Automatic Planning of 3G UMTS All-IP Release 4 Networks with Realistic Traffic

by

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A thesis submitted to The Faculty of Graduate and Postdoctoral Affairs
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Abstract

This thesis focuses on designing automatic planning tools for the planning problem of *3rd Generation* (3G) *Universal Mobile Telecommunication System* (UMTS) all-IP Release 4 networks. A new mathematical model for the design problem of such architecture was proposed. The main advantage of the proposed model is to incorporate a realistic traffic profile taken from real live networks. Two approximate algorithms based on the local search and tabu search principles are adopted to solve the problem. Numerical results show that "good" solutions are found with the proposed heuristics. Results demonstrate that the local search algorithm produces solutions that are, on average, at 4.98% of the optimal solution, and in the worst case at 11.31% of the optimal solution. Better solutions are obtained using the tabu search algorithm. Indeed, tabu search is able to provide solutions with an average gap of 2.82% and a maximum gap of 7.51% from the optimal solution.

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Finally, I would like to dedicate this thesis to my father, Eynollah, may his soul rest in peace.

To my father, Eynollah (may your soul rest in peace)

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Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
4G	Fourth Generation
ACO	Ant Colony Optimization
ACP	Automatic Cell Planning
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone Service
AMR	Adaptive Multi Rate
ATM	Asynchronous Transfer Mode
AUC	Authentication Center
BH	Busy Hour
BHCA	Busy Hour Call Attempt
BSC	Base Station Controller
BS	Base Station

BTS	Base Transiver Station
CAPEX	Capital Expenditure
CDMA	Code Division Multiple Access
CEPT	Conference on European Post and Telecommunications
CN	Core Network
CSD	Circuit Switch Data
CS	Circuit Switching
EDGE	Enhanced Data Rate for GSM Evolution
EIR	Equipment Identity Register
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FM	Frequency Modulation
GGSN	Gateway GPRS Support Node
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Service
GSM	Global Systems for Mobile
HARQ	Hybrid Automatic Repeat Request
HLR	Home Location Register
HSCSD	High Speed Circuit Switch Data
HSDPA	High Speed Downlink Packet Access
HSUPA	High Speed Uplink Packet Access
IETF	Internet Engineering Task Force
IMS	IP Multimedia Subsystem

IMT	International Mobile Telecommunications
IP	Internet Protocol
IS	Interim Standard
ITU-T	International Telecommunication Union-Telecommunication
IWO	Invasive Weed Optimization
LP	Linear Programming
LS	Local Search
LTE	Long Term Evolution
MGW	Media Gateway
MIMO	Multi-Input Multi-Output
MIP	Mixed Integer Programming
MMS	Multi Media Service
MPLS	Multi Protocol Label Switching
MS	Mobile Subscriber
MSC	Mobile Switching Center
MSS	Mobile Switching Server
MU	Mobile User
NE	Network Element
NMT	Nordic Mobile Telephony
NP-hard	Non-deterministic Polynomial-time hard
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
P2P	Point to Point
PC	Power Control

PDP	Packet Data Protocol
PS	Packet Switching
PSK	Phase Shift Keying
PSTN	Public Switch Telephony Network
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Network
RF	Radio Frequency
RNC	Radio Network Controller
RTT	Radio Transmission Technology
SGSN	Serving GPRS Support Node
SIR	Signal to Interface Ratio
SMS	Short Message Service
TACS	Total Access Communications Systems
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TIA	Telecommunications Industry Associations
TL	Time Limit
TS	Tabu Search
UMTS	Universal Mobile Telecommunication System
UTRAN	Universal Terrestrial Radio Access Network
VAS	Value Added Service
VLR	Visitor Location Register

WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

Wireless communications have a key role in human life. Innovations in microelectronics serve other sciences and result in development of various markets including telecommunications. The growth can be seen from the growth of telecom companies and increasing competition among service providers. Over the recent years, with presence of the *Internet Protocol* (IP) technology and popularity of modern cell phones, demand for new and hi-speed services has been increasing rapidly. Extraordinary success of wireless industry, and specifically cellular networks, has motivated academia and industry researchers to look for optimized planning methods for such networks. Standardization organizations, in turns, have converged several researches and studies into so-called *standards*.

Wireless cellular networks have unbelievably spread across the globe during the last two decades and currently, *3rd Generation* (3G) *Universal Mobile Telecommunication System* (UMTS) networks are very popular in the world. 3G cellular systems are very flexible, but more complex and costly compared to the older systems which make the design and planning of such networks very challenging. In this context, the competitive market of cellular networks mandates operators to capitalize on efficient design tools. Planning tools are used to optimize networks and keep both operators and users satisfied. On one side, users expect to have seamless access to different high quality services with affordable prices. On the other side, operators expect to have an always-operational network with high number of users, capacity and quality with low *Capital Expenditure* (CAPEX) and *Operational Expenditure* (OPEX).

In this thesis, we are interested in the design problem of third generation UMTS all-IP Release 4.0 networks. As a result, this introduction chapter is divided as follows. The first sub-section will provide background information on relevant topics. Then, the problem statement will be exposed followed by the research objectives and the proposed methodology. Finally, the main contributions will be outlined and an overview of the remaining parts of the thesis will be given.

1.1 Background

In this part, we first review 3G UMTS networks. Then, we outline the planning steps of cellular networks. Finally, different planning techniques in the area of cellular networks are discussed.

1.1.1 3G UMTS Networks

3G networks are designed for improved voice quality, high-speed Internet and multimedia services. The standards for 3G networks were drafted by *International Telecommunication Union* (ITU) and 3G UMTS networks were developed under *3rd Gener-*

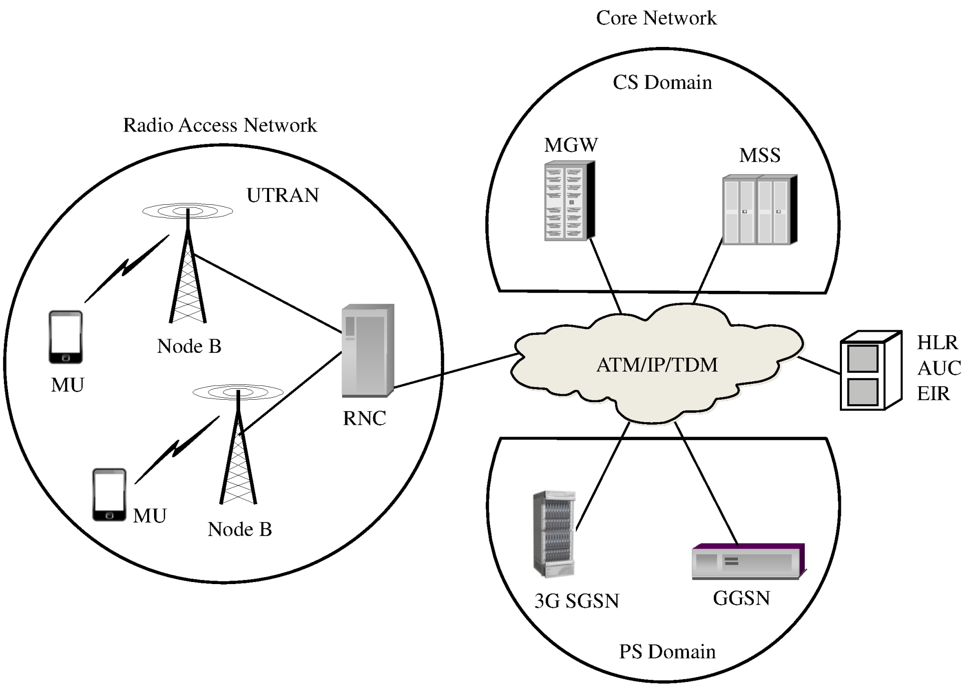

Figure 1.1: 3GPP UMTS Release 4 network architecture [1]

ation Partnership Project (3GPP) standards. 3GPP standards are structured as *Releases* whereas each Release is called to a set of main improvements respect to the old Release. The first generation of 3GPP UMTS networks, known as *Release 99* [7], was deployed in 2000 for the first time. Later, 3GPP introduced Release 4 networks with major improvements respect to the Release 99. The architecture of 3GPP UMTS Release 4 networks is shown in Figure 1.1.

UMTS networks are composed of two main sub-networks: the *Radio Access Network* (RAN), also known as *Universal Terrestrial Radio Access Network* (UTRAN) and the *Core Network* (CN). UTRAN is the geographical coverage area of UMTS network, comprising of a set of cells wherein *Mobile Users* (MUs) can successfully enjoy wireless services. In UMTS networks, the first contact point of the MUs with cellular network is known as *Node B*. The Node B equipped with antennas has similar functionalities of 2G BSs, but with new features like *soft handover* derived from WCDMA technology. Another network element in UTRAN is *Radio Network Controller* (RNC), which has the similar role of BSC in 2G networks. RNC provides connectivity between one or more Node Bs and the core network, as well as radio resource and mobility management [8].

The core network in Release 4 is divided into CS and PS domains. Unlike Release 99, the signaling and voice traffics in Release 4 are handled by separate network elements. Basically, the MSC is broken into an *MSC Server* (MSS) for *control plane* functionalities and a *Media Gateway* (MGW) for *user plane* functionalities. The control plane includes application protocols, mobility management and call control logic for circuit-switched calls, established between RNC and MSS, while the user plane corresponds to the voice streams of circuit-switched calls, established between RNC and MGW [1]. Splitting MSC into MSS and MGW makes Release 4 scalable, reliable and cost-effective with respect to Release 99 [9]. The functionalities of SGSN and GGSN in Release 4 networks are similar to those of 2.5G.

The network transport protocol in Release 99 was *Asynchronous Transfer Mode* (ATM). With the advent of IP and mechanisms like *Multi Protocol Label Switching* (MPLS), IP became a suitable replacement for costly ATM solutions. IP/MPLS was used in Release 4 core backhaul for the first time and was extended to UTRAN in next Releases. By so doing, cellular networks started enjoying *flat-IP* architecture wherein all nodes can reach each other via IP connectivity [10]. One of the main advantages of using flat-IP architecture is the capability to transport different traffic types over a common IP/MPLS network which could save cost for operators. The

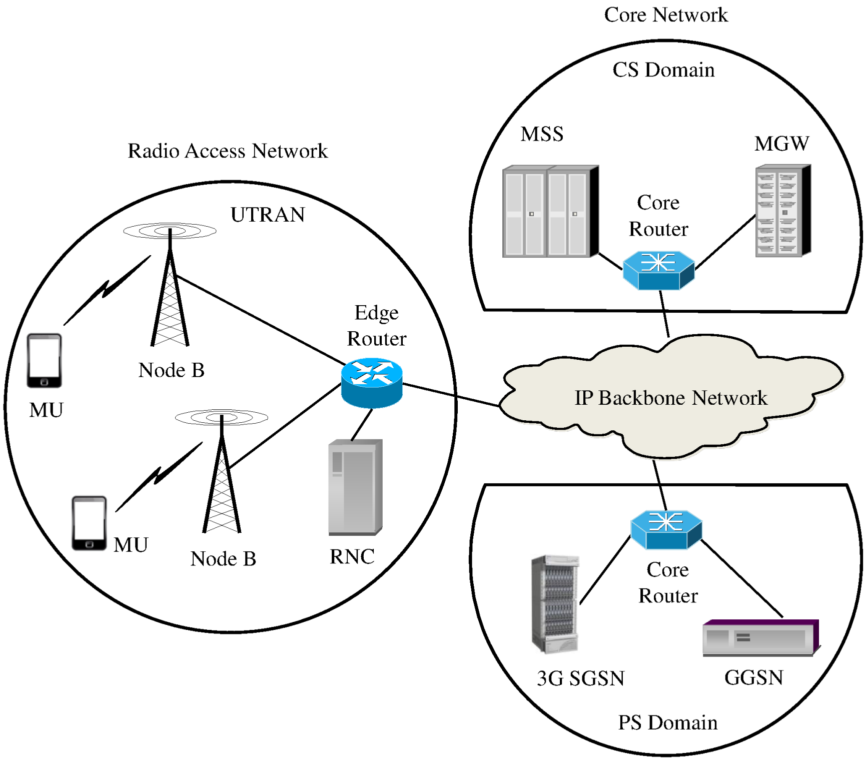

Figure 1.2: 3GPP UMTS all-IP Release 4 architecture

edge router and *core router* are the new elements which are installed in UTRAN and core sites respectively for packet routing purposes.

The idea of mixing flat-IP or all-IP architecture with Release 4 network was very attractive and was appreciated by many operators. The advantage of easily adaptation of all-IP Release 4 networks to state-of-the-art networks made it so popular in the world. A typical architecture for the 3GPP UMTS all-IP Release 4 network is shown in Figure 1.2. 3G UMTS all-IP Release 4 network will be used as the model in this thesis.

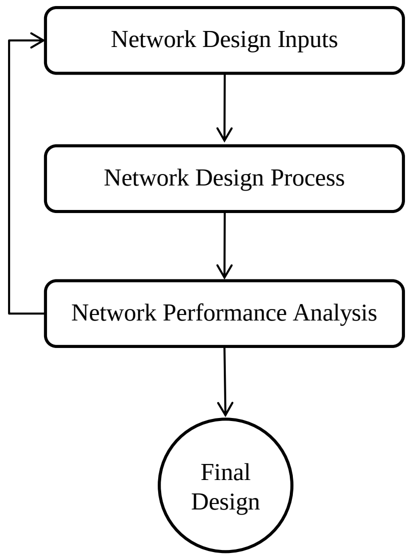

Figure 1.3: Network planning process [2]

1.1.2 Network Planning Process

Due to the highly complex nature of cellular networks, it is imperative to follow a structured and organized design process. A step by step UMTS network design can be found in reference [11]. Network Planning is an iterative process and can be summarized in three steps as show in Figure 1.3.

- **Network Design Inputs:** The first step in network planning is to gather network inputs and requirements. This involves collecting extensive amount of information like anticipated traffic volume and types, traffic distribution, equipment types and cost, candidate technologies and providers, reliability of the technologies, constraints and limitations, utilization, resources and so on. In the case of a green field network (*i.e.* there is no existing infrastructure), collecting design inputs could be a time consuming task and the unavailable inputs should be predicted or generated. For an existing network, design (or upgrade) inputs can be collected easier than green field networks, as many data can be obtained from existing resources.

- **Network Design Process:** This step requires exploring various design techniques and algorithms to create a network topology. It comprises of realizing each network element type, number and location, link and interface types, connectivity, as well as traffic routing. Due to the large number of potential combinations, especially for large size networks, this step can not be done manually and is usually done by a planning tool. The network design inputs are given to the specific tool and the tool produces a topology for the network in the output. Depending on planning tool, extra information like cost of the network can also be part of the output.

- **Network Performance Analysis:** Also known as *optimization*, network performance analysis is the last step in planning to evaluate the topology developed in design phase. The evaluation is done based on certain criteria such as cost, reliability, coverage, capacity, etc. The good solution is used as benchmark for further refinements. This step requires repeating the planning from the beginning either by revised input data (*i.e.* revised traffic forecast) or different design approach.

After a pre-defined number of iterations, the final design is produced. The final design is assumed to be the best solution among several iterations. Because network design involves exploring various alternatives, it is impossible to do it manually or without computer-based planning tools. Automatic planning tools involve optimization techniques and will be discussed in the next section.

Producing planning tools has been the interest of some researchers. Allen *et al.* [12] introduced and used CDS-SmartPlan tool in a case study for UMTS network design in London. Tutschku *et al.* [13] presented ICEPT tool based on an integrated design approach. A comprehensive research on radio planning was done by Eisenblatter *et al.* under the EU-project of *MOMENTUM* [14]. The planning tools usually are supported by industry and become commercial. *Mentum Planet 5* [15], *Atoll* [16] and *Capesso* [17] are popular planning tools for cellular networks. A list of commercial planning tools can be found in reference [18].

1.1.3 Network Planning Techniques

Early generations of cellular networks were simple and relatively small in size and it was possible to design them manually. Manual design processes are not efficient and prone to human error. On the other hand, complex and large size networks required huge amount of computations which ultimately oblige cellular operators to look for automatic computer based planning tools.

There are two major methods to approach a network design problem. The first approach is *simulation* and is used whenever the network design problem cannot be expressed in analytical or mathematical form. To do the simulation, a tool is required to build a simplified representation of the network. Then, the behavior of the simulated network is investigated under various inputs and parameters. Simulation sometimes requires a large amount of time and money, but for some cases, it might be the only solution.

The alternative approach to the network design problem is expressing the problem in a logical and mathematical way which can be tackled by *algorithms*. Algorithms are the methods, used for solving a problem within a finite number of steps [2]. The formulation of a mathematical model for the network is the prime task which characterizes the problem by using the inputs, objectives and constraints. Then, an algorithm is employed to solve the problem by performing tremendous amount of calculations to find the solutions. Algorithms are embedded inside the network planning tools. There are many ways to classify algorithm, but in the context of *combinatorial optimization*, algorithms are classified in *exact (complete)* and *approximate* categories. Combinatorial optimization is a method to solve combinatorial problems. The intention is to find a minimum or maximum for a function where the set of feasible solutions is discrete or can be reduced to discrete.

1.1.3.1 Exact Algorithms

Exact algorithms are used to find a solution by searching all potential solutions in the search space within a bounded time. However, for a very large search spaces, exact algorithms are not efficient and require high *Central Processing Unit* (CPU) time. CPU time is often referred to the time required to process a problem and find the solution. In fact, exact algorithms might need exponential computational time in practical cases [19].

Linear Programming (LP) and *Integer Programming* are examples of exact algorithms. LP is a mathematical method for optimization of linear object function. If the decision variables are required to be integer, the LP is called *Linear Integer Programming* or *Integer Programming* in short [20].

In this thesis, CPLEX *Mixed Integer Optimizer 12.1* (see reference [21] for more information about CPLEX) is used. The algorithm used in CPLEX is *branch and* *cut*. Details on the branch and cut algorithm will be described later in chapter 3.

1.1.3.2 Approximate Algorithms

Approximate algorithms are also known as *heuristics*. As their names implies, approximate algorithms provide relatively good solutions for optimization problems. Approximate algorithms sacrifice the guarantee of finding optimal solutions for the sake of providing good solutions in a significantly reduced amount of time [19]. A general class of heuristics, known as *metaheuristics*, are used in combinatorial optimization.

Local Search Methods

The local search method, denoted as LS, starts from a random initial solution and try to replace the current solution by a better solution in an appropriately defined neighborhood of the current solution [19]. A neighborhood is a new solution, achieved by applying a move over the current solution. Each move is performed if the resulting solution is better (in terms of cost) than the current solution. LS algorithm is trapped in the first local minimum, which may or may not be a global minimum.

Metaheuristics

Metaheuristics are a class of approximate algorithms introduced in 1970s. With the objective of effectively explore the search space, metaheuristics try to combine basic heuristic methods in a higher level frameworks. The class of metaheuristics includes, but is not restricted to, *Ant Colony Optimization* (ACO), *Evolutionary Computation* (EC), *Iterated Local Search* (ILS), *Simulated Annealing* (SA) and *Tabu Search* (TS) [99]. The tabu search is an advanced algorithm which is able to find global minimum.

Details of TS algorithm will be described later in chapter 3. Information about the other metaheuristics can be found in reference [19].

1.2 Problem Statement

The cellular industry is growing. Rapid increase in the demand for data services has pushed wireless operators to invest in new technologies. Operators capitalize a major portion of their money in their network infrastructure to be able to offer new services with high quality and lower rates. To survive in such a competitive market, they look for network planning tools which can design an optimized network with low cost. Furthermore, an optimized network requires less maintenance cost, meaning more saving.

The primary goal of UMTS network planning tools is to provide an optimum topology for the network. Many parameters and factors are involved to select optimum node location, node and link types, topology and so on. Several models and algorithms have been proposed to solve the planning problem of UMTS networks. However, due to the high complexity of the problem, most of the proposals only focus on a portion of the network. In fact, the entire planning problem is decomposed into three sub-problems: the cell planning sub-problem, the access network planning sub-problem and the core network planning sub-problem. There are two main approaches to tackle the planning problem: the sequential and the global. In the sequential approach, each sub-problem is solved separately. Although the sequential approach reduces the problem complexity, it neglects the interactions between sub-problems. Moreover, combining the partial solutions obtained by the sequential approach might not result in an optimal solution for the whole network planning problem. In the global approach, the three sub-problems are considered together and solved jointly. Although a global model is more complex, but it provides optimal solutions.

The planning problem of UMTS network is NP-hard [22]. NP-hard problems are so complex that is unlikely to find an exact solution in polynomial time [23]. This means that computing the optimal solution can be very long or even unfeasible. As a result, approximate methods, which provide good solutions in less CPU time, are preferred to the exact methods which require longer CPU time.

Most UMTS network models proposed in the literature deal with Release 99. Since then, new releases (or versions), such as Release 4, have been standardized. It is therefore important to consider these new releases. Moreover, most planning tools consider a very simple traffic model. In order to have a realistic planning tools, realistic traffic profile that capture all aspects of the voice and data traffics (*e.g. Busy Hour Call Attempt* (BHCA), simultaneous calls, bandwidth, signaling traffic, etc.) must be considered.

The advantage of using IP technology within Release 4 network architecture, makes it more cost-optimized and flexible. Furthermore, the realistic traffic profile reflects more attributes from the realistic networks. As a result, the planning tool developed in this thesis, would be more appropriate to be used by operators dealing with real networks.

1.3 Research Objectives

The main objective of this thesis is to develop automatic planning tools based on exact and approximate algorithms in order to solve the planning problem of 3G UMTS all-IP Release 4 networks with realistic traffic profile. More specifically, we aim to:

1. Propose a mathematical model in order to solve the planning problem of 3G UMTS all-IP Release 4 networks (at the expense of computational complexity).

2. Develop approximate algorithms (based on local search and tabu search) in order to solve the planning problem of 3G UMTS all-IP Release 4 networks. This should allow us to solve larger instances of the problem.

3. Compare the performance of the approximate algorithms with respect to a reference value.

1.4 Methodology

The inherent complexity of the cellular networks design problem obliges network planners to take a well-disciplined approach. Problem modeling and solving the model is an exhaustive task, as many parameters and variables are involved. The methodology used to approach the planning problem in this thesis is described below:

1. *Study cellular networks technologies:* In order to acquire a good knowledge about cellular networks technologies, the evolution of such networks was studied from the beginning up to now.

2. *Select technology for the thesis model:* Reviewing the literature on the area of cellular networks design problem, it was understood that, as of today, the design problem of 3G UMTS all-IP Release 4 networks has not been tackled by academia and could be a potential planning assignment. Another motivation was the fact that such architecture is adaptable to the next generation networks. To make the planning tool usable in industry, a realistic traffic profile, commonly used by operators was also an important aspect to consider.

3. *Define the network planning problem:* The architecture of the thesis model was extracted from 3GPP standards and topology of the live networks. The planning problem of 3G UMTS Release 4 networks was determined. The objective function is composed of cost of the nodes, links and interfaces and is expected to be the minimum, subject to a series of constraints.

4. *Construct a mathematical model:* Given the planning problem in previous step and by using a set of decision variables and parameters, the characteristics of the network elements, links and interfaces including their capacity, type and cost were determined and mathematical model was constructed.

5. *Implement exact algorithm:* The linear programming method was used to solve the thesis problem. Due to high number of constraints and complexity of the problem, we used C++ programming language to translate objective function, constraints and bounds into an LP file format. (For more information on LP file format, see [21]). Finally CPLEX was used to solve the LP problem.

6. *Study optimization methods:* The planning problem of UMTS networks is NP-

hard problem. NP-hard problem have not exact solution in a polynomial time. Linear integer programming used as an optimization method to find the exact solutions. Approximate solutions are also obtained from two approximate algorithms: local search and tabu search.

7. *Implement approximate algorithms:* A time-efficient way to tackle NP-hard problem is to use approximate algorithms. To solve the problem, we implemented LS and TS algorithms by using C++ programming language. Both algorithms were incorporated within the same C++ file. First LS was used to solve the problem and find solutions. Later the solution found by LS was given to TS as an initial solution. TS performed more searches and found better solutions in terms of cost.

8. *Compare solutions:* A set of problems were solved by CPLEX, LS and TS methods. The cost and CPU time of the solutions were calculated and compared together. In fact, the approximate solutions found by LS and TS were evaluated respecting to the exact solutions found by CPLEX. Finally, the efficiency of the LS and TS algorithms to solve the thesis planning problem were investigated and analyzed.

1.5 Contributions

The main contributions of this thesis are summarized as follows:

1. *Modeling UMTS Release 4.0 networks with realistic traffic profile:* A mathematical model for the design problem of such architecture was proposed and

analyzed. The results of this work were published in the following conference paper:

- M. R. Pasandideh and M. St-Hilaire, "Automatic Planning of UMTS Release 4.0 Networks using Realistic Traffic", in *Proc. IEEE International World of Wireless Mobile and Multimedia Networks (WoWMoM) Symposium.*, 2010, pp. 1-9.

2. *Modeling UMTS All-IP Release 4 networks with realistic traffic profile:* An extension to the model proposed in 1 was to include an all-IP infrastructure. The results of this work were presented to the following conferences:

   - PASANDIDEH, M. R. and ST-HILAIRE, M., "*Optimization Model for the Design of All-IP UMTS Release 4.0 Networks*", Optimization Days, Montreal, May 2010.
   - PASANDIDEH, M. R. and ST-HILAIRE, M., "*On the Planning Problem of All-IP UMTS Release 4.0 Networks with Realistic Traffic*", 10th INFORMS Telecommunications Conference, Montreal, May 2010.

3. *Proposing a local search heuristic for the design problem of UMTS all-IP Release 4 networks with realistic traffic profile:* A local search heuristics was developed to solve the design problem of such architecture.

4. *Proposing a tabu search heuristic for the design problem of UMTS all-IP Release 4 networks with realistic traffic profile, solution comparison and analysis:* A tabu search heuristic was developed to solve the design problem of such ar-

chitecture. The efficiency of the heuristic was compared with the local search and the reference model. Results will be submitted to a journal paper.

1.6 Thesis Overview

The reminder of the thesis is organized as follows: In Chapter 2, we present a selective review on cellular network planning problems found in the literature. In Chapter 3, we first present the mathematical formulation of the problem. This model will be used to find optimal solutions. In Chapter 4, we present the simulation results and compare the different algorithms. In Chapter 5, we conclude the work and suggest future directions.

Chapter 2

Literature Review on the Planning of UMTS Networks

2.1 Background

The planning problem of UMTS networks is a complex task. In order to reduce the complexity, the planning problem is usually decomposed into three sub-problems: the cell planning sub-problem, the access network planning subproblem and the core network planning sub-problem. Scholars have mainly two approaches to tackle these sub-problems: *sequential* and *global*. In the sequential approach, each sub-problem is considered separately and is solved solely; while the global approach involves more than one sub-problem at a time.

In this chapter, first we study the evolution of cellular networks. Then, we review the literature in the area of UMTS network planning in the context of sequential and global approaches. First, we describe the sequential approach and each sub-problem in detail. We present the major works in solving the three sub-problems in terms of methods and algorithms. Then, we discuss the global approach and present the related works in literature.

2.2 Evolution of Cellular Networks

History of mobile telephony dates back to the 1920s with the use of radiotelephony by the police department in United States. The initial equipment were bulky and phones were not dealing well with obstacles and buildings. Introducing *Frequency Modulation* (FM) in 1930s made some progress and helped radio communications in battlefield during World War II. The first mobile telephony was introduced in 1940s with limited capacity and manoeuvre. Mobile communications development continued for years to become commercial as we have it today.

Terminology of *generation* is used to differentiate the significant technology improvement in cellular networks which in turn, resulted in major changes in the wireless industry. The *first generation* (1G) of cellular networks was introduced in late 1970s, which was followed by the *second generation* (2G) in early 1990s, the *third generation* (3G) in early 2000 and the *fourth generation* (4G) nowadays. Changes from analog to digital technology, implementing new multiplexing and access techniques, employing new codes and frequencies, introducing IP as a substitution for legacy transmission methods and many other innovations resulted in networks with more services, higher capacity, speed and security. In the following sub-sections, we explain different generations of cellular networks and discuss their specifications.

2.2.1 1G Cellular Networks

The trial system of what is known today as the first generation (1G) of cellular networks was implemented in Chicago in 1978 and commercially launched in 1983. The technology used in the system was known as *Advanced Mobile Phone Service* (AMPS) and operated in 800 MHZ band. Japan launched a commercial AMPS system in 1979 and later in 1981, the *Nordic Mobile Telephony* (NMT) technology based network, operating in 450 MHZ and 900 MHZ bands, was launched in Nordic counties. A modified version of AMPS called *Total Access Communications Systems* (TACS) was also deployed in UK in 900 MHZ band. Many countries followed along and mobile communications spread out over the world. 1G systems used *Frequency Division Multiplexing* (FDM) technology to divide predefined spectrum into portions named *channels*. Each channel was able to serve one user at a time. All these technologies formed 1G cellular networks which were only offering analog voice service [3].

The network geographical area is divided in small sectors, each called a *cell*. Derived from this concept, the technology was named cellular and the phones were called cell phones. The first generations of cellular networks were incompatible with each others as each network had its own standards. Handsets were expensive and networks had limited capacity and mobility. Moreover, networks had difficulties with frequency use, security, roaming, power and so on. Such drawbacks resulted in a very low penetration of 1G cellular networks and mandated a significant effort to develop the second generation networks.

2.2.2 2G Cellular Networks

The second generation (2G) of cellular networks were based on digital communications and were first deployed in early 1990s. Shifting technology from analog to digital improved the quality, capacity, cost, power, speed, security and quantity of services. Like 1G cellular networks, several types of technologies were developed for the second generation. Depending on the multiplexing technique, 2G cellular networks are divided into two main groups: *Time Division Multiple Access* (TDMA) and *Code Division Multiple Access* (CDMA) based cellular networks. *Global Systems for Mobile* communications (GSM) and *Interim Standards 136* (IS-136) are key 2G systems based on TDMA and *Interim Standards 95* (IS-95) is a famous 2G system based on CDMA. More information on 2G systems is provided in the following.

Global Systems for Mobile communications

Despite introducing NMT in Europe, there were several incompatible variants of analog 1G systems deployed across Europe. The need for development of a Europe-wide digital cellular network was announced during the *Conference on European Post and Telecommunications* (CEPT) in 1982. CEPT established GSM organization to harmonize all European systems. Several researches and tests were done by GSM group before the foundation of the *European Telecommunications Standards Institute* (ETSI) in mid 1980s. ETSIs technical groups finalized the first set of specifications for GSM networks in 1989 and the first GSM network was launched in 1991. Introducing a digital technology, GSM offered new services like *Short Message Service* (SMS) and moderate *Circuit Switch Data* (CSD) services beside a better voice service. GSM became rapidly popular in Europe and was deployed in many countries over the world.

GSM is based on TDMA and operates in 900 MHZ and 1800 MHZ (850 MHZ and 1900 MHZ in North America). For the 900 MHZ, the uplink frequency band is 935-960 MHZ and the downlink frequency band is 890-915 MHZ. Thus, the bandwidth for both uplink and downlink is 25 MHZ which is able to offer 124 carriers with channel spacing of 200 KHZ. In GSM, each *Radio Frequency* (RF) channel caters 8 speech channels. Techniques like cell sizing and splitting, power control and frequency reuse are applied to increase GSM networks capacity [3].

Interim Standards 136

With the advent of digital technology and application of TDM technology, AMPS which was an analog system based of FDM, was enhanced to the first *Digital AMPS* or *D-AMPS*, known as *IS-54B* in 1990. Using TDM technique, each 30 KHZ channel became able to cater three speech channels which tripled the capacity. Only voice channels of IS-54B system were digital and still control channels were analog. Despite offering more capacity, analog control channels were limiting number of services. This problem was solved in the next version of IS-54B known as IS-136 and published by *Telecommunications Industry Associations* (TIA) in 1994. IS-136 operates both in 800 MHZ and 1900 MHZ and adds a number of features to the original IS-54B, including SMS and CSD service [3].

IS-95 CDMA

Both GSM and IS-136 use TDMA to share a single RF channel and increase network capacity, but there is another way to increase capacity and that is CDMA. In CDMA, users share the same 1.25 MHZ channel at the same time, but they employ different pseudo-random codes. These codes are known in receiver and the original signal is decoded. IS-95 is a 2G cellular system based on CDMA (also known as *CDMA2000*), developed by *Qualcomm* in United States and introduced in 1989. IS-95 system was able to offer data rate of 14.4 Kbps, with improved voice quality, coverage and security. IS-95 operates in the 800 MHZ band in North America [3].

2.2.3 2.5G Cellular Networks

2G cellular networks were designed based on *Circuit Switching* (CS) and were capable to offer good voice services, but low CSD rates (up to 14.4 Kbps). By using multiple number of 14.4 Kbps time slots, GSM successfully introduced *High Speed Circuit Switch Data* (HSCSD) which could provide data rate of 57.6 Kbps. The problem of HSCSD was a reduction in scarce voice channels and this became a motivation to introduce *Packet Switching* (PS); a technology for faster data services like *Multi Media Service* (MMS) and Internet communications. PS technology enhanced 2G cellular networks to 2.5G through adding a PS domain to the existing CS domain. Voice traffic in 2.5G systems uses circuit switching like 2G systems, but data traffic is based on packet switching. Packet switching allocates radio resources on demand, meaning that resources are utilized only when user is actually sending or receiving data. This allows efficient use of scarce radio resources and rather than dedicating a radio channel to a mobile data user for a fixed period of time, the available radio resources can be concurrently shared between multiple users.

PS technology is known as *CDMA2000 one times Radio Transmission Technology* (CDMA2000 1xRTT) in CDMA standards which can provide speed of 144 Kbps. Similarly in GSM standards, PS technology is known as *General Packet Radio Service* (GPRS), providing speed of 171 Kbps. GPRS uses *Gaussian Minimum Shift Keying*

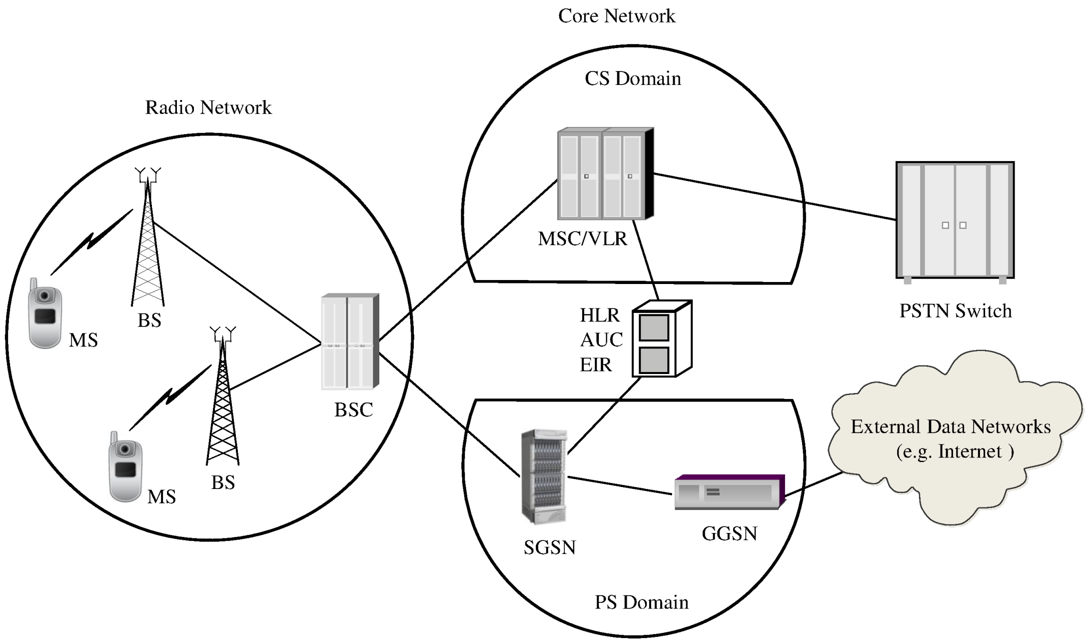

Figure 2.1: Architecture of 2.5G cellular networks

(GMSK) as the modulation scheme [3].

Implementing PS domain in 2.5G network requires introducing new *Network Elements* (NEs). As shown in Figure 2.1., the general architecture of 2.5G cellular networks is composed of *Radio Network* and *Core Network*. Radio Network comprises of *Mobile Subscriber* (MS),*Base Station* (BS) and *Base Station Controller* (BSC). As mentioned earlier, the 2.5G core network is divided in CS and PS domains from functional point of view in which *Mobile Switching Center* (MSC) performs circuit switching functions in CS domain, while *Serving GPRS Support Node* (SGSN) and *Gateway GPRS Support Node* (GGSN) perform packet switching in PS domain. MSC and GGSN also act as a gateway to the *Public Switch Telephony Network* (PSTN) switch and external data networks (*e.g.* Internet) respectively. The information of all mobile subscribers currently administrated by the associated MSC is stored in the

Visitor Location Register (VLR) which is usually a built-in unit of MSC. Another key NE is the *Home Location Register* (HLR), acting as a database of subscriber profiles. HLR could perform identity check for subscribers and mobile handsets if it is equipped with an *Authentication Center* (AUC) and an *Equipment Identity Register* (EIR), otherwise theses functionalities are performed by separate NEs. The *Value Added Services* (VAS) services such as SMS and voice mail services require integrating additional NEs to the network.

2.2.4 2.75G Cellular Networks

Enhanced Data Rate for GSM Evolution (EDGE) is an improvement over GPRS data rate by using an efficient modulation scheme. EDGE uses *8-Phase Shift Keying* (8-PSK) as modulation scheme and coexists with GMSK that is used for GPRS. EDGE provides speed of 384 Kbps which is three times more than that of GPRS, but the major advantage of EDGE is its low cost of upgrade. Major change is in software and only minor hardware changes in BS are required to upgrade a 2.5G network to 2.75G [3].

Despite high data rate in 2.75G cellular networks, they lack higher capacities and global roaming. These deficits led to keep research and enhancement to bring some convergence for the next generation of cellular networks by reducing the main cellular technologies.

2.2.5 3G Cellular Networks

In the absence of global standards, different regional standards for cellular networks were set in Europe, Japan, China, Korea, North America and other countries. In order to harmonize different variants of existing standards and promoting the next generation of cellular networks, the *International Telecommunication Union-Telecommunication* (ITU-T) defined a set of specifications for 3G networks, under the *International Mobile Telecommunications 2000* (IMT-2000) [3]. The followings are the most important specifications of IMT-2000:

- Global standard and flexible with next generation of wireless systems;
- High quality and compatible within IMT-2000 and other fixed networks;
- Worldwide roaming and common frequency band with improved spectrum efficiency;
- High speed packet data rate: 2 Mbps for fixed users, 384 Kbps for pedestrian and 144 Kbps for vehicular traffic.

Based on the above criteria, ITU-T approved five radio interfaces for IMT-2000 in 1999 and *Worldwide Interoperability for Microwave Access* (WiMAX) was added as a sixth candidate in 2007. The various radio systems under the IMT-2000 are shown in Figure 2.2.

In 1998, ETSI and the standardization organizations from Japan, China and Korea formed a consortium known as *3rd Generation Partnership Project* (3GPP) to regulate global specifications for 3G systems in scope of ITU's IMT-2000 specifications.

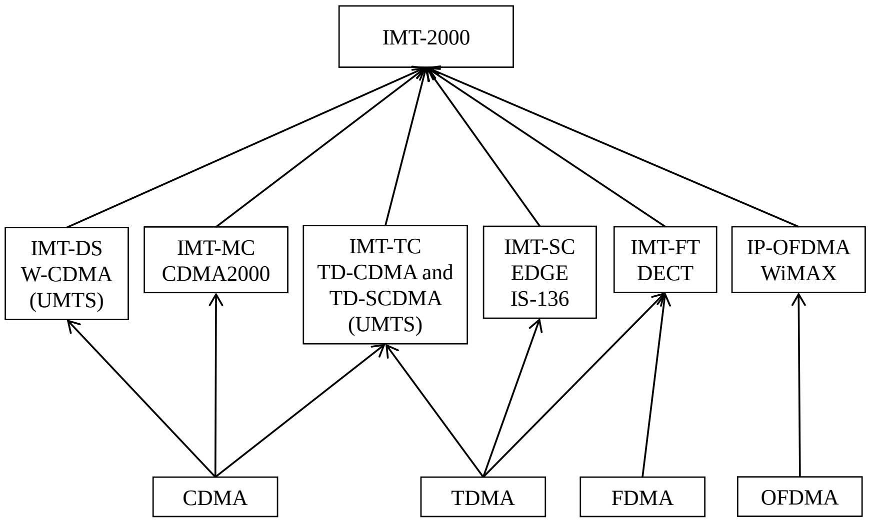

Figure 2.2: IMT-2000 radio interface standards [3]

Similarly, in the same year and for the same purpose, TIA and three telecommunications standardization organizations from Japan, China and Korea collaborated on the *3rd Generation Partnership Project 2* (3GPP2) [3].

The bottleneck of 2G cellular networks was low data transmission rate. The next generation of cellular networks would require innovations in radio access techniques to balance growing data applications with higher rates. By the time ITU defined IMT-2000 specifications for 3G networks, new radio access technologies such as *Wideband CDMA* (WCDMA) with 5 MHZ bandwidth and CDMA2000 with 1.25 MHZ bandwidth, both benefiting *Frequency Division Duplex* (FDD) and *Time Division Duplex* (TDD) solutions were introduced. Exploiting such techniques, 3GPP2 introduced *CDMA2000 1X-Enhanced Version Data Optimized* CDMA2000 (1X-EV/DO) in 1999 as the first 3G network with data rate as high as 2.4 Mbps in downlink and 153 Kbps in uplink [3].

On the other hand, 3GPP mixed the core of GSM networks with WCDMA-based radio access technology and introduced the initial generation of 3G networks, known as UMTS Release 99 in 1999. Later, 3GPP improved the architecture of the core networks and with separating voice and signaling introduced Release 4. By this time, IP-based transport technologies were mature and flat-IP architecture was promoted and implemented in Release 4 networks.

The above discussed 3G standards by 3GPP and 3GPP2 are in compliance with the IMT-2000 requirement. However research and innovations for next generation of cellular networks continued towards higher data rates with lower latency. A brief study over those enhancements is presented in the next section.

2.2.6 3G Transitional Cellular Networks

3G cellular networks have been improved gradually by 3GPP and 3GPP2 towards higher data rates and various services. New spatial multiplexing techniques like *Multi-Input and Multi-Output* (MIMO), higher order modulation, efficient scheduling, turbo-coding, *Adaptive Modulation and Coding* (AMC), *Hybrid Automatic Repeat Request* (HARQ) and many other innovations made extensions to 3G standards. These extensions are sometimes known as 3.5G, 3.75G and 3.9G series of standards.

Following CDMA2000(1X-EV/DO) and with exploiting new techniques in radio access interface, 3GPP2 introduced *EV/DO Rev A* with speed of 3.1 Mbps and *EV/DO Rev B* with speed of 14.7 Mbps. On the other hand, 3GPP introduced *Release 5* in 2002 promoting *IP Multimedia Subsystem* (IMS) and *High Speed Downlink Packet Access* (HSDPA) [24]. Employing HARQ and AMC, HSDPA is able to offer up to 14 Mbps in downlink and 384 Kbps in uplink directions [25]. To increase data throughput in uplink, 3GPP introduced *Release 6* [26], known as *High Speed Uplink Packet Access* (HSUPA) with 5.76 Mbps data rate in uplink. Combination of HSDPA and HSUPA is known as *High Speed Packet Access* (HSPA) which offers 14.4 Mbps in downlink and 5.76 Mbps in uplink [27]. As of today, HSPA is a popular and operational network in the globe. 3GPP continued development of the standards by employing *Quadrature Phase-Shift Keying* (QPSK) and *Quadrature Amplitude Modulation* (QAM) techniques in *Release 7* [28]. Release 7 was able to offer 28 Mbps in downlink and 11.5 Mbps in uplink. The Release 7 is often called *evolved* HSPA or *HSPA+*.

Beside 3GPP and 3GPP2, WiMAX introduced release 1.0 profile for 3G cellular networks in 2007 and officially entered in competition for 3G and beyond standards. WiMAX release 1.0 was able to meet IMT-2000 specifications, providing speed of 46 Mbps in downlink and 4 Mbps in uplink.

The roadmap of cellular networks from 3G has now been extended to 4G. Discussion in the next section is on the proposals for 4G standards.

2.2.7 4G Cellular Networks

The fourth generation (4G) of cellular networks is the successor to 2G and 3G standard families which supports all-IP packet switching and ultra-broadband access networks. Similar to IMT-2000, ITU has defined IMT-Advanced specifications for 4G networks which any 4G candidate standard should meet those requirements to be officially recognized and announced to the cellular world by ITU. IMT-Advanced systems encompass several attributes, including higher spectral efficiencies, scalable bandwidth up to 40 MHZ and higher data rates.

In November 2008, Qualcomm which is the main member of 3GPP2 forum, surprisingly announced ending the development of CDMA standards and decided to adapt 3GPP standards. Dispensing 3GPP2 with development of 4G standards, the competition between 3GPP and WiMAX was highly raised.

3GPP started *Long Term Evolution* (LTE) project to prepare specifications for pre-4G standards. LTE is based on all-IP architecture and it is designed to support voice in PS domain. 3GPP *Release 8* [29], based on *Orthogonal Frequency Division Multiple Access* (OFDMA), is the first set of LTE standard. Using FDD, TDD and MIMO, Release 8 provides 42.2 Mbps in downlink and 11.5 Mbps in uplink within scalable bandwidth of 1.4 MHZ to 20 MHZ. LTE was deployed first in Finland and Norway in December 2009. 3GPP enriched LTE specifications with *Release 9* and *Release 10* which are able to offer speed of 84 Mbps and 168 Mbps in downlink respectively and the same speed of 23 Mbps in uplink.

3GPP Release 10 is the first 4G standards for *LTE-Advanced*. LTE-Advanced has been designed to meet IMT-Advanced requirements and it has been shown that LTE-Advanced exceeds requirements of IMT-Advanced. On the other hand, WiMAX introduced IEEE 802.16m series of specifications, also known as Release 2.0 which is able to offer 120 Mbps in downlink and 60 Mbps in uplink direction.

In October 2010, ITU announced both LTE-Advanced and WiMAX as the official standards for 4G cellular networks.

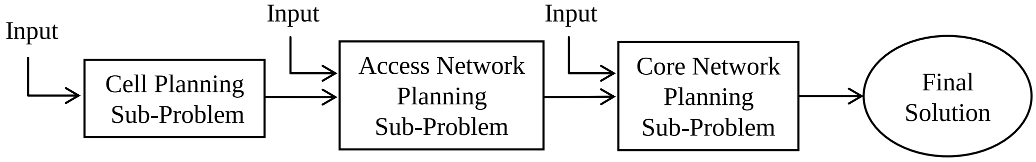

Figure 2.3: Sequential approach for UMTS planning sub-problems [4]

2.3 Sequential Approach

In a sequential (or decomposition) approach, the planning problem of UMTS network is divided in three sub-problems [30]:

1. The cell planning sub-problem;
2. The access network planning sub-problem;
3. The core network planning sub-problem.

Beside the input of each sub-problem, the output of the previous sub-problem is also used as input for the next sub-problem. As shown in Figure 2.3, the output of the cell planning is used as input for the access network sub-problem. In a similar way, the output of the access network sub-problem is given as input for core network sub-problem. The final solution is a topology which satisfies all three sub-problems.

Each sub-problem has been widely explored from different perspective. In the following sub-sections, each sub-problem is explained and the major works in solving them are presented.

2.3.1 The Cell Planning Sub-Problem

Cell planning is the process of connecting all mobile users to the Node Bs in a specific geographical area. Figure 2.4 shows a typical cell planning assignment. Cell planning

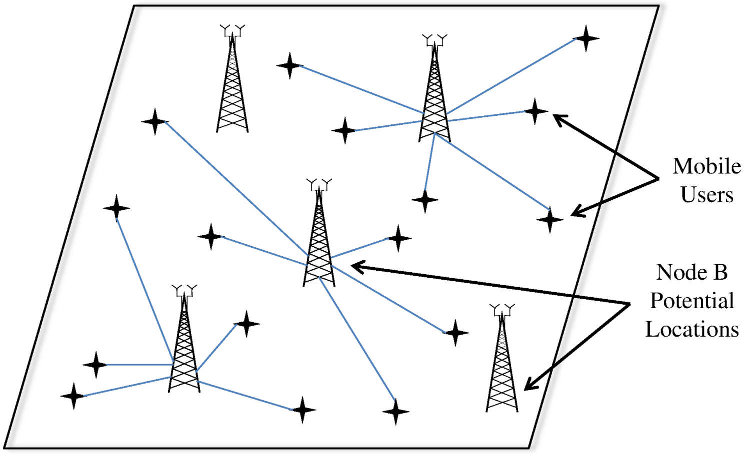

Figure 2.4: Cell planning sub-problem [4]

in 3G UMTS networks is different form that in 2G networks [31, 32]. Cell planning in 2G networks (like GSM) is divided in two steps: *coverage* and *capacity* planning. During the coverage planning phase, different propagation techniques are used to place BSs in locations where the maximum number of users can receive an acceptable level of signal power. *Signal to Interface Ratio* (SIR) is a signal quality factor which should be greater than a predefined threshold in 2G systems. Capacity planning, also known as frequency planning, is the process of channel (frequency) assignment to the BSs in order to minimize the interference in the network while being able to re-use those frequencies in other cells.

Unlike 2G networks, coverage and capacity planning in UMTS network should be done concurrently [33]. Using WCDMA technology in the air interface, mobile users in UMTS network share the whole spectrum, therefore no frequency planning is strictly required [34], but the capacity planning remains a valid and complex task. The main differences between GSM and UMTS radio network are explained by Neubauer and Toeltsch [31] and Ramzi [32].

2.3.1.1 Cell Planning Objectives

The objective of the cell planning sub-problem depends on the interests of network planners. The following objectives may be the target for a cell planning sub-problem:

1. Minimize network cost;
2. Maximize capacity;
3. Maximize coverage;
4. Maximize signal quality;
5. Minimize electromagnetic field level.

Some of the above objectives are conflicting with each other. For example, maximizing the coverage and capacity requires deploying more Node Bs, which in turn, increases the network cost. Another example of contradiction happens when the signal power is increased for maximizing signal quality, but that results in higher electromagnetic field level. If more than one criterion is considered during the cell planning, then multi-objective functions are defined. A multi-objective function can be produced in either linear and/or weighted combinations of the single objectives.

The weighted combination is inspired by the *Pareto* rule [2]. The problem is formulated by a set of decision variables (parameter space/vector) and a set of objective functions (objective vectors). A certain weight (between 0 and 1) is given to each objective function in the set. When the objective vectors can not be improved in one objective criterion without degrading the other objective criteria, the optimum solution set is found. The weighted multi-objective function provides more flexibility as it is possible to put more (less) emphasis on a given objective by assigning higher (lower) weight to it. In linear combination, the objective function is composed of different objectives with the same weight.

Theil *et al.* [35] introduce a linear combination of different objectives such as cost, interference, coverage, balanced traffic and so on. They propose a SA algorithm to solve the site selection problem. Their planning tool can be tuned for speed or quality. Wu and Pierre [36] consider location, maximum transmitted power, antenna height, assignment of demand nodes with BSs and number of BSs as the set of decision variables. Their problem objective is to minimize the cost of BSs, minimize the total emitted power by all users and maximize the total number of active connections. More cell planning multi-objective functions can be found in Maple *et al.* [37], Jamaa *et al.* [38] and Choi *et al.* [39].

Minimizing electromagnetic field level as an objective for the cell planning problem has been the interest of Crainic *et al.* [40]. They considered radio protection constraints, handover and downlink capacity constraints and formulated five objective functions, scaling five functions of electrical field levels.

2.3.1.2 Cell Planning Inputs and Outputs

As stated by Amaldi *et al.* [41], Theil *et al.* [35] and Lauther *et. al* [30], different inputs are required to solve the cell planning sub-problem. Usually, the following inputs must be known [4]:

1. The potential locations where Node Bs can be installed. Some geographical constraints are applied to restrict the location selection;

2. The types (or models) of Node Bs, which includes, but not restricted to, the cost and capacity (*e.g.* power, sensitivity, switch fabric capacity, interfaces, etc.);
3. The user distributions and their required amount of traffic (*e.g.* voice and data);
4. The coverage and propagation prediction.

Various planning algorithms are used to solve cell planning sub-problem. Each algorithm may consider one or more of the objectives mentioned previously. The goal of the cell planning sub-problem is to provide one or more of the following as output:

1. The optimal number of Node Bs;
2. The best locations to install Node Bs;
3. The types of Node Bs;
4. The configuration (height, sector orientation, tilt, power, etc.) of Node Bs;
5. The assignment of mobile users to Node Bs.

For the modeling of the cell planning sub-problem, it is required to know how to represent users (or traffic) in the model. In the following sub-section traffic modeling and related issues are discussed.

2.3.1.3 Traffic Modeling of Mobile Users

UMTS networks provide voice and data services for mobile users. It is important to decide how to represent mobile users in the cell planning sub-problem. A basic model could be to represent a user with a point in the cell. For unknown traffic distribution, a regular point grid can be used. Dealing with practical cases, as the number of users is high, a clustering or agglomeration technique is required to reduce the complexity. The cluster of users is often called *traffic node* [34] or *test point* [42]. A traffic node or test point represents several mobile users.

It is also important to consider the traffic (link) direction. Traffic direction can be uplink (from user to Node B) or downlink (from Node B to user). Uplink direction is used when planners deal with symmetric traffic like voice services. However, if the network is designed to provide data services, downlink direction is more appropriate [8], because downlink is highly utilized for services like web browsing and Internet downloads.

The type of area which is aimed to be planned is also required to be known. The area can be rural, urban, sub urban, dense urban and so on. Each of these areas has specific characteristics which need to be taken in account during cell planning assignment.

2.3.1.4 Air Interface Propagation Models

Dealing with radio frequencies, cell planners should consider signal propagation, signal power, fading, as well as interference [43]. Radio propagation prediction model is a set of mathematical expressions, diagrams, and algorithms used to represent the characteristics of a given environment [44]. Different models have been created to predict the path loss between transmitter and receiver in different environments. The application of each model varies according to frequency, link range, terrain type, land use, land cover and many other parameters. Propagation models are either *empirical* (referred to as statistical) or *deterministic* (referred to as theoretical).

Okumura [45] developed an empirical model derived from field measurements in Tokyo. This model is simple and applicable to urban, sub-urban and rural areas. Later, Hata [46] proposed an empirical model for propagation loss on the basis of Okumura curves. Okumura-Hata model does not consider terrain profile, reflection and shadowing. COST231 [47] is another propagation model which extends Okumura-Hata model to higher frequencies (1.5 GHZ to 2 GHZ). COST231 takes rooftop height, street width and orientations into account. *Ray tracing* model is a deterministic 2D or 3D physical model which considers geographical information of the planning area. Due to the complexity of the ray tracing model and the vast data requirement for accurate prediction of radio propagation, the model is used just for critical scenarios. More information on propagation models can be found in reference [22].

2.3.1.5 Air Interface Power Control

The coverage and capacity planning of UMTS network should be done mutually. The capacity of each cell is based on the actual interference level which depends on the emitted power [41]. In UMTS networks, the power of the Node B is shared among all the cell users and the allocated power to a given user depends on its distance from the Node B. The cell size is not fixed and depends on the number of users, level of interference and their distance form the Node B. Air interface in UMTS systems is *self-interference*, meaning that cell interference level is increased as it is overloaded by users. With an increase in interference level, users located at the edge of the cell are detached from the parent Node B and this in turn, results in decrease of cell size. Such users will be covered by neighbor cells. On the other hand, when call-drops occur, interference decreases for the remaining users and cell is expanded. This phenomenon is called *cell breathing*. Cell breathing is the result of constant changes in the coverage area with respect to amount of traffic.

It is important to keep the transmission power of Node Bs and users at the minimum levels to minimize interference and guarantee adequate quality at the receiver [48]. SIR in UMTS networks is highly affected by the traffic distribution in the whole area and unlike 2G networks, SIR should be equal to a given threshold. In summary, the cell capacity and coverage depends on number of users and their distribution, as well as *Power Control* (PC) mechanisms. The PC mechanisms are based on either the received power or estimated SIR [41]. More information about PC can be found in references [8, 49, 50].

2.3.1.6 Cell Planning Algorithms

The cell planning sub-problem has been studied from different perspectives: link direction (uplink/downlink), optimal location and configuration of Node Bs, channel assignment, etc. The cell planning sub-problem is NP-hard [41] and most planning methods are based on approximate algorithms. Considering different constraints, several algorithms are used to solve the cell planning sub-problem.

Zdunek and Ignor [51] use a newly introduced *Invasive Weed Optimization* (IWO) algorithm [52] to solve optimal locations of BSs, their pilot powers and channel assignments in UMTS mobile networks. They show that the IWO algorithm outperforms the algorithms like evolutionary strategies and genetic algorithms. A polynomial time approximation scheme, proposed by Galota *et al.* [53], deals with finding the location of BSs. The goal is to keep the network cost below a certain limit, provide coverage for a maximum number of users and keep the interference low. Their model does not deal with SIR and PC mechanisms. Eisenblatter *et al.* [54] describe a model for the location and configuration of BSs in UMTS network. They focus on the modeling of the configuration problem using mixed-integer variables and linear constraints. Under the *MOMENTUM* project [14], their modeling tool produces flexible network configurations. Chamaret *et al.* [55] propose a mathematical model for a given traffic demand area and potential location of BSs to solve the radio network problem using graph theory. They try to achieve a large coverage area and minimize the network cost with minimum number of BSs.

Amaldi *et al.*, in a first set of papers [41, 56–58], investigate the location problem of BS in the uplink direction. Considering a set of candidate locations for BSs, traffic distribution and propagation model, they propose two discrete mathematical programming model algorithms to find the optimal location of BSs. The uplink optimization is applicable when we deal with symmetric services like voice. The most important constraints in uplink planning are emitted power of mobile users and sensitivity of BSs. They introduce two PC mechanisms. In the first PC mechanism which is based on SIR level, power is adjusted in order to sustain SIR level in a target level. The second PC mechanism is based on controlling received power. This scheme adjusts the power such that, each channel receives the same target power value. The former mechanism is more complex, since the power emitted by each user depends on that of emitted by all other users. Since the problem in NP-hard, they proposed three greedy algorithms, followed by a tabu search heuristic to solve the problem and find sub-optimal solutions.

Amaldi *et al.* [59] in a collaboration with Signori [60], enhance their models for the uplink direction to find the optimal location of BSs, as well as their configuration (height, tilt and sector orientation). They consider SIR based PC as quality measure and a tabu search heuristic. A similar solution was proposed by Wu and Pierre [36] for the downlink direction. They introduced heuristic and stochastic optimization technique.

Amaldi *et al.*, in a second set of papers [61,62], investigate the problem in downlink direction. The major constraints in downlink direction are the maximum power of BSs and the sensitivity of the user devices. They presented an integer programming model which takes power-based and SIR-based PC mechanisms as quality measure. They proposed randomized greedy algorithms followed by a tabu search heuristic.

Amaldi *et al.*, in third set of papers [63, 64], consider both uplink and downlink (voice and data). They present a mathematical programming model (a combination of previous models) to optimize the location and configuration of BSs. The goal is to maximize the coverage and minimize the cost. They also propose a tabu search algorithm and a simpler PC mechanism to reduce the computational time.

Jamma *et al.* [65] propose manual and automatic design strategies to optimize antenna parameters and common channel powers. Their design depends on the objectives defined by the operator. Jamma *et al.* [66] also deal with capacity and coverage optimization, using multi-objective functions. Finally, Jamma *et al.* [67] propose a steered optimization strategy in UMTS networks in order to answer the following two questions: *i*) how local should an optimization problem be defined and *ii*) which stations should be considered for possible modifications to guarantee a robust and efficient optimization. They found out that too local problem reduces the efficiency of planning tool and too large problem increases number of BSs and network cost.

In a different work, Sohn and Jo [68] tackle the location problem and assign-

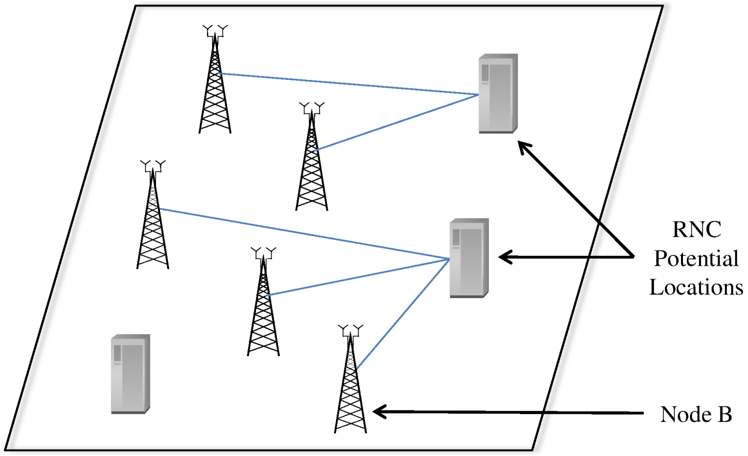

Figure 2.5: Access network planning sub-problem

ment of mobile users to appropriate BSs in 3G W-CDMA uplink environment. The authors propose a constraint satisfaction model and apply different techniques like variable ordering and value ordering to find good optimal solutions. Instead of cost minimization, the objective of their model is to minimize the total transmitted power.

Once the location and configuration of BSs are known, the next step is to study BS assignment to the higher level. This involves investigation of access network sub-problem.

2.3.2 The Access Network Planning Sub-Problem

The main elements of the access network are the Node Bs and the RNCs as shown in Figure 2.3. In order to plan a good access network, the following inputs are usually needed:

1. The physical location of Node Bs (either given or obtained from the cell planning sub-problem);

2. The traffic demand passing through each Node B (either given or obtained from the cell planning sub-problem);

3. The set of potential locations to install RNCs;

4. The different types of RNCs;

5. The different types of links to connect Node Bs to RNCs;

6. The handover frequency between adjacent cells.

Depending on the planners decision, the Node Bs might connect internally to each other based on some interconnection policies. This is also true for the RNCs. By so doing, the access network sub-problem is more extended and will include the trunks among Node Bs with themselves, as well as RNCs with themselves. In a *tree* interconnection, the Node Bs are either directly connected to RNCs or cascaded. Other types of topologies are *star*, *ring* and *mesh*. The interested reader on access network topologies can find more information in reference [69]. Given the above inputs and the type of topology, the access network planning sub-problem aims to find one or more of the following as output:

1. The optimal number of RNCs;

2. The best location to install RNCs;

3. The type of RNCs;

4. The link topology and type between Node Bs;

5. The link topology and type between RNCs;

6. The link topology and type between Node Bs and RNCs;

7. The traffic (volume and type) passing through each RNC.

The objective function is usually cost minimization, but other objectives such as reliability or combination of cost and reliability could be considered.

2.3.2.1 Cost-effective Access Networks

The cost of the access network includes the cost of RNCs, interconnection links and interfaces. Depending on the access network topology, the cost might vary. As a result, it is important to evaluate the cost subject to the topology. Harmatos *et al.* [70] propose an algorithmic network topology optimization method to simultaneously find the optimum number of location of RNCs, as well as the transmission network between BSs and RNCs. In order to solve the NP-hard sub-problem, their method uses a combination of SA and greedy algorithm to minimize the cost. They also consider a degree constraint on the number of BSs that can be supported by one RNC.

In a second paper, Harmatos *et al.* [71] found the bottleneck in their previous algorithm [70], which was the tree topology of the access network based on simple greedy algorithm. Because of the greedy principle, in many cases, the algorithm was not able to build the access tree correctly, causing a significant rise in cost. They modified their algorithm to provide more cost-effective access network topology for one RNC. The objective is to find the cost-optimal interconnection of BSs to their dedicated RNC, considering topological limitations, constraints and the originating traffic of BSs. The authors state that, although their optimization model and process is working for UMTS network, it is also applicable to any multi-constrained capacitated tree optimization problem with non-linear cost function.

Lauther *et al.* [30] approach the access planning sub-problem as a clustering problem. They try to find the optimal number and size of clusters for a set of BSs to minimize the cost. Given the location of BSs, they present two clustering procedures based on proximity graph. The first method is based on tree generation and cutting. The idea is to build a tree in the first step. In the second step, the tree is cut into sub-trees (clusters). The first step is based on an algorithm like *Prim* [72] or *Kruskal* [73], while the second step is based on the generation of sub-trees starting form the leaves. Initially, each Node B forms its own cluster. Then, two clusters are merged per iteration if the cost of the access network is reduced. Another clustering approach is also presented in a paper by Godor and Magyar [74]. They aggregate the user traffic in multi-level tree-like fashion using some intermediate concentrator nodes. Considering several constraints, the NP-hard problem is solved by heuristic algorithms to minimize the cost.

Krendzel *et al.* [75] consider the problem of physical links ring configuration between BSs in 4G network. Considering planning constraints and using dynamic programming, they try to minimize the cost of the ring configuration. In another paper, Juttner *et al.* [76] propose two network design methods to find the cost-optimal number and location of RNCs and their connection to BSs in tree topology, while respecting a number of constraints. First, a global algorithm combines a metaheuristic technique with the solution of a specific b-matching problem. Then, the tree structure made by the first method is improved by the second method, which uses a combination of Lagrangian lower bound with branch-and-bound. They demonstrate the effectiveness of their algorithms in reducing the cost by a number of test cases.

Constraint-based optimization of the access network sub-problem was considered by Wu and Pierre. In [77], they propose a model to optimally find the number and location of RNCs and solve the assignment of Node Bs to selected RNCs. Constraints like number of Node Bs supported by one RNC, number of interfaces on the RNC, the amount of traffic supported by one RNC, as well as handover volume between adjacent cells are taken into consideration. Greedy heuristic algorithms, TS and SA, are explored in the proposed model to minimize the cost. Wu and Pierre, in [78], used a three-staged hybrid constraint-based approach. In the first step, good feasible solutions are found and then improved by local search in the second step. Such solutions are considered as the upper bound. In the last step, the solution is refined by constraint optimization technique. They state that the obtained solutions can be used as initial solutions for heuristics.

Minimizing handover cost has been investigated in a series of cell-to-switch papers [79–82]. The idea is to reduce the number of handovers between two adjacent cells by linking both cells to the same RNC.

Bu *et al.* [83] investigate the access planning problem from a different perspective. Usually, *Point to Point* (P2P) transmission links (E1 and/or T1) used in 3G access network are not optimal in case of asymmetric and bursty traffic. The authors propose to use a 802.16 (WiMAX) based radio access networks to transmit data from Node Bs to RNCs. They design the access network with minimum number of 802.16 links upon position of BSs and RNCs. Charnsripinyo [84] considers the design problem of 3G access network while maintaining an acceptable level of quality of service. The problem was formulated as a *Mixed Integer Programming* (MIP) model to minimize the cost.

2.3.2.2 Reliable Access Networks

Network reliability (also known also as survivability) describes the ability of the network to function and not to disturb the services during and after a failure. The need for seamless connectivity has been a motivation for many researchers to explore new techniques for network reliability. Tripper *et al.* [85] introduce a framework to study wireless access network survivability, restoration techniques and metrics for quantifying network survivability. Cellular networks are very vulnerable to failure. Failure can happen either on node level (BSs, RNC, MSS, etc.) or link level. Simulation results on different types of failure scenarios in a GSM network shows that after a failure, mobility of users worsens network performance. For example, in the case of a BS failure, users will try to connect to the adjacent BS and that degrades the overall network performance.

Charnsripinyo and Tipper [86] proposed an optimization based model for the design of survivable 3G wireless access backhaul networks in a mesh topology. Using a two-phase algorithm, the authors first design a network with a minimum cost, considering *Quality of Service* (QoS) and then update the topology to satisfy survivability constraints. They also propose a heuristic, based on the iterative minimum cost routing to scale the design with real world networks.

Increasing reliability level imposes more cost to the network. There is a balance (best trade off) between cost and reliability and in fact, higher level of reliability will obtrudes higher cost to the network. Aiming to create a balance between reliability and cost, Szlovencsak *et al.* [87] introduce two algorithms. The first algorithm modifies the cost-minimum tree as produced in [70, 71], while respecting reliability constraints and retains the tree structure. In the second algorithm, different links are added to the most vulnerable parts of the topology to have a more reliable network. Krendzel *et al.* [88] study cost and reliability of 4G RAN in a ring topology. They estimate cost and reliability in different configurations and state that considering cost and reliability, the most preferable topology for 4G RAN is a multi-ring.

Once the access planning sub-problem is solved and the number, type, location and traffic of each RNC in known, the next step is to deal with the core planning sub-problem.

2.3.3 The Core Network Planning Sub-Problem

The core network is the central part of UMTS network. The core network is responsible for traffic switching, providing QoS, mobility management, network security and billing [89]. As described in Chapter 1, the core network consists of CS and PS domains. The key elements of CS domain are MGW and MSS, responsible for switching and controlling functions respectively. PS domains key elements are SGSN and GGSN which are responsible for packet switching. Figure 2.6 shows a typical core network planning sub-problem.

The core planning sub-problem supposes that the following inputs are known:

1. The physical location of RNCs (either given or obtained from the access planning sub-problem);

2. The traffic demand (volume and type) passing through each RNC (either given or obtained from the access planning sub-problem);

3. The potential location of core NEs;

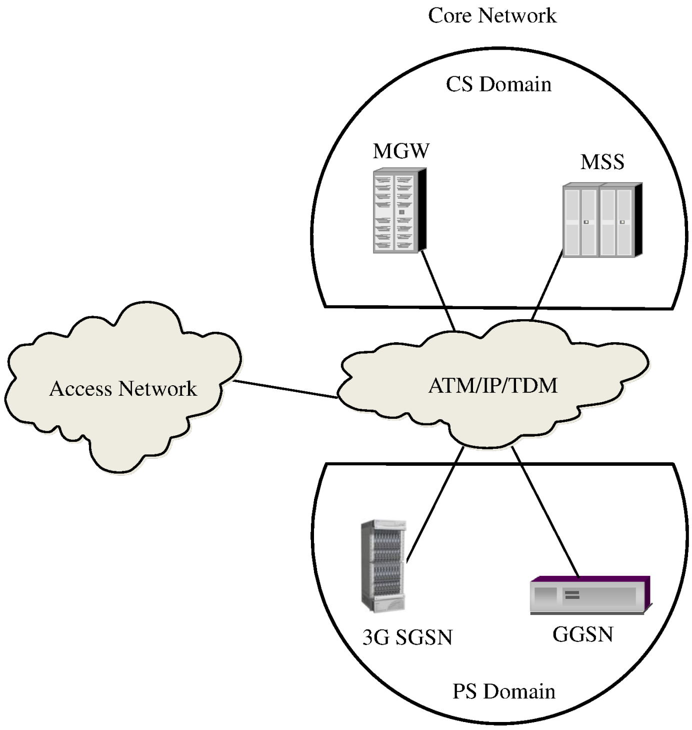

Figure 2.6: Core network planning sub-problem

4. The different types of core NEs;

5. The different types of links to connect RNCs to core NEs.

Depending on the network planner, the topology of the backbone network could be a ring, a full mesh, a mesh or a layered structure format. In the ring topology, each NE is directly attached to the backhaul ring. Full mesh topology provides point-to-point communication such that each NE is able to communicate to any other NE directly. The mesh topology is a limited version of the full mesh, whereas due to some restrictions, not every NE can communicate directly to another NE. For fast growing networks, maintaining a mesh or full mesh topologies becomes an exhaustive task. To solve this sub-problem, the layered structure was introduced. A layered structure does not provide direct link between all NEs. A tandem layer, as the nucleus of the layered structure is defined. The *tandem* layer is composed of a series of tandem (transit) nodes, usually connected in full mesh. Then, all NEs in the core network are connected to at least one of the tandem nodes. Ouyang and Fallah [90] state that a layered structure has many advantages compared to full mesh topology. Given that the above inputs are available and the type of topology is decided, the core network planning sub-problem aims to find one or more of the following as output:

1. The optimal number of core NEs;
2. The best location to install core NEs;
3. The type of core NEs;
4. The link topology and type between RNCs and core NEs;
5. The link topology and type between core NEs;
6. The traffic (volume and type) passing through core NEs.

The objective function is usually cost minimization, but other objectives like reliability could be considered. Not many researches have been concentrated on the core network planning sub-problem. The reason could be the similarity of this sub-problem to the wired network planning problem.

Shalak *et al.* [89] present a model for UMTS network architecture and discuss the required changes for upgrading core network from GSM to UMTS. They outline network planning steps and compare the products of different vendors in packet switch network.

Ricciato *et al.* [91] deal with the assignment of RNCs to SGSNs based on measured data. The optimization goals are to balance the number of RNC among the available SGSNs and minimize the inter-SGSN routing area updates. Required inputs are taken from live network and the objective function is solved by linear integer programming methods. While they focus on GPRS, they state that their approach can be applied to UMTS networks.

Harmatos *et al.* [92] deal with the interconnection of RNCs, placement of MGWs and planning core network. They split the problem in two parts. The first problem is interconnection of the RNCs which belong to the same UTRAN and the placement and selection of a MGW to connect to core network. The second problem is interconnection of MGWs together in backbone through IP or ATM network. The objective is to design a fault-tolerant network with cost-optimal routing.

2.3.4 Remarks on Sequential approach

The sequential approach used to solve the design problem of UMTS networks has many advantages, but some disadvantages. The sequential approach reduces the complexity of the problem by splitting the problem into three smaller sub-problems. By so doing, it is possible to include more details in each sub-problem for better planning. On the contrary, solving each sub-problem independently from the other sub-problems may result in local optimization, because interactions between sub-problems are not taken into account. Combining the result of sub-problems does not guarantee a final optimal solution. There is no integration technique developed yet to incorporate all partial solutions in order to obtain a global solution. Therefore, a global view from the network is required to define a global problem.

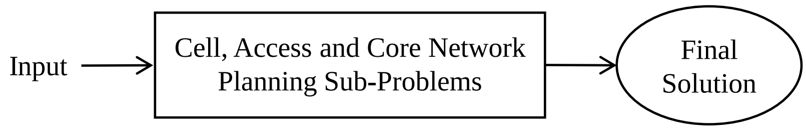

Figure 2.7: Global approach for the UMTS planning problem [4]

2.4 Global Approach

As mentioned earlier, the sequential approach breaks down the UMTS planning problem in three sub-problems and solves them solely. As shown in Figure 2.7, a global (also called integrated) approach considers more than one sub-problem at a time and solves them jointly. Since all interactions between the sub-problems are taken into account, a global approach has the advantage of providing a solution close to the global optimal, but at the expense of increasing problem complexity. The global problem of UMTS networks which is composed of three NP-hard sub-problems is also an NP-hard problem [4].

The objective of the global approach is similar to the objective of the sequential approach. Network cost minimization is the main concern, while considering network performance. Researches on the global approach are mainly divided into three directions: *i*) cell and access networks, *ii*) access and core networks and *iii*) the whole network (*i.e.* cell, access and core).

Zhang *et al.* [93] proposed a global approach to solve the UTRAN planning problem. Their model finds the number and location of Node Bs and RNCs, as well as their interconnections in order to minimize the cost. Chamberland and Pierre [94] consider access and core network planning sub-problems. Given the BSs locations, their model finds the location and types of BSCs and MSCs, types of links and topology of the network. Since such sub-problem is NP-hard, the authors propose a TS algorithm and compare the results with a proposed lower bound. While the model is targeted to GSM networks, it can be also applied to UMTS networks with minor modifications. In another paper, Chamberland [95] investigates the update problem in UMTS network. Considering an update in BSs subsystem, the expansion model accommodates the new BSs into the network. The model determines the optimal access and core networks and considers network performance issues like call and handover blocking. The author proposes a mathematical formulation of the problem, as well as a heuristic based on the TS principle.

Recently St-Hilaire *et al.* [96] proposed a global approach in which the three sub-problems are considered simultaneously. The authors developed a mathematical programming model to plan UMTS networks in the uplink direction. Through a detailed example, they compared their integrated approach with the sequential approach. They proposed two heuristics based on local search and tabu search to solve the NP-hard problem [97]. Furthermore, St-Hilaire *et al.* [98] proposed a global model for the expansion problem of UMTS networks as an extension to their previous works. They state that this model can also be used for green field networks. They also present numerical results based on branch and bound implementation.

2.5 Section Remarks

The purpose of solving the design problem of UMTS networks is to find an optimum topology for the network which satisfies all desired constraints like cost, reliability, performance and so on. Such an optimum topology is favorable for operators, as it can save money and attract more subscribers. The planning problem of UMTS networks is complex and composed of three sub-problems: the cell planning sub-problem, the access network sub-problem and the core network sub-problem.

There are two main approaches to solve planning problem of UMTS networks: the sequential and the global. In the sequential approach, the three sub-problems are tackled sequentially. Since each sub-problem is less complex than the initial problem, more details can be considered in each sub-problem. As a result, solving sub-problems is easier than solving the whole planning problem. However, since each sub-problem is solved independently from other sub-problems, the combination of the optimal solution of each sub-problem (if obtained), might not result in an optimal solution for the whole network planning problem.

A global approach deals with more than one sub-problem simultaneously and considers all interactions between the sub-problems. The global problem has the advantage of finding good solutions which are closer to the global minimum. The global problem is NP-hard and is more complex compared to three sub-problems. To find approximate solutions for global planning of UMTS networks in a polynomial time, heuristics need to be defined. It has been proven by scholars that different adaptations of heuristics are effectively able to solve the planning problem of cellular networks.

The focus of literature in the area of UMTS network planning has been over Release 99 architecture. However, the planning problem of Release 4 networks has not been considered so far. Such architecture is the base model for higher 3GPP network releases and through accommodating new multimedia servers in the core network; the thesis model can be easily adopted to support new releases.

Moreover, the all-IP architecture has been also mixed with Release 4 networks. Furthermore a realistic traffic profile has been considered. All together, it is expected that the planning algorithm proposed in this thesis would be useful for operators to plan real networks.

Chapter 3

Network Model Formulation and Planning Tools

In this chapter, we first present the step by step mathematical formulation of 3G UMTS all-IP Release 4 networks. Then, two planning tools are presented in detail and the design steps are explained. The first planning tool is based on exact algorithm on the second planning tool is based on local search and tabu search.

Before presenting the mathematical formulation, we need to describe some basic concepts in optimization for better understanding. Such definitions will be used throughout this chapter.

3.1 Basic Concepts in Optimization

Any optimization problem P, is described as triple (S, Ω, F) where:

- The *objective function* F is a mathematical function of the *decision variables* to express the objective of a problem.

- The *search space* S is the domain in which every element could be a candidate solution for the problem. The search space is defined over a finite set of decision variables.

- The *constraints* Ω are the set of conditions applied over the decision variables, which in fact are applied on the objective function [19]. Constraints reduce the search space by discarding infeasible solutions. *Structural* constraints deal with equality or inequality $(\geq, =, \leq)$, while *nonnegativity* constraints represent the positive domain of the decision variables.

It is also necessary to explain the following definitions [19]:

- The *decision variables* are the unknown quantities, defined by decision-maker to construct the objective function. If decision variables have discrete domains, the problem is called *discrete optimization* or *combinatorial optimization* problem and in case of continuous domain, the problem is known as *continues optimization.*

- The *linear (objective) function* is a mathematical function in which the decision variables appear only in first degree, meaning that variables are not multiplied to each other. Variables are indeed multiplied by constant and are combined only by addition and subtraction.

- The *feasible area* is an area within the search space of the problem in which any solution can satisfy all of the defined constraints, bounds and integrality restrictions.

- The *feasible solution* implies to any solution belonging to the feasible area.
- The *neighborhood structure* is a function that assigns a set of neighbors $N(s) \subseteq S$ to every $s \in S$. A neighbor is achieved by transformation of a solution. The transformation operator is called *move*.
- The *local optimum* is a solution $s^{'} \in S$, which for $\forall s \in N(s^{'}) : f(s^{'}) \leq f(s)$ for minimization problem or $f(s^{'}) \geq f(s)$ for maximization problem.
- The *global optimum* is a solution $s^{*} \in S$, which for $\forall s \in S : f(s^{*}) \leq f(s)$ for minimization problem or $f(s^{*}) \geq f(s)$ for maximization problem.
- The *sub-optimal (near-optimal)* is a solution $\hat{s} \in S$, which $f(s^{*}) \leq f(\hat{s}) \leq f(s^{'})$ for minimization problem or $f(s^{*}) \geq f(\hat{s}) \geq f(s^{'})$ for maximization problem. Sub-optimal solution is also known as *good* solution in literature.
- The *NP-hard* (Non-deterministic Polynomial-time hard) problem is a problem which has not exact solution in polynomial time.

Global minimum and local minimum are shown in Figure 3.1. The local minimum is the value of the function at a certain point in its domain, where the value is less than or equal to the values at all other points in the immediate vicinity, while the global minimum is the lowest point over the entire domain of the function.

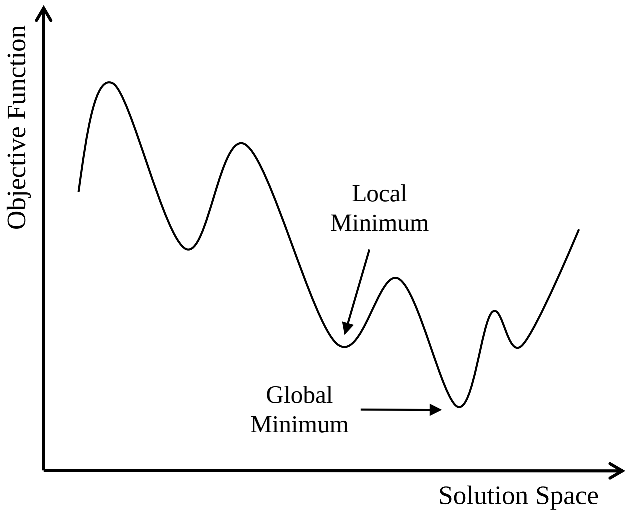

Figure 3.1: Global minimum vs. local minimum

3.2 Global Planning Problem: Inputs, Outputs and Objectives

In order to formulate the model and define the planning problem of 3G UMTS all-IP Release 4 networks, we suppose the following information is known:

- The location of Node Bs;
- The potential locations of all NEs (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers/CS routers/PS routers);
- The different types of NEs and links, their capacities and their costs;
- The installation cost for given types of facilities (including for instance: floor space, cables, racks, electric installations, labor, etc.);
- The subscriber traffic profile;

- The planning parameters;
- The number of subscribers for each Node B.

Our focus is on the development of automatic planning tools for the design of 3G UMTS all-IP Release networks. More precisely, the following problems are provided in the output:

- Selecting the number, the location and the type of NEs (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers/CS routers/PS routers);
- Selecting the number and the type of links and interfaces;
- Designing the network topology.

The objective of the planning problem in this thesis is to design a network with minimum cost (including cost of nodes, links, interfaces, installation, etc.) while having an acceptable level of quality. Such objective is favorite of operators along with maximizing profit. Profit maximization involves different streams, policies, management and marketing techniques which are beyond the scope of this thesis.

3.3 Model Formulation

The model formulation is the process of translating the characteristics of the nodes, links and interfaces; including their capacity, type and cost into a mathematical format. In this thesis, we consider each Node B as a traffic node or test point. The all-IP Release 4 networks involve different NEs for voice and data services in which every NE deals with specific aspects of the traffic. Therefore, to consider all aspects of the traffic, we need to produce a *traffic record* for each Node B.

3.3.1 Node B Traffic Record

Node B traffic record is a set of different aspects for the voice and data traffics (*i.e.* BHCA, simultaneous calls, bandwidth, signaling traffic, etc.). Considering Node Bs subscribers, such record is calculated using subscriber traffic profile and planning parameters. (An example of subscriber traffic profile and planning parameters is presented in Chapter 4). This information is given by the operator and might vary subject to traffic forecast and planning strategies.

The traffic records for five Node Bs are shown in Table 3.1. The Node B traffic record includes the number of covered subscribers, and the following information for those subscribers:

- BHCA;
- Channels for CS traffic;
- Bandwidth required for the CS traffic;
- Bandwidth required for the PS traffic;
- Attached subscribers in *Busy Hour* (BH);
- Simultaneous *Packet Data Protocol* (PDP) contexts;
- Signaling messages bandwidth for the CS traffic.

Table 3.1: Typical example of traffic record

Node B index	Subscriber (c_0)	BHCA (c_1)	CS Channels (c_2)	CS BW (Mbps) (c_3)	PS BW (Mbps) (c_4)	Attached Subscribers (c_5)	Simultaneous PDP context (c_6)	Signaling (Mbps) (c_7)
1	11,180	7,090	257	6	2	2,236	280	0.56
2	8,089	5,130	191	5	1	1,617	203	0.40
3	13,950	8,847	316	8	2	2,790	349	0.70
4	16,123	10,224	363	9	2	3,224	404	0.81
5	5,266	3,340	129	3	1	1,053	132	0.26

The first column of the table refers to the Node B index. The number of subscribers covered by the Node B is randomly generated and tabulated in column two. BHCA, in column three, shows the number of calls made by Node B subscribes at BH. The number of CS traffic channels and the associated CS traffic bandwidth are shown in columns four and five respectively. PS traffic bandwidth in column six, represents the bandwidth required for data services of the Node B subscribers. We suppose that a specific ratio of subscribers use data services (attached subscribers) in BH, and furthermore, a portion of these subscribers have PDP context. The PDP context is a set of data structure defined on SGSN and GGSN, which contains the subscriber session information when the subscriber has an active session. Columns seven and eight show BH attached subscribers and simultaneous PDP context. If a subscriber decides to use packet data services, it must first attach and then activate a PDP context. Finally, the last column gives the signaling load for the CS traffic.

When the traffic records are calculated, we need to design a network which can fulfill those traffic aspects for the subscribers. In order to accomplish this goal, in the next section, we first define a set of mathematical notions, a set of decision variables and parameters to deal with the characteristics of the network model.

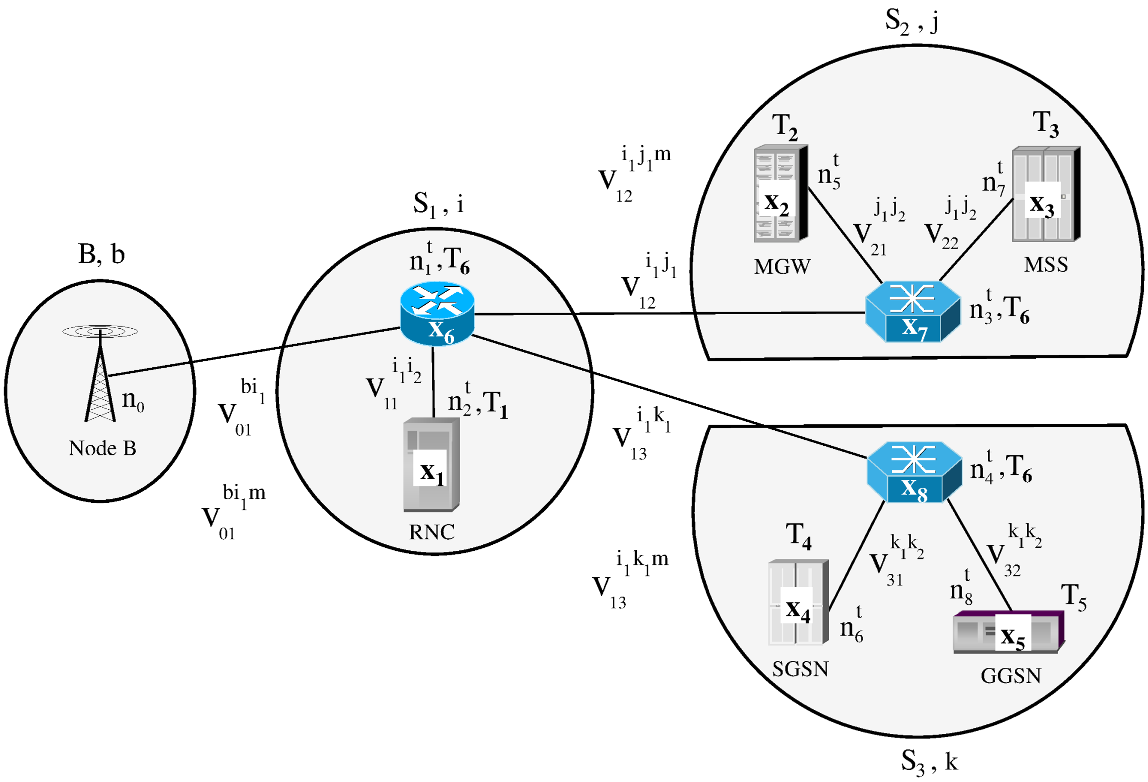

Figure 3.2: Graphical representation of the model formulation

3.3.2 Notation

The following notation, used throughout this thesis, is composed of sets, decision variables, traffic variables and cost parameters. Figure 3.2 represents, in a graphical way, a summarized version of the notation.

3.3.2.1 Sets

- B, the set of Node Bs (already installed);
  - μ_b^c, the traffic entry of type $c \in C$ for a Node B, ($b \in B$);
- C, the set of traffic characteristics such that $C = \{c_0, c_1, ..., c_7\}$ where:

- c_0: Number of subscribers;
- c_1: BHCA;
- c_2: CS traffic channel;
- c_3: CS traffic bandwidth (Mbps);
- c_4: PS traffic bandwidth (Mbps);
- c_5: BH attached subscribers;
- c_6: Simultaneous PDP context;
- c_7: Signaling message bandwidth (Mbps) for the CS traffic.

- M_0 is the set of links and interface types that can be used to connect the Node B to edge router and edge router to CS router/PS router;
- M_1 is the set of links and interface types that can be used to connect the edge router to RNC, CS router to MGW/MSS and PS router to SGSN/GGSN;
- ω^m: Capacity (in Mbps) of the link (interface) of type M_0 or M_1;
- S_1, S_2 and S_3 are respectively the sets of potential sites to install the RNCs/edge routers, the MGWs/MSSs/CS routers and the SGSNs/GGSNs/PS routers;
- T_0, T_1, T_2, T_3, T_4, T_5 and T_6 are respectively the sets of the Node B types, RNC types, MGW types, MSS types, SGSN types, GGSN types and edge router/CS router/PS Router types where:
  - SUB^t: Subscriber capacity for a node of type t;
  - $BHCA^t$: BHCA capacity for a node of type t;

- α^t: CS traffic capacity (in channel) for a node of type t;
- β^t: Switch fabric capacity (in Mbps) for a node of type t;
- PDP^t: Simultaneous PDP context capacity for a node of type t;
- n_0^t, n_1^t, n_2^t, n_3^t, n_4^t, n_5^t, n_6^t, n_7^t and n_8^t are respectively the maximum number of interfaces that can be installed in the type t of the Node B, the edge router, the RNC, the CS router, the PS router, the MGW, the SGSN, the MSS and the GGSN.

3.3.2.2 Decision Variables

- $v_{01}^{bi_1}$, a 0–1 variable such that $v_{01}^{bi_1} = 1$ if and only if the Node B ($b \in B$) is connected to the edge router installed at site $i_1 \in S_1$;
- $v_{01}^{bi_1m}$, the number of links of type $m \in M_0$ connecting the Node B ($b \in B$) to the edge router installed at site $i_1 \in S_1$;
- $v_{11}^{i_1i_2}$, a 0–1 variable such that $v_{11}^{i_1i_2} = 1$ if and only if the edge router installed at site $i_1 \in S_1$ is connected to the RNC installed at site $i_2 \in S_1$;
- $v_{11}^{i_1i_2m}$, the number of links of type $m \in M_1$ connecting the edge router installed at site $i_1 \in S_1$ to the RNC installed at site $i_2 \in S_1$;
- $v_{12}^{i_1j_1}$, a 0–1 variable such that $v_{12}^{i_1j_1} = 1$ if and only if the edge router installed at site $i_1 \in S_1$ is connected to the CS router installed at site $j_1 \in S_2$;
- $v_{12}^{i_1j_1m}$, the number of links of type $m \in M_0$ connecting the edge router installed at site $i_1 \in S_1$, to the CS router installed at site $j_1 \in S_2$;

- $v_{13}^{i_1k_1}$, a 0–1 variable such that $v_{13}^{i_1k_1} = 1$ if and only if the edge router installed at site $i_1 \in S_1$ is connected to the PS router installed at site $k_1 \in S_3$;
- $v_{13}^{i_1k_1m}$, the number of links of type $m \in M_0$ connecting the edge router installed at site $i_1 \in S_1$ to the PS router installed at site $k_1 \in S_3$;
- $v_{21}^{j_1j_2}$, a 0–1 variable such that $v_{21}^{j_1j_2} = 1$ if and only if the CS router installed at site $j_1 \in S_2$ is connected to the MGW installed at site $j_2 \in S_2$;
- $v_{21}^{j_1j_2m}$, the number of links of type $m \in M_1$ connecting the CS router installed at site $j_1 \in S_2$ to the MGW installed at site $j_2 \in S_2$;
- $v_{22}^{j_1j_2}$, a 0–1 variable such that $v_{22}^{j_1j_2} = 1$ if and only if the CS router installed at site $j_1 \in S_2$ is connected to the MSS installed at site $j_2 \in S_2$;
- $v_{22}^{j_1j_2m}$, the number of links of type $m \in M_1$ connecting the CS router installed at site $j_1 \in S_2$ to the MSS installed at site $j_2 \in S_2$;
- $v_{31}^{k_1k_2}$, a 0–1 variable such that $v_{31}^{k_1k_2} = 1$ if and only if the PS router installed at site $k_1 \in S_3$ is connected to the SGSN installed at site $k_2 \in S_3$;
- $v_{31}^{k_1k_2m}$, the number of links of type $m \in M_1$ connecting the PS router installed at site $k_1 \in S_3$ to the SGSN installed at site $k_2 \in S_3$;
- $v_{32}^{k_1k_2}$, a 0–1 variable such that $v_{31}^{k_1k_2} = 1$ if and only if the PS router installed at site $k_1 \in S_3$ is connected to the GGSN installed at site $k_2 \in S_3$;
- $v_{32}^{k_1k_2mm}$, the number of links of type $m \in M_1$ connecting the PS router installed at site $k_1 \in S_3$ to the GGSN installed at site $k_2 \in S_3$;

- $x_1^{i_2t}$, a 0–1 variable such that $x_1^{i_2t} = 1$ if and only if an RNC of type $t \in T_1$ is installed at site $i_2 \in S_1$;
- $x_2^{j_2t}$, a 0–1 variable such that $x_2^{j_2t} = 1$ if and only if a MGW of type $t \in T_2$ is installed at site $j_1 \in S_2$;
- $x_3^{j_2t}$, a 0–1 variable such that $x_3^{j_2t} = 1$ if and only if an MSS of type $t \in T_3$ is installed at site $j_2 \in S_2$;
- $x_4^{k_2t}$, a 0–1 variable such that $x_4^{k_2t} = 1$ if and only if an SGSN of type $t \in T_4$ is installed at site $k_1 \in S_3$;
- $x_5^{k_2t}$, a 0–1 variable such that $x_5^{k_2t} = 1$ if and only if a GGSN of type $t \in T_5$ is installed at site $k_2 \in S_3$;
- $x_6^{i_1t}$, a 0–1 variable such that $x_6^{i_1t} = 1$ if and only if an edge router of type $t \in T_6$ is installed at site $i_1 \in S_1$;
- $x_7^{j_1t}$, a 0–1 variable such that $x_7^{j_1t} = 1$ if and only if an CS router of type $t \in T_6$ is installed at site $j_1 \in S_2$;
- $x_8^{k_1t}$, a 0–1 variable such that $x_8^{k_1t} = 1$ if and only if an PS router of type $t \in T_6$ is installed at site $k_1 \in S_3$.

3.3.2.3 Traffic variables

- $f_{01}^{cbi_1}$, the traffic entry $c \in C$ on the link from the Node B installed at site $b \in B$ to an edge router installed at site $i_1 \in S_1$;

- $f_{11}^{ci_1i_2}$, the traffic entry $c \in C$ on the link from the edge router installed at site $i_1 \in S_1$ to an RNC installed at site $i_2 \in S_1$;

- $f_{12}^{ci_1j_1}$, the traffic entry $c \in C$ on the link from the edge router installed at site $i_1 \in S_1$ to a CS router installed at site $j_1 \in S_2$;

- $f_{13}^{ci_1k_1}$,, the traffic entry $c \in C$ on the link from the edge router installed at site $i_1 \in S_1$ to a PS router installed at site $k_1 \in S_3$;

- $f_{21}^{cj_1j_2}$, the traffic entry $c \in C$ on the link from the CS router installed at site $j_1 \in S_2$ to a MGW installed at site $j_2 \in S_2$;

- $f_{22}^{cj_1j_2}$, the traffic entry $c \in C$ on the link from the CS router installed at site $j_1 \in S_2$ to an MSS installed at site $j_2 \in S_2$;

- $f_{31}^{ck_1k_2}$, the traffic entry $c \in C$ on the link from the PS router installed at site $k_1 \in S_3$ to an SGSN installed at site $k_2 \in S_3$;

- $f_{32}^{ck_1k_2}$, the traffic entry $c \in C$ on the link from the PS router installed at site $k_1 \in S_3$ to a GGSN installed at site $k_2 \in S_3$.

3.3.2.4 Cost Parameters

- $a_{01}^{bi_1m}$, the link and interface costs (including installation cost) for connecting a Node B installed at site $b \in B$ to an edge router installed at site $i_1 \in S_1$ through a link and interface of type $m \in M_0$;

- $a_{11}^{i_1i_2m}$, the link and interface costs (including installation cost) for connecting an edge router installed at site $i_1 \in S_1$ to an RNC installed at site $i_2 \in S_1$ through a link and interface of type $m \in M_1$;

- $a_{12}^{i_1 j_1 m}$, the link and interface costs (including installation cost) for connecting an edge router installed at site $i_1 \in S_1$ to a CS router installed at site $j_1 \in S_2$ through a link and interface of type $m \in M_0$;

- $a_{13}^{i_1 k_1 m}$, the link and interface costs (including installation cost) for connecting an edge router installed at site $i_1 \in S_1$ to a PS router installed at site $k_1 \in S_3$ through a link and interface of type $m \in M_0$;

- $a_{21}^{j_1 j_2 m}$, the link and interface costs (including installation cost) for connecting a CS router installed at site $j_1 \in S_2$ to a MGW installed at site $j_2 \in S_2$ through a link and interface of type $m \in M_1$;

- $a_{22}^{j_1 j_2 m}$, the link and interface costs (including installation cost) for connecting a CS router installed at site $j_1 \in S_2$ to an MSS installed at site $j_2 \in S_2$ through a link and interface of type $m \in M_1$;

- $a_{31}^{k_1 k_2 m}$, the link and interface costs (including installation cost) for connecting a PS router installed at site $k_1 \in S_3$ to an SGSN installed at site $k_2 \in S_3$ through a link and interface of type $m \in M_1$;

- $a_{32}^{k_1 k_2 m}$, the link and interface costs (including installation cost) for connecting a PS router installed at site $k_1 \in S_3$ to a GGSN installed at site $k_2 \in S_3$ through a link and interface of type $m \in M_1$;

- b_1^t, b_2^t, b_3^t, b_4^t, b_5^t, b_6^t, b_7^t and b_8^t are respectively the cost (including installation cost) of an RNC of type $t \in T_1$, of a MGW of type $t \in T_2$, of an MSS of type

$t \in T_3$, of an SGSN of type $t \in T_4$, of a GGSN of type $t \in T_5$, of an edge router of type $t \in T_6$, of a CS router of type $t \in T_6$ and of a PS router of type $t \in T_6$.

3.4 Cost Function

The cost function, representing the total cost of the network, is composed of two terms: the cost of the links and interfaces and the cost of the nodes. The cost of the links and interfaces, noted by C_L, is given by the following equation:

$$\begin{aligned} C_L(\mathbf{v}) = & \sum_{b\in B}\sum_{i_1\in S_1}\sum_{m\in M_0} a_{01}^{bi_1m}v_{01}^{bi_1m} + \sum_{i_1\in S_1}\sum_{i_2\in S_1}\sum_{m\in M_1} a_{11}^{i_1i_2m}v_{11}^{i_1i_2m} \\ & + \sum_{i_1\in S_1}\sum_{j_1\in S_2}\sum_{m\in M_0} a_{12}^{i_1j_1m}v_{12}^{i_1j_1m} + \sum_{i_1\in S_1}\sum_{k_1\in S_3}\sum_{m\in M_0} a_{13}^{i_1k_1m}v_{13}^{i_1k_1m} \\ & + \sum_{j_1\in S_2}\sum_{j_2\in S_2}\sum_{m\in M_1} a_{21}^{j_1j_2m}v_{21}^{j_1j_2m} + \sum_{j_1\in S_2}\sum_{j_2\in S_2}\sum_{m\in M_1} a_{22}^{j_1j_2m}v_{22}^{j_1j_2m} \\ & + \sum_{k_1\in S_3}\sum_{k_2\in S_3}\sum_{m\in M_1} a_{31}^{k_1k_2m}v_{31}^{k_1k_2m} + \sum_{k_1\in S_3}\sum_{k_2\in S_3}\sum_{m\in M_1} a_{32}^{k_1k_2m}v_{32}^{k_1k_2m} \end{aligned} \tag{3.1}$$

The cost of the nodes, noted by C_N, is given by the following equation:

$$\begin{aligned} C_N(\mathbf{x}) = & \sum_{t\in T_1} b_1^t \sum_{i_2\in S_1} x_1^{i_2t} + \sum_{t\in T_2} b_2^t \sum_{j_2\in S_2} x_2^{j_2t} + \sum_{t\in T_3} b_3^t \sum_{j_2\in S_2} x_3^{j_2t} + \sum_{t\in T_4} b_4^t \sum_{k_2\in S_3} x_4^{k_2t} \\ & + \sum_{t\in T_5} b_5^t \sum_{k_2\in S_3} x_5^{k_2t} + \sum_{t\in T_6} b_6^t \sum_{i_1\in S_1} x_6^{i_1t} + \sum_{t\in T_6} b_7^t \sum_{j_1\in S_2} x_7^{j_1t} + \sum_{t\in T_6} b_8^t \sum_{k_1\in S_3} x_8^{k_1t} \end{aligned} \tag{3.2}$$

3.5 The Model

The model for the 3G UMTS all-IP Release 4 networks planning problem, denoted as ALLIPR4PP, can now be given.

ALLIPR4PP:

$$min\,(C_L(\mathbf{v}) + C_N(\mathbf{x})) \tag{3.3}$$

subject to the following constraints:

1. ***Uniqueness constraints*** impose that at most one type of a NE is installed at the site. RNC, MGW, MSS, SGSN, GGSN, edge router, CS router and PS router type uniqueness constraints are as follows:

   RNC-Type uniqueness constraints

$$\sum_{t \in T_1} x_1^{i_2 t} \leq 1 \ (i_2 \in S_1) \tag{3.4}$$

   MGW-Type uniqueness constraints

$$\sum_{t \in T_2} x_2^{j_2 t} \leq 1 \ (j_2 \in S_2) \tag{3.5}$$

   MSS-Type uniqueness constraints

$$\sum_{t \in T_3} x_3^{j_2 t} \leq 1 \ (j_2 \in S_2) \tag{3.6}$$

   SGSN-Type uniqueness constraints

$$\sum_{t \in T_4} x_4^{k_2 t} \leq 1 \ (k_2 \in S_3) \tag{3.7}$$

GGSN-Type uniqueness constraints

$$\sum_{t \in T_5} x_5^{k_2 t} \leq \ (k_2 \in S_3) \tag{3.8}$$

Edge router-Type uniqueness constraints

$$\sum_{t \in T_6} x_6^{i_1 t} \leq 1 \ (i_1 \in S_1) \tag{3.9}$$

CS router-Type uniqueness constraints

$$\sum_{t \in T_6} x_7^{j_1 t} \leq 1 \ (j_1 \in S_2) \tag{3.10}$$

PS router-Type uniqueness constraints

$$\sum_{t \in T_6} x_8^{k_1 t} \leq 1 \ (k_1 \in S_3) \tag{3.11}$$

2. ***Assignment constraints*** impose that a lower layer node is assigned to only one upper layer node. Node B, edge router, CS router and PS router assignment constraints are as follows:

   Node B assignment constraints

$$\sum_{i_1 \in S_1} v_{01}^{b i_1} = 1 \ (b \in B) \tag{3.12}$$

Edge router assignment constraints

$$\sum_{i_2 \in S_1} v_{11}^{i_1 i_2} = \sum_{t \in T_6} x_6^{i_1 t} \ (i_1 \in S_1) \tag{3.13}$$

$$\sum_{j_1 \in S_2} v_{12}^{i_1 j_1} = \sum_{t \in T_6} x_6^{i_1 t} \ (i_1 \in S_1) \tag{3.14}$$

$$\sum_{k_1 \in S_3} v_{13}^{i_1 k_1} = \sum_{t \in T_6} x_6^{i_1 t} \ (i_1 \in S_1) \tag{3.15}$$

CS router assignment constraints

$$\sum_{j_2 \in S_2} v_{21}^{j_1 j_2} = \sum_{t \in T_6} x_7^{j_1 t} \ (j_1 \in S_2) \tag{3.16}$$

$$\sum_{j_2 \in S_2} v_{22}^{j_1 j_2} = \sum_{t \in T_6} x_7^{j_1 t} \ (j_1 \in S_2) \tag{3.17}$$

PS router assignment constraints

$$\sum_{k_2 \in S_3} v_{31}^{k_1 k_2} = \sum_{t \in T_6} x_8^{k_1 t} \ (k_1 \in S_3) \tag{3.18}$$

$$\sum_{k_2 \in S_3} v_{32}^{k_1 k_2} = \sum_{t \in T_6} x_8^{k_1 t} \ (k_1 \in S_3) \tag{3.19}$$

3. ***Capacity constraints*** at the interface level impose that the number of links from lower layer nodes to upper layer node should not exceed the maximum number of interfaces on the upper layer node. Obviously, the link is only established if the upper layer node is installed. Capacity constraints of edge router, RNC, CS router, MGW, MSS, PS router, SGSN and GGSN at the interface level are as follows:

Edge router capacity constraints at the interface level

$$\sum_{m\in M_0}\sum_{b\in B} v_{01}^{bi_1m} + \sum_{m\in M_1}\sum_{i_2\in S_1} v_{11}^{i_1i_2m} + \sum_{m\in M_0}\sum_{j_1\in S_2} v_{12}^{i_1j_1m} + \sum_{m\in M_0}\sum_{k_1\in S_3} v_{13}^{i_1k_1m} \leq \sum_{t\in T_6} n_1^t x_6^{i_1t} \ (i_1 \in S_1) \tag{3.20}$$

RNC capacity constraints at the interface level

$$\sum_{m\in M_1}\sum_{i_1\in S_1} v_{11}^{i_1i_2m} \leq \sum_{t\in T_1} n_2^t x_1^{i_1t} \ (i_2 \in S_1) \tag{3.21}$$

CS Router capacity constraints at the interface level

$$\sum_{m\in M_0}\sum_{i_1\in S_1} v_{12}^{i_1j_1m} + \sum_{m\in M_1}\sum_{j_2\in S_2} v_{21}^{j_1j_2m} + \sum_{m\in M_1}\sum_{j_2\in S_2} v_{22}^{j_1j_2m} \leq \sum_{t\in T_6} n_3^t x_7^{j_1t} \ (j_1 \in S_2) \tag{3.22}$$

MGW capacity constraints at the interface level

$$\sum_{m\in M_1}\sum_{j_1\in S_2} v_{21}^{j_1j_2m} \leq \sum_{t\in T_2} n_5^t x_2^{j_2t} \ (j_2 \in S_2) \tag{3.23}$$

MSS capacity constraints at the interface level

$$\sum_{m\in M_1}\sum_{j_1\in S_2} v_{22}^{j_1j_2m} \leq \sum_{t\in T_3} n_7^t x_3^{j_2t} \ (j_2 \in S_2) \tag{3.24}$$

PS Router capacity constraints at the interface level

$$\sum_{m\in M_0}\sum_{i_1\in S_1} v_{13}^{i_1k_1m} + \sum_{m\in M_1}\sum_{k_2\in S_3} v_{31}^{k_1k_2m} + \sum_{m\in M_1}\sum_{k_2\in S_3} v_{32}^{k_1k_2m} \leq \sum_{t\in T_6} n_4^t x_8^{k_1t} \ (k_1 \in S_3) \tag{3.25}$$

SGSN capacity constraints at the interface level

$$\sum_{m \in M_1} \sum_{k_1 \in S_3} v_{31}^{k_1 k_2 m} \leq \sum_{t \in T_4} n_6^t x_4^{k_2 t} \ (k_2 \in S_3) \tag{3.26}$$

GGSN capacity constraints at the interface level

$$\sum_{m \in M_1} \sum_{k_1 \in S_3} v_{32}^{k_1 k_2 m} \leq \sum_{t \in T_4} n_8^t x_5^{k_2 t} \ (k_2 \in S_3) \tag{3.27}$$

4. ***Capacity constraints*** at the node level impose that the aggregated traffic entry of type $c \in C$ on a node should not exceed its capacity statement. Capacity constraints of edge router, RNC, CS router, MGW, MSS, PS router, SGSN and GGSN at the node level are as follows:

   Edge router capacity constraints at the node level

$$\sum_{m \in M_0} \omega^m \sum_{b \in B} v_{01}^{b i_1 m} \leq \sum_{t \in T_6} \beta^t x_6^{i_1 t} \ (i_1 \in S_1) \tag{3.28}$$

   RNC capacity constraints at the node level

$$\sum_{i_1 \in S_1} f_{11}^{c i_1 i_2} \leq \sum_{t \in T_1} SUB^t x_1^{i_2 t} \ (c \in \{c_0\}, i_2 \in S_1) \tag{3.29}$$

$$\sum_{i_1 \in S_1} f_{11}^{c i_1 i_2} \leq \sum_{t \in T_1} BHCA^t x_1^{i_2 t} \ (c \in \{c_1\}, i_2 \in S_1) \tag{3.30}$$

$$\sum_{m \in M_1} \omega^m \sum_{i_1 \in S_1} v_{11}^{i_1 i_2 m} \leq \sum_{t \in T_1} \beta^t x_1^{i_2 t} \ (i_2 \in S_1) \tag{3.31}$$

CS router capacity constraints at the node level

$$\sum_{m \in M_0} \omega^m \sum_{i_1 \in S_1} v_{12}^{i_1 j_1 m} \leq \sum_{t \in T_6} \beta^t x_7^{i_1 t} \ (j_1 \in S_2) \tag{3.32}$$

MGW capacity constraints at the node level

$$\sum_{j_1 \in S_2} f_{21}^{c j_1 j_2} \leq \sum_{t \in T_2} BHCA^t x_2^{j_2 t} \ (c \in \{c_1\}, j_2 \in S_2) \tag{3.33}$$

$$\sum_{j_1 \in S_2} f_{21}^{c j_1 j_2} \leq \sum_{t \in T_2} \alpha^t x_2^{j_2 t} \ (c \in \{c_2\}, j_2 \in S_2) \tag{3.34}$$

$$\sum_{m \in M_1} \omega^m \sum_{j_1 \in S_2} v_{21}^{j_1 j_2 m} \leq \sum_{t \in T_2} \beta^t x_2^{j_2 t} \ (j_2 \in S_2) \tag{3.35}$$

MSS capacity constraints at the node level

$$\sum_{j_1 \in S_2} f_{22}^{c j_1 j_2} \leq \sum_{t \in T_3} SUB^t x_3^{j_2 t} \ (c \in \{c_0\}, j_2 \in S_2) \tag{3.36}$$

$$\sum_{j_1 \in S_2} f_{22}^{c j_1 j_2} \leq \sum_{t \in T_3} BHCA^t x_3^{j_2 t} \ (c \in \{c_1\}, j_2 \in S_2) \tag{3.37}$$

$$\sum_{j_1 \in S_2} f_{22}^{c j_1 j_2} \leq \sum_{t \in T_3} \alpha^t x_3^{j_2 t} \ (c \in \{c_2\}, j_2 \in S_2) \tag{3.38}$$

$$\sum_{m \in M_1} \omega^m \sum_{j_1 \in S_2} v_{22}^{j_1 j_2 m} \leq \sum_{t \in T_3} \beta^t x_3^{j_2 t} \ (j_2 \in S_2) \tag{3.39}$$

PS router capacity constraints at the node level

$$\sum_{m \in M_0} \omega^m \sum_{i_1 \in S_1} v_{13}^{i_1 k_1 m} \leq \sum_{t \in T_6} \beta^t x_8^{k_1 t} \ (k_1 \in S_3) \tag{3.40}$$

SGSN capacity constraints at the node level

$$\sum_{k_1 \in S_3} f_{31}^{ck_1k_2} \leq \sum_{t \in T_4} SUB^t x_4^{k_2t} \ (c \in \{c_5\}, k_2 \in S_3) \tag{3.41}$$

$$\sum_{k_1 \in S_3} f_{31}^{ck_1k_2} \leq \sum_{t \in T_4} PDP^t x_4^{k_2t} \ (c \in \{c_6\}, k_2 \in S_3) \tag{3.42}$$

$$\sum_{m \in M_1} \omega^m \sum_{k_1 \in S_3} v_{31}^{k_1k_2m} \leq \sum_{t \in T_4} \beta^t x_4^{k_2t} \ (k_2 \in S_3) \tag{3.43}$$

GGSN capacity constraints at the node level

$$\sum_{k_1 \in S_3} f_{32}^{ck_1k_2} \leq \sum_{t \in T_5} PDP^t x_5^{k_2t} \ (c \in \{c_6\}, k_2 \in S_3) \tag{3.44}$$

$$\sum_{m \in M_1} \omega^m \sum_{k_1 \in S_3} v_{32}^{k_1k_2m} \leq \sum_{t \in T_5} \beta^t x_5^{k_2t} \ (k_2 \in S_3) \tag{3.45}$$

5. ***Capacity constraints*** at the link level impose that the traffic entry of type $c \in C$ of a node should not exceed its total links capacities to upper layer node. Capacity constraints of interconnection links for the thesis model are as follows:

Node B-edge router link capacity constraints

$$\begin{gathered}(f_{01}^{cbi_1} + f_{01}^{c'bi_1} + f_{01}^{c''bi_1}) \leq \sum_{m \in M_0} \omega^m v_{01}^{bi_1m} \\ (c \in \{c_3\}, c' \in \{c_4\}, c'' \in \{c_7\}, i_1 \in S_1, b \in B)\end{gathered} \tag{3.46}$$

Edge router-RNC link capacity constraints

$$(f_{11}^{ci_1i_2} + f_{11}^{c'i_1i_2} + f_{11}^{c''i_1i_2}) \leq \sum_{m \in M_1} \omega^m v_{11}^{i_1i_2m}$$
$$(c \in \{c_3\}, c' \in \{c_4\}, c'' \in \{c_7\}, i_1, i_2 \in S_1) \tag{3.47}$$

Edge router-CS router link capacity constraints

$$(f_{12}^{ci_1j_1} + f_{12}^{c'i_1j_1}) \leq \sum_{m \in M_0} \omega^m v_{12}^{i_1j_1m}$$
$$(c \in \{c_3\}, c' \in \{c_7\}, i_1 \in S_1, j_1 \in S_2) \tag{3.48}$$

CS router-MGW link capacity constraints

$$f_{21}^{cj_1j_2} \leq \sum_{m \in M_1} \omega^m v_{21}^{j_1j_2m} \ (c \in \{c_3\}, j_1, j_2 \in S_2) \tag{3.49}$$

CS router-MSS link capacity constraints

$$f_{22}^{cj_1j_2} \leq \sum_{m \in M_1} \omega^m v_{22}^{j_1j_2m} \ (c \in \{c_7\}, j_1, j_2 \in S_2) \tag{3.50}$$

Edge router-PS router link capacity constraints

$$f_{12}^{ci_1k_1} \leq \sum_{m \in M_0} \omega^m v_{12}^{i_1k_1m} \ (c \in \{c_4\}, i_1 \in S_1, k_1 \in S_3) \tag{3.51}$$

PS router-SGSN link capacity constraints

$$f_{31}^{ck_1k_2} \leq \sum_{m \in M_1} \omega^m v_{31}^{k_1k_2m} \ (c \in \{c_4\}, k_1, k_2 \in S_3) \tag{3.52}$$

PS router-GGSN link capacity constraints

$$f_{32}^{ck_1k_2} \leq \sum_{m \in M_1} \omega^m v_{32}^{k_1k_2m} \; (c \in \{c_4\}, k_1, k_2 \in S_3) \tag{3.53}$$

6. ***Traffic flow conservation constraints*** state that sum of the input traffic type $c \in C$ to a node should be equal to the output traffic of the same type from the node.

$$\mu_b^c v_{01}^{bi_1} = f_{01}^{cbi_1} (c \in \{c_0, \ldots, c_7\}, b \in B, i_1 \in S_1) \tag{3.54}$$

$$\sum_{b \in B} f_{01}^{cbi_1} = \sum_{i_2 \in S_1} f_{11}^{ci_1i_2} (c \in \{c_0, c_1, c_3, c_4, c_7\}, i_1 \in S_1) \tag{3.55}$$

$$\sum_{b \in B} f_{01}^{cbi_1} = \sum_{j_1 \in S_2} f_{12}^{ci_1j_1} (c \in \{c_0, \ldots, c_3, c_7\}, i_1 \in S_1) \tag{3.56}$$

$$\sum_{b \in B} f_{01}^{cbi_1} = \sum_{k_1 \in S_3} f_{13}^{ci_1k_1} (c \in \{c_4, c_5, c_6\}, i_1 \in S_1) \tag{3.57}$$

$$\sum_{i_1 \in S_1} f_{12}^{ci_1j_1} = \sum_{j_2 \in S_2} f_{21}^{cj_1j_2} (c \in \{c_1, c_2, c_3\}, j_1 \in S_2) \tag{3.58}$$

$$\sum_{i_1 \in S_1} f_{12}^{ci_1j_1} = \sum_{j_2 \in S_2} f_{22}^{cj_1j_2} (c \in \{c_0, c_1, c_2, c_7\}, j_1 \in S_2) \tag{3.59}$$

$$\sum_{i_1 \in S_1} f_{13}^{ci_1k_1} = \sum_{k_2 \in S_3} f_{31}^{ck_1k_2} (c \in \{c_4, c_5, c_6\}, k_1 \in S_2) \tag{3.60}$$

$$\sum_{i_1 \in S_1} f_{13}^{ci_1k_1} = \sum_{k_2 \in S_3} f_{32}^{ck_1k_2} (c \in \{c_4, c_6\}, k_1 \in S_2) \tag{3.61}$$

7. ***Additional constraints*** state that if a lower layer node is connected to an upper layer node, there will be at least one link between them, but the number

of links should not exceed the maximum number of interfaces on the lower layer node.

Note that n_1^t, n_3^t and n_4^t are total number of interface on the edge router, CS router and PS router. Total number of router interfaces is divided between the groups of interconnection links. For this purpose, a K coefficient is defined by the network planner. The value of K would vary for each group of links connecting to the same router.

$$v_{01}^{bi_1} \leq \sum_{m \in M_0} v_{01}^{bi_1 m} (b \in B, i_1 \in S_1) \tag{3.62}$$

$$v_{01}^{bi_1} \max\{n_0^t\} \geq \sum_{m \in M_0} v_{01}^{bi_1 m} (b \in B, i_1 \in S_1, t \in T_0) \tag{3.63}$$

$$K v_{01}^{bi_1} \max\{n_1^t\} \geq \sum_{m \in M_0} v_{01}^{bi_1 m} (b \in B, i_1 \in S_1, t \in T_6) \tag{3.64}$$

$$v_{11}^{i_1 i_2} \leq \sum_{m \in M_1} v_{11}^{i_1 i_2 m} (i_1, i_2 \in S_1) \tag{3.65}$$

$$K v_{11}^{i_1 i_2} \max\{n_1^t\} \geq \sum_{m \in M_1} v_{11}^{i_1 i_2 m} (i_1, i_2 \in S_1, t \in T_6) \tag{3.66}$$

$$v_{12}^{i_1 j_1} \leq \sum_{m \in M_0} v_{12}^{i_1 j_1 m} (i_1 \in S_1, j_1 \in S_2) \tag{3.67}$$

$$K v_{12}^{i_1 j_1} \max\{n_1^t\} \geq \sum_{m \in M_0} v_{12}^{i_1 j_1 m} (i_1 \in S_1, j_1 \in S_2, t \in T_6) \tag{3.68}$$

$$K v_{12}^{i_1 j_1} \max\{n_1^t\} \geq \sum_{m \in M_0} v_{12}^{i_1 j_1 m} (i_1 \in S_1, j_1 \in S_2, t \in T_6) \tag{3.69}$$

$$v_{13}^{i_1 k_1} \leq \sum_{m \in M_0} v_{13}^{i_1 k_1 m} (i_1 \in S_1, k_1 \in S_3) \tag{3.70}$$

$$Kv_{13}^{i_1k_1}\max\{n_1^t\} \geq \sum_{m\in M_0} v_{13}^{i_1k_1m}(i_1 \in S_1, k_1 \in S_3, t \in T_6) \tag{3.71}$$

$$v_{21}^{j_1j_2} \leq \sum_{m\in M_1} v_{21}^{j_1j_2m}(j_1, j_2 \in S_2) \tag{3.72}$$

$$Kv_{21}^{j_1j_2}\max\{n_3^t\} \geq \sum_{m\in M_1} v_{21}^{j_1j_2m}(j_1, j_2 \in S_2, t \in T_6) \tag{3.73}$$

$$v_{22}^{j_1j_2} \leq \sum_{m\in M_1} v_{22}^{j_1j_2m}(j_1, j_2 \in S_2) \tag{3.74}$$

$$Kv_{22}^{j_1j_2}\max\{n_3^t\} \geq \sum_{m\in M_1} v_{22}^{j_1j_2m}(j_1, j_2 \in S_2, t \in T_6) \tag{3.75}$$

$$v_{31}^{k_1k_2} \leq \sum_{m\in M_1} v_{31}^{k_1k_2m}(k_1, k_2 \in S_3) \tag{3.76}$$

$$Kv_{31}^{k_1k_2}\max\{n_4^t\} \geq \sum_{m\in M_1} v_{31}^{k_1k_2m}(k_1, k_2 \in S_3, t \in T_6) \tag{3.77}$$

$$v_{32}^{k_1k_2} \leq \sum_{m\in M_1} v_{32}^{k_1k_2m}(k_1, k_2 \in S_3) \tag{3.78}$$

$$Kv_{32}^{k_1k_2}\max\{n_4^t\} \geq \sum_{m\in M_1} v_{32}^{k_1k_2m}(k_1, k_2 \in S_3, t \in T_6) \tag{3.79}$$

8. ***Non-negativity constraints*** identify the domain of the variables used in the model. They state that the domain of traffic variables is set of all positive real numbers.

$$\mathbf{f} \in \mathbb{R}_+{}^{|C|(|S_1|(|B|+|S_1|+|S_2|+|S_3|)+|S_2|^2+|S_3|^2)} \tag{3.80}$$

9. ***Integrality constraints*** state that the domain of the following decision variables is set of binary numbers and can hold either 0 or 1.

$$\mathbf{v} \in \mathbb{B}^{|S_1|(|B|+|S_1|+|S_2|+|S_3|)+|S_2|^2+|S_3|^2} \tag{3.81}$$

$$\mathbf{x} \in \mathbb{B}^{|S_1|(|T_1|+|T_6|)+|S_2|(|T_2|+|T_3|+|T_6|)+|S_3|(|T_4|+|T_5|+|T_6|)} \tag{3.82}$$

The following variables are defined as general variables, stating that domain is set of all natural numbers.

$$\mathbf{v} \in \mathbb{N}^{|M_0||S_1|(|B|+|S_2|+|S_3|)+|M_1|(|S_2|^2+|S_3|^2)} \tag{3.83}$$

The ALLIPR4PP is classified as NP-hard. As a result, we hope to find optimal solutions for the problem by using exact algorithms within a predefined finite amount of time.

3.6 Exact Methods for the Design Problem

A linear programming method is proposed for the implementation of the exact algorithm. We translate the objective function, constraints and other inputs into linear programming file format which can be read by a solver. In this thesis, we used CPLEX solver. The implemented algorithm in CPLEX is branch and cut. In branch and cut algorithm, a series of continues sub-problems are solved. To manage those sub-problems, CPLEX builds a *tree* in which each sub-problem is defined as a *node*. The root of the tree is a continuous relaxation of the original problem. In case the solution to the relaxation has any fractional variables, CPLEX will try to find *cuts* in the first step. Cuts are constraints that cut away areas of the feasible region of the relaxation which contain fractional solutions. When an integer feasible solution is found or no further cuts are found, CPLEX continues with branch and bound algorithm in the second step. Branching includes splitting the search space into smaller spaces, while bounding is the procedure of computing minimum and maximum of the function within the subsets of the search space [19, 21].

Since ALLIPR4PP is NP-hard and exact algorithms might require longer computational time to find optimal solutions, we concentrate our efforts on the development of efficient heuristics to find sub-optimal solutions.

3.7 Heuristics for the Design Problem

In this section, we propose a local search and a tabu search heuristics to find 'good" solutions for the global planning problem within reasonable amount of time. Both heuristics start from an initial solution and explore the search space to find a better solution. Before introducing these heuristics, we need to describe the solution representation and initial solution.

3.7.1 Solution Representation and Initial Solution

The initial step of the LS and TS algorithms is to determine an initial solution, but first we need to find a way to represent the solutions. For this purpose, we use the binary and the non-binary encoding schemes. In the binary encoding scheme, a decision variable is represented by 0 or 1. The binary scheme is good for dual state cases, but is not efficient (suitable) for multi state cases. For such cases, non-binary schemes are used in which the decision variables may hold more than two values.

In the UMTS network planning problem, the binary coding scheme is used to indicate if the corresponding site (*i.e.* potential location) is installed with a NE or not. On the other hand, the non-binary scheme is used to represent different types

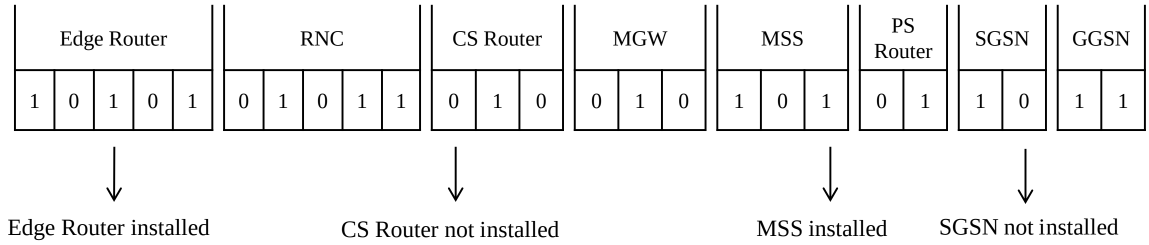

Figure 3.3: Example of the NE-Install vector

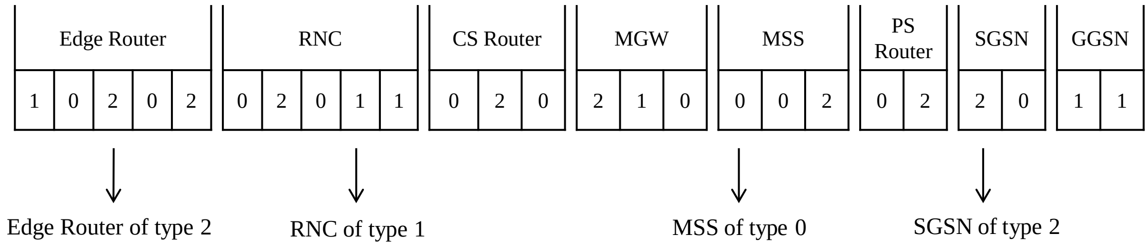

Figure 3.4: Example of the NE-Type vector

of NEs, installed in each site. In order to represent a solution, first we need to know whether a NE is installed on a specific site and then determine its type. For this purpose, we defined a vector, called *NE-Install*, where the size of the vector is equal to the number of potential sites for all NE. Figure 3.3 shows an example of the NE-Install vector with 5 potential sites for each edge router/RNC, 3 potential sites for CS Router/MGW/MSS and 2 potential sites for each PS router/SGSN/GGSN. A value of 1 means that the corresponding node is installed on that site whereas the value 0 indicates that no NE is installed in that site.

The next step is to determine the type of all NEs, if they are already installed in a given site. As we deal with more than two types of NEs, we used non-binary scheme. For this purpose, a second vector, called *NE-Type* was defined. As shown in Figure 3.4, this vector has the same size as the NE-Install vector. For example, in this thesis, each NE has three types. Therefore, each site in the NE-Type vector can hold any of the defined values (0, 1 or 2), representing the type of the corresponding NE installed on that site. We use a combination of the NE-Install and the NE-Type vectors to represent a solution, including the initial solution.

3.7.2 Local Search Heuristic

Local search heuristic starts with an initial solution and explores the neighborhood to find a better solution. LS can sometimes provide the global optimum. However, it will be trapped in the first local minimum. The local search heuristic algorithm used in this thesis is shown in Figure 3.5.

The first step is to find an initial solution to start with. In this thesis, we suppose that in the initial solution, all NEs (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers/CS routers/PS routers) are installed in all potential locations with their most powerful type. To design interconnecting links, we break down the global problem into eight sub-problems: the Node B to edge router, the edge router to RNC, the edge router to CS router, the edge router to PS router, the CS router to MGW, the CS router to MSS, the PS router to SGSN and the PS router to GGSN. Each of these assignment sub-problems is NP-hard and to solve them, we use shortest augmentation path algorithm LAPJV [99] as proposed in [95]. The LAPJV algorithm, developed by *Jonker* and *Volgenant*, contains new initialization routines and a special implementation of *Dijkstra's* [100] shortest path method. An implementation of LAPJV algorithm in C++ is used in this thesis.

Objective of the eight assignment sub-problems is to minimize the cost of the interconnecting links between the lower and the higher level nodes. The traffic volume

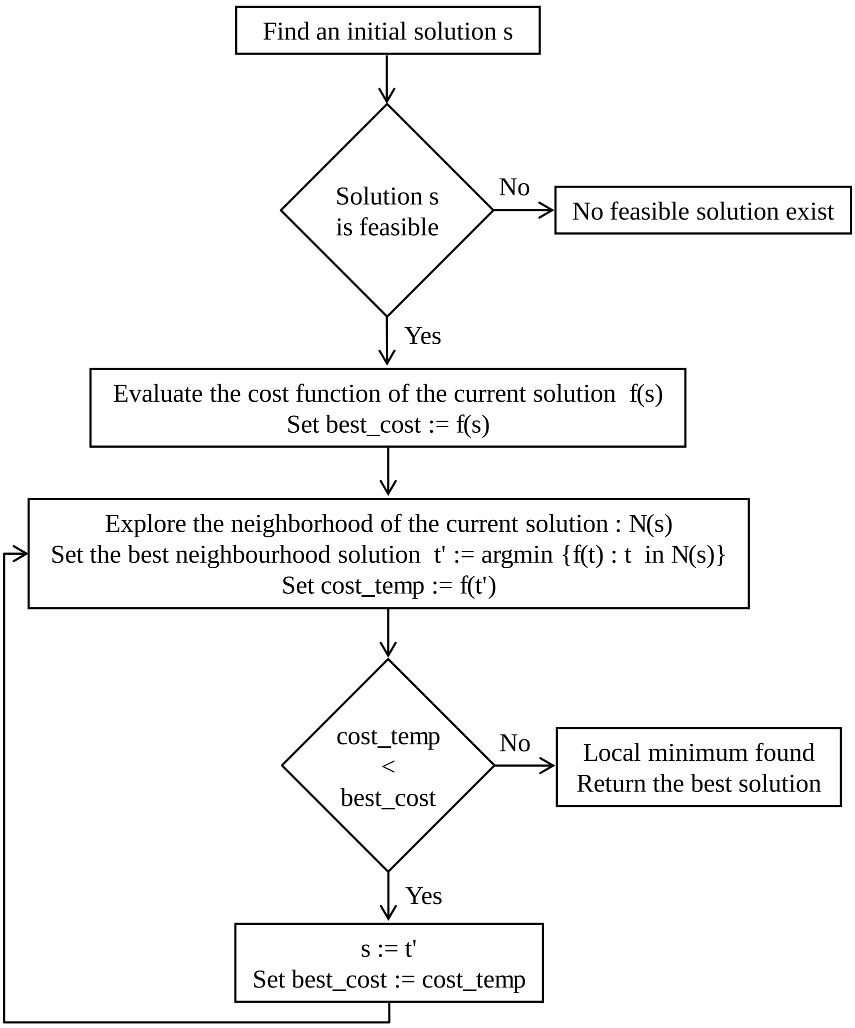

Figure 3.5: Local search algorithm [5]

passing from a node determines the number and type of its interconnecting links and interfaces. Starting from the first sub-problem, LAPJV uses the cost matrix of the interconnection links among the lower layer to the upper layer node to find the cost-optimal interconnections. LAPJV repeats the same task for the rest of the sub-problems. At the end, an initial solution is found for the whole planning problem. If the initial solution does not respect all constraints, then it is not feasible and the program will terminate. Otherwise, the cost of the feasible solution is calculated and is stored as the *best cost* found so far. The solution is also stored as the *current solution*.

The second step consists of exploring the neighborhood of the current solution. This type of operation is called *move*. A move is transformation of the current solution to produce a new solution. The following types of move can be made from a current solution:

1. Remove a NE (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers/CS routers/PS routers) that is already installed.

2. Change the type of a NE (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers/CS routers/PS routers) that is already installed.

Starting from the first sub-problem, a new solution is created by a move. Considering the new solution, the number and type of the interconnecting links and interfaces for the entire problem are recalculated. Then, the feasibility check is done. If the new solution is not feasible, the corresponding move is returned and another move is performed. But if the new solution is feasible, its cost is calculated and is stored in *cost_temp*. If value of cost_temp is less that the best cost calculated in the previous step, the new solution is accepted and is considered as the current solution. In the similar way, cost_temp is also taken as the best cost.

Exploring the neighborhood of the current solution is a continuous duty of LS, in the hope of finding a better solution (*i.e.* a solution with a lower cost). If a move results in a feasible solution with higher cost than the current solution, the algorithm will suppose that no further improvement can be made. Therefore, a local minimum is found and ultimately, the current solution is considered as the final solution.

3.7.3 Tabu Search Heuristic

The tabu search was first formalized by *Fred Glover* and *Manuel Laguna* in 1986 [101]. TS uses *short term memory* in the form of so-called *tabu list* and *aspiration criteria* to avoid cycling and escape from local minimum. Tabu list guides the search direction by storing the features of recently visited solutions to prevent returning to them. The solutions from the neighborhood of the current solution, which their features are currently found in tabu list are excluded. Such action allows for the possibility of losing unvisited high quality solutions. In order to overcome this problem, the aspiration criteria are defined. Aspiration criteria allow to accept a tabu move despite violating the tabu condition. However, the included solution should be better than the best solution found so far [19].

The tabu search heuristic presented in this thesis is shown in Figure 3.6. Similar to LS, the global planning problem is broken into eight sub-problems. The procedure to find the initial solution is the same as mentioned for the LS. However, a better way consists to use the final solution produced by LS as the initial solution for TS.

The initial solution (current solution) and its cost (best cost) are kept in memory for further improvements. The next step is to determine the *best move* in the neighborhood of the current solution. The following types of move can be made from a current solution:

1. Remove a NE (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers/CS routers/PS routers) that is already installed

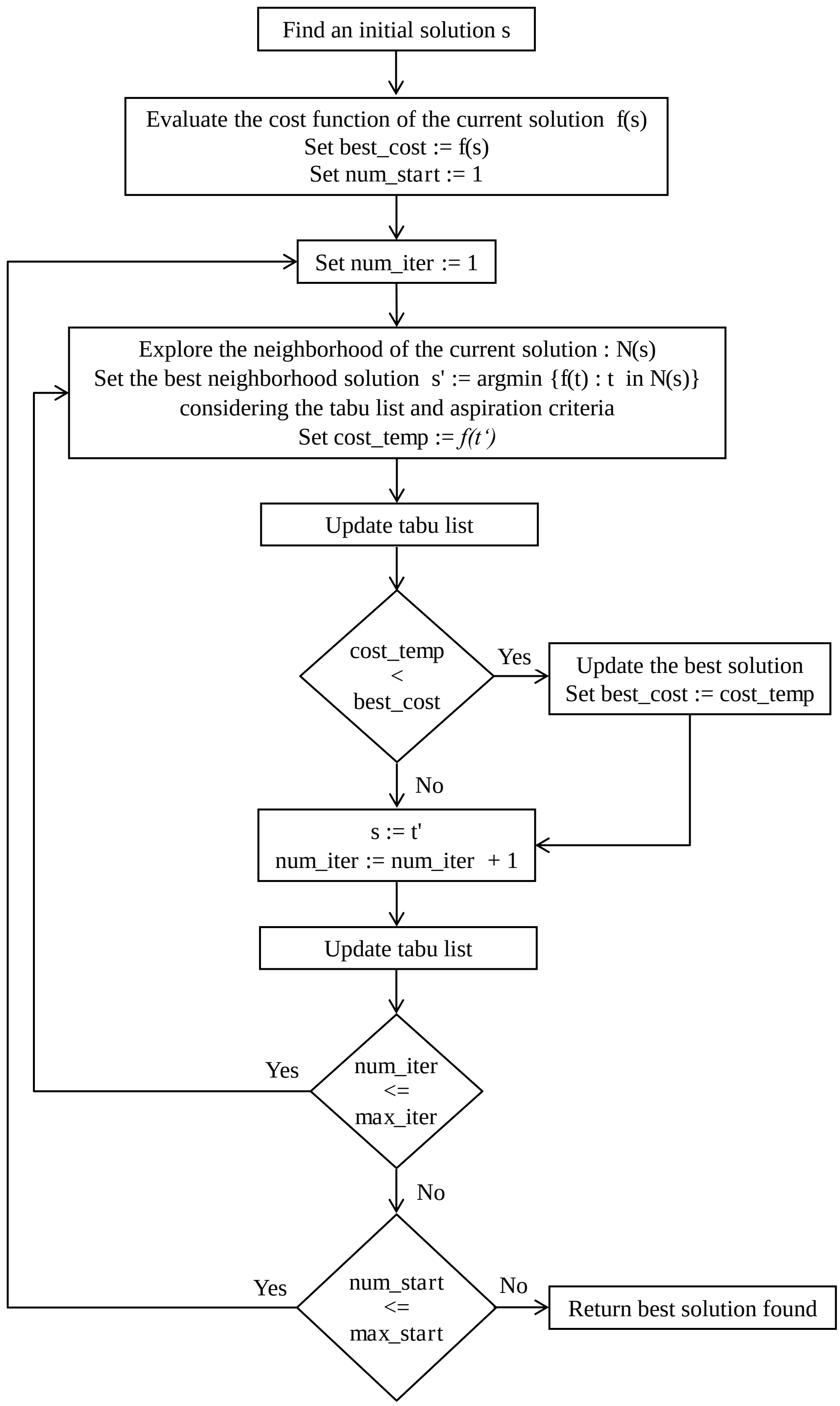

Figure 3.6: Tabu search algorithm [6]

Table 3.2: Structure of the tabu list size

NE	Tabu tenure	Tabu tenure representation
Edge router	No. of potential locations for the edge router	L1
RNC	L1 + No. of potential locations for the RNC	L2
CS router	L2 + No. of potential locations for the CS router	L3
MGW	L3 + No. of potential locations for the MGW	L4
MSS	L4 + No. of potential locations for the MSS	L5
PS router	L5 + No. of potential locations for the PS router	L6
SGSN	L6 + No. of potential locations for the SGSN	L7
GGSN	L7 + No. of potential locations for the GGSN	L8

2. Add a NE (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers/CS routers/PS routers) of type t.

3. Change the type of a NE (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers/CS routers/PS routers) that is already installed

We have defined the tabu list as a non-binary vector with a variable length. The length of the tabu list, know as *tabu tenure*, depends on the NE which the move is made over. For example, in the first sub-problem, the move is applied on the edge router and the tabu tenure is equal to the number of potential locations for the edge routers. As we proceed with the second sub-problem, the tabu tenure will grow and will include the number of potential locations for the RNCs plus the number of the potential locations for the edge routers. The tabu tenure grows up as the algorithm makes moves in the subsequent sub-problem. Table 3.2 shows the size of the tabu list, when a move is made over an specific NE.

For each iteration, TS determines the best move while considering the tabu list and the aspiration criteria. Among all possible neighbors, the best move is the one which produces a solution with lower cost than the best cost in the neighborhood. However, the best move also can be an inferior solution (not been in tabu list) which can be accepted temporary in order to prevents entrapment in a local minimum. If the resulting solution has a lower cost than the best cost, it is taken as the best solution found so far. Otherwise, if the solution is not in tabu list, it is accepted even though the solution quality is not better than the best found so far. At the start of the algorithm, the tabu list is empty, but if a new solution is accepted, it is added to tabu list. The purpose of such an action is to avoid cycling and revisiting instances that have been seen in the recent past. Any solution is kept in tabu list for a given number of iteration. To simplify the definition, we call it *tabu life time*.

TS configuration parameters are problem specific and are acquired through multiple tests. Selecting a proper duration for tabu conditions is so important. It was shown that assigning a very small number to tabu life time, causes cycling, but as this number is increased, the probability of visiting several good solutions increases. However, the tabu life time should not be a very large number, because it then becomes less probable to find good local minimum for lack of available moves [102]. It is also shown that randomly selecting the tabu life time can direct the search towards good solutions [19]. The number of iterations is randomly chosen between a lower bound (L) and an upper bound (U). Due to this randomness, running the algorithm for multiple times can yield different solutions. As a result, a multi-start TS algorithm is proposed [97].

TS can be configured to stop either at the end of the search or by some conditions. Examples of stopping conditions can be that the neighborhood is empty, the maximum number of solutions to be explored is fixed or the total number of iteration is reached.

After each iteration, the life time of solutions in the tabu list is decreased by one.

During the overall search process, the current solution will be compared with the best solution found so far to keep the best solution up to date. When the whole search process ends, the best solution over the whole search process will be the final output.

Tabu search is a metaheuristic technique that must be adapted to the problem at hand for it to be efficient. The choice of moves that generate the neighborhoods is problem-specific. Different implementations can be generated by varying the definition and the structure of the tabu list, the aspiration criteria and other attributes [103].

In the next chapter, the simulation results based on these algorithms are presented and analyzed.

Chapter 4

Experiment Design and Result Analysis

In this chapter, we will first describe how the simulations were developed. We introduce simulation environments and data used to run the simulations. Later, we explain the simulation procedures and present the results and analysis.

4.1 Experiment Design

In this thesis, we supposed that Node Bs are already installed and their number and locations are known. We also assume that the potential location for all other NEs (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers, CS routers, PS routers) is known.

For traffic modeling, we suppose that the subscriber traffic profile and the planning parameters are known. This information is usually provided by the operator

Table 4.1: The subscriber traffic profile

	Call Type				
Circuit services	**Voice**	**CS Data**	**PS Data**		
Average rate	AMR 12.2 Kbps	16 Kbps	64 Kbps	144 Kbps	384 Kbps
Monthly usage	300 Min	10 Min	200 Mbps	100 Mbps	50 Mbps
Activity factor	0.5	1	0.4	0.4	0.4

Table 4.2: The planning parameters

AMR rate in active mode	18.9 Kbps
AMR rate in silent mode	4.5 Kbps
Mean holding time	120 seconds
Soft handover ratio	0.4
IP over head	0.38
Attached subscriber ratio	0.2
Active BH PDP ratio	0.5
Average PDP duration	900 seconds
Retransmission factor	0.25
Iub interface blocking factor	0.02
Iub utilization factor	0.75
Busy days per month	22
Busy days call ratio	0.9
Busy hour call ratio	0.1

and might vary subject to traffic forecast and planning strategies. The subscriber traffic profile and the traffic planning parameters used in this thesis are respectively presented in Tables 4.1 and 4.2. These values are considered based on practical work experience of the author with mobile operators.

The *Adaptive Multi Rate* (AMR) codec is used by voice users. The activity factor of a traffic channel is defined as the percentage of time, where traffic is present in the channel. We suppose that the activity factor for voice is 0.5 (and 0.5 silence), while for CS-data and PS-data traffic the activity factor is 1 and 0.4 respectively. It is supposed that network operators define a monthly limited amount for voice and data traffic per subscriber. The network is supposed to be designed to deliver the required capacity for the specific number of subscribers.

We first started with the subscriber allocation for each Node B. We assigned a random number of subscribers to each Node B in a range of 5,000 to 20,000 subscribers. Then, using the subscriber traffic profile and traffic planning parameters, we created a traffic record for each Node B. A sample traffic record was introduced in Chapter 3. The detail calculations of the Node B traffic records are presented in Appendix A.

We supposed that three types are available for each NE (type A, B and C) and four different types of links/interfaces can be used. It is also supposed that the specifications such as the processing capacity, the interface capacity and cost are given for each type of equipment. Similarly, we assumed that the capacity and cost for all types of the links/interfaces are provided. The cost includes all related costs such as floor space, cables, racks, electric installations, labor, etc. The specifications for the nodes, links and interfaces used in this thesis are shown in Tables 4.3 to 4.10. These values are considered based on practical work experience of the author with mobile operators. The up-to-date values for these parameters in real market might vary in time with what presented in this thesis.

Using a C++ based program, we created a text file containing the number and location of all NEs (*i.e.* Node Bs, RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers, CS routers, PS routers), as well as the traffic records for each Node B. This file is used as input for both exact and approximate algorithms. A MATLAB file was also created to graphically depict the potential locations of all NEs.

Table 4.3: Features of the Node B types

	Type A
No. of edge router interfaces	10

Table 4.4: Features of the RNC types

	Type A	Type B	Type C
Capacity (channels)	181,000	284,000	463,000
Capacity (BHCA)	147,000	231,000	443,000
Capacity (Mbps)	1,950	2,800	3,600
No. of edge router interfaces	12	16	32
Cost ($)	100,000	150,000	250,000

Table 4.5: Features of the MGW types

	Type A	Type B	Type C
Capacity (channels)	4,048	12,600	22,000
Capacity (BHCA)	200,000	600,000	900,000
No. of CS router interfaces	12	16	32
Cost ($)	200,000	350,000	500,000

Table 4.6: Features of the MSS types

	Type A	Type B	Type C
Capacity (Mbps)	500	1,00	2,000
Capacity (channels)	15,000	20,000	41,500
Capacity (BHCA)	400,000	600,000	1,000,000
Capacity (subscribers)	400,000	600,000	1,000,000
No. of CS router interfaces	12	16	32
Cost ($)	300,000	500,000	600,000

Table 4.7: Features of the SGSN types

	Type A	Type B	Type C
Capacity (Mbps)	500	750	1,000
Capacity (PDP context)	480,000	720,000	960,000
Capacity (subscribers)	500,000	750,000	1,000,000
No. of PS router interfaces	12	16	32
Cost ($)	200,000	300,000	400,000

Table 4.8: Features of the GGSN types

	Type A	Type B	Type C
Capacity (Mbps)	333	666	1,000
Capacity (PDP context)	333,000	666,000	960,000
No. of PS router interfaces	12	16	32
Cost ($)	300,000	400,000	500,000

Table 4.9: Features of the router types

	Type A	Type B	Type C
Capacity (Mbps)	2,000	4,000	8,000
No. of interfaces	32	48	64
Cost ($)	80,000	120,000	160,000

Table 4.10: Costs of the link and interface types

Type	Interface Cost ($)	Link Cost ($/km)
DS-1	300	700
DS-3	1,500	1,500
FE	300	700
GE	1,500	1,500

4.1.1 Implementation of the Exact Algorithm

We used the linear programming method for the implementation of the exact algorithm to solve the planning problem of 3G UMTS all-IP Release 4 networks. For this purpose, we developed a C++ based program to minimize the constructed cost function subjects to the corresponding constraints. Using the input file (explained in previous section), the problem (including the cost function, the constraints and all inputs) was properly converted into a linear programming (.lp) file format which can be read by the CPLEX solver.

We used CPLEX solver 12.1 with all default setting to solve the problem, under a Linux server with one 2.39 GHZ CPU (AMD Opteron Processor 250 family) and 16 GB RAM. Considering the nature of the problem and the high number of constraints, we expected a long computation time. As a result, we set up a *Time Limit* (TL) of 24 hours. This means that after 24 hours of computation time, CPLEX will return the best solution found so far.

If the problem can be solved within the time limit, then the output of the CPLEX solver is the optimal solution. The solution consists of the number, the location and the type of all NEs, links, interfaces, as well as the topology of access and core networks. The solution also provides the cost and the CPU time for the problem. These costs will be used as benchmark for comparison with the results from the approximate algorithms. For the simplicity of depiction, a C++ program converts the solution into a MATLAB file to produce a graphical topology.

4.1.2 Implementation of Approximate Algorithms

Among different heuristics, local search and tabu search were implemented to solve the planning problem of 3G UMTS all-IP Release 4 networks.

We decided to use the local optimum solution found by LS as the initial solution for TS. For this purpose, we implemented LS and TS both in the same C++ based program, such that, a local minimum is first found by LS. Then, the quality of such solution is improved by TS with the hope of finding a global optimum. The program aims to minimize the cost function as presented in equation 3.3.

We start from the initial solution in which NEs are installed in all their potential locations with their most powerful type. It means that the all elements of NE-Install and NE-Type vectors are respectively equal to 1 and 2. To design the interconnecting links, we break down the ALLIPR4PP into eight sub-problems: the Node B to edge router, the edge router to RNC, the edge router to CS router, the edge router to PS router, the CS router to MGW, the CS router to MSS, the PS router to SGSN and the PS router to GGSN.

4.1.2.1 Local Search

Beside the number, type and location of NEs, we require to find the cost-optimal interconnecting topology as a part of the initial solution. We started from the first sub-problem. The link type and capacity between each Node B and edge router is determined based on amount of Node B traffic. Node B traffic is ultimately accumulated on the selected edge routers. Knowing the number and types of the links, a cost matrix of interconnection links between the Node Bs and the edge routers is constructed, while considering corresponding constraints.

The cost matrix contains several possible assignment combinations and is used as input for LAPJV function to find the cost-optimal interconnections between all Node Bs and the edge routers. Once the solution of the first sub-problem is found, the upcoming sub-problems are similarly tackled. Once the eight sub-problems are solved, the obtained solution will be the current solution. The cost of the current solution is then calculated and is stored as the best cost so far.

The second step consists of exploring the neighborhood of the current solution. For this purpose, a move is made and and is accepted, if it has a lower cost than the best cost found so far. Otherwise, LS will suppose that no further improvement can be made and will stop. At this point a local minimum is found and ultimately, the current solution will be the final solution. To execute LS, we used *Linux g++* compiler with the same platform as before.

4.1.2.2 Tabu Search

The local minimum found by LS is used as the initial (current) solution for TS. The current solution and its cost are respectively known as the best solution and the best cost. For further improvement, TS determines the best move in the neighborhood of the current solution. The best move is chosen based on tabu list and aspiration criteria. TS performs three types of moves: *i*) remove a NE, *ii*) add a NE and *iii*) change the type of a NE.

We implemented add(remove) a NE by changing the corresponding location in NE-Install vector to 1(0), while the type change of a NE is done by modifying the corresponding location in NE-Type vector to the new type value.

We configured TS with the following parameters:

- Tabu life time in tabu list randomly chosen between 5 and 9;
- Maximum number of iterations (max_iter)=100;
- Maximum number of start (max_start)=2.

To chose the tabu life time, different values are tested and the optimum results were obtained with a random number between 5 to 9. To fix a value for the number of iteration, we repeated the search for several times. In fact, the main improvement was happened in the early iterations. We set an upper bound of 100 iterations to fit for all set of problems. It was also seen that, with running the tabu program for more than 2 times, minor quality improvement is achieved over some problems, in the expense of longer CPU time.

TS performs 100 iterations for 2 times. At each iteration, the current solution is compared with the best solution found so far. When the whole search is completed, the best solution is returned as the final solution. The solution consists of the number, the location and the type of all NEs, type and number of the links and interfaces, as well as the topology of access and core networks. The solution also includes the cost and the CPU time for the solution. Similar to LS, we used Linux g++ compiler with the same platform as before.

4.2 Illustrative Example

In this section, we select a sample problem and attempt to solve it using the exact and the approximate algorithms. We use local search, tabu search and integer

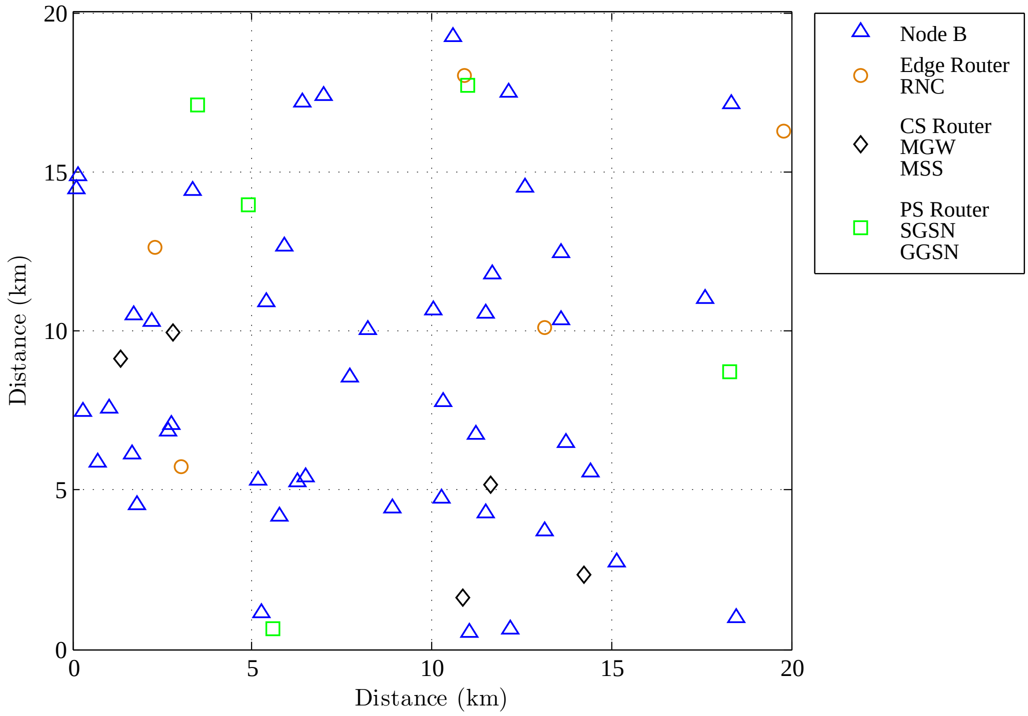

Figure 4.1: Potential locations for the illustrated example

programming methods.

The example problem depicted in Figure 4.1, comprises of 45 installed Node Bs, 5 potential sites to install the edge routers (RNCs), 5 potential sites to install the CS routers (MGWs/MSSs) and 5 potential sites to install the PS routers (SGSNs/GGSNs) (*i.e.* $|S_1| = 5$, $|S_2| = 5$, $|S_3| = 5$). The input for the problem consists of randomly generated locations for these NEs, as well as traffic records for the Node Bs.

In order to design the network, three types of NEs (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers, CS routers, PS routers) and four types of links (interfaces) are available with the features presented in Tables 4.3 to 4.10.

In the first step, we used the local search heuristic to solve the example problem.

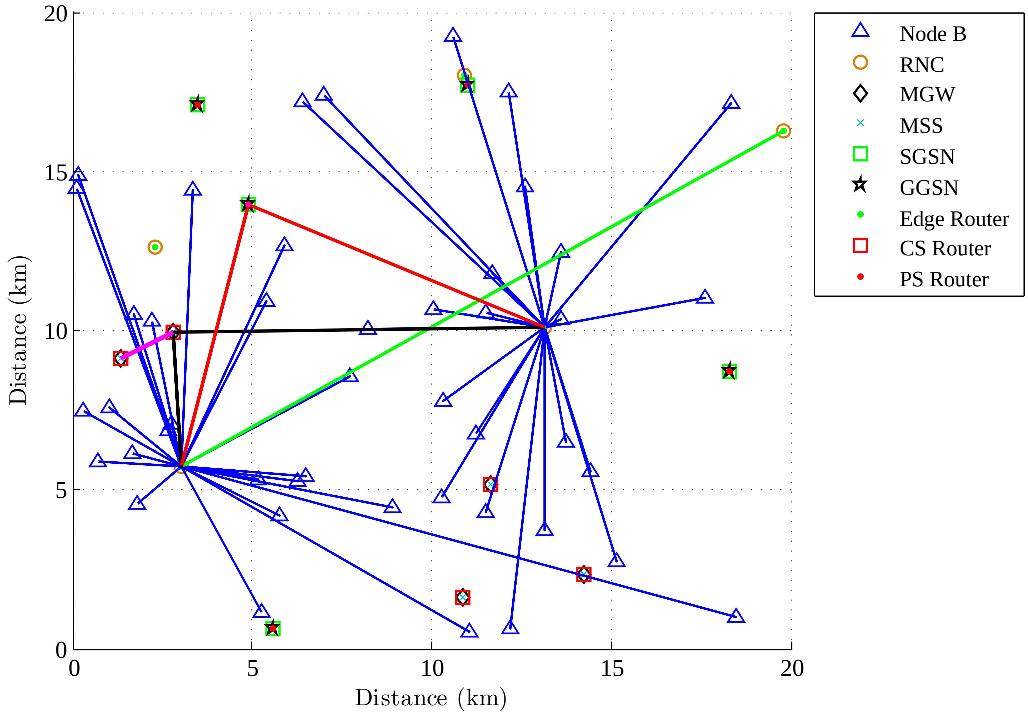

Figure 4.2: Solution for the illustrated problem obtained with LS

Figure 4.2 shows the designed network with the LS method. The network comprises of two RNCs (one of type B and one of type C), one MGW (of type C), one MSS (of type B), one SGSN (of type A), one GGSN (of type A), two edge routers (both of type B), one CS routers (of type A) and one PS routers (of type A). The network cost and CPU time are $2,975,949 and 743 seconds respectively.

In the second step, tabu search was used to find a solution with lower cost. As shown in Figure 4.3 the network designed by tabu search includes two RNCs (one of type A and one of type C), one MGW (of type C), one MSS (of type B), one SGSN (of type A), one GGSN (of type A), three edge routers (all of type A), one CS router (of type A) and one PS router (of type A). The network cost and CPU time are $2,862,127 and 2,427 seconds respectively. The designed network with TS has an

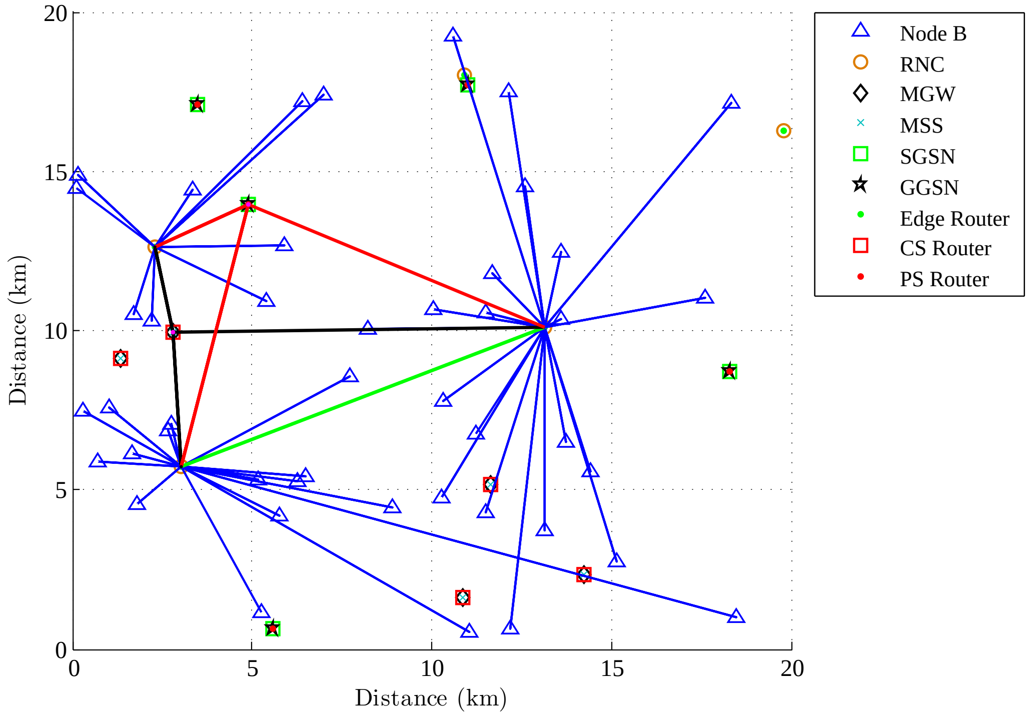

Figure 4.3: Solution for the illustrated problem obtained with TS

optimized topology with lower cost compared to LS.

In the last step, we used the integer programing method. To solve the example, the CPLEX Mixed Integer Optimizer 12.1 was used with all the default settings. CPLEX spent 16,319 seconds to complete and the returned objective value is $2,833,406 after exploration of 44,538,161 iterations and 1,078,504 nodes. Figure 4.4 is the output of CPLEX, showing the topology and configuration with two RNCs (one of type A and one of type C), one MGW (of type C), one MSS (of type B), one SGSN (of type A), one GGSN (of type A), two edge routers (one of type A and one of type B), one CS router (of type A) and one PS router (of type A).

The gap of the solution provided by local search is 5.03% from the solution provided by CPLEX, while the solution provided by TS has gap of 1.01% from the

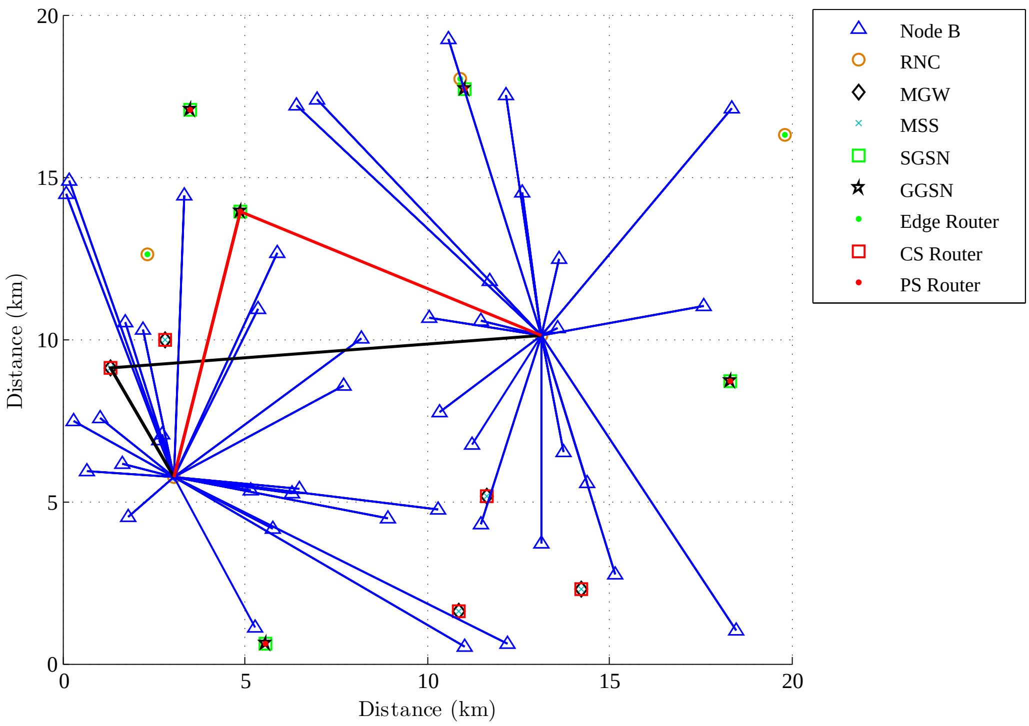

Figure 4.4: Solution for the illustrated problem obtained with CPLEX

optimal solution.

4.3 Result Analysis

In this section, we present the experiment results and analyze the performance of the proposed algorithms. Two problem sets of 15 sizes, each set with four different instances (120 problems in total) were randomly generated within an area. The size of the area for small and large size problems are respectively 100 km^2 and 400 km^2.

Table 4.11: Problem sizes - set#1

Problem No.	Area (km^2)	No. of Node B	No. of edge router, RNC (S_1)	No. of CS router, MGW, MSS (S_2)	No. of PS router, SGSN, GGSN (S_3)
1	100	10	5	5	5
2	100	15	5	5	5
3	100	20	5	5	5
4	100	25	5	5	5
5	400	30	5	5	5
6	400	35	5	5	5
7	400	40	5	5	5
8	400	45	5	5	5
9	400	50	5	5	5
10	400	55	5	5	5
11	400	60	5	5	5
12	400	65	5	5	5
13	400	70	5	5	5
14	400	75	5	5	5
15	400	80	5	5	5

4.3.1 Numerical Analysis

Table 4.11 shows the 15 problem sizes, where the first and second columns represent the problem number and the area size. The third column shows the number of Node Bs that are already installed. The number of potential locations for the edge router (RNC) is presented in column four. The fifth column shows the potential locations for CS router (MGW/MSS). Finally, the number of potential locations for PS router (SGSN/GGSN) are presented in column six. In this set of problems, we intended to represent real live networks where the problem's complexity is mainly proportional to the number Node Bs. A more complex set of problems are presented in Table 4.12 in which the potential locations for edge router (RNC) is increased from 5 to 10.

For each problem sets, four instances were randomly generated and solved by

Table 4.12: Problem sizes - set#2

Problem No.	Area (km^2)	No. of Node B	No. of edge router, RNC (S_1)	No. of CS router, MGW, MSS (S_2)	No. of PS router, SGSN, GGSN (S_3)
1	100	10	10	5	5
2	100	15	10	5	5
3	100	20	10	5	5
4	100	25	10	5	5
5	400	30	10	5	5
6	400	35	10	5	5
7	400	40	10	5	5
8	400	45	10	5	5
9	400	50	10	5	5
10	400	55	10	5	5
11	400	60	10	5	5
12	400	65	10	5	5
13	400	70	10	5	5
14	400	75	10	5	5
15	400	80	10	5	5

CPLEX, LS and TS. Tables 4.13 and 4.14 show the numerical results for the first instance of the problem set#1 and set#2. The first column shows the problem number which corresponds to the first column of Tables 4.11 and 4.12. The following two columns provide the results obtained by CPLEX solver. Columns 4 and 5 provide the best results and the corresponding CPU time obtained with the local search. Column 6 shows the gap (expressed in percentage) between the solution values obtained by the local search and the optimal solution. The following three columns show the best solutions, the corresponding computation time, as well as the gap for the tabu search.

As mentioned earlier, a CPU time limit of 24 hours (86,400 seconds) is set for CPLEX. Since the problems are NP-hard, CPLEX is not able to solve some of the problems in the defined TL. Once the TL is reached, CPLEX stops and returns the best solution found so far. It should be noted that problems facing the time limit are

Table 4.13: Numerical results for the first instance of set#1

	CPLEX		**Local Search**			**Tabu Search**		
Problem No.	Cost ($)	CPU (s)	Cost ($)	CPU (s)	Gap (%)	Cost ($)	CPU (s)	Gap (%)
1	1,462,335	152	1,499,944	200	2.58	1,462,335	220	0
2	1,499,105	54	1,520,426	285	1.43	1,500,627	322	0.11
3	1,760,827	1,435	1,776,100	373	0.87	1,760,827	462	0
4	1,850,368	945	1,974,095	458	6.69	1,944,718	743	5.1
5	2,100,229	1,893	2,221,985	540	5.8	2,145,767	1,014	2.17
6	2,444,225	4,026	2,596,044	605	6.22	2,472,978	1,196	1.18
7	2,514,815	434	2,599,864	715	3.39	2,574,839	1,955	2.39
8	2,788,062	650	2,975,949	743	6.74	2,862,127	2,427	2.66
9	2,877,196	898	3,007,039	858	4.52	2,931,825	2,134	1.9
10	3,133,179	3,839	3,354,674	934	7.07	3,295,990	3,732	5.2
11	3,233,417	48,275	3,441,074	938	6.43	3,413,646	4,333	5.58
12	3,274,512	13,291	3,498,771	1,093	6.85	3,440,937	3,535	5.09
13	3,320,597	30,260	3,551,861	1,137	6.97	3,479,220	4,064	4.78
14	3,576,809	45,666	3,819,732	1,241	6.8	3,791,646	7,094	6.01
15	3,551,323	78,102	3,771,826	1,174	6.21	3,737,246	6,299	5.24

set aside and are not involved in the GAP and CPU time calculations. The numerical results for the other six instances are presented in Appendix B.

The comparison in terms of the solution quality (cost) among CPLEX, LS and TS is presented in Figures 4.5 and 4.6. The cost comparisons for other six instances are presented in Appendix B.

We evaluate the quality of the approximate algorithms by using CPLEX solutions as the reference. Analyzing Figures 4.5 and 4.6, we can see that LS and TS are able to provide solutions which are relatively close to the optimal solutions. The graphs show that the solutions provided by LS and TS are closer to the optimal solution for the small size problems rather than the large size problems. This complies with

Table 4.14: Numerical results for the first instance of set#2

	CPLEX		**Local Search**			**Tabu Search**		
Problem No.	Cost ($)	CPU (s)	Cost ($)	CPU (s)	Gap (%)	Cost ($)	CPU (s)	Gap (%)
1	1,455,778	507	1,469,132	1,356	0.92	1,456,191	1,391	0.03
2	1,498,893	3,069	1,518,248	2,015	1.3	1,498,893	2,071	0
3	1,744,211	869	1,792,572	2,724	2.78	1,744,211	2,849	0
4	1,851,255	19,165	1,962,585	3,250	6.02	1,945,253	3,638	5.08
5	2,083,141	832	2,218,899	3,844	6.52	2,123,207	4,463	1.93
6	2,406,642	32,327	2,505,148	4,506	4.1	2,431,723	5,004	1.05
7	2,458,280	2,713	2,627,218	5,035	6.88	2,572,914	6,046	4.67
8	2,790,753	1,424	3,050,053	5,524	9.3	2,918,001	7,066	4.56
9	2,861,354	1,550	2,966,178	6,083	3.67	2,923,737	7,650	2.19
10	3,089,932	3,284	3,321,133	7,987	7.49	3,286,329	11,775	6.36
11	3,146,851	(TL) 86,400	3,430,440	7,458	–	3,260,640	11,239	–
12	3,195,625	(TL) 86,400	3,376,065	7,935	–	3,339,825	11,236	–
13	3,408,300	(TL) 86,400	3,592,251	8,360	–	3,528,878	13,904	–
14	3,405,885	(TL) 86,400	3,557,004	8,768	–	3,549,322	18,321	–
15	3,517,579	(TL) 86,400	3,737,430	9,206	–	3,714,285	18,649	–

the fact that smaller problems have a smaller search space and heuristics can explore more neighborhoods and more likely find solutions close to optimal. Similarly, we can see that the quality of the solutions provided by LS and TS decays as the problem size grows. Furthermore, as the problem size grows, the cost also increases as more NEs are required to cover all of the users.

Another comparison in terms of the CPU time of the solutions among CPLEX, LS and TS is presented in Figures 4.7 and 4.8. The CPU time comparisons for the other six instances are presented in Appendix B.

We use the CPU time returned by CPLEX as the reference for the comparison. Analyzing the Figures 4.7 and 4.8, we can see that LS and TS are able to provide

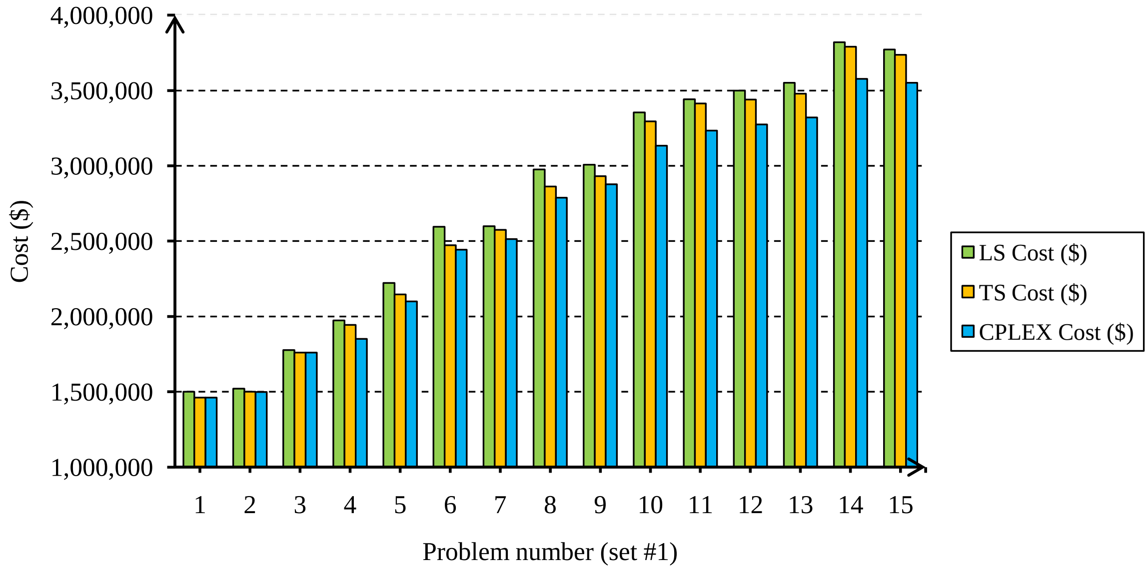

Figure 4.5: Solution comparison for the first instance of set#1 (cost)

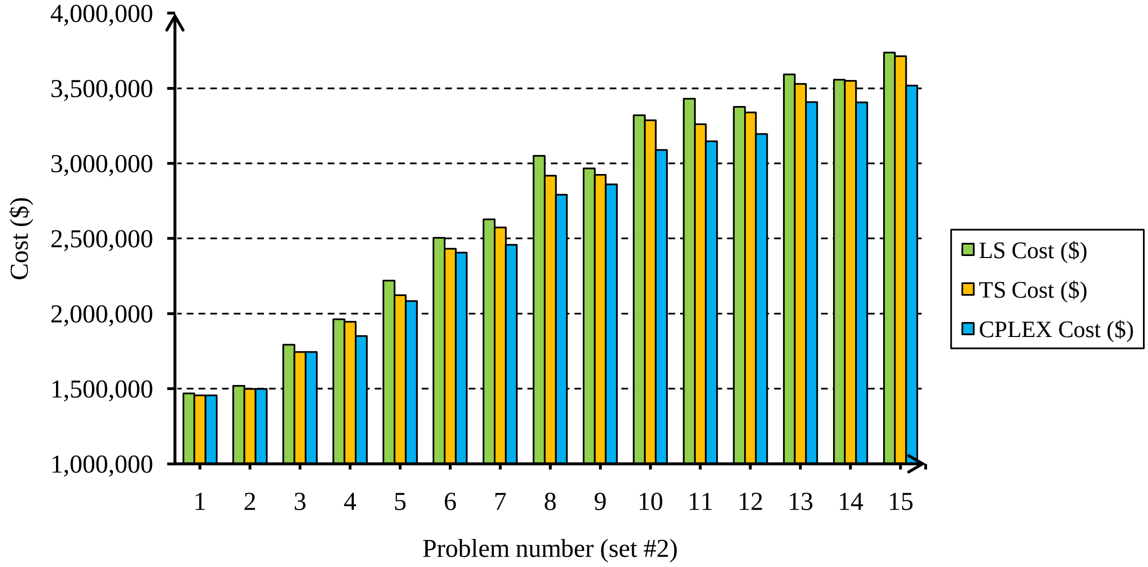

Figure 4.6: Solution comparison for the first instance of set#2 (cost)

good solutions in reasonable amount of time. CPU time for TS is more than LS, because TS performs more iterations than LS. CPU time of LS and TS increases with

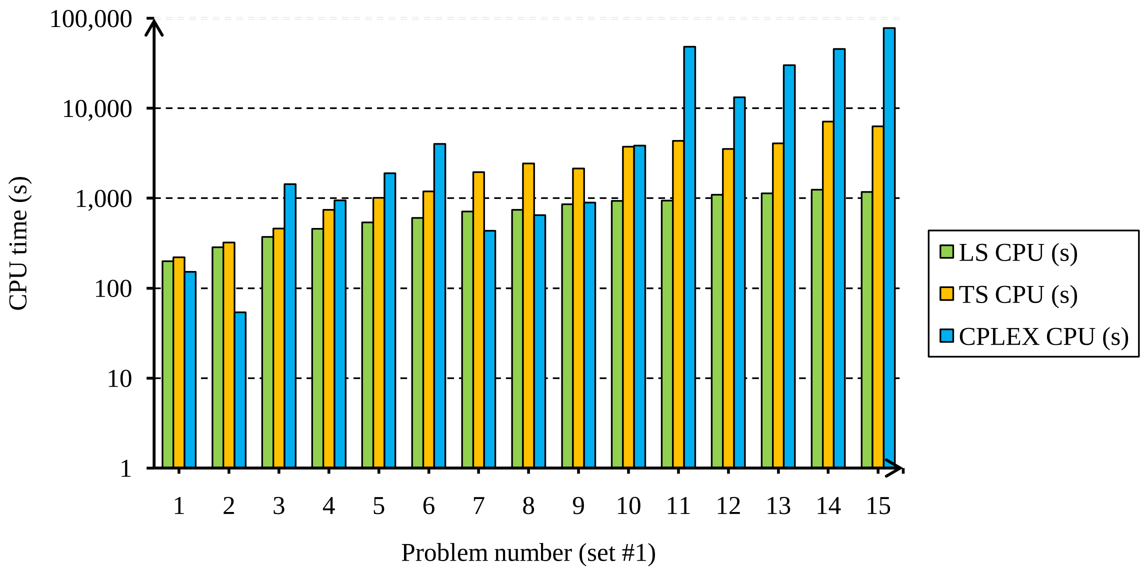

Figure 4.7: Solution comparison for the first instance of set#1 (CPU)

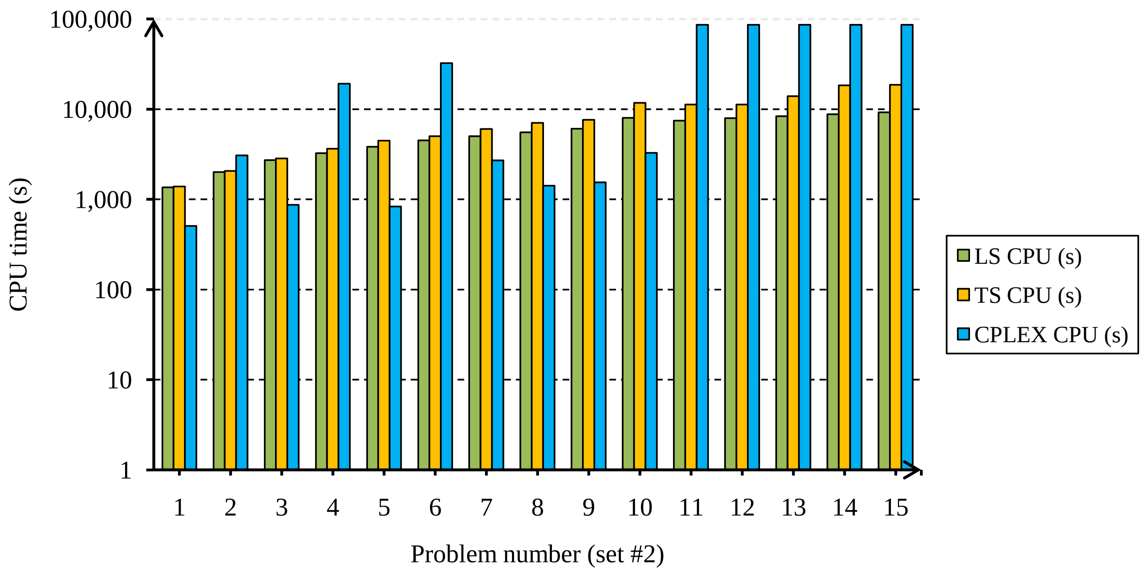

Figure 4.8: Solution comparison for the first instance of set#2 (CPU)

a constant rate with respect to the problem size. Most of the problems are solve within10,000 seconds. It is seen that CPLEX is faster than LS and TS for the small size problems, as it is using the branch and cut algorithm. On the contrary, CPLEX becomes inefficient as the problem size increases. It should be noticed that a time limit of 24 hours was set for CPLEX and as Figure 4.4 shows, CPLEX was not able to solve five large problems and would need more time to find optimal solutions. This was expected as the global planning problem of UMTS networks is NP-hard.

4.3.2 Statistical Analysis

From a total of 120 different problems, CPLEX and tabu search were able to provide the optimal solution for 92 (%77) and 19 (16%) problems respectively, while no optimal solution was found by the local search.

The statistical cost analysis is presented in Table 4.15. In this analysis, we have just considered the problems which CPLEX was able to find the optimal solutions. The first column shows the algorithm and the next three columns represent respectively the minimum, the maximum and the average solution gaps. The last two columns present the standard deviation and the *confidence interval* for the average solution gaps. We can state that with 95% confidence, local search provides a solution which its true mean gap is within the interval [4.42 , 5.54]. Similarly, tabu search has 95% confidence that the true mean solution gap is within the interval [2.37 , 3.27]. We can summarize that TS provides a better solution quality compared to LS. In fact, TS is able to provide the average gap of 2.82% on network cost which shows 43% improvement compared to LS (4.98%).

We also performed statistical CPU time analysis and presented in Table 4.16. Similarly, in this analysis, we have just considered the problems which CPLEX was able to find the optimal solutions. We can state that with 95% confidence, tabu

Table 4.15: Solution gap comparison for the total simulations

Algorithm	Min. gap (%)	Max. gap (%)	Ave. gap (%)	Standard deviation (%)	95% Confidence interval (%)
Local search	0.27	11.31	4.98	2.73	4.98 ± 0.56
Tabu search	0.00	7.51	2.82	2.20	2.82 ± 0.45

Table 4.16: CPU time comparison for the total simulations

Algorithm	Min. CPU (s)	Max. CPU (s)	Ave. CPU (s)	Standard deviation (s)	95% Confidence interval (s)
Local search	196	8,108	2,032	2,042	$2,032 \pm 417$
Tabu search	216	11,775	3,256	2,631	$3,256 \pm 538$
CPLEX	31	85,242	15,515	21,925	$15,515 \pm 4,480$

search provides a better solution with the true mean CPU time within in the interval [2,718 , 3,794] seconds as shown in Table 4.16. We can also conclude that CPLEX will require a lot higher time to solve some of the problems which faced time limit and were stopped before optimal solution.

4.4 Section Remarks

The main idea of using approximate algorithms is to find an acceptable trade off between the quality of a solution and the computation time required to find the solution. We realized that TS is able to search a larger solution space to find good solutions which are close to the optimal solutions. Real world UMTS Release 4 networks are very large and complex. Considering new NEs and different types of traffic, the planning problem of such networks becomes more complex. Using CPLEX to solve the planning problems will be a good idea for small size networks, but for the large networks, CPLEX will require a lot of time. As a result, the proposed algorithms, especially TS, are more appropriate for large cases to provide good solutions in reasonable computation time.

In the real world scenarios with very large areas, the model is first used to design regional networks. Once the regional networks are designed, the transit traffic from(to) one regional network to(from) all other regional network are calculated and all regional networks are updated to accommodate extra transit traffic. To interconnect regional network together and construct a fully connected network, different type of topologies are used. The most common topology is layered ring topology with alternative paths for higher reliably.

Chapter 5

Conclusions and Future Work

The primary goal of the UMTS network planning is the topology planning. To help network operators gain a long term profit, efficient planning tools are necessary in order to make a trade off between network investment and performance. Since the global UMTS network planning problem is shown to be NP-hard, approximate algorithms (based on metaheuristics) must be used to find a balance between solution quality and computation time. The efficiency of the algorithm is problem dependent, therefore an appropriate selection and design of the metaheuristics is the key factor for the success of a planning tool.

In this thesis, we introduced a new mathematical model in order to plan 3G UMTS all-IP Release 4 networks with realistic traffic profile. The aim of the model is to design the network topology which can provide a satisfactory level of service to the subscribers with minimum network cost. More precisely, the model selects the location and the type of the NEs (*i.e.* RNCs, MGWs, MSSs, SGSNs, GGSNs, edge routers, CS routers, PS routers), their links and interfaces, as well as the access and core topologies. As a second contribution, we proposed metaheuristics to solve the design problem of the model. In fact, we adapted the local search and the tabu search metaheuristics, to our specific problem and developed planning tools to solve the design problem. These algorithms use the global approach and consider the access and core network planning sub-problems simultaneously.

During the simulations, two problem sets of 15 sizes, each set with four different instances (120 problems in total), were randomly generated and solved with the proposed algorithms. In order to assess the performance of those algorithms, we compared the results with the optimal solutions obtained from a commercial solver (CPLEX). The results demonstrated that the local search is able to find solutions that, with 95 percent confidence, the true mean gap is within the interval of [4.42% , 5.54%] from the optimal solutions. Further improvement was achieved by employing the tabu search. With 95 percent confidence interval, tabu search provides solutions where the true mean gap lies within the interval of [2.37% , 3.27%] from the optimal solutions. Comparing results from the local search and tabu search with the exact algorithm, we realized that the main advantage of such metaheuristics is the low CPU time. Therefore, larger problem sizes can be tackled.

This research work showed that the proposed algorithms are able to find 'good' solutions for planning problem of UTMS all-IP Release 4 networks within reasonable amount of time. Nevertheless, some more improvement could be done. In this simulation, the number of subscribers were randomly generated which might be different from real live networks. Another limitation is that CPLEX is not very useful for medium and upper medium size problems. As shown in the simulation results, several problems were not solved within the time limit. Therefore, it is difficult to evaluate the quality of the proposed algorithms for medium and upper medium problems. Different parameter settings for CPLEX could be tested to increase the solution progress in the best bound. Moreover, we considered the access and the core networks in a tree topology. Other more reliable topologies could also be explored. Out model is sensitive to changes in input values and to justify such shortcoming, it is recommended to design the network for some extra capacity.

Some future works of this thesis may consist of considering other interconnection topologies like the ring, the star and the layered in access and core networks. Another works can be performing sensitivity analysis over the model as well as finding efficient algorithms to reduce the problem complexity while dwindling the size of the feasibility area in the preliminary steps. Nowadays, network updates are more frequent that designing a green field network. A potential future work can include adaptation of the model to cover update problems by modifying the tabu search procedure. Finally, investigating newly introduced hybrid-metaheuristics to solve the planning problem may be another potential research direction as well.

Appendix A

In this appendix, we present the detail calculations of traffic records. The traffic profile of subscribers and the planning parameters, shown in Tables 4.1 and 4.2, are used as inputs. Another input is the number of subscribers for each Node B, which is randomly generated between 5,000 to 20,000. Using this information, CS voice, CS data and PS data traffic is calculated over the Node B-edge router interface (Iub). We also present the C++ code of the Erlangb-to-Channel function, used in the traffic profile calculations.

Iub CS voice traffic

$$CsVoiceTraffic = (UserMonthlyCSVoiceTraffic \times BusyDaysCallRatio \times BHcallRatio)/(BusyDaysPerMonth \times 60)$$

$$CSVoiceBHCA = CSVoiceTraffic \times 3600/MHT$$

$$IubCSVoiceTraffic = NodeBSubscriber \times CSVoiceTraffic$$

$$TotalCSVoiceChannel = ErlbChs(IubCSVoiceTraffic, IubInterfaceBlocking)$$

$$IubCSVoiceBW = (1 + IPOH) \times (IubCSVoiceChannel) \times (AMRAM \times CSVAF + AMRSM \times CSVAF) \times (1 + SHO)$$

$$IubCSVoiceBHCA = NodeBSubscriber \times CSVoiceBHCA$$

Iub CS Data Traffic Calculations

$$CSData64Traffic = (UserMonthlyCSDataTraffic \times BusyDaysCallRatio \times BHCallRatio)/(BusyDaysPerMonth \times 60)$$

$$CSData64BHCA = CSData64Traffic \times 3600/MHT$$

$$IubCSDataTraffic = NodeBSubscriber \times CSData64Traffic$$

$$TotalCSDataChannel = ErlbChs(IubCSDataTraffic, IubInterfaceBlocking)$$

$$IubCSDataBW = (1+IPOH) \times (IubCSVoiceChannel) \times (CSDataServiceRate1 \times CSDAF) \times (1+SHO)$$

$$IubCSDataBHCA = NodeBSubscriber \times CSData64BHCA$$

Iub PS Data Traffic Calculations

$$BHPSData64Rate = (UserMonthlyPS64 \times BusyDaysCallRatio \times BHCallRatio \times 1024 \times 8)/BusyDaysPerMonth$$

$$BHPsData144Rate = (UserMonthlyPS144 \times BusyDaysCallRatio \times BHCallRatio \times 1024 \times 8)/BusyDaysPerMonth$$

$$BHPSData384Rate = (UserMonthlyPS384 \times BusyDaysCallRatio \times BHCallRatio \times 1024 \times 8)/BusyDaysPerMonth$$

$$IubPSData64BW = (1+IPOH) \times (BHPSData64Rate/3600) \times (1+SHO) \times (1+RTF) \times PSAF$$

$$IubPSData144BW = (1+IPOH) \times (BHPSData144Rate/3600) \times (1+SHO) \times (1+RTF) \times PSAF$$

$$IubPSData384BW = (1 + IPOH) \times (BHPSData384Rate/3600) \times (1 + SHO) \times (1 + RTF) \times PSAF$$

$$NodeBBHCA = IubCSVoiceBHCA + IubCSDataBHCA$$

$$IubCSChannel = TotalCSVoiceChannel + TotalCSDataChannel$$

$$IubCSTotalBW = IubCSVoiceBW + IubCSDataBW$$

$$NodeAttachedSubscriber = NodeBSubscriber \times PSAttachedSubscriberRatio$$

$$NodeBSimultaneousPDP = NodeAttachedSubscriber \times PDPDurration \times ActiveBHPDPRatio/3600$$

$$IubpsTotalBW = NodeBSimultaneousPDP \times (IubPsData64BW + IubPsData144BW + IubPSData384BW)/IubInterfaceUtilization$$

$$CSSignalling = CSsignalingRatio \times NodeBBHCA$$

$$(CSSignalingRatio = 50Kbps, includingSMS)$$

Erlangb-to-Channel Function

```
double ErlbChannel(double traffic_erlang, double blocking_probability)
  {
    double blocking, new_blocking, channel, i;
    blocking = 1;
    i = 0;
      if(blocking_probability >= 1 || blocking_probability <= 0) {
        printf("Blocking probability must be between 1 and 0 !");
        system("pause");
        exit(1);
       }

     while(blocking > blocking_probability){
        i=i+1;
        new_blocking = blocking;
        blocking = traffic_erlang × blocking/(traffic_erlang ×
blocking+i);
       }

     channel = ceil(i -1+(blocking_probability - new_blocking)/(blocking
- new_blocking));
     return channel;
     }
```

Appendix B

In this appendix, we present numerical results for the second, third and fourth instances of the problem set#1 and set#2. We also present the solution comparison in terms of cost and CPU for these instances.

Table B.1: Numerical results for the second instance of set#1

	CPLEX		**Local Search**			**Tabu Search**		
Problem No.	Cost ($)	CPU (s)	Cost ($)	CPU (s)	Gap (%)	Cost ($)	CPU (s)	Gap (%)
1	1,462,546	212	1,474,446	196	0.82	1,462,546	217	0
2	1,523,483	64	1,559,653	281	2.38	1,523,483	318	0
3	1,788,382	3,798	1,810,073	376	1.22	1,788,382	468	0
4	1,832,247	43	1,922,349	456	4.92	1,922,247	779	4.92
5	2,052,402	1893	2,193,170	542	6.86	2,144,476	869	4.49
6	2,375,804	237	2,433,809	622	2.45	2,416,404	1,107	1.71
7	2,463,846	419	2,579,788	676	4.71	2,532,407	1,614	2.79
8	2,749,368	1,365	3,028,984	834	10.18	2,892,067	2,010	5.2
9	2,975,960	43,856	3,113,601	822	4.63	3,083,586	1,790	3.62
10	3,144,911	26,422	3,375,871	876	7.35	3,271,590	3,533	4.03
11	3,158,770	9,598	3,377,694	1,005	6.94	3,276,712	3,650	3.74
12	3,296,197	12,303	3,508,579	1,165	6.45	3,454,386	3,627	4.8
13	3,366,534	86,401	3,648,237	1,136	8.37	3,59,4750	5,518	6.78
14	3,467,456	85,243	3,716,717	1,215	7.19	3,657,303	6,257	5.48
15	3,583,633	40,838	3,831,462	1,249	6.92	3,730,874	5,216	4.11

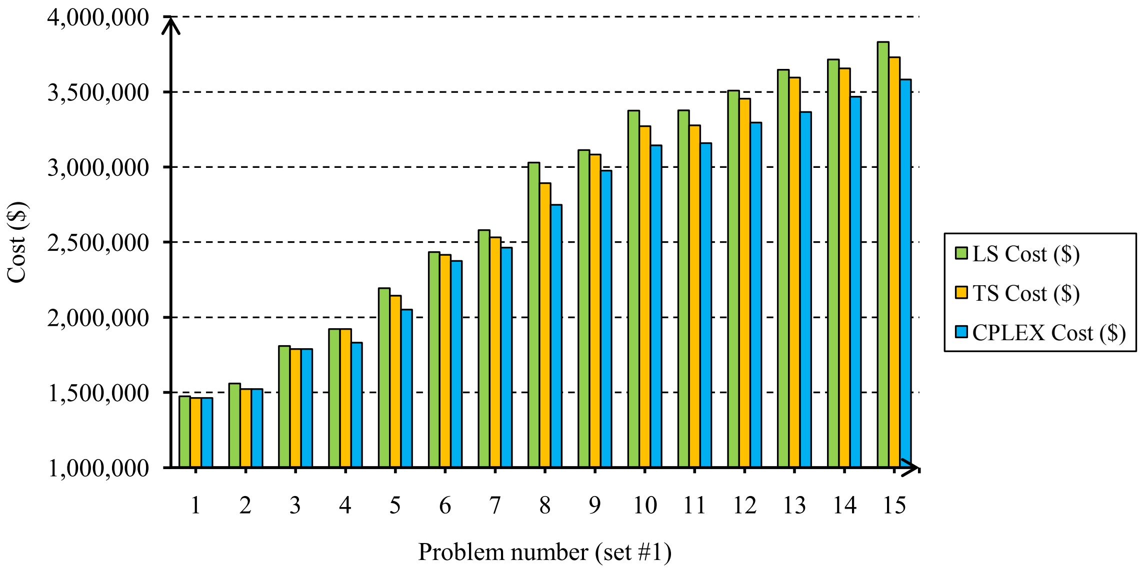

Figure B.1: Solution comparison for the second instance of set#1 (cost)

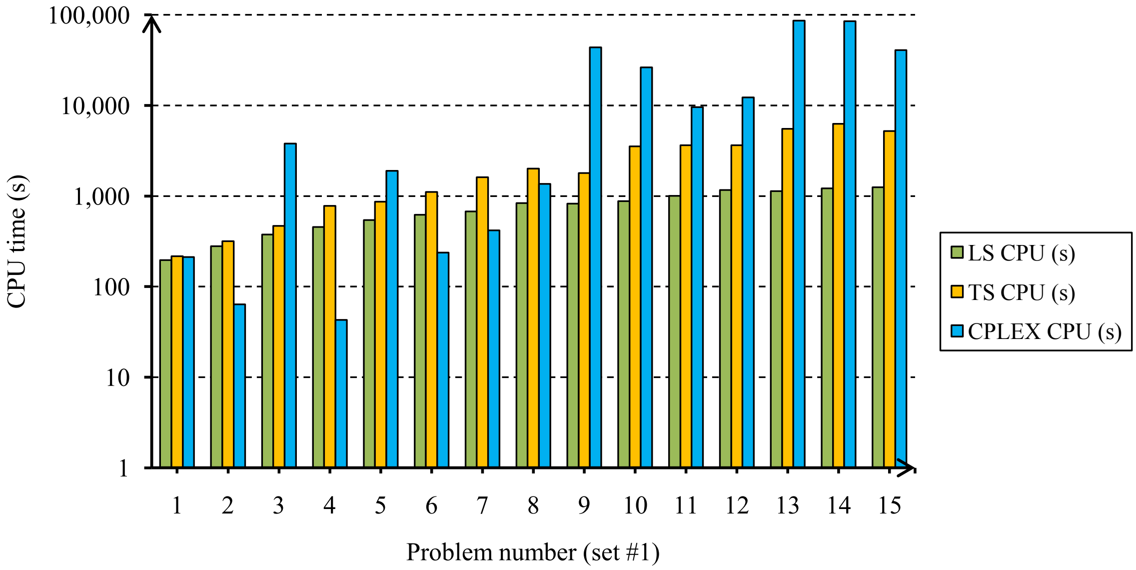

Figure B.2: Solution comparison for the second instance of set#1 (CPU)

Table B.2: Numerical results for the second instance of set#2

	CPLEX		**Local Search**			**Tabu Search**		
Problem No.	Cost ($)	CPU (s)	Cost ($)	CPU (s)	Gap (%)	Cost ($)	CPU (s)	Gap (%)
1	1,470,998	2,472	1,477,890	1,374	0.47	1,473,894	1,412	0.2
2	1,700,094	252	1,712,577	2,005	0.74	1,700,094	2,117	0
3	1,725,619	82,917	1,802,183	2,645	4.44	1,725,619	2,852	0
4	1,856,107	86,401	1,951,955	3,283	5.17	1,948,935	3,639	5.01
5	2,272,955	1,357	2,319,753	3,687	2.06	2,313,669	4,206	1.8
6	2,214,235	26,498	2,372,665	4,542	7.16	2,226,231	5,316	0.55
7	2,519,670	86,401	2,686,698	5,005	6.63	2,652,274	6,479	5.27
8	2,717,701	9,391	2,949,973	5,643	8.55	2,867,028	6,988	5.5
9	2,861,509	16,522	3,156,674	6,148	10.32	2,940,846	8,745	2.78
10	3,086,501	86,401	3,232,497	8,003	4.74	3,176,917	10,811	2.93
11	3,156,552	35,582	3,310,931	7,344	4.9	3,241,527	10,677	2.7
12	3,300,188	86,401	3,564,358	7,505	8.01	3,478,062	12,218	5.39
13	3,417,571	86,401	3,626,591	8,722	6.12	3,560,311	12,912	4.18
14	3,374,091	86,401	3,619,818	9,323	7.29	3,516,029	14,304	4.21
15	3,447,617	86,401	3,667,700	9,996	6.39	3,639,485	19,486	5.57

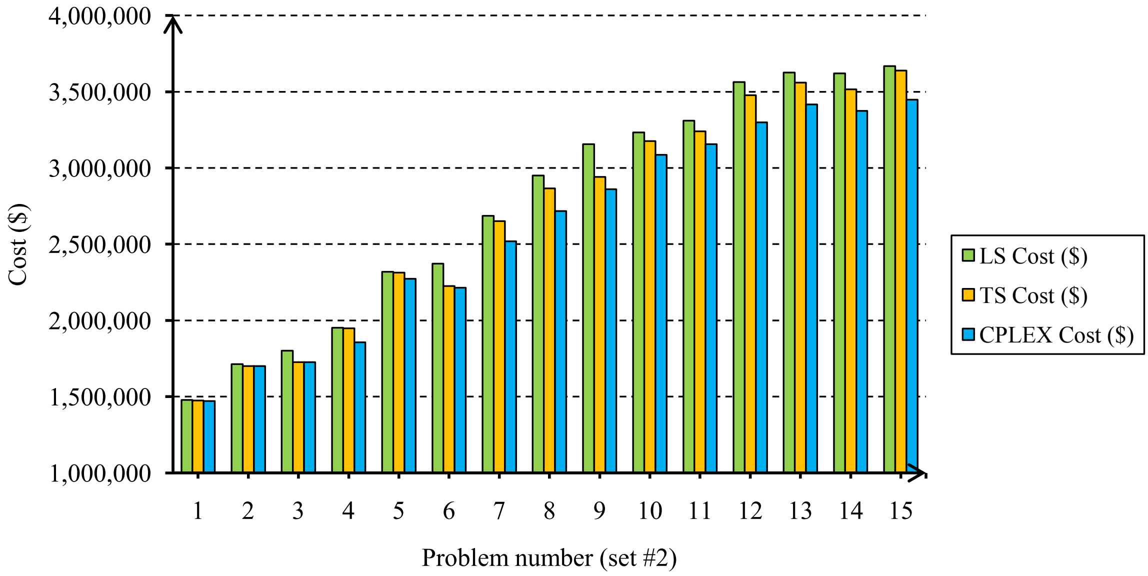

Figure B.3: Solution comparison for the second instance of set#2 (cost)

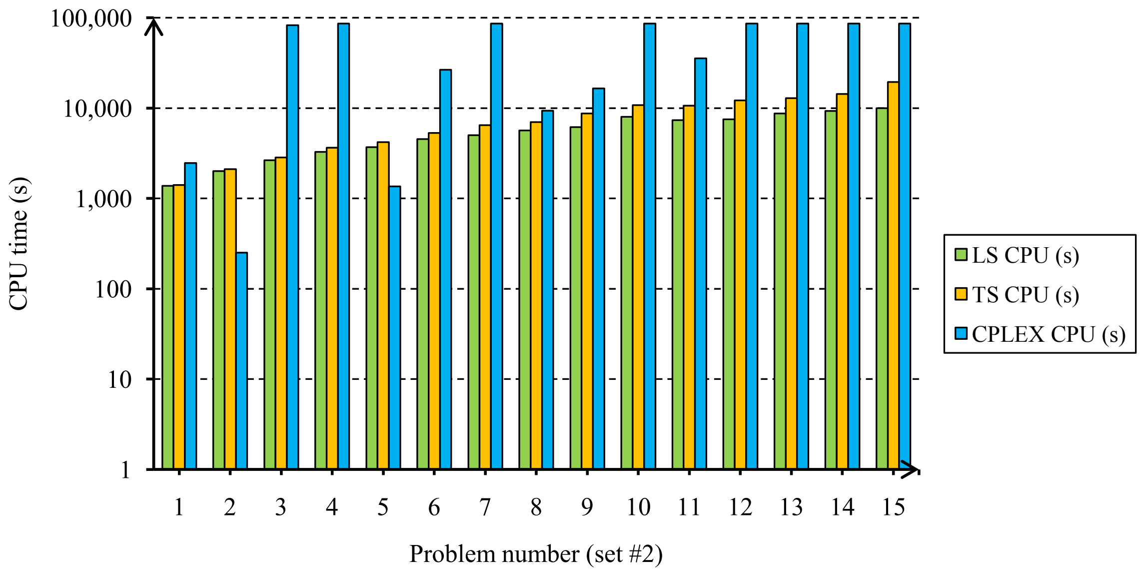

Figure B.4: Solution comparison for the second instance of set#2 (CPU)

Table B.3: Numerical results for the third instance of set#1

	CPLEX		Local Search			Tabu Search		
Problem No.	Cost ($)	CPU (s)	Cost ($)	CPU (s)	Gap (%)	Cost ($)	CPU (s)	Gap (%)
1	1,454,159	87	1,458,670	199	0.32	1,454,159	220	0
2	1,713,522	300	1,748,924	281	2.07	1,713,522	320	0
3	1,765,694	45	1,791,613	371	1.47	1,767,017	413	0.08
4	1,878,338	369	1,998,871	472	6.42	1,969,269	639	4.85
5	2,092,727	4,894	2,223,933	546	6.27	2,172,594	741	3.82
6	2,401,390	26,749	2,489,275	622	3.66	2,450,484	961	2.05
7	2,449,102	31	2,541,504	706	3.78	2,526,346	1,156	3.16
8	2,597,390	167	2,703,037	803	4.07	2,660,941	1,633	2.45
9	3,085,255	86,400	3,225,803	865	4.56	3,198,590	1,535	3.68
10	3,271,414	23,691	3,395,273	920	3.79	3,358,316	2,391	2.66
11	3,229,246	37,409	3,498,413	1,062	8.34	3,388,753	3,096	4.94
12	3,289,069	26,143	3,474,950	1,038	5.66	3,444,641	3,564	4.73
13	3,362,035	15,970	3,709,740	1,139	10.35	3,593,545	4,841	6.89
14	3,523,300	62,306	3,905,738	1,306	10.86	3,707,437	3,889	5.23
15	3,678,604	17,050	4,094,613	1,245	11.31	3,954,830	4,876	7.51

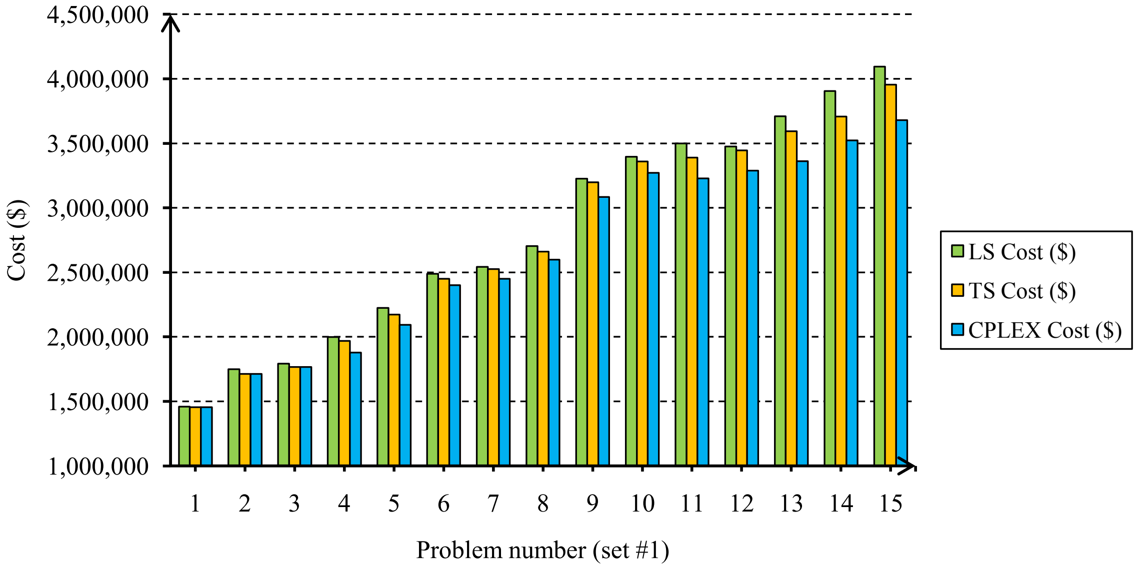

Figure B.5: Solution comparison for the third instance of set#1 (cost)

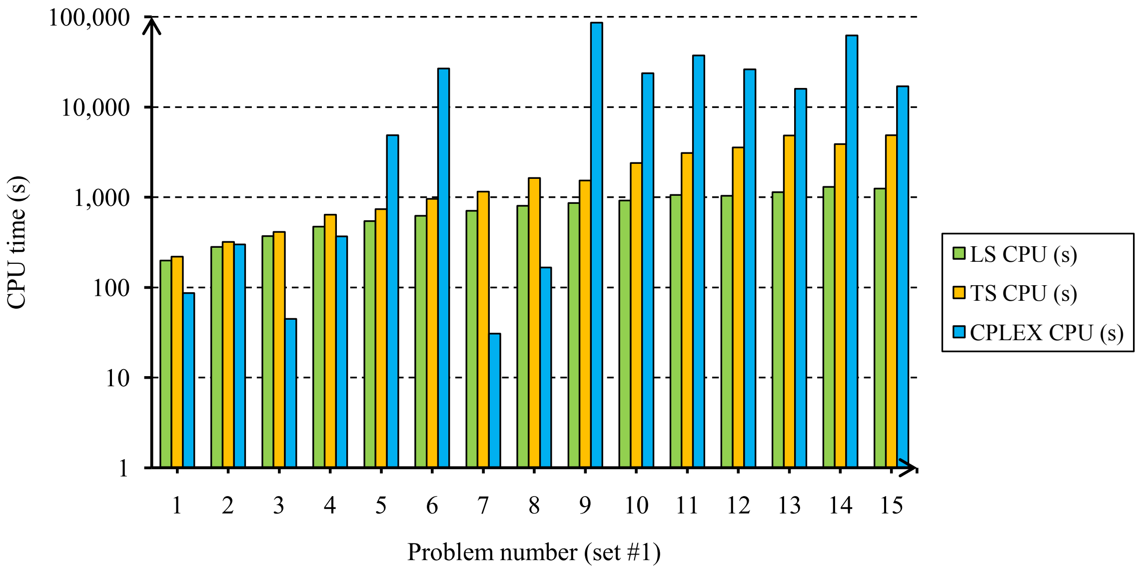

Figure B.6: Solution comparison for the third instance of set#1 (CPU)

Table B.4: Numerical results for the third instance of set#2

	CPLEX		**Local Search**			**Tabu Search**		
Problem No.	Cost ($)	CPU (s)	Cost ($)	CPU (s)	Gap (%)	Cost ($)	CPU (s)	Gap (%)
1	1,460,621	4,987	1,468,665	1,369	0.56	1,460,621	1,409	0
2	1,499,760	2,400	1,511,370	1,999	0.78	1,499,760	2,046	0
3	1,760,691	2,271	1,798,530	2,657	2.15	1,763,175	2,740	0.15
4	1,856,922	55,433	1,999,047	3,306	7.66	1,950,422	3,530	5.04
5	2,071,852	6,694	2,193,243	3,899	5.86	2,148,956	4,165	3.73
6	2,126,368	17,813	2,178,716	4,501	2.47	2,166,368	5,039	1.89
7	2,435,825	37,054	2,549,958	5,012	4.69	2,449,068	5,433	0.55
8	2,653,473	76,777	2,862,206	5,685	7.87	2,784,288	6,551	4.93
9	3,055,835	58,726	3,214,880	6,319	5.21	3,123,217	7,602	2.21
10	3,251,984	86,401	3,466,103	8,011	6.59	3,294,964	9,133	1.33
11	3,159,905	86,401	3,436,831	7,363	8.77	3,360,972	9,979	6.37
12	3,284,133	79,054	3,472,010	8,108	5.73	3,428,313	11,266	4.4
13	3,325,781	86,401	3,539,307	8,488	6.43	3,462,434	13,213	4.11
14	3,479,229	86,401	3,839,552	8,803	10.36	3,698,382	13,651	6.3
15	3,530,957	86,401	3,902,832	9,872	10.54	3,857,497	22,703	9.25

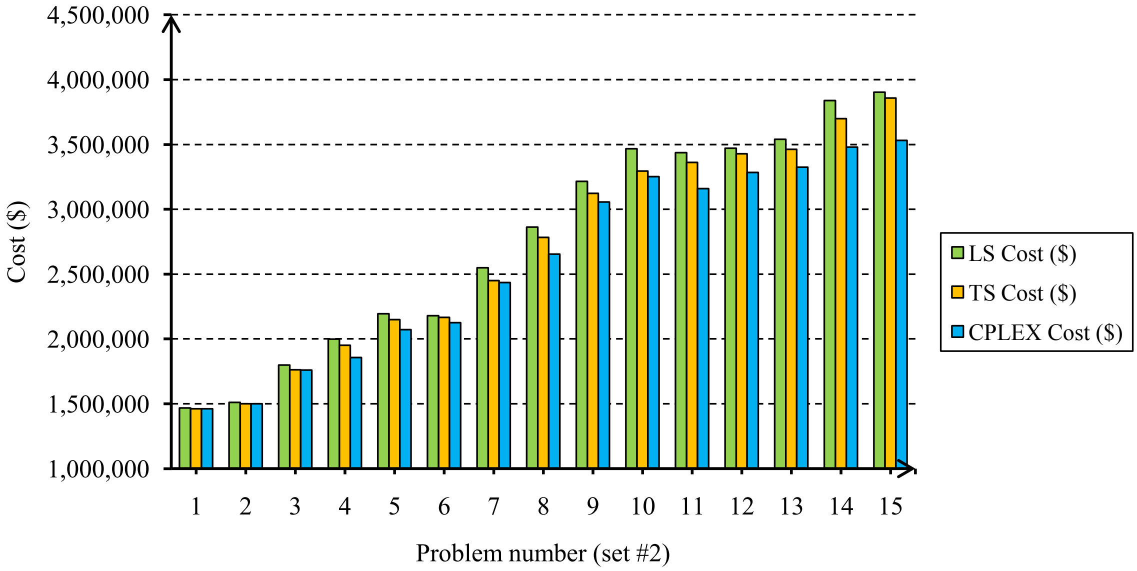

Figure B.7: Solution comparison for the third instance of set#2 (cost)

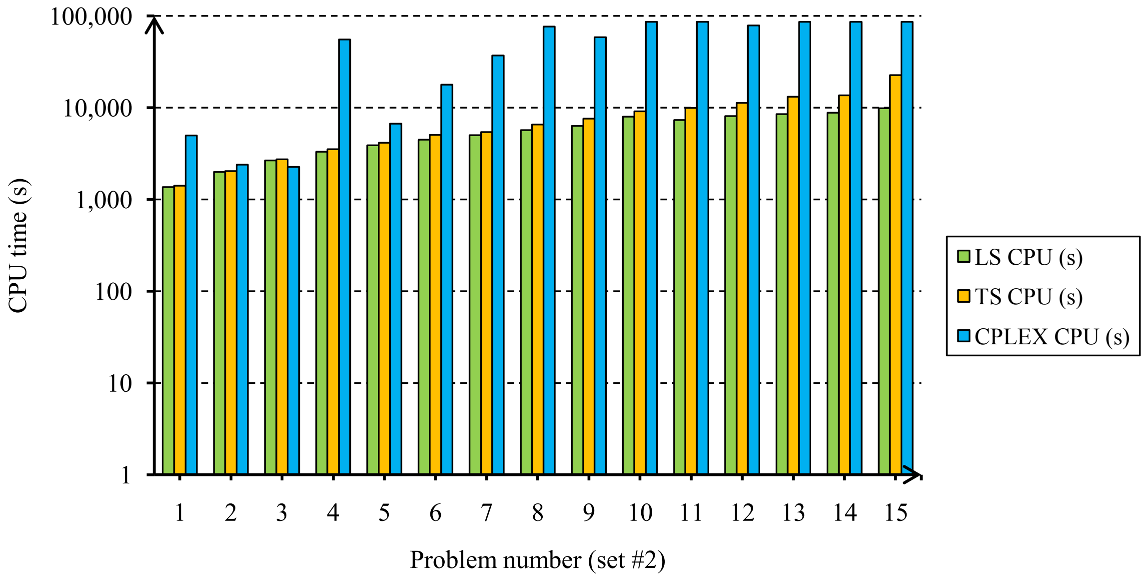

Figure B.8: Solution comparison for the third instance of set#2(CPU)

Table B.5: Numerical results for the fourth instance of set#1

	CPLEX		Local Search			Tabu Search		
Problem No.	Cost ($)	CPU (s)	Cost ($)	CPU (s)	Gap (%)	Cost ($)	CPU (s)	Gap (%)
1	1,454,159	87	1,458,670	199	0.32	1,454,159	220	0
2	1,713,522	300	1,748,924	281	2.07	1,713,522	320	0
3	1,765,694	45	1,791,613	371	1.47	1,767,017	413	0.08
4	1,878,338	369	1,998,871	472	6.42	1,969,269	639	4.85
5	2,092,727	4,894	2,223,933	546	6.27	2,172,594	741	3.82
6	2,401,390	26,749	2,489,275	622	3.66	2,450,484	961	2.05
7	2,449,102	31	2,541,504	706	3.78	2,526,346	1,156	3.16
8	2,597,390	167	2,703,037	803	4.07	2,660,941	1,633	2.45
9	3,085,255	86,400	3,225,803	865	4.56	3,198,590	1,535	3.68
10	3,271,414	23,691	3,395,273	920	3.79	3,358,316	2,391	2.66
11	3,229,246	37,409	3,498,413	1,062	8.34	3,388,753	3,096	4.94
12	3,289,069	26,143	3,474,950	1,038	5.66	3,444,641	3,564	4.73
13	3,362,035	15,970	3,709,740	1,139	10.35	3,593,545	4,841	6.89
14	3,523,300	62,306	3,905,738	1,306	10.86	3,707,437	3,889	5.23
15	3,678,604	17,050	4,094,613	1,245	11.31	3,954,830	4,876	7.51

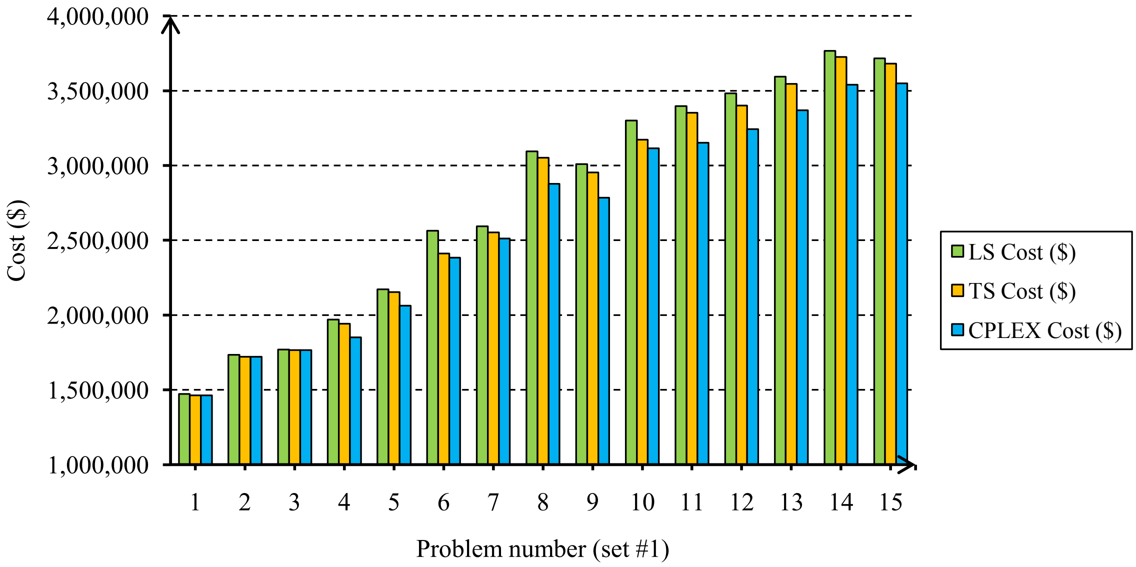

Figure B.9: Solution comparison for the fourth instance of set#1 (cost)

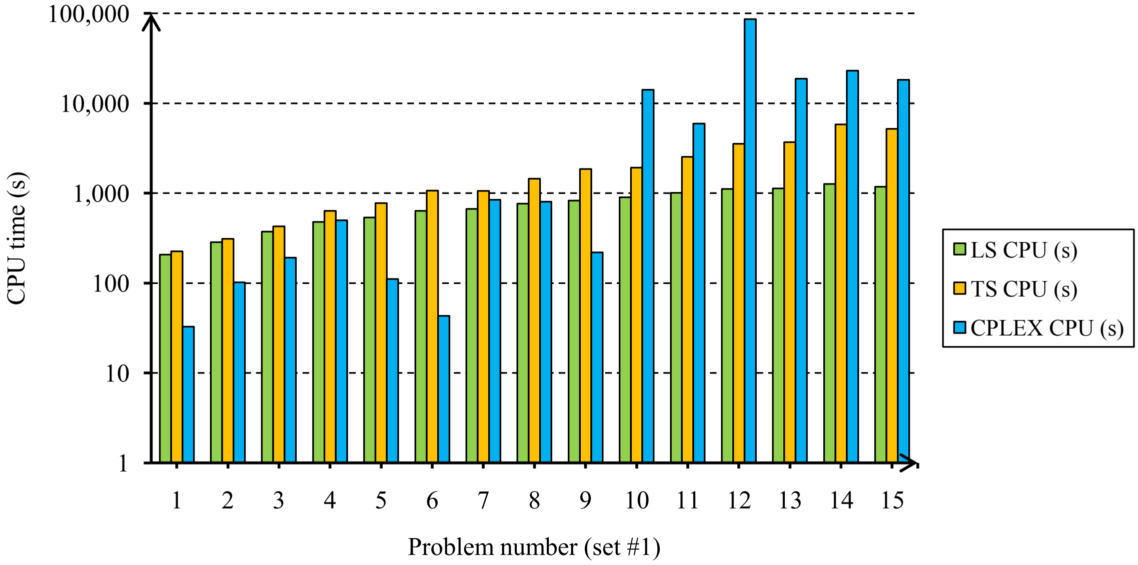

Figure B.10: Solution comparison for the fourth instance of set#1 (CPU)

Table B.6: Numerical results for the fourth instance of set#2

	CPLEX		**Local Search**			**Tabu Search**		
Problem No.	Cost ($)	CPU (s)	Cost ($)	CPU (s)	Gap (%)	Cost ($)	CPU (s)	Gap (%)
1	1,460,621	4,987	1,468,665	1,369	0.56	1,460,621	1,409	0
2	1,499,760	2,400	1,511,370	1,999	0.78	1,499,760	2,046	0
3	1,760,691	2,271	1,798,530	2,657	2.15	1,763,175	2,740	0.15
4	1,856,922	55,433	1,999,047	3,306	7.66	1,950,422	3,530	5.04
5	2,071,852	6,694	2,193,243	3,899	5.86	2,148,956	4,165	3.73
6	2,126,368	17,813	2,178,716	4,501	2.47	2,166,368	5,039	1.89
7	2,435,825	37,054	2,549,958	5,012	4.69	2,449,068	5,433	0.55
8	2,653,473	76,777	2,862,206	5,685	7.87	2,784,288	6,551	4.93
9	3,055,835	58,726	3,214,880	6,319	5.21	3,123,217	7,602	2.21
10	3,251,984	86,401	3,466,103	8,011	6.59	3,294,964	9,133	1.33
11	3,159,905	86,401	3,436,831	7,363	8.77	3,360,972	9,979	6.37
12	3,284,133	79,054	3,472,010	8,108	5.73	3,428,313	11,266	4.4
13	3,325,781	86,401	3,539,307	8,488	6.43	3,462,434	13,213	4.11
14	3,479,229	86,401	3,839,552	8,803	10.36	3,698,382	13,651	6.3
15	3,530,957	86,401	3,902,832	9,872	10.54	3,857,497	22,703	9.25

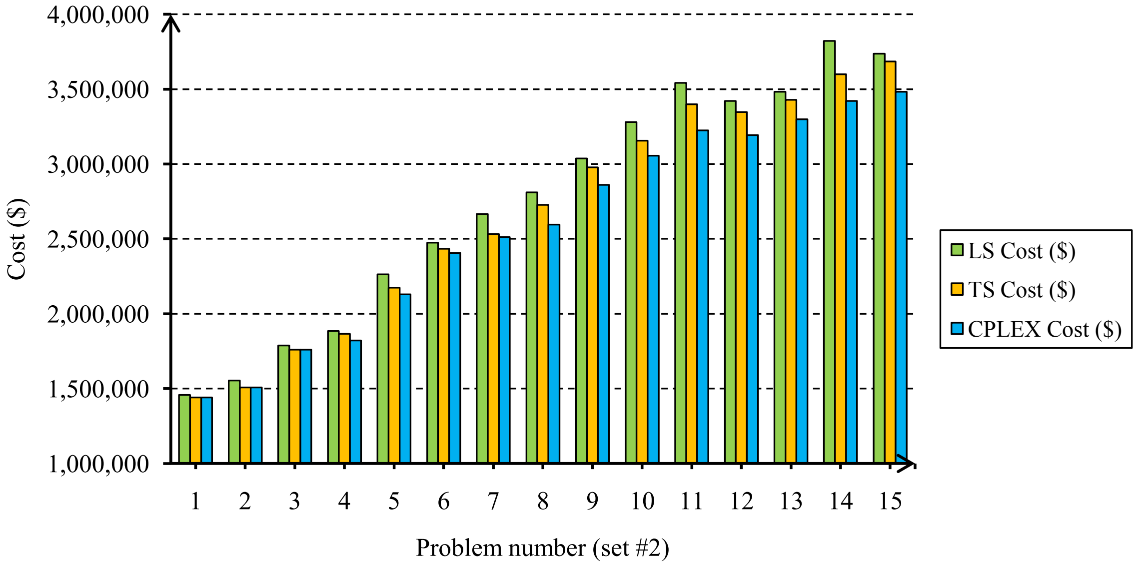

Figure B.11: Solution comparison for the fourth instance of set#2 (cost)

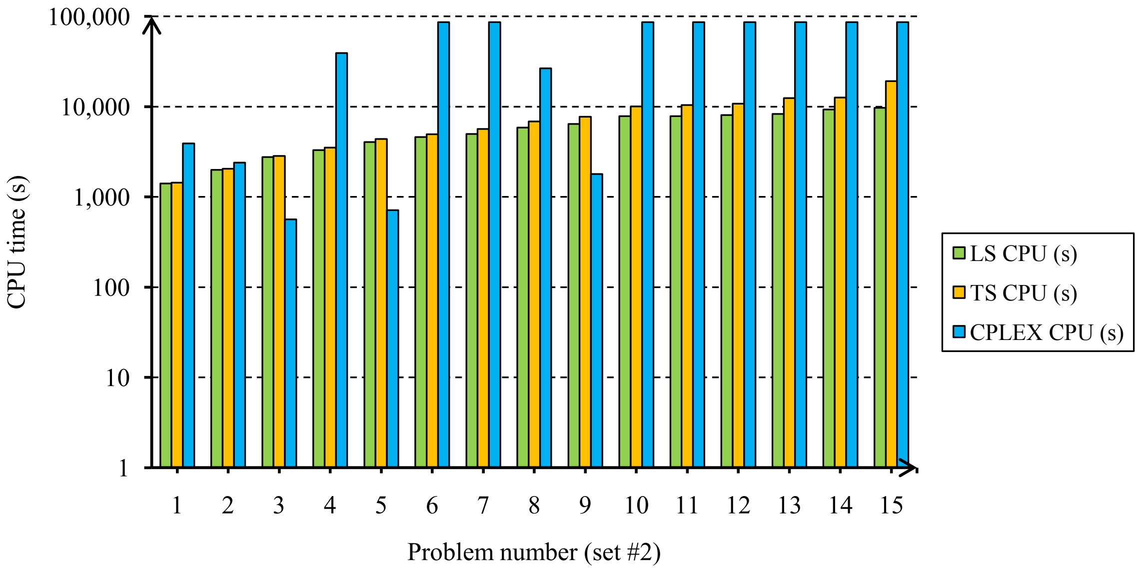

Figure B.12: Solution comparison for the fourth instance of set#2 (CPU)

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