BASE STATION LOCATION AND TERMINAL ASSIGNMENT PROBLEM IN WiMAX NETWORKS

by

Vahit Hanoğlu

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ABSTRACT

BASE STATION LOCATION AND TERMINAL ASSIGNMENT PROBLEM IN WiMAX NETWORKS

Although the base station location and terminal assignment problem in cellular networks has been extensively studied, the previous work in the literature cannot be directly applied to wireless networks that support multiple classes of connections, such as WiMAX. This situation arises from the fact that WiMAX incorporates several service flows at each subscriber station for QoS provisioning. In this thesis, time slots are used to represent the requirements and the constraints as opposed to the classical representation that uses the bit rates. An optimization problem, which includes both the base station location and the terminal assignment problems, is defined and formulated. As the solution, two deterministic heuristic algorithms, DEAR (DEploy-Assign-dRop) and CLEAN (Cluster-dEploy-AssigN), are proposed, which follow elimination and divide-and-conquer techniques, respectively. Integer linear programming (ILP) solutions show that formulating real life cases with the defined formulation and using heuristic algorithms are suitable and reasonable.

ÖZET

WİMAX AĞLARI'NDA BAZ İSTASYONU YERLEŞTİRME VE UÇBİRİM ATAMA PROBLEMİ

Baz istasyonu yerleştirme ve uçbirim atama problemleri ağırlıklı bir şekilde çalışılmış olmasına rağmen literatürdeki çalışmalar WiMAX gibi birden fazla bağlantı sınıflarını destekleyen kablosuz ağlar üzerine doğrudan uygulanamamaktadır. Bu durum, WiMAX'te her abonenin servis kalitesini artırmak için birçok servis akışının kapsanmasından ileri gelmektedir. Bu tezde, kullanıcı ihtiyaçları ve problem kısıtlamaları ikil hızı gibi klasik birimlerin aksine zaman dilimleri kullanılarak temsil edilmiştir. Hem baz istasyonu yerleştirme hem de uçbirim atama problemlerini kapsayan bir optimizasyon problemi tasarlanmıştır. Çözüm olarak iki adet rastgele olmayan deneysel algoritma, DEAR ve CLEAN, önerilmiştir. Bu algoritmalar sırasıyla, eleme ve böl-ve-yönet tekniklerini kullanmaktadır. Tam sayı programlama çözümleri gerçek hayattaki sorunları önerilen şekilde formülleştirmek ve önerilen çözümleri uygulamak makul ve yerinde olduğunu göstermektedir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

f^{nrt}	Required Slot for nrtPS and BE
f^{rt}	Required Slot for ertPS and rtPS
f^{UGS}	Required Slot for UGS
G_{bs}	BS Antenna Gain
G_{ss}	SS Antenna Gain
P_{ecc}	Path Loss of ECC-33
P_{tx}	Transmission Power
r^{nrt}	Traffic Requirement for nrtPS and BE
r^{rt}	Traffic Requirement for ertPS and rtPS
r^{UGS}	Traffic Requirement for UGS
s^{nrt}	Slack for nrtPS and BE
s^{rt}	Slack for ertPS and rtPS
u^{nrt}	User Satisfaction for nrtPS and BE
u^{rt}	User Satisfaction for ertPS and rtPS
β^{rt}	Sustained flow coefficient for ertPS and rtPS
β^{nrt}	Sustained flow coefficient for nrtPS and BE
ρ	Utilization of BS

LIST OF ABBREVIATIONS

ARQ	Automatic Repeat Request
ATM	Asynchronous Transfer Mode
B	Budget
BE	Best Effort
bps	Bit Per Secons
BPSK	Binary Phase Shift Keying
BS	Base Station
BSLP	Base Station Location Problem
BW	Bandwidth
BWA	Broadband Wireless Access
c	Cost of BS deployment
CBR	Constant Bit Rate
CID	Connection Identifier
CLEAN	Cluster-Deploy-Assign Algorithm
CPS	Common Part Sublayer
CS	Convergence Sublayer
d	Distance
DCD	Downlink Channel Descriptor
DEAR	Deploy-Assign-Drop Algorithm
DL	Downlink
DVE	Distributed Virtual Environment
ertPS	Extended Real-time Polling Service
EVDO	Evolution-Data Optimized
F	Frame Size
FCH	Frame Header Control
FDD	Frequency-Division Duplex
HiperMAN	High Performance Radio Metropolitan Area Network
HSPA	High Speed Packet Access
I	Set of SSs

ILP	Integer Linear Programming
J	Set of Candidate BS Locations
LOS	Line of Sight
LTE	Long Term Evolution
LWRBND	Lower Bound
MAC	Media Access Control
MIB	Management Information Base
MIMO	Multiple Input Multiple Output
MPEG	Motion Picture Expert Group
N	Thermal Noise
NLOS	Non Line of Sight
nrtPS	Non-real-time Polling Service
OFDM	Orthogonal Frequency-Division Multiplexing
PDU	Packet Data Unit
PHS	Packet Header Suppression
PHY	Physical
PL	Propagation Loss
PMP	Point-to-Multipoint
PS	Physical Slot
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RS	Relay Station
rtPS	Real-time Polling Service
S	Satisfied Customer Ratio
SC	Single Carrier
SDU	Segment Data Unit
SF	Service Flow
SFID	Service Flow Identifier
SME	Small-to-Medium Size Enterprise
SNR	Signal-to-Noise Ratio

SOHO	Small Office / Home Office
SS	Subscriber Station
TAP	Terminal Assignment Problem
TDD	Time-Division Duplex
TDM	Time-Division Multiplexing
TDMA	Time-Division Multiple Access
UCD	Uplink Channel Descriptor
UGS	Unsolicited Grant Service
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VBR	Variable Bit Rate
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WMAN	Wireless Metropolitan Area Network
xDSL	x High Data Rate

1. INTRODUCTION

The demand for being always online brings out the need for increasing bandwith requirements in wireless communication systems. Wireless Metropolitan Area Networks (WMAN) can provide Internet access for large cities [1]. Worldwide Interoperability for Microwave Access (WiMAX) is the commonly known name of IEEE 802.16, which is a solution to Broadband Wireless Access (BWA) [2]. WiMAX is a wireless broadband standard that promises high bandwidth over long-range transmission [3, 4]. As other wireless networks, it has a cellular structure. IEEE 802.16 is capable of supporting multimedia transmissions with differentiated quality of service (QoS) requirements.

The standard includes two operating modes: Point-to-Multipoint (PMP) mode and Mesh mode. The PMP mode is based on an infrastructure, which consists of one base station (BS) and several subscriber stations (SS) for each cell. Multiple subscribers are served by a centralized service provider. The Mesh mode has a distributed infrastructure in which each SS is connected to the BS via multiple hops. Each SS is able to establish direct communication to other SSs. In this thesis, we consider the base station location and terminal assignment problem only for the PMP mode.

IEEE 802.16 defines a service flow concept where a set of QoS parameters are used. These parameters include traffic priority, the maximum sustained traffic rate, the minimum tolerable rate, and the maximum burst rate. To support a wide variety of applications, five scheduling services are defined for the BS MAC scheduler: Unsolicited Grant Services (UGS), Extended-Real-Time Polling Service (ertPS), Real-Time Polling Service (rtPS), Non-Real-Time Polling Service (nrtPS), and Best-Effort service (BE).

In WiMAX, data exchange is performed using fixed-size frames. A frame is divided into a number of slots as predefined in the IEEE 802.16 standard. Slot is the minimum unit for WiMAX communication. The physical layer modulation and the communication end point cannot be changed during a slot. Enough slots are reserved by the scheduling of the BS for each SS according to the requirement.

One of the important concerns in BWA networks is the deployment of the minimum number of BSs, because of the deployment costs. Accordingly, another concern is the selection of the optimum BS locations among a set of predefined potential locations. If selecting the location of BSs not carefully, the number of served SSs and their perceived QoS may decrease. These concerns are known as the Base Station Location Problem (BSLP). It has been shown in the literature that while a uniform network layout is the best for uniformly distributed traffic, for non-uniform distributions BSs need to be located at the traffic hot-spots [5].

Another important requirement during the design process is to distribute the traffic over BSs by assigning approximately equal load on every BS. This can be formulated as the Terminal Assignment Problem (TAP). By distributing the traffic uniformly, the network infrastructure is efficiently used [6] and the load is evenly distributed. Also, it has been proven that higher channel homogenization provides better frequency assignment [7].

1.1. Contribution of the Thesis

The key contribution of this thesis is our approach to BSLP and TAP simultaneously by considering the service flow concept of WiMAX. The previous studies on cellular networks do not have such separation of the wireless traffic. Since the spirit of WiMAX is based on the separation of wireless traffic according to the service flow types, our work provides more flexible and suitable solutions for the composed problem in the WiMAX domain. Therefore, the existing techniques are insufficient for WiMAX. Also, the previous studies focusing on these problems have used the classical capacity and requirement metrics such as data rate (bps) and number of terminals. In the WiMAX domain, these metrics do not allow precise and realistic calculation of QoS related parameters. Instead, using slots enables us to handle QoS constraints by allowing different modulation and coding rates for each connection in accordance with the IEEE 802.16 standard.

To represent the combined problem, we have formulated a minimization problem in which the maximum of the BS utilizations is the objective while the budget, SS requirements, BS capacities, and the operating environment are the constraints. For small sized problems, integer linear programming (ILP) tools which perfectly handle the problem formulation have been used. For the solution of the larger real life scaled problems, two deterministic heuristic algorithms have been developed.

1.2. Organization of the Thesis

We first give an overview of IEEE 802.16 WiMAX technology in Chapter 2 where the PMP mode and the Mesh mode are briefly described. The frame structure of PMP mode is presented as background information. The literature survey is summarized in Chapter 3. It covers important studies about BSLP and TAP in wireless communication networks. The similarities and the superiorities of our work are compared against the previous studies. In Section 4.1, the problem formulation and definition are described. The minimization problem is presented as an ILP model. DEAR and CLEAN algorithms are studied in detail under Section 4.3. The computational experiments are presented in Chapter 5. The problem sets and their input parameters are shown. The results of DEAR and CLEAN and their comparison charts with CPLEX are presented in Section 5.3. Finally, Chapter 6 concludes this thesis by summarizing achieved performance of DEAR and CLEAN against CPLEX and suggesting several future works.

2. OVERVIEW of WiMAX

BWA emerges as an economically applicable alternative to the existing wire-based broadband access technologies as xDSL, cable modems, and fiber [8] for serving residential, small-to-medium-size enterprises (SME) and small office/ home office (SOHO) markets. To support applications like interactive video distribution, high-speed Internet access, and multimedia services, WiMAX is offered under the roof of BWA. In theory, a WiMAX BS can serve up to thousands of SSs in a range of 60 km for fixed stations and in a range of 20 km for mobile stations with the data rates up to 100 Mbps. The information about the nominal data rates [9] of emerging BWA systems are shown in Table 2.1. In addition, IEEE 802.16m provides 5 Gbps data rate for fixed subscribers.

Table 2.1. Ranges and Data Rates for Existing and Emerging BWA Systems.

System	**Nominal Data Rate**
WiMAX	70 Mbps
LTE	60 Mbps
HiperMAN	25 Mbps
HSPA	14 Mbps
UMTS	7.2 Mbps
EVDO	2.4 Mbps

The basis for the design and deployment of WMAN to provide BWA in the 10-to-60 GHz licensed frequency bands are clarified primarily in the IEEE 802.16 standard as a part of the specification for the radio interfaces. According to the specification of the radio interface in the IEEE 802.16 standard, the medium access control (MAC) layer and physical (PHY) layer of fixed point-to-multipoint BWA systems, WiMAX protocol can be implemented by any vendor.

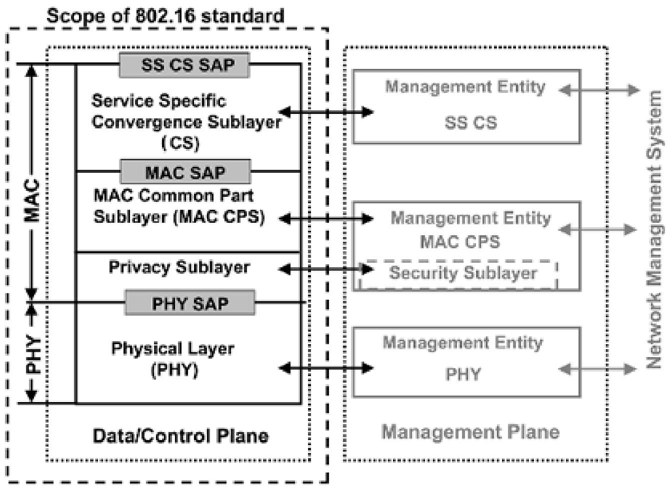

Figure 2.1. Scope of IEEE 802.16 radio interface standard.
(Redrawn according to [4])

This specification also includes the concept of multiple services and multiple service flow types. Multiple PHY layer specifications for the application's frequency bands are supported in the MAC layer with optimizations. For the systems operating between 10-to-60 GHz frequency band, a PHY layer specification is included in the standard. The scope of the radio interface specification is illustrated in Figure 2.1. All entities in this figure are applicable to the BSs and SSs in the network.

In the Convergence Sublayer (CS), network layer data units are converted into MAC segment data units (SDU) and they are mapped into 802.16 connections. By the function "Packet Header Suppression" (PHS), repetitive information in the network layer data unit headers are suppressed. This is followed by the forwarding of the payloads to the MAC Common Part Sublayer. Currently, there are only Packet CS and ATM CS, but for different network layer protocols, there can be different CSs.

In the MAC Common Part Sublayer (CPS), MAC SDUs coming from several CSs are converted into MAC packet data units (PDU). Either large SDUs are fragmented into smaller PDUs or small SDUs are concatenated to bigger PDUs. Also, management of connection establishment, bandwidth allocation, and QoS are handled in this layer. Similar to IEEE 802.11 [10], an acknowledgement mechanism is included.

In the last sublayer of CPS, which is the Security Sublayer, the encryption and authentication mechanism are implemented. MAC PDU's are encrypted and decrypted using an encryption algorithm allowed by the BS. This layer also utilizes a Key Management Protocol for secure key distributions.

The line-of-sight (LOS) propagation and minimal multipath fading over the transmission path are assumed in the IEEE 802.16-2002 PHY layer specification, which is designed for the 10- to 66-GHz band. IEEE 802.16-2009 standard supports several air interface variants [11] based on Orthogonal Frequency Division Multiplexing (OFDM) such as WirelessMAN-SC Release 1.0, Fixed WirelessMAN-OFDM, WirelessMAN-OFDMA, WirelessMAN-OFDM TDD Release 1.0, WirelessMAN-OFDM TDD Release 1.5, WirelessMAN-OFDM FDD Release 1.5, WirelessHUMAN.

Transmission performed by the BS is called the dowlink (DL). A single carrier (SC) modulation is selected on the DL on which the base station transmits a time division multiplex (TDM) signal, with individual subscriber stations assigned time slots in a serial manner. Transmission towards the BS is named the uplink (UL). Subscriber stations utilize the time division multiple access (TDMA) method to access the UL channel. Adaptive burst profiles on TDD or frequency division multiplex (FDD) are implemented to use different modulation and channel coding methods dynamically to the individual subscriber stations on a burst-by-burst basis, depending on the operating environment conditions [12].

Table 2.2. Channel sizes and number of PS per frame.

Channel Size (MHz)	**Symbol rate (MBd)**	**Bit rate (Mbps) QPSK**	**Bit rate (Mbps) 16-QAM**	**Bit rate (Mbps) 64-QAM**	**Number of PSs/Frame**
20	16	32	64	96	4000
25	20	40	80	120	5000
28	22.4	44.8	89.6	134.4	5600

In WiMAX, the communication between nodes is performed using fixed size structures called frames. According to the standard, only predefined values can be set as the frame duration. Once the frame duration set on the BS, it cannot be changed since it requires the resynchronization of all SSs. The smallest unit for WiMAX communication the is physical slot (PS). A frame consists of a fixed number of PS. In each PS, different modulation schemes can be used and only one SS is served during a PS. For several channel sizes, the predefined values for the number of PS per frame are shown in Table 2.2.

2.1. WiMAX Standardization

Even the fixed-broadband access market is addressed in the initial WiMAX specifications and products, the focus of the industry turned to enable mobility for expanding the market opportunities and deployment models. Mobile WiMAX is positioned and accepted as an IMT2000 technology and a promising contender for IMT-advanced or the so-called *4G systems*. According to WiMAX Forum tracking data [13], as of February 2011 there have been 582 deployments in 150 countries.

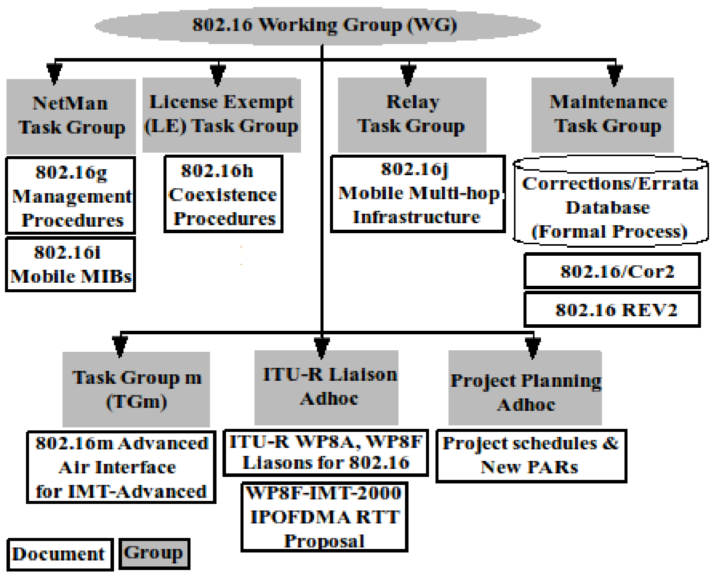

Figure 2.2. IEEE 802.16 work group organization.

(Redrawn according to [14])

The initial versions of the standard, 802.16a-2003 [15], focused on fixed access. Many new features and functionalities needed to support enhanced QoS, security, and mobility is included in the later versions, 802.16e-2005 [16] and 802.16-2009 [11]. Recently, the IEEE 802.16 Working Group [17] has been focusing on the specification for next-generation systems under the IEEE 802.16m Task Group. The IEEE 802.16 work group organization is shown in Figure 2.2. The following summarizes the history of IEEE 802.16 specifications as they relate to WiMAX technology [14]:

- IEEE 802.16 is the first version of the LOS air-interface standard with frequency range 10-66 GHz for fixed wireless access, completed in December 2001.
- IEEE 802.16a, the first version of the non-line-of-sight (NLOS) air-interface standards with frequency less than 11 GHz for fixed wireless access, was completed in January 2003.
- IEEE 802.16-2004 or IEEE 802.16d, completed in June 2004, was the first version of this standard that was considered by the WiMAX Forum to enable fixed broadband access, or the so-called "fixed WiMAX." The IEEE 802.16d based systems do not support mobility but they have been deployed as the last mile wireless broadband access alternative to cable and DSL.
- IEEE 802.16e-2005, also referred to as IEEE 802.16e, is an amendment to IEEE 802.16-2004 to add mobility and other MAC and PHY enhancements. It was completed in December 2005. This version of the standards, which is the basis for Mobile WiMAX Release 1.0 products, also adds scalable OFDMA and enhanced multiple input multiple output (MIMO) schemes in addition to some new MAC features such as hybrid automatic repeat request (ARQ) and multicast and broadcast services.
- IEEE 802.16-2009, previously called 802.16-REV2 before its finalization, is a revision of IEEE 802.16 that combines IEEE 802.16e-2005 along with corrigendum 2 and other pertinent amendments produced by IEEE 802.16 task groups, including IEEE 802.16i (management information bases -MIB- for fixed WiMAX), IEEE 802.16f (management procedures), and IEEE 802.16g (MIBs for mobile WiMAX), into one specification. This revision of this standard, which is the reference for Mobile WiMAX System Profiles Release 1.0/1.5 and includes clarifications and

enhancements in FDD mode of operation and other MACs, was completed in May 2009.

- IEEE 802.16m, the latest version of the IEEE 802.16 standards, is being developed as a candidate for IMT-advanced technologies and includes major enhancements in PHY and MAC to improve high mobility support, user experience, and system efficiency. IEEE 802.16m was completed in the fourth quarter of 2010.

2.2. WiMAX PMP Mode

WiMAX PMP mode utilizes an infrastructure, which consists of one base station and several subscriber stations for each cell as seen in Figure 2.3. Multiple subscribers are served by a centralized service provider. UL transmissions from SSs to BS occur in separate time slots, while BS transmits a burst of data in the DL subframe. Since the DL transmission is broadcast, a SS listening the data transmitted from BS is required to process only if the data is addressed to itself. UL is shared between SSs based on demand. Both DL and UL are duplexed either using FDD or TDD.

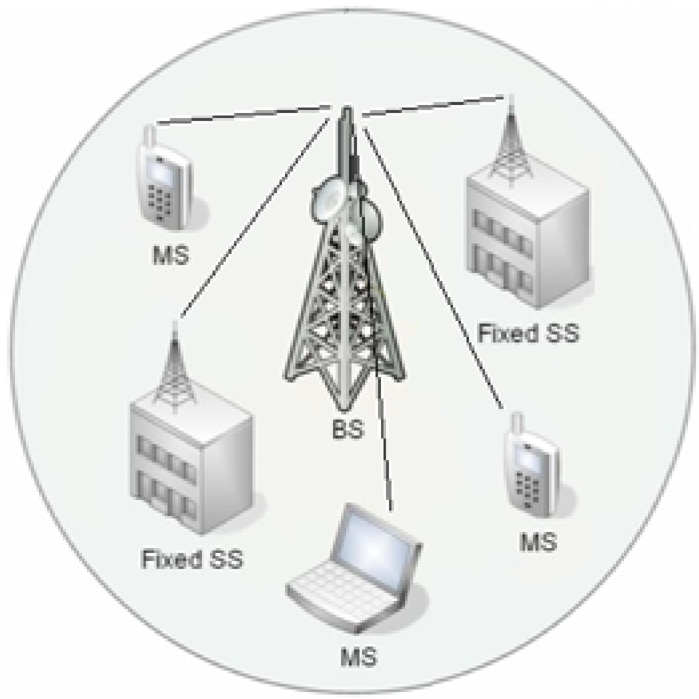

Figure 2.3. WiMAX PMP mode topology.

In every frame using the UL-MAP and the DL-MAP messages, UL and DL schedules are exchanged between the BS and the managed SSs. The MAC layer is connection-oriented and all data communication is associated with a connection. Each connection with its scheduling service (QoS type) parameters forms a service flow and is identified by a 16-bit connection identifier (CID).

A transport service that provides the transmission of MAC PDUs between two nodes is called Service Flow (SF). Each SF has a 32-bit identifier, called an SF identifier (SFID). An SS has a number of SFs at the same time, each with different service parameters. An SF defines various characteristics regarding the traffic supported. Each SF has a scheduling service, which defines QoS parameters regarding the traffic associated with the SF. There are five scheduling services in IEEE 802.16 standard.

- Unsolicited Grant Service (UGS): UGS has the highest priority over all other scheduling service types. Fixed size bandwidth allocation is done to support T1/E1 and Voice over IP (VoIP) services. It provides a constant bir rate (CBR) for a single connection. BS always allocates enough PS to these connections as agreed on SF establisment. So, the overhead of request/grant mechanism is avoided. SSs are assigned to receive and transmit during assigned time intervals. SS can use the poll me bit in the header to indicate that it wants to be polled to send data for another service. When the BS receives the poll me bit, it sends a polling message allowing SS to send data independent of UGS.
- Extended Real-time Polling Service (ertPS): ertPS is used for VoIP and similar applications, which have variable bit rates (VBR). PS allocation is similar to UGS and the avoidance of request/grant mechanism is also utilized. However, when the SS does not utilize the connection completely or not at all, the BS can decrease the allocation size. In the case of increased traffic, PSs are allocated again.
- Real-time Polling Service (rtPS): rtPS is designed to support VBR traffic such as Motion Picture Expert Group (MPEG) video traffic. PSs in UL are allocated for each rtPS SF. These PSs are used by the SS for bandwidth requests. This request/grant mechanism leads to an overhead in the MAC layer.

- Non-real-time Polling Service (nrtPS): Non-real-time applications use this class. A bandwidth mechanism similar to rtPS SFs is used, but the period of these requests is longer than that of the rtPS SFs. Contention based request opportunities are also used in this class.
- Best Effort (BE): SSs can only use bandwidth requests in the contention based periods. The BE never allocates dedicated slots for bandwidth requests to the BE SFs. This class is suitable for non-time-ciritical applications, such as file download.

2.2.1. PMP Mode Frame Structure

Although, many frame structures are defined for WiMAX PMP mode using different air interfaces, OFDM frame structure is mentioned in this section since we use OFDM air interface in our work. Detailed information about other frame structures of other air interfaces can be found in IEEE 802.16-2004 standard [4]. For OFDM air interface, there are two frame structures, which use TDD and FDD schemes for the duplexing method. Both frame structures are illustrated in the Figures 2.4 and 2.5.

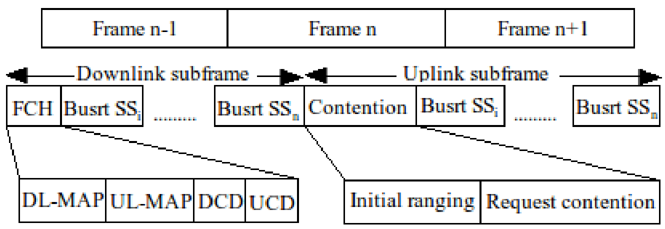

Figure 2.4. PMP OFDM frame structure using TDD.
(Redrawn according to [4])

Each frame consists of two subframes; DL and UL subframes. At the start of the DL subframe, there is a special part, Frame Header Control (FCH), which includes four messages; DL-MAP, UL-MAP, Downlink Channel Descriptor (DCD) and Uplink Channel Descriptor (UCD). DL-MAP and UL-MAP have the information about how the allocation of DL and UL subframes to SSs among connections are performed. The burst profile for each connection and the duration of each connection's allocation are included in these MAP messages. DCD and UCD of FCH describe how the channels will be used and the burst profiles for downlink and uplink, respectively. The following burst parts of the DL subframe contain the data for served SSs.

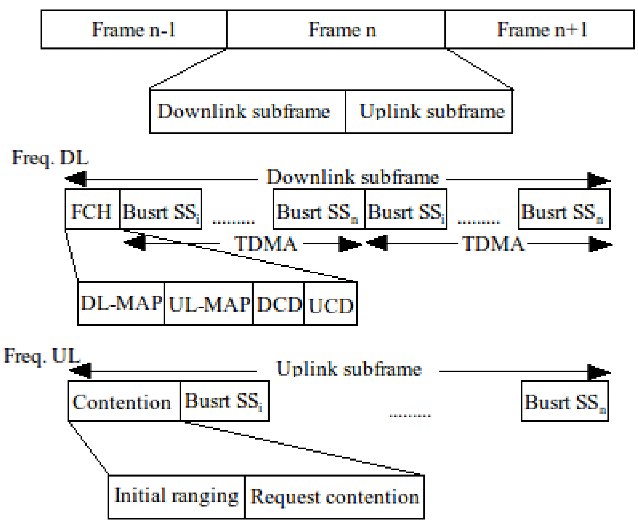

Figure 2.5. PMP OFDM frame structure using FDD.
(Redrawn according to [4])

There are contention-based parts in the beginning of the UL subframe. The first contention part is used for the initial ranging and the initialization of new SSs. The second contention part is used for bandwidth requests of SSs for nrtPS and BE connections. The length of these contention periods affect the overall performance of the UL subframe. The remainder of the UL subframe consists of the bursts towards to the BS for data transmission.

In TDD scheme, DL and UL transmissions are executed consecutively using the same channel. The length of a frame is the total of the sizes of DL and UL subframes. In FDD scheme, DL and UL transmissions are executed concurently using different channels. The length of a frame is equal to DL and UL subframes in FDD, because the subframes are not consecutive, but concurent.

2.3. WiMAX Mesh Mode

Because our work is on the PMP mode, skindeep information about the Mesh mode is given in this text. The detailed information can be found in the survey by Kas et. al [18]. In the Mesh mode, SSs can exchange data with each other in addition to the transmission executed with the BS. The infrastructure of this mode is presented in Figure 2.6. There is a centralized BS and multiple SSs which are directly connected to the BS or connected through several other SSs. A SS can send/receive a data packet to/from the BS by using other SSs on the route as relay nodes. In this way, SSs which are out of the BS's transmission range can join the network, and also the shadow effect due to obstacles can be overcome.

Each SS within the transmitting range of a SS is called a neighbour node. The parent node of a SS is one of the neighbour nodes over which the SS communicates with the BS. In the opposite direction, the communicating SS is called the child node.

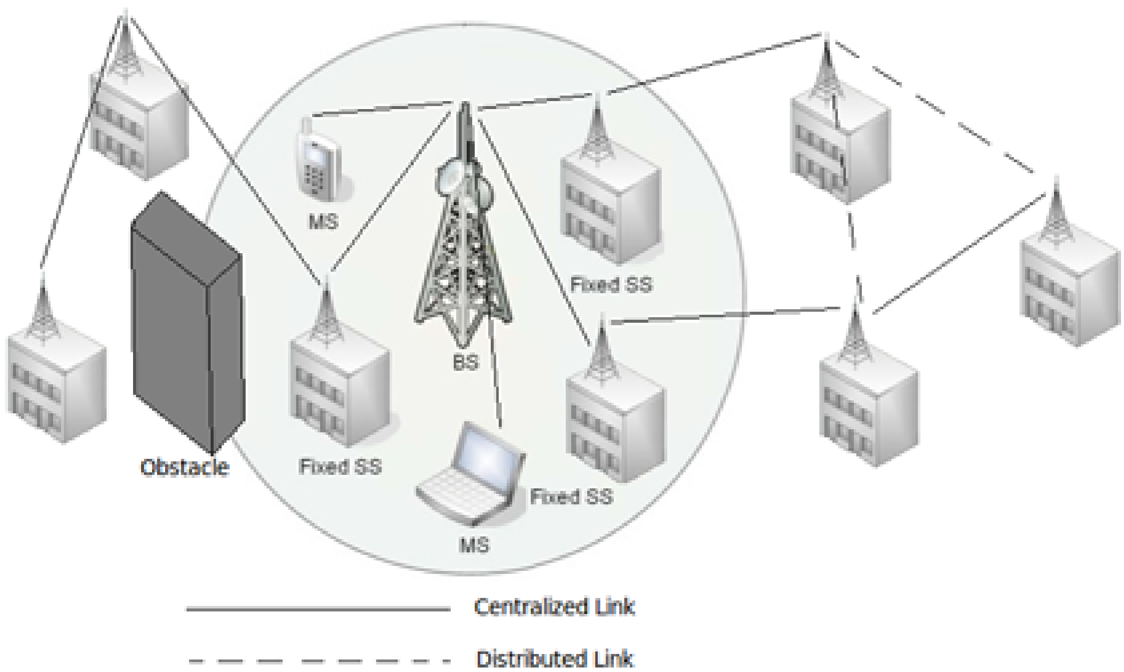

Figure 2.6. WiMAX Mesh mode topology.

In the Mesh mode topology there are two types of links between nodes, centralized links and distributed links. A centralized link is the link established between an SS and its parent node during the network initialization phase. A distributed link is the link formed with the neighbour nodes other than the parent node.

3. LITERATURE SURVEY

The concentrator location problem has been studied extensively in the literature [19, 20, 21]. The concentrator location problem evolved into the Base Station Location Problem (BSLP) with the evolution of the classical network into the wireless network, in which BSs correspond to the concentrators. The BSLP extends the concentrator location problem in its core, but it has several additional concerns. In the concentrator location problem, the communication is performed through the wired channel as opposed to the BSLP in which the communication is done on the air interface. Therefore, the constraints of the first problem generally depends on the construction cost of lines between nodes and the latency on these lines while the latter has cost contraints depending on the wireless communication concerns, such as noise, interference, and shadowing effect. Also, the cost of deploying BS towers is an extra cost constraint for the BSLP in addition to the hardware cost.

The Terminal Assignment Problem (TAP) [22] is as old as the concentrator location problem. Since the *terminals* are required components of the communication networks, their assignment to the base stations is a major factor that determines network performance. With the introduction of wireless communication, the constraints of the problem have changed but the name remained the same. In this problem, the aim is to assign as many terminals as possible to the BSs that have been deployed to known locations beforehand.

The TAP has been widely studied in the wireless network domain, but there are no recent studies specifically focusing on WiMAX. The previous works in the literature consider a variety of perspectives, but they have never differentiated the traffic requirements according to the service flows. Uniqueness of our work comes from approaching WiMAX with the concept of service flow types. We treat each service flow separately in the formulation and the solution. A novel metric, slot, which is more suitable than the classical metrics, such as bandwidth, for WiMAX is also introduced for BS capacities and SS traffic requirements.

The previous studies have the separation of BSLP and TAP; they handle the problems separately. When the problems are handled together, all considerations about BSLP and TAP are combined. In this way, a strictly constrained problem is created and a more efficient approach is applied.

Our literature survey is divided into two categories: studies on BSLP, and studies on TAP.

3.1. Studies on BSLP

In [23], the BS location planning is not the main focus but; the impact of BS location in MIMO using cooperative transmission is studied. The influence of the displacement of the BS location on BS cooperation scheme is considered. A system model is described in which the deployment area is divided into same sized hexagonal cells. Normally BSs are located at the center of each cell. In the case of inappropriate placement, the nearest points to the centers are preferred as BS locations. As the system design, the authors prefer to use two types of BS cooperation schemes as mentioned in a previous work on the same topic [24]: cooperation without data sharing and cooperation with data sharing. The performance of transmission algorithms with and without BS cooperation is evaluated through simulations. The effect of BS locations is tested by displacing them in the network with respect to signal-to-noise ratio (SNR) of the system.

In [25], a divide-and-conquer based clustering method is studied for the IEEE 802.16j Multi-Hop Relay Networks in addition to the development of the ILP formulation. The authors target the gain of execution time against service flow with the similar hardware as superior to other solutions. As the system model, the authors formulate a minimization problem which takes a set of inputs and includes a set of constraints. A state space reduction is applied to the problem as described in the previous work of the authors [26]. In the first step, the original problem is divided into a number of clusters, and then each cluster is solved as a separate problem. As a final optimization, issues arising at the boundaries of the clusters are reduced. The results of the study are represented by comparison, based on both the time taken to obtain a solution and the quality of the resulting solution. Problem instances are created in a random manner with realistic values. In another study [27], similat to the solution of WCDMA planning problems, k-means clustering algorithm is used for clustering, and each cluster is handled as an integer linear programming problem.

To maximize utility of the mobile multihop relay networks, an optimization framework for relay stations (RS) are presented in [28]. The placement and bandwidth reservation problems are combined in the study. An extended service with multiple mobile subscribers and one RS is considered as the problem related area of the whole system model. The problem is separated into three parts: Transmission Selection, Bandwidth Reservation, and RS Placement. The first part is solved with a dynamic looping algorithm depending on the RS utilization and the transmission quality. Bandwidth reservation is performed by using a Markov Decision Process [29] formulation and a Stochastic Programming formulation. The RS placement is solved as a maximization problem where the objective is the total revenue gained from subscribers.

For planning of BS and RS locations, two formulations are proposed in [30]: a complex ILP model and a simpler decomposition approach. The objective functions of both formulations include the cost of BS and RS deployments and the path loss between nodes. A shortcoming of this objective is the summation of terms with different units. For different sizes of the networks, the results of both solutions are compared and the appropriate matching is performed. No other studies are used for comparisons and for showing the quality of the work. To improve the network throughput for IEEE 802.16j networks, a relay station deployment mechanism is proposed in [31]. Bandwidth requirements of SSs and frame constraints are considered while RS deployments are being performed. A relay placement mechanism with maximal network capacity is applied as the solution. This mechanism consists of one partitioning phase and three identification phases. For each partition as the output of the first phase, the latter three phases are repeatedly executed to reach the solution.

In [32], heuristic algorithms inspired by Iterative-Search and Tabu-Search [33] approaches are introduced to model BSLP as an optimization problem for the UMTS network. Add and remove heuristic algorithms are proposed for this purpose. In the add algorithm, BSs are iteratively added to the solution while the remove algorithm takes a starting solution in which all sites are activated, and then BSs are iteratively deactivated. The bandwidth allocation and the RS location problems are studied in [34]. Decode amplify-forward scheme [35] is adopted for the relaying system and a system model is defined for the problems in the paper. Based on the selected scheme and the Gaussian approximation method [36], the optimal RS location and bandwidth division are computed for the maximization of the system capacity.

The work in this thesis can be classified together with [25], [27], [30], and [32] according to ILP formulation of the studied problems, but the latter studies fail to consider cost of BS and RS deployments. In [30], although the cost of BS and RS deployments are considered, the combination of the cost metric with other metrics in the formulation leads to a shortcoming. The terms in different metrics is not scaled into the equal interval which leads to unbalanced weighting of the terms. The traffic requirements are taken into account as constraints in [31] and [28]. However they fail to reflect WiMAX specific requirements per flow as we do with the sot concept. Add and drop based heuristics, which are also the underlying methods of our algorithms, are proposed for BSLP in UMTS networks in [32], but the results of this study are not compared with any previous work, any random solution, or results of optimization tools. On the contrary, we compare our results with the near best solutions of an ILP tool.

3.2. Studies on TAP

In [37], Heder et al. propose a genetic site diversity algorithm to adaptively optimize SS-BS assignments from the point of view of the interference in a BWA service area. In this study, the rain attenuation effect is considered and dynamically changing optimization scheme is executed. The uplink and downlink satisfaction of SSs are improved by assigning them to BSs with the proposed algorithm. The interference and noise are heavily important factors for the decision mechanism in the method. The authors have improved their work in their next study by providing various objective functions in which different goals are achieved [38].

An optimized traffic flow assignment is introduced in [39] to minimize the cost. The authors provide an analytical formulation for the problem. A volume-based charging model is adopted due to its simplicity and fairness for both users and network operators which is utilized today for mobile access in roaming scenarios. In the analytical formulation, the maximization of the total profit is targeted without violating the knapsack constraints [40]. They approximate to the optimal solution by a heuristic algorithm based on local search. It starts from initial problem solutions and repeatedly improves them towards the actual solution. Initial problem solutions are obtained through heuristic construction algorithms.

In [41], the terminal assignment problem is solved by a Hybrid Scatter Search algorithm, which was first introduced in [42]. The proposed algorithm is coupled with Tabu-Search algorithm [33] for locating the global minimum. The basic algorithm consists of five steps : generation and improvement of solutions, construction of the reference set, subset selection, combination, and reference set update. Here, an initial set of solutions is named as a reference set. The algorithm stops when the reference set cannot be updated, however regeneration of the reference set enchances the algorithmic scheme.

A polynomial time sequential algorithm is introduced in [43] to minimize the maximum load on concentrators. Also, the min-max load assignment is investigated in the study. As the problem inputs, a set of terminals and a set of concentrators with predefined locations are given. During the execution of the algorithm, breadth first tree constructions are utilized to improve the solution in which terminals and concentrators are the nodes and the assignments are the edges.

In Distributed Virtual Environments (DVE), such as online games, military simulations, the client assignment problem is studied by designing a solution that uses greedy algorithms [44]. The authors focus on virtual environments, which adopt a multi-server architecture and the zone-based approach, since it is commonly used in large scale virtual environments. The purpose of the study is to find a good assignment of clients to servers in order to enhance the interactivity of DVE where the interactivity has an opposite relation with the round-trip delay between clients and servers. Two greedy heuristic algorithms are proposed in order to reduce the round-trip client-to-server delay.

In this thesis, we consider the SNR as an important factor in assignment procedure,s similar to the considerations in [37], and [38]. These studies only consider the rain attenuation while we use the ECC-33 propagation model [45] for the operating environment. We target the minimization of the cost with constraints where an analogy can be made with [39]. However, in our problem we handle QoS constraints by considering the service flow concept of WiMAX. A similar but simpler restriction, which is in terms of delay is used in [41] and [44]. We consider the saturation of BSs with the novel metric. Similar considerations are taken into account with the classical capacity metrics in the studies [43] and [44] as concentrator and server saturations.

3.3. Other Related Studies

Besides the studies focused on the location planning and the terminal assignment problems, there are other studies on WiMAX such as an initial ranging algorithm [46] and hierarchical dimensioning [47] in which the SS requirements and BS capacities are considered as constraints. However, using these requirements without considering the service flow concept does not reflect the core of WiMAX. Therefore, they are not considered in this thesis.

4. BASE STATION LOCATION AND TERMINAL ASSIGNMENT JOINT PROBLEM

In this thesis, we focus on the base station location and terminal assignment problem for minimizing the maximum utilization of BSs while not exceeding the total budget and not violating the other constraints. By minimizing the maximum utilization, we provide the network infrastructure be used in a balanced manner due to channel homogenization as proven in [6]. For the sake of simplicity, we group extended real-time and real-time polling services into real-time; non-real-time polling and best-effort services into non-real-time without loss of generality. Thus, we end up with three flow types namely guaranteed, real-time, and non-real-time.

4.1. Problem Formulation

The BSLP aims to find the optimal points to place BSs in the area where the wireless network is deployed. On the other hand, TAP aims connecting the subscribers to the most suitable BSs. By considering network efficiency, the combination of these two problems is heavily constrained since many different factors influence the positioning of BSs and the terminal assignment decisions.

4.1.1. Input Parameters

Given the number of SSs with traffic requirements, capacities of BSs, candidate BS locations with deployment costs, topographic information of the area, and a total budget, our problem is to deploy BSs and assign SSs without violating the constraints. The problem inputs are defined as follows:

B	:	Total budget
$J = \{j \mid 1 \leq j \leq m\}$	:	Candidate BS deployment locations
$I = \{i \mid 1 \leq i \leq n\}$	:	Subscribers

c_j	$(j \in J)$	: Cost of deployment at location j
$\vec{r_i} = \begin{pmatrix} r_i^{UGS} \\ r_i^{rt} \\ r_i^{nrt} \end{pmatrix}$	$(i \in I)$	: SS traffic requirements
β_i^{rt}	$(i \in I)$	: Sustained flow coefficient for rtPS
β_i^{nrt}	$(i \in I)$	: Sustained flow coefficient for nrtPS
d_{ij}	$(i \in I, j \in J)$	: Distance between SS_i and BS_j
s^{rt}		: Slack for rtPS
s^{nrt}		: Slack for nrtPS
u^{rt}		: Percentage of aimed user satisfaction for rtPS
u^{nrt}		: Percentage of aimed user satisfaction for nrtPS
S		: Satisfied customer ratio (number of assigned SS / number of total SSs)

The total budget (B) defines the maximum budget the designer is willing to spend. Candidate BS locations (J) is the set of locations where the service provider is able to rent for deploying BSs. Subscribers (I) is the set of WiMAX users to be serviced. Deployment cost of base station j (c_j) varies for urban, suburban, and rural areas.

For simplicity, we have three service flow types: guaranteed, real-time, and non-real-time. Each subscriber has different requirements ($\vec{r_i}$) for each service flow. Even though the requirements of each service flow are given, the sustained flows for real-time and non-real-time traffic for each user are obtained according to the β coefficient since a connection sustains only a fraction of the requested bandwidth in the long run. In addition to β, there is another parameter, u, for the targeted user satisfaction for these service flows.

A slot is the smallest unit of a WiMAX frame, in which only one SS is served with an unchanged modulation scheme. Different SSs with different modulation schemes can be used in each slot. We partition the slots in a WiMAX frame into three groups to decide the number of slots that will be assigned to different service flows. This partitioning is done by using the slack coefficients. There are two slack coefficients given for real-time (s^{rtPS}) and non-real-time service (s^{nrtPS}) flows. The coefficient for guaranteed service flow is easily calculated by subtracting these two coefficients from 1.

The distance d_{ij} between each SS_i and BS_j is used to calculate the propagation loss for deciding the modulations to be used. As the last parameter, the ratio of satisfied customers (S) relaxes the number of subscribers served.

4.1.2. Internal Variables

ρ^j	: Utilization of BS_j
ρ^{max}	: Network-wide maximum BS utilization
q	: WiMAX service flow type (UGS, rtPS, or nrtPS)
$R(d)$	: Maximum data rate for distance d
BW	: Available bandwidth for a BS
F	: Frame size (in terms of slots)
$f_{ij}^q = F \cdot r_i^q \cdot R(d_{ij})/BW$	: Number of required slots for service flow q in a frame to assign SS_i to BS_j

The fixed frame size, F, represents the capacity of a BS. It consists of time slots. The possible values for F are predefined in the IEEE 802.16 standard [4]. While performing the terminal assignments, a number of slots in a frame are reserved for each subscriber according to the subscriber requirements.

The function $R(d)$ is used to calculate the maximum data rate between a SS and its serving BS according to the distance d between them. In this function, firstly SNR is found by using d and the propagation model depending on the operation area

$$SNR(dB) = P_{tx} - PL + G_{bs} + G_{ss} - N$$

where P_{tx} is the transmission power, PL is the propagation loss, G_{bs} and G_{ss} are BS and SS antenna gains respectively and N is the thermal noise. Then, we select the modulation scheme using the SNR-modulation table given in [48]. Finally, by using the orthogonal frequency division multiplexing specifications [4], the maximum data rate is calculated according to the given modulation scheme.

Since WiMAX BSs use a fixed size frame, the required number of slots, f, for a specific flow is a more precise way of representing the requirement of a subscriber. The slot is a more natural way of expressing the assignment of resources in WiMAX compared to the classical use of bps, because different modulation schemes can be used for different subscribers in the same frame. Therefore, the use of variable f includes the effect of distance between SS and BS in the requirement. The representation of the request in terms of slots enables incorporating the effect of the selected modulation (as a factor of the distance between BS and SS) in the assignment of resources. Furthermore, the slot is the smallest unit of assignment in resource management in WiMAX.

4.1.3. Decision Variables and The Objective Function

The following binary variables are the decision variables of the problem. The binary variables in Eq. 4.1 represent if a candidate BS exists at location j and the second set of variables in Eq. 4.2 show whether SS_i is connected to BS_j.

$$y_j = \begin{cases} 1, \text{ if } BS_j \text{is deployed} \\ 0, \text{ otherwise} \end{cases} \qquad (j \in J) \tag{4.1}$$

$$x_{ij} = \begin{cases} 1, \text{ if } SS_i \text{assigned to } BS_j \\ 0, \text{ otherwise} \end{cases} \qquad (i \in I, j \in J) \tag{4.2}$$

Our objective function is the minimization of the maximum BS utilization

$$min(\rho^{max}) \tag{4.3}$$

subject to the following constraints:

$$\sum_{i}^{n}\sum_{j}^{m} x_{ij} \geq S \cdot N(I) \tag{4.4}$$

$$\sum_{j}^{m} c_j \cdot y_j \leq B \tag{4.5}$$

$$\sum_{i}^{n} \lceil f_{ij}^{UGS} \rceil \cdot x_{ij} \leq (F - \lfloor F \cdot s^{rt} \rfloor - \lfloor F \cdot s^{nrt} \rfloor) \cdot y_j \tag{4.6}$$

$$\sum_{i}^{n} \lceil f_{ij}^{rt} \cdot \beta_i^{rt} \cdot u^{rt} \rceil \cdot x_{ij} \leq \lfloor F \cdot s^{rt} \rfloor \cdot y_j \tag{4.7}$$

$$\sum_{i}^{n} \lceil f_{ij}^{nrt} \cdot \beta_i^{nrt} \cdot u^{nrt} \rceil \cdot x_{ij} \leq \lfloor F \cdot s^{nrt} \rfloor \cdot y_j \tag{4.8}$$

$$\sum_{j}^{m} x_{ij} \leq 1 \tag{4.9}$$

In Eq. 4.4, we guarantee that the ratio of the number of assigned subscribers to the total number of subscribers is greater than or equal to S. Please note that S can be chosen as 1 for satisfying all SSs. With the restriction in Eq. 4.5, we control the number of BSs not to exceed the total budget. In Eq. 4.6, it is guaranteed that the capacity reserved for guaranteed service flow for each BS is not exceeded by the total requirements of subscribers connected to that BS. Similar guarantees for real-time and non-real-time service flows are provided in Eq. 4.7 and Eq. 4.8, respectively.

In Eq. 4.6 - 4.8, the ceiling function is used to calculate the actual number of slots required for a subscriber since the multiplication of f, β, and u can give a non-integer number. To ensure that the subscriber gets the required number of slots, the minimum integer number of slots that is larger than the required number of slots is given. In the right hand side of the equations, the floor function is used to calculate the capacity reserved for each service flow at a BS as an integer number of reserved slots. In Eq. 4.9, it is guaranteed that a SS is not assigned to more than one BS.

4.2. Complexity of The Problem

As separate problems, BSLP and TAP are already non-polynomial (NP) hard problems. When they are combined and strictly constrained, the joint problem becomes harder. The number of constraints and the number of decision variables of the problem depend on the number of BSs and SSs. Let m be the number of BSs and n be the number of SSs. Then, the number of constraints is $3 \cdot m + n + 2$ and the number of decision variables is $m + m \cdot n$. Since m and n can be very large for urban network planning cases, the overall complexity of the problem becomes prohibitive for ILP tools like CPLEX. Hence, we propose heuristic algorithms for solving this problem. However, we use CPLEX for the small size problems.

4.3. DEAR and CLEAN Algorithms

In this section, we present two deterministic heuristic algorithms which minimize the maximum BS utilization without violating the constraints. DEAR, which is a kind of drop algorithm, starts with a fully BS-deployed and fully SS-assigned environment. Then it drops BSs one by one and re-orders the assignments to satisfy the constraints. CLEAN starts with an environment without any deployment and assignment. Then it deploys a number of BSs and assigns SSs to those BSs while not violating the constraints.

As the first step, a requirement list is created with the size of $N(I) \times N(J)$ according to the given input in the ascending order of requirements. In each element of the list, the (SS_i, BS_j, f_{ij}) triplet is stored. This triplet denotes that SS_i needs f_{ij} slots to be served by BS_j. If SS_i is out of the range of BS_j, the value of f_{ij} is set to infinity. Each SS has a set of candidate BSs. If a SS resides in the cell of a BS, then that BS is in the candidate set of that SS.

4.3.1. Procedures of DEAR and CLEAN

DEAR and CLEAN utilize three procedures: *Assignment of SSs*, *Minimization of the Maximum Utilization*, and *Dropping Excessive SSs*. Details of these procedures are shown in Figures 4.1-4.3.

In the *Assignment of SSs* procedure, we assign each unconnected SS to one of its candidate BSs without violating the constraints.

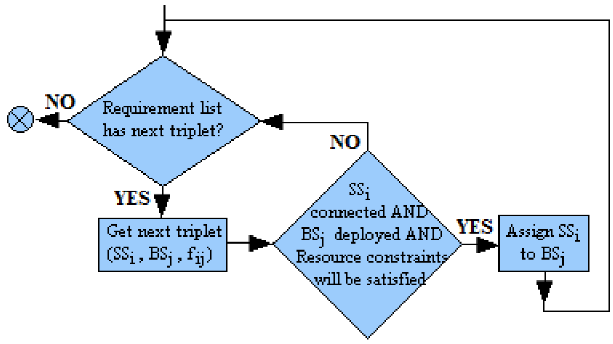

Figure 4.1. Assignment of SSs procedure.

(func_SS_assignment)

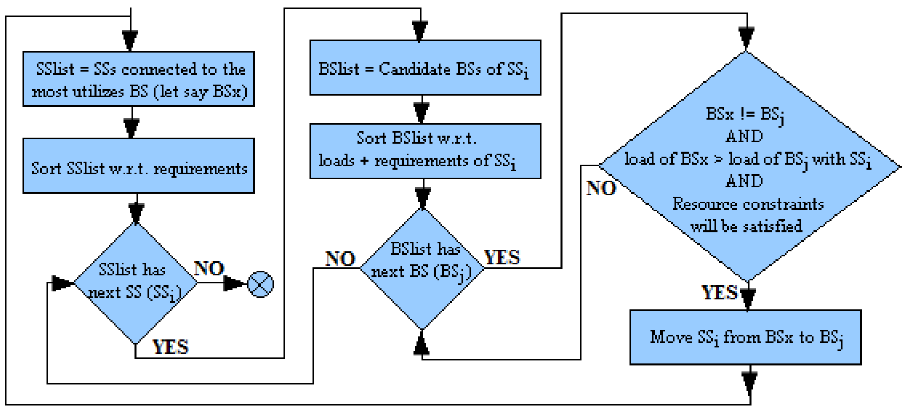

Figure 4.2. Minimization of the Maximum Utilization procedure.

(func_maxUtil_minimization)

The algorithms minimize the maximum utilization of BSs in the *Minimization of the Maximum Utilization* procedure. This procedure executes a loop until no minimization can be achieved. In each turn of the loop, the network-wide maximum utilization is reduced (if possible) and handed over BSs.

The *Dropping Excessive SSs* procedure is used when the number of assigned SSs is larger than the targeted number of SSs after the initial assignments. Excessive SSs are disconnected one by one until the satisfaction ratio of SSs is decreased to S as in Eq. 4.4.

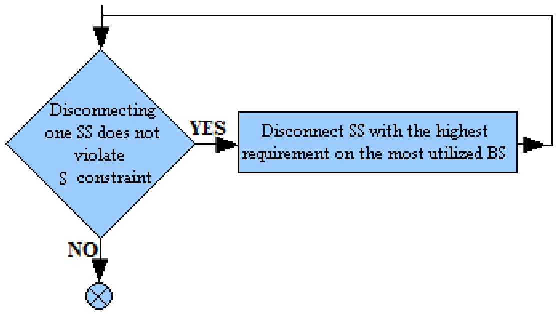

Figure 4.3. Dropping Excessive SSs procedure.
(func_SS_dropping)

4.3.2. CLEAN Algorithm

In this algorithm, the deployment locations among the candidate locations are selected by running a k-means clustering algorithm [49] on SS locations. In lines 2-7, k-means algorithm is executed more than once to find the candidate locations which best fit to the total budget, B. The initial value for k is calculated in line 1. Then, BS deployments are performed once and never changed again. After deployment, SS assignment and minimization of the maximum utilization procedures are executed in lines 9 and 10, respectively. In the rest of the algorithm, lines 11-16, either new assignments are done or excessive ones are deleted according to the user satisfaction ratio.

```
 1. k = floor(total cost of BSs / average cost of BSs)
 2. find k locations by using k-means algorithm
 3. select the closest candidate locations from them
 4. if cost constraint will be violated
 5.     decrement k by 1
 6.     goto line 2
 7. endif
 8. deploy BSs on the selected candidate locations
 9. func_SS_assignment()
10. func_maxUtil_minimization()
11. if S constraint is violated
12.     func_SS_assignment()
13. else
14.     func_SS_dropping()
15.     func_maxUtil_minimization()
16. endif
```

Figure 4.4. CLEAN Algorithm.

4.3.3. DEAR Algorithm

In the first two lines of the algorithm, one BS is deployed at each candidate location and the *Assignment of SSs* procedure is executed for the initial assignments. To satisfy the cost constraint, in lines 3-6, BSs are dropped according to the cost-based utilization, and new SS assignments are performed. The cost-based utilization is the ratio of load to cost for a BS. After satisfying the cost constraint, the *Minimization of the Maximum Utilization* procedure is executed in line 7. Finally, according to the user satisfaction ratio, secondary assignments are performed in line 9, or excessive assignments are deleted and utilization minimization is re-executed in lines 11 and 12.

```
deploy one BS at each candidate location
func_SS_assignment()
while cost constraint is violated
    drop the least cost utilized BS
    func_SS_assignment()
endwhile
func_maxUtil_minimization()
if S constraint is violated
    func_SS_assignment()
else
    func_SS_dropping()
    func_maxUtil_minimization()
endif
```

Figure 4.5. DEAR Algorithm.

5. COMPUTATIONAL EXPERIMENTS

This section compares the proposed algorithms, DEAR and CLEAN, against the solutions of CPLEX where a variety of test cases including different densities of maps and variable SS requirements are used as problem instances.

5.1. Operating Environmnet

An urban area model is used in which ECC-33 propagation model [45] shows the closest agreement with the real environment measurements among a variety of propagation models [50, 51]. In this model, both path loss and antenna gains are included. Therefore, if we rewrite the SNR equation, we get

$$SNR(dB) = P_{tx} - P_{ecc} - N$$

where P_{ecc} is the path loss calculated by ECC-33 model. For the thermal, noise we use Johnson-Nyquist noise formula [52]. Values used for SNR calculation are represented in Table 5.1.

Table 5.1. SNR Calculation Parameters.

Parameter Name	**Value**
Temperature	27 C°
Height of BSs	50 m
Average height of SSs	5 m
Operating frequency	3.5 GHz
Transmission Power	30 Watts

For the frame size F and the available bandwidth BW, we use 4000 slots and 20 MHz, respectively, as defined in the IEEE802.16 standard [4]. Table 5.2 shows the relationship between SNR, modulation scheme and the maximum data rate as described in [48].

Table 5.2. SNR, modulation, and data rate relations (BW: 20 MHz).

SNR(dB)	Modulation Scheme	Max. Data Rate (Mbps)
6.4	BPSK - 1/2	8
9.4	QPSK - 1/2	16
11.2	QPSK - 3/4	24
16.4	16 QAM - 1/2	32
18.2	16 QAM - 3/4	48
22.7	64 QAM - 2/3	64
24.4	64 QAM - 3/4	72

5.2. Test Cases

We execute the experimental studies in two separate parts, *the comparison with ILP* and *the effect of factorized parameters*. In the first part, we compare DEAR and CLEAN against the ILP tool, CPLEX, and lower bounds by solving a variety of problem instances. These instances are created by factorizing the parameters for a number of different scenarios. The second part is executed for observing the behaviour of DEAR and CLEAN together with the CPLEX solution by changing a single parameter while all other parameters are fixed. For this purpose, several parameters are factorized for these tests. Five different values are considered for each factorized parameter.

5.2.1. Comparison with ILP

5.2.1.1. Problem Sets. We use two sets of problem instances for the comparison CPLEX solution and the lower bounds. *The small set* has instances with 1000-2500 SSs while *the large set* contains 4000-10000 SSs. By employing these sets, we analyze the performances of DEAR, CLEAN, and the CPLEX solution for problems of different size. In the small set, DEAR and CLEAN produce results that are close to CPLEX results and the lower bounds. In the large set, the superiority of DEAR and CLEAN are proven by finding better results than CPLEX and much closer results to the lower bounds.

In each set, the problem instances are grouped as scenarios. The first and second sets have base, dense map, sparse map, light load, and heavy load scenarios. From the base scenario to the dense map scenario, the number of SSs increases, and consequently the sparse map scenario has fewer SSs. The requirements of SSs in the heavy load scenario are higher than those of the base scenario while the requirements of SSs in the light load scenario are lower. The number of SSs and the map size in the large set scenarios are four times that of the small set scenarios.

Hundred problem instances, for each of the ten scenarios with ten instances, are created for the experiments. Each problem instance is solved by our deterministic heuristic algorithms and the quality of their results are measured by comparing them with the results of CPLEX. The input values for the base scenario in the small set are shown in Table 5.3.

For the small set, the number of randomly distributed SSs is increased to 2500 in the dense map scenario and decreased to 1000 in the sparse map scenario. In the heavy load scenario, requirements of SSs for UGS, rtPS, and nrtPS are between 0.45 - 0.75 Mpbs, 0.35 - 0.50 Mbps, and 0.30 - 0.4 0 Mbps, respectively. Also, S is decreased to 0.7 to let the algorithms find feasible solutions. For the light load scenario, the requirements are between 0.20 - 0.40 Mbps, 0.15 - 0.25 Mbps, and 0.10 - 0.15 Mbps for each service flow.

Table 5.3. Input values for the base scenario.

Input Name	**Value**
Operation area	10 km x 10 km
Communication range	2975 m
Number of candidate BSs	80
Number of SSs	1750
Total budget	$500K
Costs of BSs	Between $15K and $25K
Slack for real-time service flow	0.20
Slack for non-real-time service flow	0.15
Satisfied Customer Ratio (S)	0.8
Aimed user satisfaction ratio for rtPS	0.8
Aimed user satisfaction ratio for nrtPS	0.5
Sustained flow of rtPS for all SSs	40%
Sustained flow of nrtPS for all SSs	60%
Requirement for UGS	Between 0.25 - 0.45 Mbps
Requirement for rtPS	Between 0.20 - 0.35 Mbps
Requirement for nrtPS	Between 0.20 - 0.30 Mbps

For all scenarios of the large set, the map size is enlarged to 20 km x 20 km, the number of candidate BSs is increased to 300, and the total budget is raised to $2M. The number of randomly distributed SSs for the dense map, and the sparse map scenarios are 10000 and 4000, respectively. For the light load, and the heavy load scenarios, the number of randomly distributed SSs is set to 7000. The values of other input parameters remain same as the values in the small set. As the experiment environment, we use a blade system with 10 nodes running Linux CentOS where each node has 2 processors with quadcores and 8 GB memory.

5.2.1.2. Results. The averages of results of the DEAR and CLEAN algorithms and CPLEX (CX) for the small and large sets are listed in Tables 5.4-5.7. The detailed information about individual instances can be found in Appendix A. Also, lower bounds (LB) and the gap values with respect to the lower bounds (G_LB) are shown in the tables. Each lower bound is calculated by CPLEX while solving the related problem instance using Linear Programming Relaxation. The size of problems and the duration of executions affect the value of the lower bound. We run CPLEX for 2 hours for each instance. As the size of the problem decreases, a tighter lower bound value is calculated. By keeping the execution duration constant, the size of the problem remains as the only factor that affects the lower bound values. In addition, for a clear comparison of the algorithms with CPLEX, the gap values with respect to CPLEX results (G_CX) are given in the tables. The G_LB and G_CX values for each instance are calculated as follows:

$$G\_LB = \frac{[DEAR|CLEAN] - LB}{LB}$$
$$G\_CX = \frac{[DEAR|CLEAN] - CX}{CX}$$

In Tables 5.4 and 5.5, the comparisons of the average results for the small set are represented. Each result in the tables is the average of all ten instances. The detailed information of individual instances is represented in the tables in Appendix A.

For the light load and the base scenarios, the results show that DEAR generally outperforms CLEAN. However, the results of both algorithms are worse than the CPLEX results. In the base scenario, DEAR achieves far better results than CLEAN, and their results approach CPLEX results. While the requirements of SSs increase as in the heavy load scenario, CPLEX starts to lose its supremacy over DEAR and CLEAN. Also, CLEAN becomes superior against DEAR in heavy load scenarios. Its clustering module makes the algorithm more suitable for heavy traffic requirements.

Table 5.4. Comparisons of different loads in the small set.

	LWRBND	**CPLEX**	**DEAR**	**CLEAN**
Light Load	0.2365	0.3554	0.4251	0.4402
Base	0.2990	0.4402	0.5154	0.5484
Heavy Load	0.4110	0.5916	0.7068	0.7002

While the density of the operating environment increases, DEAR and CLEAN find closer results to CPLEX results. In more complex problems as in the dense map scenario, DEAR and CLEAN outperform CPLEX. Also, CLEAN outperforms DEAR in the dense map scenario.

Table 5.5. Comparisons of different map densities in the small set.

	LWRBND	**CPLEX**	**DEAR**	**CLEAN**
Sparse Map	0.1579	0.2588	0.3162	0.3368
Base	0.2990	0.4402	0.5154	0.5484
Dense Map	0.4400	0.9439	0.7604	0.7594

From the whole picture of the small set results, it can be concluded that CPLEX is stressed to find better solutions than DEAR and CLEAN while the problem complexity increases. Furthermore, the results returned by CPLEX render to be useless since it finds values greater than 0.95 for BS utilizations while DEAR and CLEAN find values near 0.75 as seen in the dense map scenario. While CPLEX is executed for two hours to find solutions, DEAD and CLEAN find the solutions under 30 seconds in the same environment. The execution time is important because of the renewal of deployments with the arrival of new subscribers. Another important point is the insufficiency of CPLEX against the real life cases. Despite executing for six days on our computation servers, CPLEX did not find solutions to many of the real life problems and prematurely terminated with memory error.

Table 5.6. Comparisons of different loads in the large set.

	LB	**CX**			**DEAR**			**CLEAN**		
	ρ^{max}	ρ^{max}	G_LB	Success	ρ^{max}	G_LB	G_CX	ρ^{max}	G_LB	G_CX
Light Load	0.2033	0.9369	361	50%	0.4081	100	-57	0.4458	120	-53
Base	0.2188	0.9797	347	40%	0.4122	88	-58	0.4470	104	-55
Heavy Load	0.3843	0.9912	158	60%	0.6707	75	-33	0.7027	83	-29

Due to the computation power and execution time limitations, the lower bound values for the large set are not tight as calculated in the small set. Therefore, the G_LB values in the large set are larger than those in the small set. In this case, the G_CX values, which are tighter and more meaningful than the G_LB values, are used for the comparison of DEAR and CLEAN with CPLEX. A G_LB value is as meaningful as the closeness of its LB and CX values. In Tables of Appendix A, where the results of individual instances are represented, there are many rows with dashes. These rows mean that for the related problem instance, CPLEX cannot find a solution in the given execution time and consequently cannot find a lower bound value. This prevents the calculation of the G_LB and G_CX values for these instances.

Table 5.7. Comparisons of different map densities in the large set.

	LB	**CX**			**DEAR**			**CLEAN**		
	ρ^{max}	ρ^{max}	G_LB	Success	ρ^{max}	G_LB	G_CX	ρ^{max}	G_LB	G_CX
Sparse Map	0.1523	0.9784	542	100%	0.2979	96	-70	0.3361	120	-66
Base	0.2188	0.9797	347	40%	0.4122	88	-58	0.4470	104	-55
Dense Map	-	-	-	0%	0.7280	-	-	0.7720	-	-

In the large set, the real life examples are tested. According to the results represented in Tables 5.6 and 5.7, DEAR and CLEAN find a solution for each instance where CPLEX cannot find a solution for the majority of the instances. The ratio of feasible solutions to the number of problem instances is represented by the columm "*Success*." Moreover, for all the cases studied, DEAR and CLEAN find better results than CPLEX. For the dense map scenario, CPLEX has 0% as the success ratio. For none of the problem instances, it cannot find a solution. The result of the minimization problem, which is the maximum BS utilization, becomes better as it decreases. Depending on the size of problem, DEAR and CLEAN find the solution at most in two minutes while CPLEX cannot find any solution even it runs for days until arising an insufficient memory error. It is completely reasonable to conclude that our deterministic heuristic algorithms are more suitable for WiMAX planning problems, because the real life cases involve large areas and many subscribers with heavy service requirements.

5.2.2. The Effect of Factorized Parameters

For each test value of the factorized parameters, ten problem instances are created. For rendering the effect of the parameter, the average result value of ten instances are calculated and utilized.

Table 5.8. Fixed parameter values.

Input Name	**Value**
Communication range	2975 m
Number of candidate BSs	300
Total budget	$2M
Costs of BSs	Between $15K and $25K
Slack for real-time service flow	0.20
Slack for non-real-time service flow	0.15
Satisfied Customer Ratio (S)	0.8
Aimed user satisfaction ratio for rtPS	0.8
Aimed user satisfaction ratio for nrtPS	0.5
Sustained flow of rtPS for all SSs	40%
Sustained flow of nrtPS for all SSs	60%

On the charts in Figures 5.1-5.3, the values are the average of the results of ten instances for each test value. If DEAR, CLEAN, or CPLEX find solutions for all ten instances, a large icon is used to represent the average result. If none of the ten instances can be solved, no icon is put on the chart for the corresponding input value and only a gap is represented. In the case where some instances are solved and some cannot be solved, a smaller icon is used to show the average value. Also, the success percentages are written next to the small icons to show how many instances are solved and how many cannot be solved. The fixed parameters for all test cases are listed in Table 5.8.

5.2.2.1. Effect of the Number of Subscribers. To observe the effect of subscriber density on the fixed size area, five different values, 2000, 4000, 6000, 8000 and 10000, are used as the number of subscribers while all other input parameters are fixed. Also, the requirements of subscribers are set as the values in the base scenario.

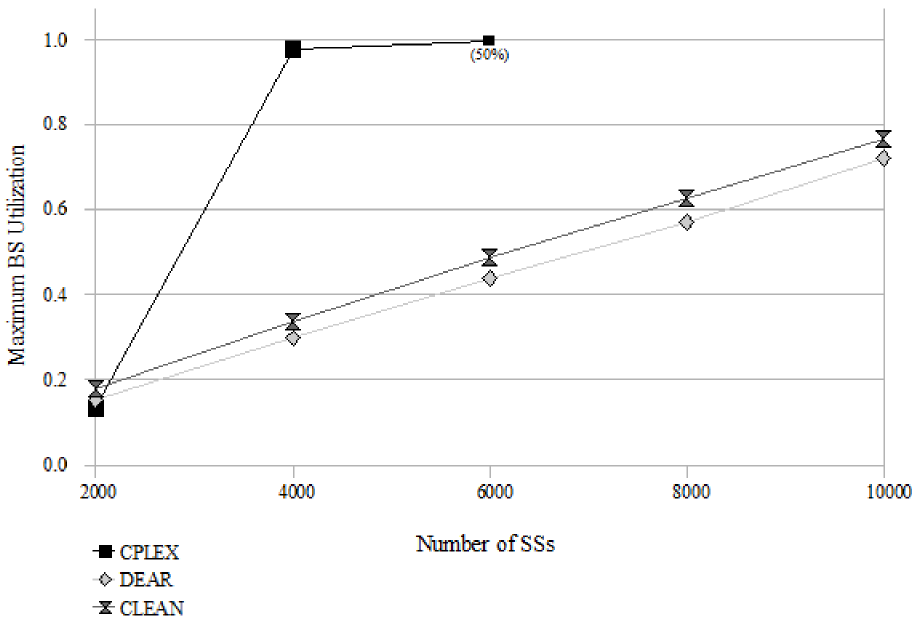

Figure 5.1. Effect of the number of subscribers.

As shown in Figure 5.1, DEAR and CLEAN have a linearly increasing trend in their results with the increasing number of subscribers. This is caused by the larger total requirement of all subscribers. They find a solution to each instance of each test case, so their success ratio is 100%. When we focus on the results of CPLEX, we clearly see two refraction boundaries on which the performance of CPLEX totally changes. When there are less than 4000 subscribers in the network, CPLEX finds a better solution than DEAR and CLEAN for each problem instance. When the number of subscribers is set to 4000 or 6000, CPLEX fails to a find useful solution to each problem instance. Also, it has a success ratio of 50% for 6000 subscribers. Even worse, when there are more than 6000 subscribers as in the last two cases, we cannot find any solution with the ILP tool, CPLEX.

5.2.2.2. Effect of the Service Area Size. While executing tests on the effect of service area size, different sized square maps are used. In addition to fixing all input parameters, the location of subscribers and the candidate base station locations are also fixed relative to each other. The maps have 10 km, 15 km, 20 km, 25 km, and 30 km as edge lengths. The number of subscribers are 4000 and the traffic requirements are same as in the base scenario. Other parameter are fixed to the values presented in Table 5.8.

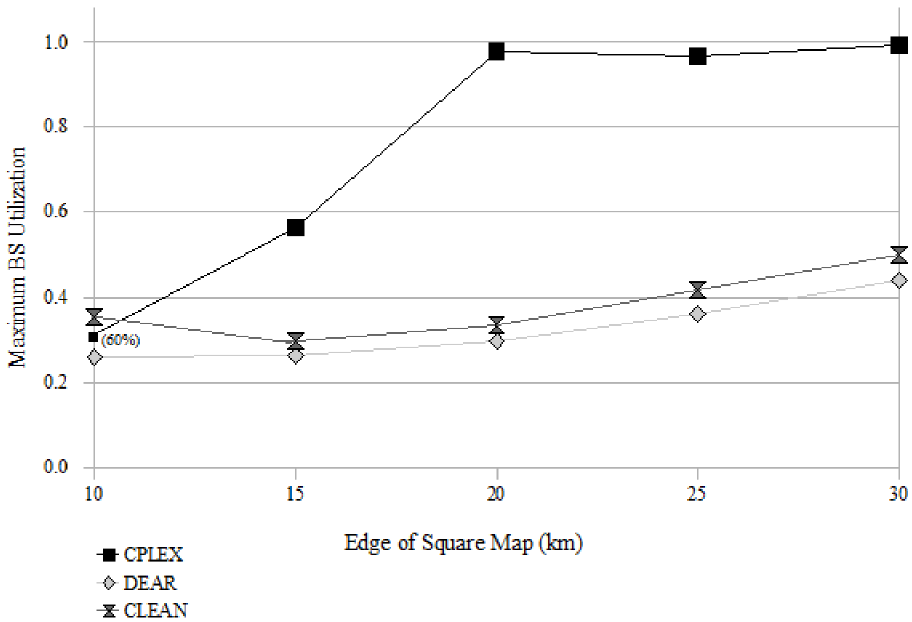

Figure 5.2. Effect of the service area size.

As the size of the service area increases, the distances between subscribers and base stations increase. Due to the effect of the increase in distance, the traffic requirements of subscribers are provided by using more robust modulation schemes. On chart in the Figure 5.2, we see DEAR and CLEAN find results that do not vary much with the growth of the service area. The trend of increase in the results are caused by the change in modulation scheme as explained. The number of required slots for the transmission of a packet increases when the modulation scheme supports lower data rates. Therefore, the load of base stations increases with the allocation of larger number of slots in a frame.

When we look at the result of CLEAN in a service area of 10 km x 10 km, an unexpected result with respect to other cases is observed. This situation occurs because of the clustering algorithm utilized in CLEAN. When the area size decreases while keeping the number of subscribers the same, unbalanced clusters are created and base station deployment is performed at less suitable locations, as proven in our tests. In the first case, CPLEX fails to find a solution for 40% of the problem instances. Since the resource constraints are relaxed with smaller area, the state space increases. As a result, in some of the instances, CPLEX cannot pick up the right branch that leads to a solution. Also, after the boundary where the map size is 20 km x 20 km, CPLEX starts to give useless values which are approximately 100% for the maximum BS utilization.

5.2.2.3. Effect of Subscriber Traffic Requirements. For traffic requirements, five cases which are lighter, light, normal, heavy and heavier, are created. The information about the cases are presented in Table 5.9 for each service flow type. The subscriber number is fixed to 4000 and map size is 20 km x 20 km. For other parameters, the values listed in Table 5.8 are used.

Table 5.9. Traffic requirements for each service flow.

	UGS (Mbps)	**rtPS (Mbps)**	**nrtPS (Mbps)**
Lighter	0.15 - 0.30	0.10 - 0.20	0.06 - 0.10
Light	0.20 - 0.40	0.15 - 0.25	0.10 - 0.15
Normal	0.25 - 0.45	0.20 - 0.35	0.20 - 0.30
Heavy	0.45 - 0.75	0.35 - 0.50	0.30 - 0.40
Heavier	0.60 - 0.90	0.45 - 0.60	0.35 - 0.50

There is a refraction boundary in the normal test case where CPLEX fails to find useful solutions for instances. Beyond this boundary, the success ratio of CPLEX decreases to 60% and 50% for heavy and heavier cases, respectively. However, when subscribers have light and lighter requirements, CPLEX finds better values with the success ratio of 100%.

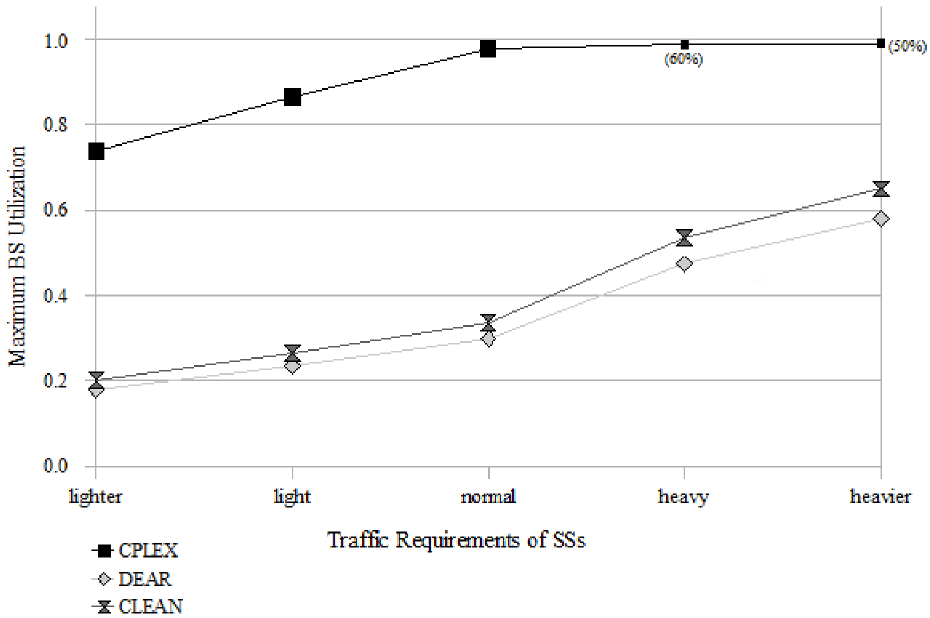

Figure 5.3. Effect of the subscriber traffic requirements.

DEAR and CLEAN represent a linear increase in their results as the subscriber requirements increase. In this increase period, the superiority of DEAR against CLEAN, which is verified by the chart in Figure 5.3, becomes more apparent. The larger gaps between the results of DEAR and CLEAN for heavy and heavier cases prove this fact. From the whole picture of the chart, we can say that from the lighter case to the heavier case, DEAR becomes well ahead from CLEAN. Therefore, with increasing traffic requirements, DEAR is more suitable for the network planning.

6. CONCLUSIONS

In this thesis, we introduce an optimization problem, which is an ILP model, for jointly solving BSLP and TAP for WiMAX. We also introduce the novel use of slots as a metric of requirements and capacities. For the problem, we suggest two deterministic heuristic algorithms called DEAR and CLEAN. Also for small instances, we solve the problem using CPLEX for showing the quality of our results. Then, we form the problem sets consisting of different scenarios and test instances.

According to the results of the quality tests, we observe that in the small set of problems, CPLEX gives better solutions than DEAR and CLEAN, except for the dense map scenario. However, the results of DEAR and CLEAN are close to CPLEX results. In the dense map scenario, DEAR and CLEAN outperform CPLEX. If we compare DEAR and CLEAN for the small size problems, we see that the results are similar. So, the better one can be picked and used as the solution after executing both algorithms. When the problem size increases, i.e. , real life size problems are considered, DEAR finds the best solutions and CLEAN finds better solutions in minutes while CPLEX cannot produce any solution in hours. We conclude that WiMAX planning problems in real life can be formulated and the planning can be made according to the solutions of DEAR.

The results of the tests with factorized parameters (i.e., the number of subscribers, the service area size, and the subscriber traffic requirements) show that DEAR and CLEAN always have a linearly increasing trend with increasing number of subscribers as the factorized parameter. The situation for CPLEX is a little bit different. CPLEX has several refraction boundaries where the results keenly change between different cases. By our behaviour tests, we figure out the limits of CPLEX for many varients of our problem.

As the future work, operating environment conditions other than the propagation model can be included in the formulation. Also, this problem can be taken one step forward by considering additional BS deployments and re-assignments of SSs in an existing network. Beyond theoretical studies, an initial assignment procedure can be implemented in practice to apply our work in the real life.

APPENDIX A: THE RESULT OF QUALITY TESTS

Table A.1. Result and gap comparisons of Heay Load and Dense Map for the small set.

	LB	**CX**		**DEAR**			**CLEAN**		
	ρ^{max}	ρ^{max}	G_LB	ρ^{max}	G_LB	G_CX	ρ^{max}	G_LB	G_CX
Heavy	0.3978	0.5865	47	0.6535	64	11	0.6700	68	14
Load	0.4080	0.6020	47	0.7543	84	25	0.7135	74	18
	0.4093	0.6110	49	0.7158	74	17	0.7238	76	18
	0.4753	0.6058	27	0.7273	53	20	0.7363	54	21
	0.3893	0.5675	45	0.6590	69	16	0.6780	74	19
	0.4035	0.5950	47	0.7808	93	31	0.7163	77	20
	0.4143	0.5943	43	0.7083	70	19	0.6833	64	14
	0.4018	0.5583	38	0.6573	63	17	0.6900	71	23
	0.4055	0.6110	50	0.7063	74	15	0.6688	64	9
	0.4050	0.5850	44	0.7058	74	20	0.7218	78	23
Dense	0.4338	0.9630	121	0.7133	64	-26	0.7068	63	-27
Map	0.4435	0.9815	121	0.7608	71	-23	0.7703	73	-22
	0.4383	0.9178	109	0.7165	63	-22	0.7423	69	-20
	0.4415	0.9450	114	0.8338	88	-12	0.7768	75	-18
	0.4515	0.9965	120	0.8083	79	-19	0.7698	70	-23
	0.4358	0.8228	88	0.7408	69	-10	0.7330	68	-11
	0.4418	0.9313	110	0.8058	82	-14	0.7788	76	-17
	0.4428	0.9680	118	0.7868	77	-19	0.7745	74	-20
	0.4388	0.9305	112	0.7145	62	-24	0.7660	74	-18
	0.4325	0.9825	127	0.7238	67	-27	0.7755	79	-21

Table A.2. Result and gap comparisons of Sparse Map, Light Load, and Base for the small set.

	LB	**CX**		**DEAR**			**CLEAN**		
	ρ^{max}	ρ^{max}	G_LB	ρ^{max}	G_LB	G_CX	ρ^{max}	G_LB	G_CX
Sparse	0.1590	0.2510	57	0.3065	92	22	0.3093	94	23
Map	0.1550	0.2558	65	0.3295	112	28	0.3275	111	28
	0.1610	0.2610	62	0.3218	99	23	0.3328	106	27
	0.1575	0.2558	62	0.2955	87	15	0.3010	91	17
	0.1530	0.2510	64	0.3075	100	22	0.3455	125	37
	0.1605	0.2505	56	0.3040	89	21	0.3398	111	35
	0.1625	0.2800	72	0.3463	113	23	0.3425	110	22
	0.1603	0.2628	63	0.3103	93	18	0.3700	130	40
	0.1558	0.2525	62	0.3333	113	31	0.3498	124	38
	0.1540	0.2680	74	0.3070	99	14	0.3495	126	30
Light	0.2403	0.3528	46	0.4515	87	27	0.4590	91	30
Load	0.2350	0.3928	67	0.4418	87	12	0.4453	89	13
	0.2298	0.3513	52	0.3948	71	12	0.4183	82	19
	0.2293	0.3528	53	0.4365	90	23	0.4638	102	31
	0.2313	0.3608	56	0.4160	79	15	0.4475	93	24
	0.2285	0.3415	49	0.4093	79	19	0.4113	79	20
	0.2708	0.3573	31	0.4363	61	22	0.4343	60	21
	0.2315	0.3478	50	0.4123	78	18	0.4433	91	27
	0.2350	0.3340	42	0.4263	81	27	0.4243	80	27
	0.2338	0.3633	55	0.4263	82	17	0.4548	94	25
Base	0.2915	0.4315	48	0.5075	74	17	0.5108	75	18
	0.2990	0.4448	48	0.5280	76	18	0.5895	97	32
	0.3065	0.4398	43	0.5350	74	21	0.5428	77	23
	0.2963	0.4540	53	0.5180	74	14	0.5385	81	18
	0.2993	0.4570	52	0.5398	80	18	0.5818	94	27
	0.3035	0.4473	47	0.5288	74	18	0.5868	93	31
	0.2963	0.4335	46	0.4825	62	11	0.5443	83	25
	0.3158	0.4553	44	0.5555	75	22	0.5658	79	24
	0.2923	0.4115	40	0.4848	65	17	0.4923	68	19
	0.2893	0.4270	47	0.4740	63	11	0.5313	83	24

Table A.3. Result and gap comparisons of Sparse Map, Light Load, and Base for the large set.

	LB	CX		DEAR			CLEAN		
	ρ^{max}	ρ^{max}	G_LB	ρ^{max}	G_LB	G_CX	ρ^{max}	G_LB	G_CX
Sparse	0.1488	0.9860	562	0.2870	92	-71	0.3355	125	-66
Map	0.1530	0.9638	529	0.2960	93	-70	0.3285	114	-66
	0.1550	0.9528	514	0.3080	98	-68	0.3495	125	-64
	0.1520	0.9928	553	0.2880	89	-71	0.3378	122	-66
	0.1508	0.9890	556	0.3000	99	-70	0.3265	116	-67
	0.1503	0.9678	544	0.2903	93	-71	0.3223	114	-67
	0.1548	0.9898	539	0.3020	95	-70	0.3363	117	-67
	0.1555	0.9928	538	0.2990	92	-70	0.3575	129	-64
	0.1508	0.9668	541	0.2975	97	-70	0.3290	118	-66
	0.1518	0.9823	547	0.3115	105	-69	0.3383	122	-66
Light	0.2290	0.9965	335	0.4083	78	-60	0.4575	99	-55
Load	——	——	——	0.4225	——	——	0.4398	——	——
	——	——	——	0.4163	——	——	0.4468	——	——
	0.2355	0.9020	283	0.4133	75	-55	0.4375	85	-52
	0.2290	0.7965	247	0.3990	74	-50	0.4548	98	-43
	——	——	——	0.3913	——	——	0.4438	——	——
	——	——	——	0.4083	——	——	0.4380	——	——
	——	——	——	0.4073	——	——	0.4618	——	——
	0.1628	0.9928	509	0.4095	151	-59	0.4405	170	-56
	0.1600	0.9965	522	0.4050	153	-60	0.4378	173	-57
Base	——	——	——	0.4160	——	——	0.4465	——	——
	0.1750	0.9965	467	0.4085	133	-59	0.4240	142	-57
	——	——	——	0.4170	——	——	0.4493	——	——
	——	——	——	0.4155	——	——	0.4713	——	——
	0.2563	0.9964	288	0.4235	65	-57	0.4838	88	-51
	——	——	——	0.4128	——	——	0.4458	——	——
	——	——	——	0.4170	——	——	0.4383	——	——
	0.1957	0.9965	409	0.4065	107	-59	0.4368	123	-56
	——	——	——	0.4055	——	——	0.4413	——	——
	0.2485	0.9593	286	0.3995	61	-58	0.4330	74	-55

Table A.4. Result and gap comparisons of Heavy Load and Dense Map for the large set.

	LB	CX		DEAR			CLEAN		
	ρ^{max}	ρ^{max}	G_LB	ρ^{max}	G_LB	G_CX	ρ^{max}	G_LB	G_CX
Heavy	0.3815	0.9858	158	0.6883	80	-31	0.7073	85	-29
Load	0.3493	0.9965	185	0.6415	83	-36	0.6790	94	-32
	0.3830	0.9895	158	0.6670	74	-33	0.7188	87	-28
	0.3960	0.9968	151	0.6923	74	-31	0.7415	87	-26
	—	—	—	0.6875	—	—	0.7083	—	—
	0.3848	0.9895	157	0.6718	74	-33	0.7015	82	-30
	—	—	—	0.6783	—	—	0.6953	—	—
	0.4110	0.9890	140	0.6618	61	-34	0.6950	69	-30
	—	—	—	0.6735	—	—	0.7020	—	—
	—	—	—	0.6453	—	—	0.6783	—	—
Dense	—	—	—	0.7305	—	—	0.7538	—	—
Map	—	—	—	0.7258	—	—	0.7900	—	—
	—	—	—	0.7215	—	—	0.7555	—	—
	—	—	—	0.7300	—	—	0.7778	—	—
	—	—	—	0.7555	—	—	0.7925	—	—
	—	—	—	0.7133	—	—	0.7578	—	—
	—	—	—	0.7243	—	—	0.7803	—	—
	—	—	—	0.7373	—	—	0.7690	—	—
	—	—	—	0.7365	—	—	0.7588	—	—
	—	—	—	0.7050	—	—	0.7843	—	—

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