^(-10.5)*10^9;
  revenue1=rate*0.02.*price/1000;

  revenue=(rate*0.02.*price/1000)+(qos);                       %added in september,2005

  f=reshape(revenue',20,1);

  h=4;
  t=4*n;
  a1=[ones(1,4) zeros(1,t-4);];

  for i=1:(t./4)-1
        a3=[zeros(1,h) ones(1,4) zeros(1,t-h-4)];
        a1=[a1;a3];
        h=h+4;
  end

  a2=reshape(RoT',1,20);
  a=[a2;a1];
  b=[4 ones(1,n)]';

% BNB calculation
  options=optimset('Display','iter');
  [x, fval, exitflag, output]=bintprog(-f,a,b,[],[],[],options);

% output results
 y=reshape(x,4,5)';
 sparse(y)
 RoT_use=a2*x
 fval
 output
```

3). HAI Algorithm Subroutine

(a). HAI without QoS consideration

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% HAI SOLUTION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Select start point from the sorted list
 start =input('start point[1]? ');

% Calculate RoT and revenue
 RoT=10.^((Pt*TPR)./80).*10^(-10.5)*10^9;
 revenue=rate*0.02.*price/1000;
 C=4;

% Loop=1;
 FINAL=zeros(1,3);

% Calculate ratio
 ratio=revenue./RoT;
 [ratio_row ratio_col]=size(ratio);

% SORT IN DECREASING ORDER
 clock_start=clock;                                    %start timer

 REVENUE=0;
 ROT_REST=4;
 SEL=zeros(ratio_row,ratio_col);
 temp=0;
 serve=zeros(ratio_row,1);

%start=k;
%disp(k);

 [row,col,E_tmp]=find(ratio);
 [E,IX]=sort(E_tmp,'descend');
 [E_row E_col]=size(E);

 for i=start:E_row                                     % sort by row
       x=row(IX(i),1);
       y=col(IX(i),1);

       if serve(x,1)==0
              ROT_REST=ROT_REST-RoT(x,y);              % calculate consumed RoT

              if ROT_REST >= 0                         % RoT resource hasnot used up

                     SEL(x,y)=1;
                     REVENUE=REVENUE+revenue(x,y);
                     serve(x,1)=1;

                     if ROT_REST<0.03
```

```
                        break;
                end

            else
                ROT_REST=ROT_REST+RoT(x,y);
            end

    end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The following part could be used to get the solution of having search
% process start from different startpoint.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% CONTINUED, START FROM THE FIRST RECORD OF THE LIST---ESPECAILLY FOR THE
% STARTPOINT IS NOT EQUAL TO 1

for i=1:start-1                          % sort by row
    x=row(IX(i),1);
    y=col(IX(i),1);

    if serve(x,1)==0                     % the current rate request is served.

        ROT_REST=ROT_REST-RoT(x,y);      % calculate consumed RoT

        if ROT_REST >= 0                 % RoT resource hasnot used up
            SEL(x,y)=1;
            REVENUE=REVENUE+revenue(x,y);
            serve(x,1)=1;

            if ROT_REST<0.03
                break;
            end

        else
            ROT_REST=ROT_REST+RoT(x,y);
        end

    end

end

FINAL(1,1)=REVENUE;
%FINAL(k,2)=sparse(SEL);
FINAL(1,3)=C-ROT_REST;

clock_end=clock;                         % timer stop
```

```
% OURPUT RESULTS

  RUNTIME=clock_end-clock_start           % processing time
  sparse(SEL)                             % user selection
  [M N]=max(FINAL(:,1));                  % obtain the maximum revenue and associated
                                          %consumed RoT value
  REV=M                                   % generated revenue
  ROT=FINAL(N,3)                          % used RoT resource
```

(b). HAI with QoS consideration

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function is to test HAI with QoS consideration
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Proposed algorithm I test
 start =input('start point[1]? ');                  %setup startpoint, default value=1

 RoT=10.^((Pt*TPR)./80).*10^(-10.5)*10^9;

 k1=input('input the number of k[1000]? ');         %input k1 for user1
 k=[k1;1000;1000;1000;1000];

 qosratio=[1; 0.3; 0.7; 0.05; 0.5];                 %let user1's buffer be full
 qos=[k.*qosratio k.*qosratio k.*qosratio k.*qosratio];

 revenue1=(rate*0.02.*price/1000)+qos;
 revenue=rate*0.02.*price/1000;

 C=4;

%loop=1;
 FINAL=zeros(1,3);
 ratio=revenue1./RoT;
 [ratio_row ratio_col]=size(ratio);

%SORT
 clock_start=clock;                     % Start timer
 REVENUE=0;                             % Given the initial value of revenue
 ROT_REST=4;                            % Given the maximum value of RoT
 SEL=zeros(ratio_row,ratio_col);
 temp=0;
 serve=zeros(ratio_row,1);

%Startpoint=k;
 [row,col,E_tmp]=find(ratio);
 [E,IX]=sort(E_tmp,'descend');
```

```
[E_row E_col]=size(E);

for i=start:E_row                               % sort by row
        x=row(IX(i),1);
        y=col(IX(i),1);

        if serve(x,1)==0
                ROT_REST=ROT_REST-RoT(x,y);          % calculate the rest of RoT resource

                if ROT_REST >= 0                     % RoT hasnot been used up
                        SEL(x,y)=1;
                        REVENUE=REVENUE+revenue(x,y);
                        serve(x,1)=1;

                        if ROT_REST<0.03
                                break;
                        end

                else
                        ROT_REST=ROT_REST+RoT(x,y);
                end

        end

end

% Second loop, start from the beginning
for i=1:start-1                                   %sort by row
        x=row(IX(i),1);
        y=col(IX(i),1);

        if serve(x,1)==0
                ROT_REST=ROT_REST-RoT(x,y);

                if ROT_REST >= 0
                        SEL(x,y)=1;
                        REVENUE=REVENUE+revenue(x,y);
                        serve(x,1)=1;

                        if ROT_REST<0.03
                                break;
                        end
                else
                        ROT_REST=ROT_REST+RoT(x,y);
                end

        end

end
```

```
FINAL(1,1)=REVENUE;
%FINAL(k,2)=sparse(SEL);
FINAL(1,3)=C-ROT_REST;

clock_end=clock;                     % timer stops
RUNTIME=clock_end-clock_start        % calculate processing time
sparse(SEL)                          % display user selection
[M N]=max(FINAL(:,1));               % calculate maximum revenue and RoT value
REV=M                                % display the maximum revenue
ROT=FINAL(N,3)                       % display the RoT consumption
```

4). HAII Solution Subroutine

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% HAII    SOLUTION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% CALCULATE RoT AND REVENUE
RoT=10.^((Pt*TPR)./80).*10^(-10.5)*10^9;
revenue=rate*0.02.*price/1000;
C=4;
start=2;
d=1;
loop=1;
h=0;
FINAL=[];
ratio=revenue./RoT;
[ratio_row ratio_col]=size(ratio);

%SORT IN DECREASING ORDER

clock_start=clock;

while start >= 0
    REVENUE=0;
    ROT_REST=4;
    SEL=zeros(ratio_row,ratio_col);
    temp=0;
    serve=zeros(ratio_row,1);
    %start=k;
    [row,col,E_tmp]=find(ratio);
    [E,IX]=sort(E_tmp,'descend');
    [E_row E_col]=size(E);

    for i=d:E_row                                % sort by row
        x=row(IX(i),1);
        y=col(IX(i),1);
```

```
        if serve(x,1)==0
                ROT_REST=ROT_REST-RoT(x,y);

                 if ROT_REST >= 0
                        SEL(x,y)=1;
                        REVENUE=REVENUE+revenue(x,y);
                         serve(x,1)=1;

                        if ROT_REST<0.03
                                break;
                        end

                else
                        ROT_REST=ROT_REST+RoT(x,y);
                end

        end

    end

% second loop, start from the beginning
  for i=1:d-1                                                    %sort by row
     x=row(IX(i),1);
     y=col(IX(i),1);

     if serve(x,1)==0
        ROT_REST=ROT_REST-RoT(x,y);

        if ROT_REST >= 0
                SEL(x,y)=1;
                REVENUE=REVENUE+revenue(x,y);
                serve(x,1)=1;

                if ROT_REST<0.03
                        break;
                end

        else
                ROT_REST=ROT_REST+RoT(x,y);
        end

    end

  end

  %COLLECTING DATA AFTER EACH LOOP
  FINAL_TMP=[REVENUE d C-ROT_REST];
  FINAL=[FINAL; FINAL_TMP];
```

```
    t=E(start,1);
    start_tmp=start;
    z=t;
    while t==z
        start_tmp=start_tmp+1;

        if start_tmp<E_row
            z=E(start_tmp,1);
        else
            break;
        end

    end

    over=start_tmp-1;
    c=over+1-start;
    d=floor(rand*c)+start;

    start=start+c;
    if start > E_row
        break;
    end

end

clock_end=clock;
RUNTIME=clock_end-clock_start
[M N]=max(FINAL(:,1));
REV=M
ROT=FINAL(N,3)
STARTPOINT=FINAL(N,2)
```