MODELS FOR GREENFIELD AND INCREMENTAL CELLULAR NETWORK PLANNING

BY

CAROL OVON

Bachelor of Science in Electrical Engineering, Makerere University, 2003

Submitted to the Graduate Faculty of

School of Information Sciences, in partial fulfillment of the requirements for the degree of
Master of Telecommunications

University of Pittsburgh

2012

UNIVERSITY OF PITTSBURGH

SCHOOL OF INFORMATION SCIENCES

This thesis was presented

by

Carol Ovon

It was defended on

May 17th, 2012

and approved by

Dr. Martin Weiss, Associate Professor – School of Information Sciences

Dr. Konstatinos Pelechrinis, Assistant Professor – School of Information Sciences

Thesis Director: Dr. David Tipper, Associate Professor – School of Information Sciences

MODELS FOR GREENFIELD AND INCREMENTAL CELLULAR NETWORK PLANNING

Carol Ovon, MST

University of Pittsburgh, 2012

Mobility, as provided in cellular networks, is largely affected by the location of the base stations. To a large extent, the location of base stations is determined by the quantity of base stations available to provide coverage. It is therefore not surprising that the quantity and subsequent location of base stations will not only impact service delivery but also have a large associated cost for implementation. Generally, the higher the quantity of base stations required to provide coverage, the greater the cost of implementation and operation of the radio network.

This thesis proposes a modified optimization model to aid the cell planning process. This model, unlike those surveyed, is applicable to both green field and incremental network designs. The variation in model design is fundamental in ensuring cost effective growth and expansion of cellular networks. Numerical studies of the modified model applied to both abstract and real system configurations are carried out using MATLAB. Terrain data from Kampala, Uganda, was used to aid the study.

Results show that the antenna height significantly determines the solution of the objective function. In addition, it is shown that slight variations in the cost association between the antenna height and the site construction requirements can be decisively used for predefined targeted network planning. A comparison is also made between an actual network installation and the estimates provided by the model. As expected, results from the study show that the difference between the estimated count and the actual count can be adequately minimized by slight variations in antenna height requirements.

Table of Contents

PREFACE

I am grateful to the Fulbright program and the Telecommunications and Networking program of the University of Pittsburgh's School of Information Sciences. Through them, I was granted the opportunity and financial support that allowed me to comfortably undertake my studies leading to a master's degree. This was such a wonderful experience.

Special thanks go to my thesis and program advisor, Dr. David Tipper, for all the advice and guidance that he gave me for both my academic pursuits and also in the preparation of this work. I would also like to thank my fellow students at the iSchool that supported me in the preparation of this work.

My family, my mother – Jane Rose Nabwire and my dear departed father, I am really grateful for all your support and encouragement. To my beautiful sisters Gloria, Filda, Annette, Cathy and "Baaba"; and my brothers Joseph and Jimmy, I am blessed to have you all in my life.

To my friends Tisha, Merab, Hana, Lois and Laura whose continued communication and encouragement kept me going for the whole time I was away from home. You all mean a lot to me and I am very grateful for the time that you put in to maintain our friendship. I also thank the Ugandan community in Pittsburgh that was instrumental in helping me settle comfortably – Ronald, Charlie and Silver.

Most importantly, I thank God for the gift of life and all the opportunities that He has placed in my way.

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

1G – First Generation

2G – Second Generation

3G – Third Generation

3GPP – Third Generation Partnership Project

BS – Base Station

ACTS – Advanced Communication Technologies and Services

CAT – Combination Algorithm for Total optimization

CDMA – Code Division Multiple Access

C/I – Carrier to interference ratio

DS-CDMA – Direct Sequence CDMA

FDD – Frequency Division Duplex

FCC – Federal Communication Commission

GA – Genetic Algorithm

GR – GReedy algorithm

GSM – Global System for Mobile communication

IMT-2000 – International Mobile Telecommunications for the year 2000

ISDN – Integrated Services Digital Network

ITU – International Telecommunications Union

LTE – Long Term Evolution

ME – Mobile Equipment

OCA – Original Combinatorial Algorithm

PC – Power Control

PLANTON – Planning Tool for UMTS radio Networks

QoS – Quality of Service

RACE – Research and development in Advanced Communication technologies in Europe

RF – Radio frequency

RNC – Radio Network Controller

RNS – Radio Network Subsystem

TP – Test Point

UE – User Equipment

UFLP – Uncapacitated Facility Location Problem

UMTS – Universal Mobile Telecommunications Systems

USIM – UMTS Subscriber Identity Module

UTRAN – UMTS Terrestrial Radio Access Network

WCDMA – Wideband Code Division Multiple Access

I: INTRODUCTION

1.1 Background

The advent of the first generation (1G) cordless and cellular telephone services introduced the concept and beauty of mobility in the telecommunications industry. Mobility was further enhanced with the development and implementation of second generation (2G) cellular telecommunications systems which enjoyed an unprecedented global success and also allowed for international roaming. While the services provided to customers in the early stages of mobile communication were largely operator determined, to the largest extent now, consumer demand influences the trend adopted in the evolution of telecommunications technologies. The enormous demand for high speed services has spiraled innovation in the industry and heightened the required investment by network operators. On the other hand, the cost of services keeps dropping.

Mobility in cellular networks is largely affected by the location of the base stations providing coverage. The location of 2G base stations was guided by two major planning factors – coverage predictions and frequency planning. This criterion was adequate for the low data rate services that such technologies could offer. Third generation (3G) systems however, are developed to provide a large cross-section of services ranging from voice and low-rate data services just like 2G systems, to high-rate data services for up to 2 Mbps. The ability to provide high-rate data services required significant innovation and variation of the network parameters which in effect renders the 2G planning criterion of limited use in locating and estimating the number of 3G base stations.

Universal Mobile Telecommunications System (UMTS) is a 3G standard considered by the International Telecommunications Union (ITU) as one of the standards for the International Mobile Telecommunications for the year 2000 (IMT-2000) specification. The UMTS network architecture allows for the upgrade of the GSM core network environment to provide 3G services in addition to the lower generation services. However, the UMTS Terrestrial Radio Access Network (UTRAN) is significantly different from GSM's Radio Access Network (RAN) and as such provides limited flexibility in equipment reuse. Wideband Code Division Multiple Access

(WCDMA) in combination with frequency division duplexing (FDD), time division duplexing or synchronization is used in the implementation of the UTRAN.

Downlink data speeds of 2 Mbps, 384 kbps and 144 kbps for indoor, pedestrian and vehicular services respectively, are among the UMTS standard specifications [2]. Delay, jitter and error tolerance are major determinants of the achievable data speeds and as such provide a basis for the categorization of UMTS services into four classes – conversational, streaming, interactive and background. Each of these classes has varying requirements for delay, jitter and error tolerance. While the conversational class of services is characterized by low delay, low jitter and low error tolerance, the background class is marginally constrained by the delay requirement.

UMTS radio network planning involves configuring the network resources and parameters in a way that guarantees performance for the end users according to the following three main attributes:

1. Coverage
2. Capacity
3. Quality of Service.

The European Union has funded research activities in UMTS network planning, such as the Research in Advanced Communication Technology in Europe (RACE) project. The Planning Tool for UMTS radio Networks (PLATON) is part of the output from the RACE program that aims at defining a base line for automatic radio planning for UMTS networks [5]. PLATON is an initiative that is aimed at shifting the network planning process from the analytical style that is employed by the available tools, to more optimized automatic planning criteria with standardized considerations. Vendor proprietary tools for cell planning such as TEMS from Ericsson, Atoll from Forsk, Planet from Mentum, etc, are available on the market.

In addition to the necessary expertise in radio network planning, two approaches are generally available to aid network planners to effectively plan and locate UMTS base stations:

1. Path loss-based approach.
2. Simulation-based approach.

The path loss-based approach can be implemented using a 2G radio network planning tool but requires that the link budget results be adjusted to fit the 3G planning criteria. The simulation-based approach requires a 3G radio network planning tool. It offers a choice between static simulations (such as those implemented using the Monte Carlo) or dynamic simulations which are generally more time consuming than the static and the results take more time to generate and to interpret. In general, dynamic simulations are more time consuming as compared to the static ones. The 3G simulation-based approach to radio network planning requires inputs such as 3G site candidates with their physical configuration, propagation model, digital terrain map, 3G parameter assumptions, and 3G traffic profiles.

1.2 Problem Statement

Cell planning in cellular networks is strongly driven by the required coverage, network capacity and quality of service. These considerations in turn influence network parameters such as transmit power, antenna heights, user distribution and the associated signal to interference ratio. Several proprietary UMTS radio planning tools are available on the market today from vendors such as Ericsson (TEMS), Forsk (Atoll), Planet from Mentum, etc. In addition, research in automating the UMTS cell planning process has been undertaken by the European Union, which proposed PLANTON.

However, the application of these tools in the estimation of the required number of base stations for a given area on the network requires the user to proceed as if they were planning for the implementation of the base station and its associated configurations. Effectively, the count of base stations that would provide the required coverage for the specified area would then be used as the estimate for the required number of base stations. Applying this method for estimation purposes for network design is not only time consuming, but implies that the network planner repeats the same process for the actual planning for network implementation. As earlier mentioned, the available tools are proprietary and are only limited to persons in possession of the appropriate software licenses. While these tools simplify the planning process, they also hide all the decision mechanisms from the user.

To overcome the above constraints, a number of estimation methods have been proposed by researchers and a survey of some of them is presented in the literature review of this thesis. Unfortunately, the surveyed models were found to only apply to green field designs. This explicitly implies that their application to incremental network designs would return misleading results. In addition, the need for estimation still remains for network operators when planning for network growth and expansion.

This thesis proposes an estimation model applicable to both green field and incremental network designs for the required number of base stations in a UMTS network. This work uses the surveyed models as a base line and makes design alterations for a select number of network parameters – transmit power, antenna and user distribution. This effectively allows for the addition and/ or elimination of network base stations to meet a set expansion and/or growth target as required by the network planner for a specified network area.

Solutions to both the base line model and the proposed modified model are derived using MATLAB. A careful comparison of the results is made to ensure that the integrity of the results from the base line model is maintained in the modified model when applied to a green field design. In addition, results showing the application of the modified model to an incremental network design are also presented.

1.3 Thesis Outline

Chapter 2 of this thesis discusses and highlights the technical importance of a select group of network parameters considered for the base station location optimization models surveyed. In here, a general description of the network parameters is given to allow for their intelligent application in the subsequent modeling problem formulations. These network parameters are mixed and matched in four different combinations as in the surveyed optimization models. This section presents portions of the models as extracted from their publications only to emphasize the motivations behind the choice of network parameters for the problem formulation. It offers an analytical comparison of the models highlighting their strengths and weaknesses.

The methodology used in the formulation of the proposed optimization problem is presented in Chapter 3, for the estimation of the required number of base stations in both green field and incremental network designs. The considerations and choices made in the problem formulation are discussed and also justified as the most appropriate.

Chapter 4 presents the results from the numerical studies carried out for both green field and incremental network designs. A comparison of the results for the green field design from both the base model and the proposed model are presented and discussed. Similarly, results from the incremental design too are presented. Conclusions from the simulation results are drawn and justified here too. Other open research areas related to this problem are also suggested in future work.

II: LITERATURE REVIEW

2.1 Overview of UMTS

While 2G systems enjoyed an unprecedented global success, they also highlighted various limitations around the achievable system capacity, global standardization of the products and services, and system flexibility to customer demands. The current trend suggests that the demand for high data rate services will keep growing. It is expected that services such as real-time gaming applications, interactive file download and upload applications, television, etc, which require minimum delay are to be in high demand. Ideally, all envisioned services requiring high data rates would also require the lowest possible delay and the lowest jitter that the system can provide.

Table 1: A subset of proposed teleservices for 3G UMTS [5]

Teleservice	Throughput (kbps)	Target bit error rate
Telephony	8 – 32	10^{-3}
Teleconference	32	10^{-3}
Voice mail	32	10^{-3}
Program sound	128	10^{-6}
Video telephony	64	10^{-7}
Video conference	384 – 768	10^{-7}
Remote terminal	1.2 – 9.6	10^{-6}
User profile editing	1.2 – 9.6	10^{-6}
Telefax (group 4)	64	10^{-6}
Voiceband data	64	10^{-6}
Database access	2.4 – 768	10^{-6}
Message broadcast	2.4	10^{-6}
Unrestricted digital information	64 – 1920	10^{-6}
Navigation	2.4 – 64	10^{-6}
Location	2.4 – 64	10^{-6}

Table 1 illustrates a subset of the UMTS teleservices with their associated planned throughput (kbps) and the target bit error rate. The UMTS network allows mobile and fixed high data rate services to bundle several data channels where necessary to provide data rates of up to 2 Mbps, 384 kbps and 144 kbps for indoor, pedestrian and vehicular access [2]. Delay, jitter and error tolerance are major contributors to the achievable data speeds and as such provide a basis for the categorization of UMTS services into four classes – conversational, interactive, streaming and background [2]. Generally, all service categories are specified with a low tolerance for error. Each of these classes has varying demands for these three system parameters.

- Conversational: voice traffic is one of the applications in this service category. Applications are characterized by low delay tolerance, low jitter and low error tolerance.
- Interactive: request-/response-type transactions; interactive services have a low tolerance for error but with a larger tolerance for delay than conversational services.
- Streaming: one-way services with a low error tolerance but generally a high tolerance for delay and jitter.
- Background: applications such as email, that have minimal or no delay requirements are grouped in this service category.

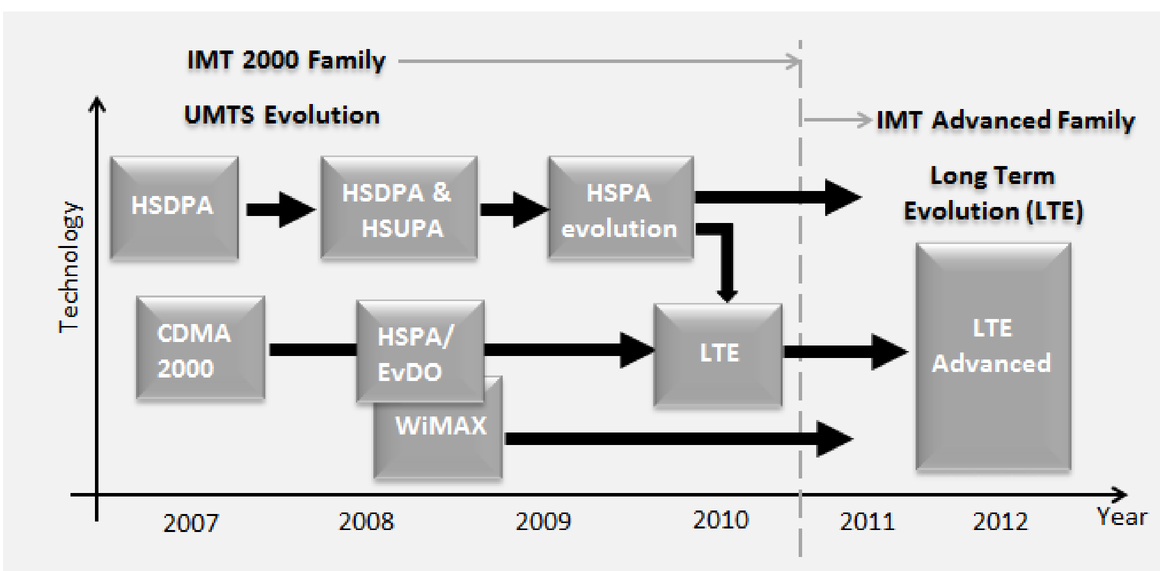


Figure 1: Evolution time frame for network systems (NSN) [8]

Network delay can be segmented and apportioned to the network element that causes it. More significance, however, is attached to the end-to-end delay that relates to the overall network design and in particular the time associated to the path the network connection has to traverse from start to finish. The success of UMTS generally relies mostly on the development of a flexible air interface, efficient coding techniques, and handset technology.

The planned time frame for the evolution of these technologies leading up to the Long Term Evolution (LTE) is also illustrated in Figure 1. It is important to note that the evolution of UMTS is planned to accommodate the GSM legacy core network nodes. Thus the 1G/2G platforms have 3G enhancements available to allow for their upgrade to provide both lower generation and 3G services.

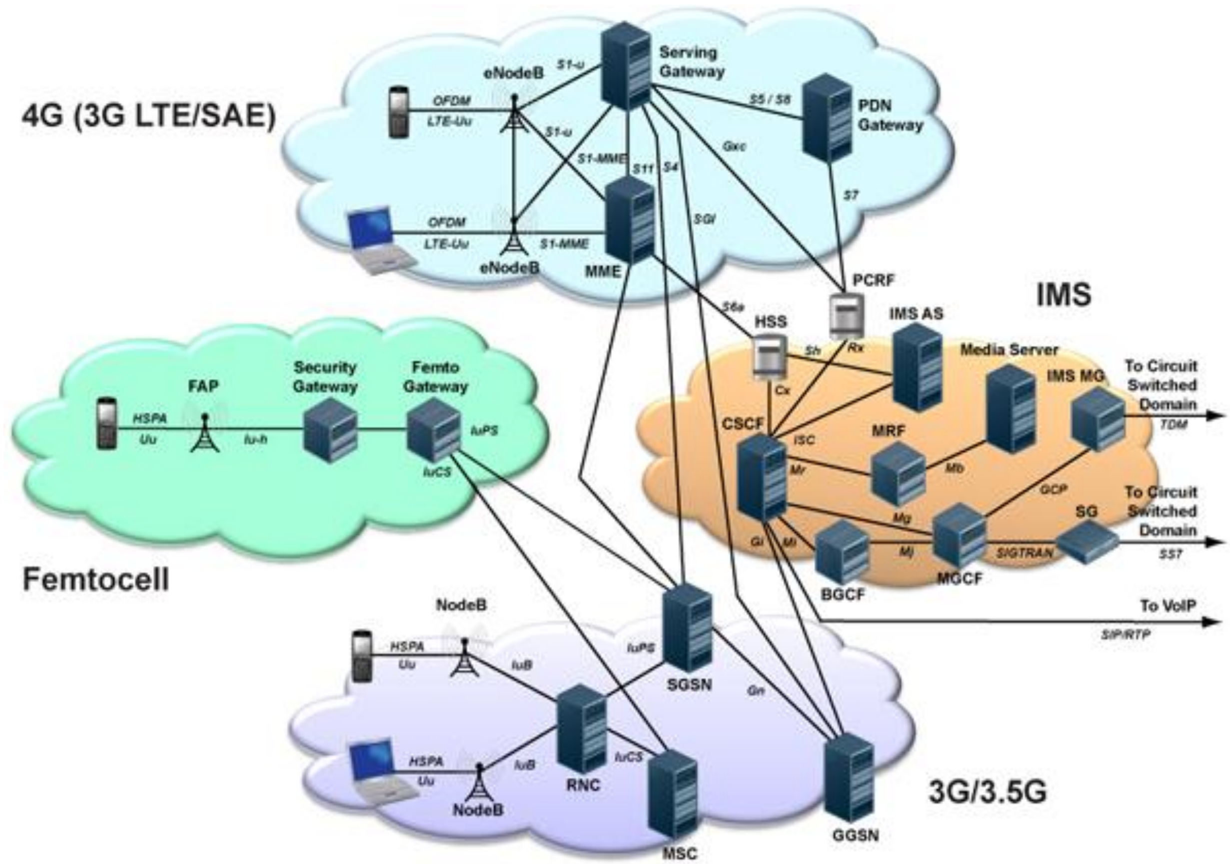


Figure 2: 3G and LTE networks [7]

Harmonization of high generation technologies is only expected from the fourth generation (4G) and beyond. 4G is planned to be fully Internet Protocol (IP)-based solution and will allow for seamless mobility between 3G wireless networks and fixed wireless [2]. Figure 2 captures the different component parts that make the 3G network and also places the 3G in relation to the other telecommunications technologies as planned by the Third Generation Partnership Project (3GPP).

2.2 Important Aspects of UMTS Cell Planning

IMT 2000 is a set of standards aimed at harmonizing the global market and ensuring a smooth transition from lower generation networks to 3G and higher generation operations and services. The UMTS design is aimed at combining the GSM and the Integrated Services Digital Networks (ISDN) standards. UMTS offers new high data rate services including multimedia and access to Internet for data rates up to 2 Mbps for a single indoor user.

The UTRAN is comprised of 2 nodes: the Radio Network Controller (RNC) and the NodeB. The RNC is comparable to the Base Station Controller (BSC) in GSM systems and the NodeB to the base transceiver station (BTS). Each RNC controls one or more NodeBs and is responsible for the control of radio resource parameters of the cells managed by those NodeBs. The RNC and the connected NodeBs together make the Radio Network Subsystem (RNS). Each NodeB can manage one or more cells. A common arrangement comprises of three 120^0-segment shaped cells per NodeB, formed using fixed direction antennas. Figure 3 pays special attention to the system components that make up the UTRAN and the associated interfaces between system nodes.

The user equipment (UE) consists of the mobile equipment (ME) and the UMTS subscriber identity module (USIM), which contains subscription-related information plus security keys [2]. The interface between the UE and the network is a WCDMA interface called the Uu. The design of 3G as a wideband system makes it more robust against multipath fading and narrowband interference. WCDMA is characterized by its flexibility in the use of radio resources. In particular, there is no a priori limit on the number of simultaneous connections per cell (hard capacity) as with time division multiple access (TDMA) or frequency division multiple access

(FDMA) systems. With WCDMA, resources are dynamically assigned according to interference levels and traffic distribution (softy capacity). This clearly implies an increased complexity in the network planning processes.

Connectivity between RNCs is implemented through the Iur interface. This facilitates mobility and soft handover between NodeBs connected to different RNCs. The UTRAN connects to the core network through the Iu interface, further subdivided into the Iu-cs and Iu-ps for connectivity to the circuit-switched and packet-switched core network parts respectively.

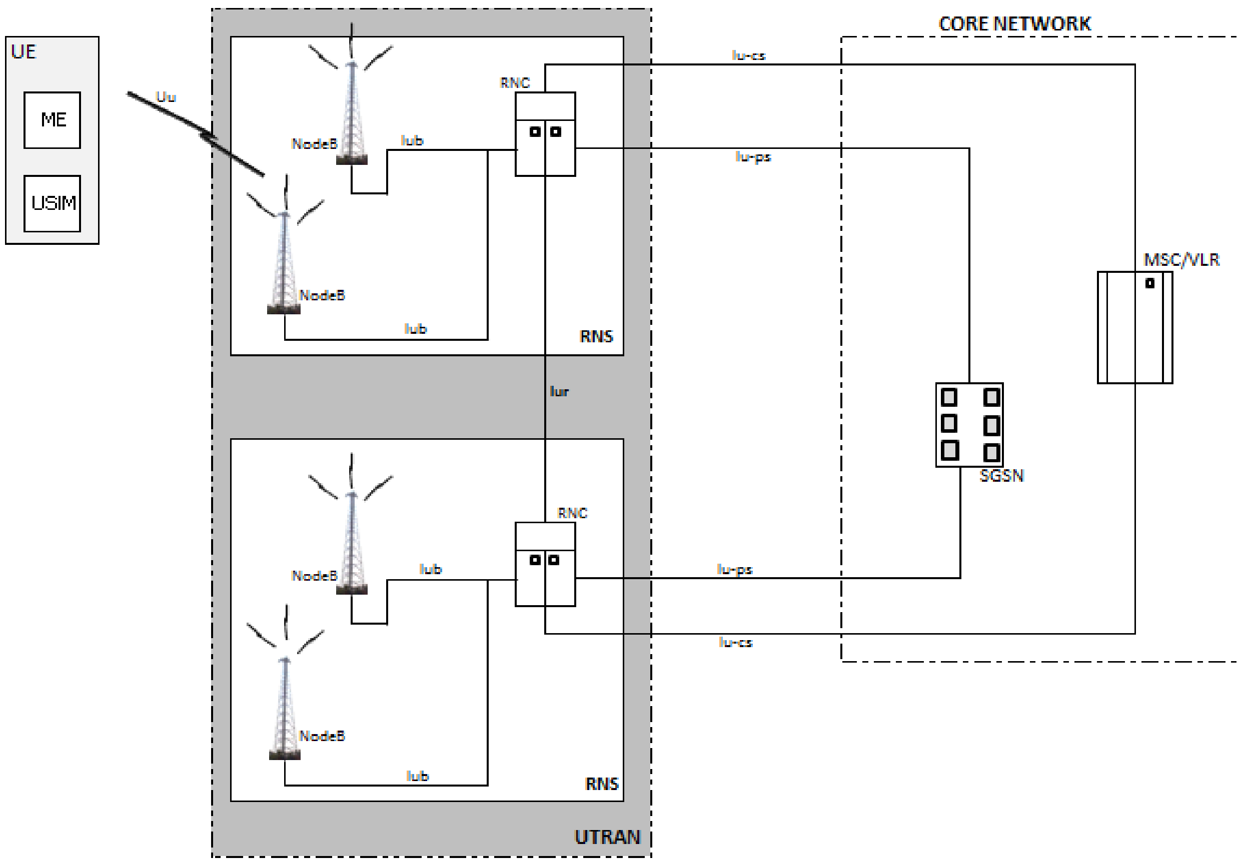


Figure 3: The UMTS Terrestrial Radio Accesss Network (UTRAN) [2]

The UTRAN accounts for 70 - 80% of an operator's total expenditure on the network [13]. This further emphasizes the need for careful planning of the radio network to minimize costs while meeting set performance targets. Radio frequency (RF) design for a wireless network is an ongoing process of refinement and adjustment based on the network variables [2]. The use of propagation modeling is a requirement for the RF design process to characterize the propagation conditions. A variety of propagation models exist and their application is determined by the morphology category under consideration – dense urban, suburban and rural [2]. Propagation models are fundamental in estimating the attenuation of the radio wave as it traverses its path. It is important to note that each model has associated advantages and disadvantages. The Okumura-Hata propagation model is one of the popular models used to characterize the radio path from the transmitting antenna to the receiving antenna. Irrespective of the choice of propagation model, the transmit power, receiver sensitivity, antenna gain and antenna height play a critical role in determining the attenuation.

Radio planning normally follows the dimensioning exercise where inputs from customer complaints, present and projected network usage are combined to estimate the required network resources. Defining the required coverage area is a critical first step in the UTRAN design process. A set of site locations and their respective NodeB configurations is necessary to realize the coverage and capacity figures derived from dimensioning. Key to successful planning is the fast and accurate assessment of network performance in terms of coverage, capacity and QoS [1]. WCDMA and the respective variations are the dominant solution for the radio access of 3G systems. It has been adopted by most countries deploying UMTS networks.

Planning tools with WCDMA traffic models for capacity planning are advantageous in their usability in terms of RF modeling, frequency allocation and channel modeling. The configuration involves antenna height, number of sectors, assigned frequencies or major channel groups, types of antenna, azimuth and down tilt, equipment type, and RF power. The final radio plan defines the site locations and their respective configuration and can be tested against various KPI requirements, mainly in developing a planning process. It can thus be correctly said that the planning process largely depends on the tool used.

There are 2 fundamental approaches to UMTS radio network planning [1]:

1. Path loss-based approach
2. Simulation-based approach.

The path loss-based approach can be completed using a 2G network planning tool. The tool must be capable of completing path loss calculations and displaying areas where specific loss thresholds are exceeded. Results from the 2G planning tool must however, be adjusted to fit the 3G planning criteria. The use of the carrier to interference ratio (c/i) in this approach is fundamental in characterizing the levels of inter-cell interference. This effectively determines the degree of cell isolation in terms of spectrum usage.

The simulation-based approach requires the use of a WCDMA radio network planning tool, the majority of which are based on the Monte Carlo simulation. These are static rather than dynamic simulations and as such the system performance is evaluated by considering a series of consecutive instants in time. In general, dynamic simulations are more time consuming than the static ones. The simulation is able to provide an indication of the average performance metrics such as cell throughput and downlink transmit power. The inputs required for the 3G simulation-based approach to radio network planning are [2]:

1. 3G site candidates with their physical configuration
2. Propagation model
3. Digital terrain map
4. 3G parameter assumptions
5. 3G traffic profile.

The first 3 inputs are the same as those used for the path loss-based approach. Most 3G tools allow UEs to be distributed within polygons, along vectors, or based upon the clutter type. Some tools also allow the import of traffic maps which can be generated outside the planning tool. The simulation-based approach to network planning is more time consuming, the results take more time to generate and to interpret [2]. The time required to generate simulation results depends upon the size of the geographic area being modeled and also the quantity of traffic loading the network.

Typically, the simulation-based approach is used for focused studies rather than wide area cellular network planning. Focused studies may be used to evaluate the capacity of a section of the network or they may be used to estimate the soft handover overhead to the path loss-based approach to 3G planning.

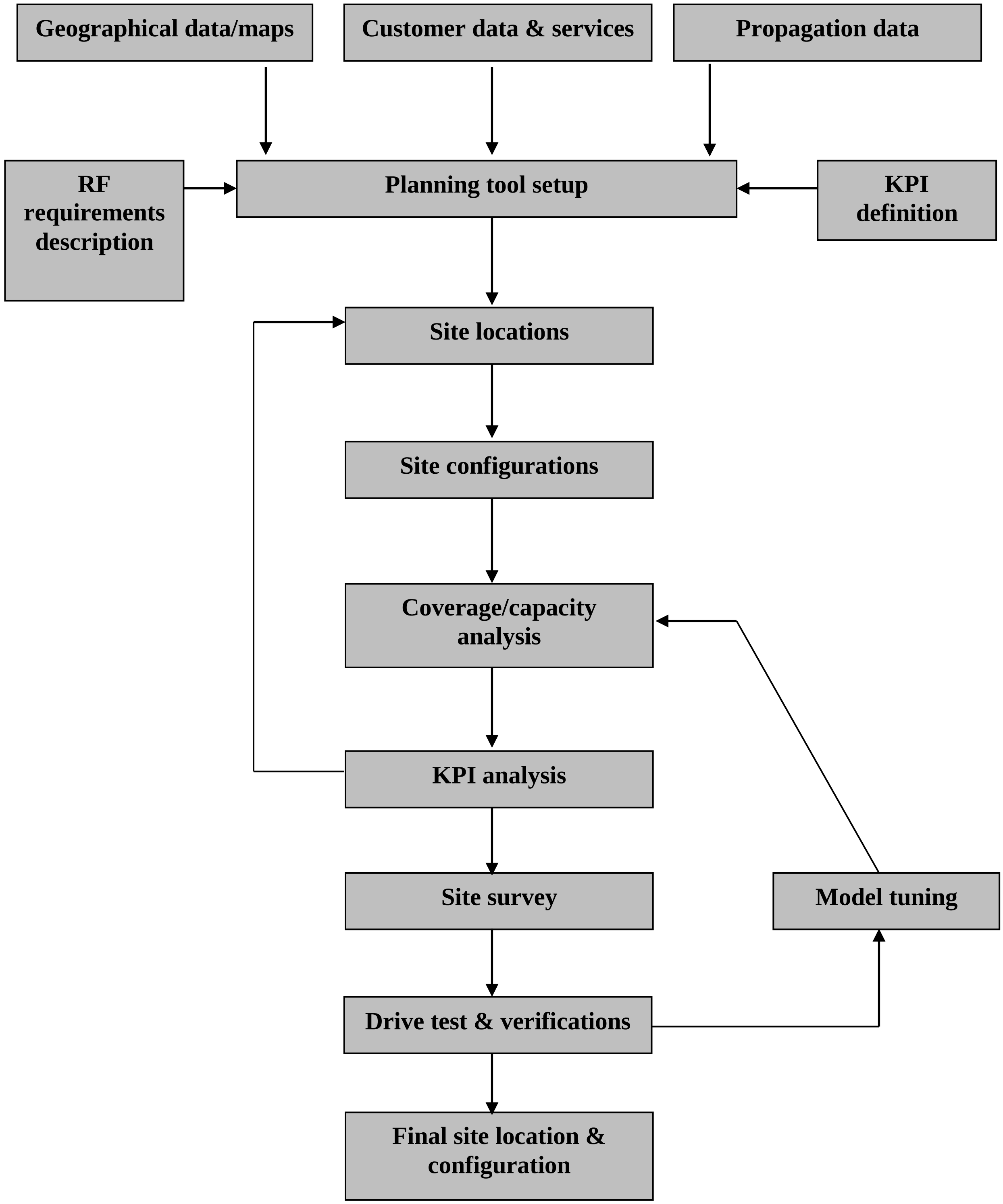


Figure 4: WCDM radio planning process [1]

Figure 4 gives a step-by-step approach that can be used as a guide in developing a planning process [1]. WCDMA radio planning involves a number of steps ranging from tool setup to site survey, and the eventual site configuration and implementation. The cell planning process is similar to any wireless network. WCDMA differs from other technologies for the actual site configuration, KPIs and the propagation environment.

This is mainly because WCDMA may support mobile and fixed users where the later may employ directional rooftop antennas [1]. The final radio plan defines the site locations and their respective configuration. The configuration involves antenna height, number of sectors, assigned frequencies or major channel groups, types of antennas, azimuth and down tilt, equipment type, coverage criteria and capacity [1].

Notice the feedback loops from KPI analysis back to site locations, and from drive test and verifications through model tuning and back to coverage/capacity analysis. These loops provide important planning check points to optimize the process. The planning process in the figure includes a drive test and verification after the site survey. This procedure is not mandatory for all sites if the site count is too high [1]. Usually, the site survey and KPI analysis give an indication of which areas are expected to have poor RF quality and which sites are involved. This can be done when the candidate sites are not located in ideal locations or if site surveys find some discrepancies with the candidates.

2.2.1 Site Selection Criteria

Fundamentally, a wireless communication system has three possible system designs [2]:

1. Existing system expansion (no new access platforms)
2. New system design
3. Introduction of a new technology platform to an existing system

The investment made for any of the above categories will generally depend on the scope and technology of the design. More specifically, expansion of existing systems can be considered as one that would only require additions and/ or enhancement of existing network components. Cellular base stations are expensive long-term investments for the operator and as such, any operator will prefer to deploy the minimum number of sites to provide the optimal required coverage. The ideal site maximizes coverage in the intended area while minimizing interference. Different approaches and criteria must however be laid down and each of the sites considered must be selected for exclusion or inclusion into the network design based on its performance against the set criteria. It is reasonable however, to include a site that does not satisfy the set criteria if there are no alternatives to it and the benefit of introducing the site is believed to justify its cost. Next generation mobile communication systems are expected to face a generalized cell size reduction due to the need of strongly improving bandwidth efficiency through radio channel reuse mechanisms [10]. Most planning tools provide the Okumura-Hata model and the Walfisch-Ikegami model for propagation modeling. The main differences between the applicability of the two are presented in Table 2 [1]. Radio network planning is often completed using a set of propagation models rather than a single propagation model.

Table 2: Applying the Okumura-Hata and Walfisch-Ikegami models [1]

	Okumura-Hata	**Walfisch-Ikegami**
Frequency range	150 MHz to 1.0 GHz 1.5 to 2.0 GHz	800 MHz to 2.0 GHz
NodeB antenna height	30 to 200m above rooftop	4 to 50m above rooftop
UE antenna height	1 to 10m	1 to 3m
Range	1 to 20 km	30m to 6 km
Applicable to	Macrocells	Microcells

2.2.2 Transmit Power and Signal to Interference Ratio (SIR)

A radio link represents the physical connection across the air interface between connected terminals and/or nodes in a wireless network. Admission control functionality within the RNC is responsible for determining the maximum, minimum and initial transmit power for each radio link. All sites in a WCDMA network are planned and operated on the same shared frequency. While this clearly simplifies the frequency planning required, it also introduces significant interference among users if the transmitted power is poorly controlled, leading to the near-far problem. The near-far problem occurs when users close to the base station transmit at the same power level as users much displaced from the base station. This effectively results in the drowning out of the signal from the user that is far away since their signal reaches the base station at a significantly lower power than that of the nearest user. The signal from the user that is far away would thus be difficult to recover.

To manage the near-far problem, power control (PC) mechanisms that dictate on the appropriate transmit power, are employed by both the UE and the base stations. The transmitted power is varied up or down in predefined steps to allow for conformity to a target signal to interference ratio (SIR) value. The base station monitors the deviations of the SIR values and instructs the affected UE to accordingly adjust the transmit power. PC mechanisms effectively limit the capacity of the system which in turn depends on the user positions and propagation conditions. PC in WCDMA uses two main techniques; open-loop power control and closed-loop power control. With open-loop power control, the terminal estimates the required transmission power based on the signal power received from the base station and information broadcast from the base station regarding the transmit power from the base station [20]. Since open-loop PC only provides estimates of the appropriate power required, its use is limited to cases where a UE needs to make initial access. Closed-loop PC (fast power control) allows the base station or the UE to instruct its associated far end to adjust the transmit power when the SIR deviates from the target value. In addition, another PC mechanism, the outer-loop PC is primarily concerned with maintaining optimal quality of service and similarly achieves this through the adjustment of the transmit powers to allow for conformity to a set SIR value.

In addition, WCDMA employs channelization and scrambling sequences to differentiate a user's own signal from others and to combat the effect of multipath and multiuser interference. The UMTS air interface uses Direct-Sequence CDMA (DS-CDMA) to spread the user data over a much wider bandwidth using a much higher rate (chip rate) of a pseudorandom sequence of bits, called the scrambling sequence or spreading code [2]. Effectively, the transmitted signal contains the user data with pseudorandom characteristics. Data from different users is spread using different spreading sequences to allow for their transmission on shared medium and eventual separation on the receiving. Spreading the user data in this way is advantageous since it makes the transmitted signal more robust to multipath. In addition, signals spread with a different code look like noise compared to the signal of interest. However, the more noise is introduced from other users, the higher the interference in the network. The ability to fully recover a given user's signal is directly influenced by the spreading factor, defined as the ratio of the chip rate to the user data rate [2]. The magnitude of the spreading factor can be considered a type of gain known as the processing gain. The spreading factor for 3G services ranges from 4 – 256 for the uplink and 4 – 512 for the downlink [2].

In an ideal environment, the dispreading process performed at the receiving end can completely avoid interference of orthogonal signals and reduce that of non-orthogonal signals by the spreading factor. In wireless environments however, due to multipath propagation, the interference of orthogonal signals cannot be completely avoided. As a result, SIR is used to measure the relative relationship between the signal and the prevailing interference. The expected SIR is given by:

$$SIR = SF \frac{P_{rx}}{\alpha I_{in} + I_{out} + \eta} \qquad (1)$$

Where:

P_{rx} is the received signal power,

I_{in} is the total interference due to the signals transmitted by the same NodeB (intracell interference)

I_{out} is due to the signals emitted by the other NodeBs (intercell interference)

α is the orthogonality loss factor ($0 \le \alpha \le 1$)

η is the thermal noise power.

On the uplink, no orthogonality must be accounted for and α is 1. A simplified and commonly adopted model assumes that the interference due to the neighboring cells I_{out} can be expressed as a fraction *f* of the interference due to the other transmissions in the same cell, so that the SIR can be expressed as below, and the thermal noise is omitted since it is assumed to be much smaller than the interference [16].

$$SIR = SF \frac{P_{rx}}{I_{in}(1+f)} \qquad (2)$$

This simplified model is accurate when the traffic distribution among cells is homogenous, while it is inappropriate in all the other cases where the contribution to intercell interference is different for each cell. Values of *f* in the 0.3 – 0.5 range are usually considered.

2.2.3 User Distribution, System Capacity and Quality of Service

Handover is a critical feature in UMTS, just like it is in lower generation networks [10]. A high handover success rate enhances the quality of service in the network. UMTS networks allow for inter-RNC handovers which effectively reduces the signaling load. Specifically, the measured SIR level for a given user connection plays a major role in the handover decision. As the SIR levels depend on both traffic distribution and NodeB positions, NodeB location in UMTS networks cannot only be based on coverage but must also be capacity driven [12]. Based on the limitations placed on transmit power, mobile stations that are far from the NodeB may not reach the minimum SIR when the interference level is too high. Therefore the area actually covered by each NodeB is heavily affected by traffic distribution and its size can vary with changes in interference levels (cell breathing effect). It is worth emphasizing that since the interference levels depend on both the connections within a cell and on those in neighboring cells, the SIR values and the capacity are highly affected by the traffic distribution in the whole area.

UMTS provides additional degrees of freedom in cell planning due to the introduction of new and flexible radio interfaces, more sophisticated cellular architectures, dynamic resource allocation (DCA) strategies and other capacity enhancement options such as adaptive antennas [11]. Some of the 3G features such as the hierarchical cells, are aimed at maximizing network capacity. Hierarchical cells can be arranged as concentric cells or as micro and macro cells.

Table 3 shows typical characteristics of the varied range of UMTS cell structures. In particular, microcells with low transmission power are favorites for deployment in urban areas while the other cell structures are used according to the operational environment to provide ubiquitous coverage. In the two layers of concentric cells, the underlay and the overlay are used to implement the concentric cells within the same service area. The underlay cell is equipped with traffic and signaling channels, while the overlay cell is assigned only traffic channels. In the hierarchical cells, different strategies for the distribution of traffic between macrocells and microcells can be applied.

Table 3: Cell structure to support UMTS [5]

Cell Type	Range (m)	Transmission Power	Antenna Heights	Comments
Macrocell	> 1000	1 - 10	> 30	Provide maximized coverage in areas with low terminal density.
Microcell	< 1000	0.1 - 1	< 10	Deployed mostly in urban areas to provide ubiquitous coverage.
Picocell	5 – 30	0.01 – 0.1	Indoor	Deployed in indoor areas with high terminal density.
Umbrella cell	> 1000	1 – 10	> 30	Used to maintain continuous coverage and to assist handover for mobile terminals that traverse through microcells at high speed.
Highway cell	100 - 1000	< 1	< 10	Used to provide coverage for sections of the road.

2.3 Related Work

Considering the enormous success of 2G systems, a large number of operators have to find ways in which to make new UMTS deployments in the presence of existing lower generation networks. It is logical that the easiest deployment method would be to co-locate the UMTS base stations with those on the lower generation networks. While this option might minimize the costs associated to the site acquisition process, it may not be the most optimal method, and may lead to high deployment costs. The selection of a BS location by UMTS network operators is based on the use of radio network planning tools that take as input, network parameters and dimensioning, as provided by the network planner. The planning tools return performance measurements calculated on the basis of specified propagation models. Associated with the cell layout are site specifications such as transmit power, frequency allocation, achievable capacity, user distribution and installation cost.

Any of the above site specifications can be minimized or maximized, separately or in combination with others, to achieve a specified network planning objective. This process is formalized through the creation of an optimization model to allow for optimal calculation of the number of UMTS base stations required for a given area. The optimization model is specified in a mathematical equation whose solution should be returned in a finite time. However, such optimization problem formulations are nonpolynomial (NP)-hard and as such their solutions cannot be found in finite time. Consequently, such NP-hard problems are popularly solved through the use of heuristic algorithms. The application of the different algorithms to a given BS optimization model restricts the possible number of BSs that can be considered for a given network. However, the algorithm used must allow for complete coverage of all control nodes using the smallest sub-set of possible BSs within the set bounds.

The greedy algorithm (GR) is implemented by [13] to solve the BS optimization problem. The GR is built on a given number of BSs and control nodes and begins by selecting the BS that covers the most control nodes. The BS and the control nodes are then removed from the area of study and the same is repeated until there are no control nodes left to cover. The speed of the GR is obviously a function of the number of possible BSs, which is set in the planning area by the user. In general, the run-time of the GR algorithm is lower than that required for other similar algorithms [13].

Related to the GR is the genetic algorithm (GA), based on the selection of a group of possible solutions or set of solutions that evolve towards an optimum solution, under the selective pressure of the fitness function. The GA is a nature-inspired algorithmic technique based on the principles of natural evolution and widely applied in solving optimization problems. The major drawback of the GA is its runtime which becomes unpredictable (very high in many cases) when the size of the population is large [5].

The choice of algorithm used in solving the optimization problem is majorly driven by the objective of the formulation, the time taken to return a solution and the degree of accuracy of the solution. Specifically, the use of combinatorial optimization methods aims at finding the minimum or maximum of a function where the set of feasible solutions is discrete or can be reduced to discrete [20]. Exact algorithms return a solution from the search space within bounded time. Approximate algorithms (heuristics) on the other hand sacrifice the guarantee of finding optimal solutions for the sake of providing good solutions in a significantly reduced amount of time [20].

2.3.1 Problem Formulation Basis

All surveyed models base their formulations on the classical uncapacitated facility location problem (UFLP). The UFLP is the simplest subgroup of the mixed-integer programming models. Mixed-integer programming models accept as input, parameters as defined by the user. UFLPs take different forms depending on the nature of the objective function, the time horizon under consideration, the existence of hierarchical relationships between the facilities and the inclusion or not of stochastic elements in their formulation [19]. Uncapacitated problems assume that each facility can produce and ship unlimited quantities of the commodity under consideration. This basic UFLP formulation is adopted by [12], [13], [14], and [16] and the model is summarized as below.

Consider a territory to be covered by a UMTS service. The following definitions are applied:

$S = \{1, 2, 3, ... , m\}$ is a set of candidate sites where a BS can be installed.

C_j – Cost associated with each candidate site j, $j \in S$.

$G = \lfloor g_{ij} \rfloor_{(1<i\leq n),(1\leq j\leq m)}$ – is the propagation gain matrix estimated according to an approximate propagation model.

I = {1, 2, 3, . . . , n} is a set of test points (TP) and each TP, $i \in I$

g_{ij} $0 < g_{ij} \leq 1$ – the propagation factor of the radio link between TP *i*, $1 < i \leq n$ and a candidate site j, $1 < j \leq m$.

U_i – Required number of simultaneously active connections of TP *i*. U_i is a function of the traffic demand given by $u_i = \phi(d_i)$ u_i = □(d_i) where d_i is the amount of traffic (in Erlangs) associated to a TP *i*, with a given SIR.

Considering two decision variables, the core of the basic integer programming model proposed for the uplink case is the classical uncapacitated facility location model.

$$\min \sum_{j=1}^{m} c_j y_j + \lambda \sum_{i=1}^{n} \sum_{j=1}^{m} u_i \frac{1}{g_{ij}} x_{ij} \quad \text{--------------------} \quad (3)$$

Decision variables:

$$y_j = \begin{cases} 1 & \text{if a BS is installed in } j \\ 0 & \text{otherwise} \end{cases} \quad \text{for } j \in S \quad \text{------------} \quad (4)$$

$$x_{ij} = \begin{cases} 1 & \text{if test point } i \text{ is assigned to BS } j \\ 0 & \text{otherwise} \end{cases} \quad \text{for } i \in I \text{ and } j \in S \quad \text{-----} \quad (5)$$

Subject to:

$$\sum_{j=1}^{m} x_{ij} = 1, \quad i \in I \quad \text{----------------------------} \quad (6)$$

$$x_{i=j} \leq y_j \quad i \in I, j \in S \quad \text{--------------------------} \quad (7)$$

$$x_{i=j}, y_j \in \{0,1\} \quad i \in I, j \in S \quad \text{-------------------------} \quad (8)$$

The first term in the objective function corresponds to the total installation cost. Since $1/g_{ij}$ is proportional to the power emitted from TP i, when assigned to BS j, the second term aims at favoring assignments which require a smaller total emission power. $\lambda \geq 0$ is a tradeoff parameter between these two objectives. Constraint 4 makes sure that each TP *i* is assigned to a single BS. Constraint 5 imposes that TPs are only assigned to sites where a BS is installed. Note that by restricting the assignment variables x_{ij} to take on binary values, it is required that in every feasible solution, all active connections must be assigned to a single BS. To account for the power limit on the user terminals, constraint (9) is applied to each pair of TPs $i \in I$ and the candidate sites $j \in S$:

$$\frac{P_{target}}{g_{ij}} x_{ij} \le P_{\max} y_j \quad ----------------------------- \quad (9)$$

Where:

$P_{\max}$ is the maximum emission power.

P_{target}/g_{ij} is the corresponding emission power required by a mobile in TP i to guarantee the target received power P_{target} at site j.

Note that if $g_{ij} P_{\max}/P_{target} < 1$, the TP i cannot be assigned to candidate site j due to power limits, and therefore, the variable x_{ij} can be omitted from the model. Otherwise constraint 9 is implied by the corresponding constraint 5.

2.3.2 Other Problem Formulations

The quality of the signal received at each BS is used by [14] to modify the UFLP and formulate a more specific problem to the reality of UMTS operation. The simplest way to express the quality constraints is either to neglect the intercell interference or to consider that it amounts to a given fraction of the intracell interference as given in equation (2) of chapter 2, for nonzero values of the parameter f. For each connection, the quality constraint can be written as:

$$SF \frac{P_{rx}}{I_{in}(1+f)} \ge SIR_{\min} \quad or \quad \frac{I_{in}}{P_{rx}} \le \frac{SF}{SIR_{\min}(1+f)} \quad -------- \quad (10)$$

Considering a power-based PC mechanism, the power received P_{rx} at BS j from each mobile station in a TP assigned to it is equal to P_{target} and the quality constraint amounts to imposing an upper bound on the number $\sum_{i=1}^{n} u_i x_{ij}$ of connections that can be assigned to that BS.

Specifically, we have

$$\sum_{i=1}^{n} u_i x_{ij} \leq \frac{SF}{SIR_{\min}(1+f)} + 1 ------------------ \quad (11)$$

For the typical values of f = 0.4, SF = 128 and SIR_{target} = 6 dB. Unfortunately even medium sized instances of these nonpolynomial NP-hard capacitated location problems turn out to be out of reach of state-of-the-art optimization algorithms [14]. But, even more importantly, the capacity constraints do not capture the distinctive features of the WCDMA technology. To make the model more realistic, intercell interference needs to be considered explicitly and independently from intracell interference. This consideration modifies the constraint for each connection to $\left(\frac{P_{rx}}{(I_{in} + I_{out} + \eta)}\right) \geq SIR_{\min}$, where $SIR_{\min} = \frac{\tau}{SF}$ is the minimum SIR before dispreading. The use of pseudorandom spreading codes implies that for a specific uplink connection between TP i and BS j, there is no significant difference between the two types of interference and thus, $\alpha = 1$ in the SIR formula. In the presence of power-based PC mechanism, the thermal noise is omitted. For each candidate site $j \in S$, the signal quality constraint can be expressed as:

$$\frac{P_{target}}{(I_{in} + I_{out} + \eta)\sum_{h=1}^{n} u_h g_{hj} \sum_{t=1}^{m} \frac{P_{target}}{g_{ht}} x_{ht} - P_{target}} \geq SIR_{\min} y_j \quad ---------- \quad (12)$$

P_{target} is by definition the power received from each assigned TP.

A similar approach as built in the basis formulation is taken by [14] by minimizing the BS cost and emitted power while maximizing the number of active connections. In this downlink optimization problem, maximum transmitted power, antenna height and assignment of demand nodes with NodeBs are the decision variables given by discrete sets. The candidate NodeB sites and the demand nodes are fixed input parameters. The downlink optimization problem is formulated as a combinatorial optimization problem with the objective function is formulated as:

"Minimize the total NodeBs' cost while minimizing the total emitted power by all active mobile units and maximizing the total number of active connections in the service area."

$$\min \sum_{j=1}^{m}\sum_{k=1}^{w}\sum_{q=1}^{z} c_{jkq} y_{jkq} + \alpha \sum_{i=1}^{n}\sum_{j=1}^{m} u_i \frac{P_{tar}}{g_{ij}} x_{ij} - \beta \sum_{i=1}^{n}\sum_{j=1}^{m} u_i x_{ij} \quad ------ \quad (13)$$

A site placement problem formulation to optimize the initial locations of the BSs is presented by [9] as a joint uplink/ downlink site placement for a weighted combination of two objectives: *"Minimize the downlink power expenditure" and "minimize the link outage".*

The inputs to this problem are similar to those applied to the base case – specified area of interest, user distribution, fixed number of BSs and the initial location of BSs. Initial locations of BSs in [9] are obtained from the site placement problem resulting into a select set of optimal locations of BSs from the initial possible BS locations.

$$\min_{x,y} \sum_{k=1}^{U} P_{b(k),k}^{d} + \alpha \sum_{k=1}^{U} \left(P_k^u - P_{\max}^u\right)^{+} \quad --------------------- \quad (14)$$

Where:

$P_{b(k),k}^{d}$ - transmit power allocated to MS *k* by its serving BS

P_k^u - user terminal transmit power

$P_{\max}^u$ - maximum allowed user terminal transmit power

Equation (16) is the weighted objective and α is a constant that determines the relative weight of each of the two components. The uplink channel is limited by the power capabilities of the UEs, which is by far less than that of the BSs. Thus it is important to ensure that uplink transmissions can still reach the BSs at a reasonable power subject to their handset limitations while satisfying the minimum SIR threshold for acceptable performance. Effectively, each UE requiring power in excess of $P_{\max}^u$ will be considered in the second objective. If all UEs do not exceed the threshold, this will be a vector of zeros, which is essentially disregarded from the objective. The outage conditions are defined networkwide and for each BS. The site selection algorithm selects the minimal cardinality set of BSs that satisfies the coverage and SIR requirements. The objective of the problem is to minimize the number of candidate set of BSs. The problem presented in [9] can be thus formulated as a nested optimization problem given by

$$\min_{c} \sum_{i=1}^{N_0} C_i \qquad (15)$$

subject to the same constraints as those in the site placement problem. The inner problem finds the set of BSs that minimizes the cost function and the outer problem finds the minimal cardinality set of such BSs. The main difference between the site placement and site selection problems is that the decision variables in site selection are not the BS locations, instead, these locations are fixed and the decision variables are Boolean C_i; where $C_i = 1$ if the BS *i* is to be used in the optimal network configuration and $C_i = 0$ otherwise.

A very important observation is that minimizing the total power expenditure implicitly reduces the variance of BS powers by converging to a solution that nearly equally distributes the power load among BSs. To generalize the model to handle both voice and data concurrently, a given percentage of data users in the network is selected and these data users are independently and randomly picked from the set of all users. The requirement for higher data rate services naturally increases the network load and makes the QoS requirements more stringent.

The BS location problem formulation is presented by [15] as an optimization problem that minimizes the SNR as elaborated below. From the SNR equation,

$$SNR_j = \frac{W}{v_j R_j} \times \frac{P_j^{rx}}{P_{NF} + I_j^{(c)}} \qquad (16)$$

Where:

W is the chip rate, 3.84 Mcps

v_j is the activity factor of user j at the physical layer, 0.67 for speech and 1.0 for data

R_j is the bit rate of user j

P_j^{rx} is the received power from user j

P_{NF} is the background noise level including thermal noise and noise from any man-made transmitters within other communication systems.

$I_j^{(c)}$ is the co-channel interference related to user j, the interference power coming from other links operating at the same frequency band within the same system.

I_{total} is the total received power that can be expressed as the summation of the background noise level, co-channel interference and the received power from user j.

From a set of BS locations, evaluations of the maximum uplink path loss are made on the basis of mobile transmitting power, system loading and the presence of background uplink noise floor. Coverage and throughput evaluations are then made to determine the most suitable BS locations. A genetic matching is then performed to find the most optimized solution for the BS locations. Just like in [9], [15] supplements the site selection problem with the site placement problem to determine optimal locations of a fixed number of UMTS BSs. The user distribution model is assumed to be a snapshot based representing only a set of users (test points) using the physical channel at a given instant of time.

2.3.3 Comparison of Problem Formulations

The estimation of the number of BSs required is considered to be NP hard by all the papers that were surveyed. On this basis, a general trend of using heuristics algorithms to provide optimal estimates is adopted by all the papers. Emphasis is placed on the transmit power and the user distribution and as such, the authors propose varying adaptations to tweak these parameters using the available power control mechanisms.

Formulations on the downlink direction were generally considered to be more complex than those in the uplink, due to the higher bandwidth requirements that the downlink has to offer and the asymmetric distribution of the traffic. The maximum base station transmit power and the limited sensitivity of the user devices presents major concerns in the formulations.

Algorithms and/or methods such as the GR, GA, fuzzy logic, are selectively employed by the authors. The choice of algorithm is driven by its required run time and feasibility to optimally manage a large set of data input for estimation. The GR and GA are separately applied by [13] in different scenarios to aid the selection of the most suitable site locations out of the many available possibilities. It is reported that the runtime of the GR is lower than that required for similar algorithms, while that of the GA becomes very unpredictable in the majority of cases when the size of the population is large. The GR and a tabu search algorithm are employed by [12].

All models considered in this paper incorporate a count of the optimal number of sites required within a specified area to provide the target network requirements, and the associated cost. Specifically, this consideration is formulated to provide the lowest possible cost of implementation. Other considerations such as user distribution, SIR, downlink and uplink power are selectively applied to the problem formulation to emphasize the minimum cost objective. It is important to note that the application of the network considerations, independently or in combination results in a variation in the number of base stations required and therefore the cost of implementation.

Of critical importance is the fact that all models considered in this paper can only find application in green field designs. They were not formulated to take care of incremental designs that would arise from network growth and expansion, which is a fundamental feature of network operations.

III: METHODOLOGY

As elaborated in the previous chapters, network planning is an iterative process that is aided by the use of network planning tools. Several commercial/ proprietary tools are available. In addition, a lot of research interest in this area has resulted in several optimization models as was discussed in Chapter 2. Network planning can generally be summarized in three steps:

1. Network design inputs – current network usage, projected network demand, customer complaints, etc.
2. Network design process – creation of a network topology using a network planning tool.
3. Network performance analysis – evaluation of the network topology based on specified criteria.

Behind the scenes, network planning tools are founded on algorithms formulated to solve the network planning problems. This allows for the expression of the network problem in a mathematical formation that can be solved in a finite amount of time. By definition, an algorithm is a step-by-step method of solving a problem. Algorithms are characterized by their inputs, outputs, precision, determinism, finiteness, correctness and generality. In the context of combinatorial optimization, algorithms are classified into two categories – exact and approximate. The traveling salesman problem (TSP) and the minimum spanning tree (MST) are popular examples involving combinatorial optimization. More specifically, approximate algorithms (heuristics) produce near-optimal solutions that in many applications are sufficient. Examples of approximate algorithms include the greedy algorithm – tabu search, simulated annealing, etc.

Approximate algorithms based on the local search (LS) principle provide a solution to a problem by starting with an attempted solution of the problem and continuously modifying it locally for an improved final solution. Conversely, the metaheuristics category of approximate algorithms attempts to improve the output of the local search by effectively exploring the search space thereby reducing the probability of the solution being trapped at a local minimum which may not be the global minimum. The choice and use of algorithms in computations is dependent on its associated running time, which can be linear, quadratic, cubic, etc. A time bound of the form

$O(n^k)$ for some fixed k, is called polynomial time. Algorithms running in polynomial time are considered efficient in the sense that they can be implemented and run for reasonably large inputs [21].

Network capacity, coverage, cost, SIR and base station transmit power are the most popular parameters that are used to define optimization objectives in cell planning problems. While each objective can be considered independent of any other, it is not foreign to find cell planning problem objectives that combine two or more of the mentioned network parameters. Formulation objectives such as those listed below have been the focus of research interest in optimizing cell planning:

1. Maximize capacity,
2. Maximize coverage,
3. Minimize cost,
4. Maximize SIR and
5. Minimize transmit power

Problem formulation for any of the above listed objectives is easier to attempt in second generation networks due to the fact that considerations need only be made for the frequency allocations and coverage predictions. Attempting a similar task in 3G networks has increased complexity since the realization of any of the required objective function is inherently tied to all network parameters. The conflict in combining the maximization of coverage and capacity in relation to minimizing cost should not be lost on the reader. Similarly, combining the SIR and transmit power objectives in a formulation can result in contradictions if not carefully handled.

Such conflicting targets make it imperative for one to clearly define and bound the desired network target when formulating the optimization problem. A multi-objective function can be produced in either linear and/or weighted combinations of the single objectives using a set of decision variables and a set of object functions [20]. A weighted objective function allows for greater flexibility and also highlights critical points on which informed decisions can be made in relation to the desired network target.

This thesis formulates a general problem to minimize cost based on the count of the estimated required number of base stations. User distribution, antenna height and transmit power are used as the drivers for the formulation. The general problem formulated for green field designs is later modified to apply to incremental designs too.

3.1 The Cell Planning Problem

This basic UFLP formulation of section 2.1 is adopted for this thesis. It is used as the basis on which further modifications are made to reflect the design problem. The classical UFLP is given by [12], [13], [14] and [16] as:

$$\min \sum_{j=1}^{m} c_j y_j + \lambda \sum_{i=1}^{n} \sum_{j=1}^{m} u_i \frac{1}{g_{ij}} x_{ij} \qquad (17)$$

Decision variables:

$$y_j = \begin{cases} 1 & \text{if a BS is installed in } j \\ 0 & \text{otherwise} \end{cases} \quad \text{for } j \in S \qquad (18)$$

$$x_{ij} = \begin{cases} 1 & \text{if test point } i \text{ is assigned to BS } j \\ 0 & \text{otherwise} \end{cases} \quad \text{for } j \in S \qquad (19)$$

Subject to:

$$\sum_{j=1}^{m} x_{ij} = 1, \quad i \in I \qquad (20)$$

$$x_{i=j} \leq y_j \quad i \in I, j \in S \qquad (21)$$

$$x_{i=j}, y_j \in \{0,1\} \quad i \in I, j \in S \qquad (22)$$

Decision variable x_{ij} ensures that a specific user distribution is assigned to one base station. Thus the combined use of $x_{i=j}$ and y_j confines that the selection and attachment of users to base stations within the defined network limits.

S = {1, 2, 3, ... , m} is a set of candidate sites where a BS can be installed.

C_j – Cost associated with each candidate site j, $j \in S$.

I = {1, 2, 3, . . . , n} is a set of test points (TP) and each TP, $i \in I$

$G = \lfloor g_{ij} \rfloor_{(1<i\leq n),(1\leq j\leq m)}$ – is the propagation gain matrix estimated according to an approximate propagation model.

U_i – Required number of simultaneously active connections of TP *i*. U_i is a function of the traffic demand given by $u_i = \phi(d_i)$ where d_i is the amount of traffic (in Erlangs) associated to a TP *i*, with a given SIR.

g_{ij} $0 < g_{ij} \leq 1$ – the propagation factor of the radio link between TP *i*, $1 < i \leq n$ and a candidate site j, $1 < j \leq m$.

Table 4 highlights the generic system parameters for a suburban environment that are applicable to this design problem [1], [23]. Specifically, the SIR (E_b/N_o), receiver sensitivity and the maximum transmit power values will be emphasized in this design to create a correlation and justify the design simplifications made. The quoted figures in the table only indicate the minimum requirements. Applying the Walfisch-Ikegami propagation model for clear line of sight in the 800 MHz – 2000 MHz frequency band:

$$Pathloss = 42.6 + 26\log d + 20\log f \qquad (23)$$

Where:

d is the radius of coverage in km

f is the carrier frequency in MHz.

For the lower and upper frequency bounds, the Walfisch-Ikegami propagation model returns a path loss of approximately 119 dB and 127 dB respectively, for an coverage radius of 5km. Note that the path loss for a shorter radius of coverage would be smaller. For this coverage, a base station would need to transmit at least 6 dB to ensure conformance to the recommendations for receiver sensitivity as shown in table 4. The Federal Communication Commission (FCC) limits the maximum transmit power from a cellular base station at 33 dB. Operators are at liberty to improve the figures to provide a higher quality of service. The maximum base station transmit power influences the achieved SIR and the allowable propagation loss, and hence the necessary receiver sensitivity.

Table 4: Generic system parameters considered

Parameter	Baseline 3GPP Requirements		
	Speech	Circuit-switched Data	Packet-switched Data
Required E_b/N_o (dB)	4.4	2.0	2.0
Receiver sensitivity	-122.6	-117.8	-117.8
Allowed propagation loss (dB)	139.5	139.7	139.7
Modulation and coding	QPSK	QPSK	QPSK
Maximum UE transmit power (mW)	125		
Maximum BS transmit power (W)	20		
Maximum antenna gain (dBi)	15		

3.2 Greenfield Design

The goal of this formulation exercise was to produce and avail a simple tool to allow for the optimal estimation of the number of BSs required to provide unlimited coverage and capacity for a specified area. The following simplifying assumptions were made:

- Unlimited network capacity
- Only downlink transmit power is considered and lumped in three segments.
- Antenna height requirements drive the construction requirements of the tower and subsequently the total cost of the site. This too is lumped in three consecutive groupings.
- The cost of the tower makes the largest contribution to the estimation problem and is also categorized in three groups depending on the available line of sight conditions.
- A set target SIR limit determines the choice of one of three groups of transmit power categories to be used and effectively manages the effects of both the intracell and intercell interference.

- The contribution of the user distribution and transmit power are jointly considered and their summation weighted at a fixed value.
- 95% minimum success call rate at busy hour. This effectively specifies the probability that a network call will be successfully admitted based on the available network resources.

The foregoing considerations provide uniformity for the formulation and result in a value that can be used as the count of the required number of base stations. The inputs into the formulation are as listed below:

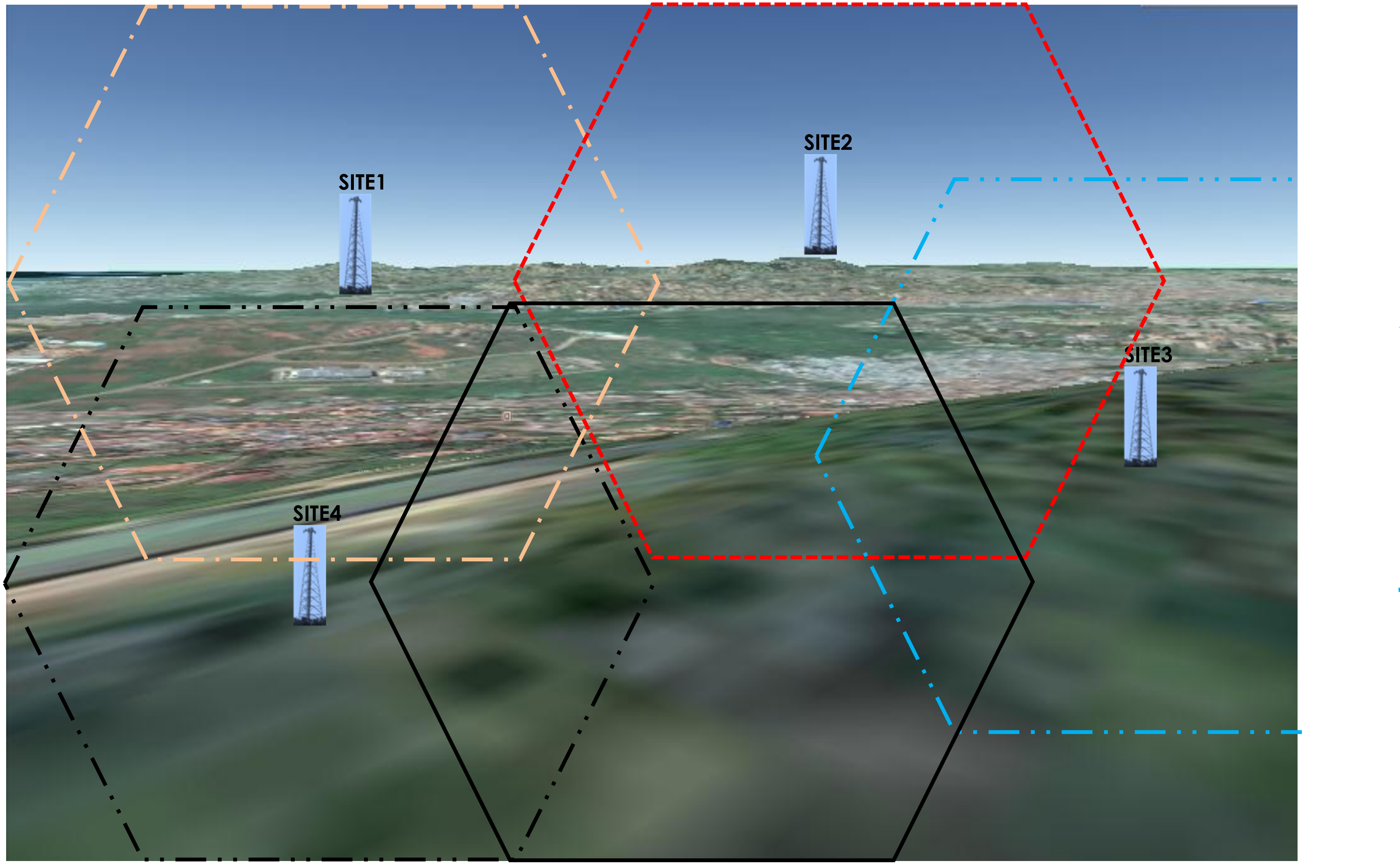
1. Selected potential locations of base stations.

   It is assumed that a specified set of sites, whose requirement for user distribution can be appropriately determined, are available to the network planner. The discretion for dimensioning the requirements for transmit power and antenna heights is left to the network planner. This effectively eliminates the association of a test point to a selected site.

   Figure 4 – Terrain challenges in cell planning – illustrates this simplification strategy as applied for this modeling. Four sites labeled SITE1 through SITE4 are in this case proposed as potential locations for the provision of services to the area illustrated.

   Assume, in this case, that each of the sites has no acquisition limitations and would be available if selected. The effects of cell breathing notwithstanding, the coverage hexagons, with each color representing a coverage area, in figure 5 clearly overlap in a significant manner. This emphasizes the fact that complete coverage of the area can be possible with a smaller number of sites. As such, the discretion to select the most appropriate site locations considering the projected user distributions is with the network planner. The unbroken black color hexagon is used to suggest the possibility of relocating SITE4 to provide coverage in the said hexagon. Similarly, it is possible to do away with SITE3 all together considering that SITE2 overlaps its coverage by more than 50%.

Figure 5: Terrain challenges in cell planning



The purpose of this illustration is to show the fact that such considerations are part of the network planning thought process. In the original problem formulation, however, this selection process is automated and is based on the association of the available TPs to the possible site with the appropriate signal strength. It is also important to note that the many high rise areas in figure 5 can result in coverage shadows if inappropriate site locations are selected and used.

2. The antenna heights required to provide the targeted network coverage.

   Three categories are considered, 100% clearance, moderately obstructed line of sight and severely obstructed line of site. The 100% clearance scenario requires the lowest antenna height while the severely obstructed category requires the highest antenna height. As earlier noted, the lowest antenna height requirement presents the lowest site construction cost requirement. Considering figure 5, the antenna heights for all the site locations need to be appropriately selected to restrict the base station transmissions to the intended area of coverage. While this illustration seems to favor the hill tops, this is not always the most suitable location of sites.

3. User distribution

   Users will be represented as a lump sum and applied to the associated potential site location. A range of 800 to 1000 simultaneous users that can be accommodated per base station is assumed. Only the site allocated the maximum allowable transmit power is expected to support the maximum number of simultaneous users. It is also assumed that the sites allocated the lowest transmit power due to their lower user distribution can completely satisfy the coverage and performance requirements in their areas of coverage.

4. The transmit power

   The transmit power is assumed to be associated to both the LOS conditions and the user distribution. It increases with an increase in user distribution to allow for provision of the target signal strength to all users. Allocations for transmit power are made in 3 categories. A baseline transmit power is selected based on figure 6 to allow for an optimal radiation-limited area for a uniform user distribution. The other two categories of transmit power are allocated in upward steps of 5 dB from the baseline value.

3.2.1 Antenna Height

The antenna heights allocated to a given potential base station location is predetermined using the degree of clearance obtained between the base station and three 120^0 segments of the area to be covered. The baseline value of 30m is referenced from [5] for a microcell structure as illustrated in Table 3: Cell structure to support UMTS. The antenna height consideration is categorized into 3 groups as summarized in Table 5 to simplify the design process. The applicable antenna height is assigned a value that effectively represents the requirement for site construction in that location. A base antenna height of 30m is adopted with a corresponding tower height of 40m. This effectively presents a site count of one for that location. All other antenna height requirements are referenced from this base configuration. Upward increases in the applied value are made to apportion the additional construction cost incurred based on the additional antenna height required. This is calculated as the difference between the reference point and the requirement under consideration. In the presence of actual site construction cost data, the assigned values can still be calculated as the additional difference in the required costs.

Table 5: Antenna height formulation considerations

Antenna Height (m)	Tower Height (m)	Clearance Category (120^0 sectors)	Assigned Site Count Value
0.0 – 30.0	40	3	1.0
30.1 – 40.0	50	2	1.2
41.1 – 50 .0	60	1.5	1.3

This categorization of antenna heights was selected to uniformly apply to all three morphologies – rural, suburban and urban. For the most part, the terrain and clutter in the intended area of coverage predicates the choice of antenna height to be applied. Such choices however, are expected to be guided by the network planner’s knowledge of the area and the network.

Considering that site construction pricing information is not readily available, this categorization will be further investigated and tuned for a predefined maximum allowable additional site count. Table 5 shows the different subdivisions made to cater for the site antenna height requirements. The following proposed categorizations are aided by the use of the Walfisch-Ikegami propagation model to ensure conformity to target minimum receive power. These categorizations are subjective and only serve to allow for uniformity in the design decisions. In addition, it is also assumed that coverage gaps in a given area can be adequately compensated by coverage from other sites within the network.

1. A minimum of 80% line of sight clearance for each of the three 120^0 segments, for a minimum of 3 km, is considered for this purpose to be equivalent to the lowest possible antenna height set at 30m. This correspondingly requires the site tower to be no more than 40m. In the formulation, this value will be used to represent the cost associated with the candidate site and will thus represent a count of 1 base station location. At this height, the site provides complete coverage of the area to support an unlimited number of users.

2. Moderately obstructed line of sight clearance is for this purpose considered to be equivalent to obstructions in the propagation of the radio signal for at most one 120^0 segment of the area to be covered. This translates into the base station location requiring antenna heights between 30m and 40m. The additional cost that this additional antenna height requirement places on the tower height results into an additional base station location cost of one and two parts (1.2) sites.

3. Highly obstructed LOS clearance is that which presents obstructions in radio propagation for at most half of the area to be covered equal to 180^0. This is formulated to require antenna height between 40m and 50m. This height requirement is considered equivalent to a count of one and three parts (1.3) sites. This category of antenna heights caters for situations were nature inadvertently obstructs signal propagation in say, mountainous areas.

4. The site count values associated to each category are calculated as the ratio of the additional cost incurred as a result of the extra antenna height required from the basic antenna cost. The assigned value caters for all site costs needed to provide the required antenna height.

3.2.2 Transmit Power

A reference base station downlink transmit power is set at 20 dB. It is chosen to be the lowest base station downlink power configuration. This power provides coverage for a hexagonal cell and achieves the set SIR value at the edge of the cell. Based on the Walfisch-Ikegami propagation model, this power is sufficient in the provision of network services based on the recommendations in Table 4: Generic system parameters considered. The highest downlink power configuration is set at 30 dB, (3 dB less than the FCC maximum) for a dense user distribution, and 25 dB for a moderate user distribution. Applying these transmit power categories for the minimum antenna height on the free space propagation model returns values of received power within the recommended receiver sensitivity values as specified in Table 4.

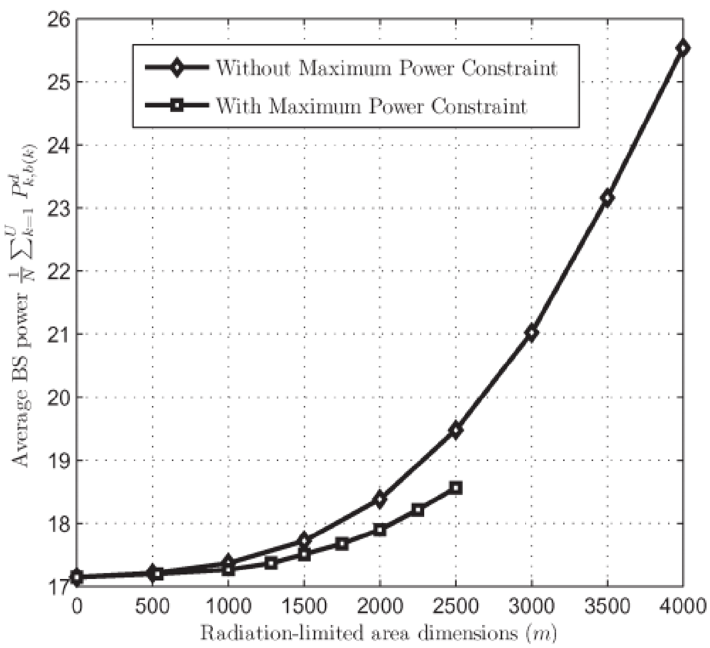


Figure 6: Pareto-optimal set that provides the tradeoff between BS power and the dimensions of the radiation-limited area for a uniform user distribution [24]

For the purpose of this formulation, this transmit power is considered sufficient to provide quality signal simultaneously for at least eighty percent (80%) of the user population at busy hour. This transmit power is also considered sufficient to provide 100% busy hour call success rate for sparsely populated areas of service. As shown in figure 6 below, the choice of transmit power allocations are expected to provide up to 2.5 km of coverage. However, the optimal allocation of base station transmit power is dependent on not only the user distribution, but also on the allocations made on other sites within the network. Network performance monitoring and optimization is essential in determining the optimal base station transmit power requirements. It is equally as important in harnessing the effects of cell breathing.

Table 6 below represents this categorization of the transmit power considerations. The transmit power increases in steps of 5dB from the sparse user population category for every shift into a higher category of user population. The purpose of this variation in transmit power is both to represent the effect of intracell and intercell interference as a result of user population growth, and also to provide a defense mechanism against this phenomenon within set SIR limits. Inter cell interference is assumed to be effectively curbed by set limits on target maximum SIR. Effectively, this translates into an increase the value of the second portion of the objective function resulting into an increase in the count of base stations required for the network.

Table 6: Categorization and considerations for downlink transmit power

Transmit Power (dB)	User Distribution	Assigned Value
30	Dense	0.90
25	Moderate	0.95
20	Sparse	1.00

3.2.3 User Distribution

A uniform user distribution is assumed for all sites and is subdivided into three categorizations for this formulation:

- Sparsely populated
- Moderately populated
- Densely populated

Each site is planned at a 95% busy hour call success rate. Sparsely populated areas represent the baseline case, linearly related to both the antenna heights and transmit power parameters of the design. Considering that the required antenna height effectively translates into a site count of at least one, it is expected that this site provides adequate planned coverage for the lowest user population. This consideration thus requires that the second part of the objective function does not increase the site count for the minimum user distribution. As such, it is appropriate to represent the lowest user distribution with a value of zero to neutralize its contribution to the site count. This is only to emphasize the ideal antenna height conditions at the site (up to 30m) and total propagation clearance. For the rest of the user distribution categories, the combined contribution of user distribution and transmit power serves to increase the total number of base stations required.

Table 7: User distribution categorization

User Distribution Category	Formulation Assignment Value
Sparse	0.000
Moderate	0.125
Dense	0.250

The moderately and densely populated user distribution scenarios attract a 0.125 and a 0.25 value for the user distribution parameter thus resulting into an additional contribution to the count of the base stations. The associated value of user distribution is the fraction by which any given category exceeds the baseline value of 800 simultaneous users. This value is calculated as the ratio of the expected demand to the target 95% busy hour call success rate of the expected coverage of 1000 subscribers per cell. Notice that the higher the transmit power required, the higher the weighted contribution will be. Also note that the allocation of a transmit power category that is higher than is required would not return any addition benefits to the site and the network as a whole.

3.3 Incremental Design

The incremental design problem is formulated as a smaller problem that only considers the planned additions to a specified network area in relation to the existing base stations. All the categorizations and considerations made for the green field design problem are applied to this problem in the same way. Consider the basic integer programming model for the UFLP below:

$$\min \sum_{j=1}^{m} c_j y_j + \lambda \sum_{i=1}^{n} \sum_{j=1}^{m} u_i \frac{1}{g_{ij}} x_{ij} \quad \text{-------------------} \tag{24}$$

Decision variables:

$$y_j = \begin{cases} 1 & \text{if a BS is installed in } j \\ 0 & \text{otherwise} \end{cases} \quad \text{for } j \in S \quad \text{------------} \tag{25}$$

$$x_{ij} = \begin{cases} 1 & \text{if test point } i \text{ is assigned to BS } j \\ 0 & \text{otherwise} \end{cases} \quad \text{for } i \in I \text{ and } j \in S \quad \text{---} \tag{26}$$

Subject to:

$$\sum_{j=1}^{m} x_{ij} = 1, \qquad i \in I \quad \text{------------------------} \tag{27}$$

$$x_{i=j} \le y_j \qquad i \in I, j \in S \text{------------------------} \tag{28}$$

$$x_{i=j}, y_j \in \{0,1\} \qquad i \in I, j \in S \text{-----------------------} \tag{29}$$

The following definitions as applied to the greenfield design remain applicable in the incremental network design formulation:

S = {1, 2, 3, ... , m} is a set of candidate sites where a BS can be installed.

C_j – Cost associated with each candidate site j, $j \in S$.

I = {1, 2, 3, . . . , n} is a set of test points (TP) and each TP, $i \in I$

$G = \lfloor g_{ij} \rfloor_{(1<i\le n),(1\le j\le m)}$ – is the propagation gain matrix estimated according to an approximate propagation model.

U_i – Required number of simultaneously active connections of TP *i*. U_i is a function of the traffic demand given by $u_i = \phi(d_i)$ u_i = □(d_i) where d_i is the amount of traffic (in Erlangs) associated to a TP *i*, with a given SIR.

g_{ij} $0 < g_{ij} \leq 1$ – the propagation factor of the radio link between TP *i*, $1 < i \leq n$ and a candidate site j, $1 < j \leq m$.

Below is a summary of the alterations made to the basic formulation to suit the incremental design problem.

- The green field formulation is only applied to the potential base station locations and all the existing network sites that completely surround the proposed location.
- Reductions in transmit power for the surrounding sites is permitted. This is in recognition of the fact that the new site will reduce the coverage burden on the existing sites. An existing site can only maintain or move to the next lower level of transmit power in the presence of a new site.
- Redistribution of the users is permitted to allow for the association of existing users to the new site. An existing site can only move to the next lower level of user distribution in the presence of a new site.
- The summation of the new values from the problem solution for all the planned network expansion gives the required number of base stations.

3.4 Implementation

Together, the three categories of each of the three system parameters – antenna height, user distribution and power – make 27 permutations of configurations. Table 8 shows the different arrangements possible of these system parameters. Each of these arrangements was implemented in MATLAB for a fixed set of proposed site counts and the optimal number of required site counts estimated. The symbols MIN, MDM and MAX are adopted to represent the minimum, medium and maximum allowable system parameter configuration representing antenna height, user distribution and transmit power in that order. Considering that the use of the minimum user distribution neutralizes the contribution of the second part of the objective function, it can be expected that results involving this parameter value will keep the same value as that of the input.

Table 8: Considered permutations of the system configurations

	COST	USERS	POWER
1	MIN	MIN	MIN
2	MIN	MIN	MDM
3	MIN	MIN	MAX
4	MIN	MDM	MIN
5	MIN	MDM	MDM
6	MIN	MDM	MAX
7	MIN	MAX	MIN
8	MIN	MAX	MDM
9	MIN	MAX	MAX
10	MDM	MIN	MIN
11	MDM	MIN	MDM
12	MDM	MIN	MAX
13	MDM	MDM	MIN
14	MDM	MDM	MDM
15	MDM	MDM	MAX
16	MDM	MAX	MIN
17	MDM	MAX	MDM
18	MDM	MAX	MAX
19	MAX	MIN	MIN
20	MAX	MIN	MDM
21	MAX	MIN	MAX
22	MAX	MDM	MIN
23	MAX	MDM	MDM
24	MAX	MDM	MAX
25	MAX	MAX	MIN
26	MAX	MAX	MDM
27	MAX	MAX	MAX

This is only to emphasize the interplay of users and their impact on base station transmit power variations. Since the model assumes the allocation of transmit power on the basis of user distribution, such outputs can be justified. In light of this, system configurations for combinations 1 to 3, 10 to 12 and 19 to 21 can be expected to maintain their count as that contributed by adjusting the antenna height parameter. Each of these permutations is revisited and separately varied and then applied to the formulation to study its effect and highlight the potential for decision-making based on each parameter in the design.

The implementation of the formulation is graphically represented using two flow charts shown in figures 7 and 8. Summary actions such as “Start and complete user distribution analysis” and many more are used to keep the size of the flow chart within reasonable limits. The implementation starts with the creation of three matrices each to represent one of the considered system parameters. The power matrix is a 2-dimensional one since it interacts with both the antenna height and user distribution parameters that are each 1-dimensional.

When a site is selected as that which is to be used from all the available possible locations, decisions have to be made to determine its associated antenna height requirement. The appropriate value of the antenna height contribution to the optimization problem must then be allocated to the site and an entry made into the respective matrix.

The network planner subsequently then starts and completes the user distribution analysis for the selected site in relation to the network utilization and projections. In this case too, a decision has to be taken to appropriately allocate the most suitable user distribution for the area to be covered.

Finally, the analysis of the required transmit power must also be started and completed with the application of the appropriate propagation model to ensure that the target received power is met. In this modeling, the Okumura-Hata propagation model is applied to all sites as discussed in section 2.2.1.

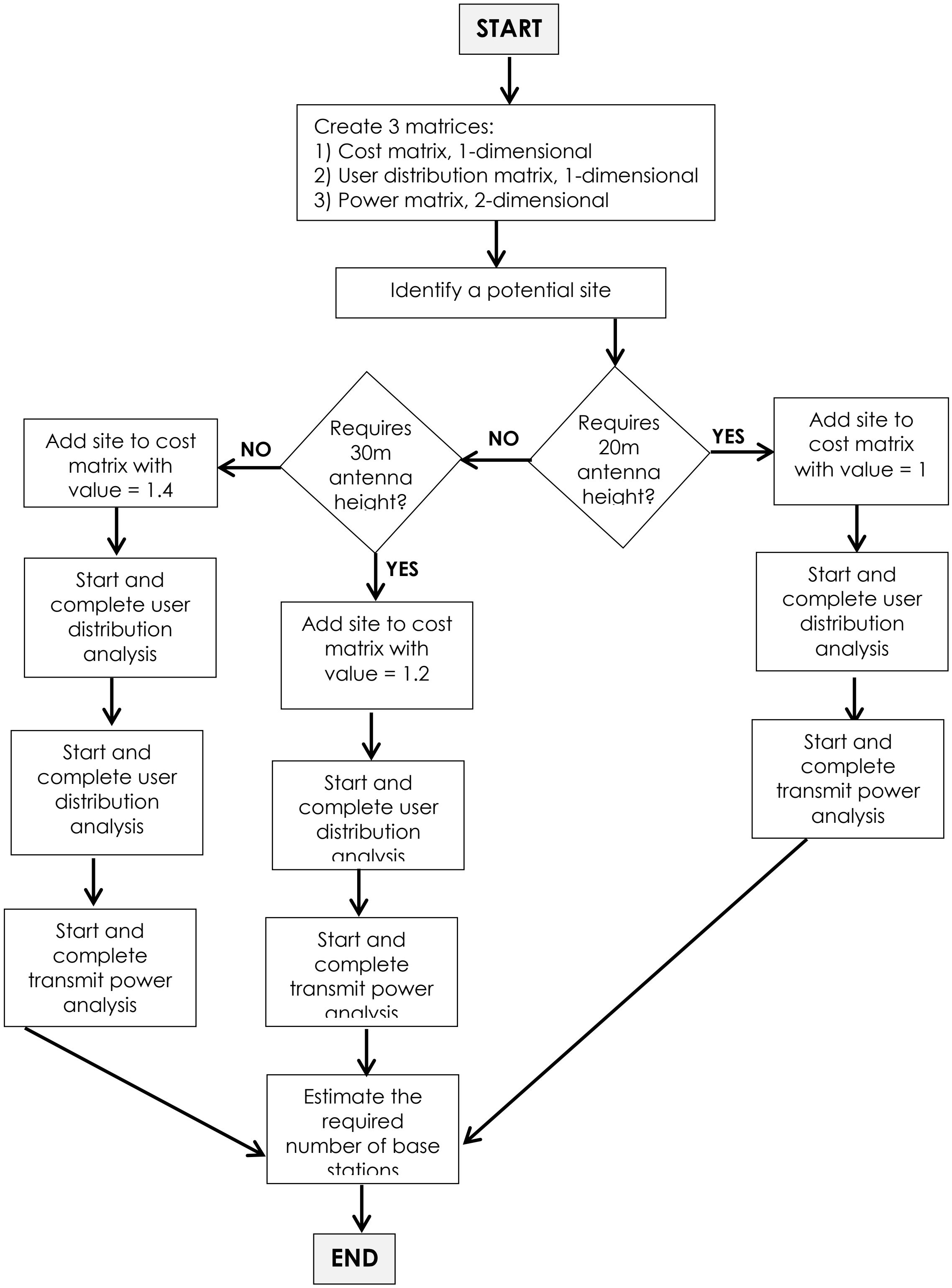


Figure 7: Illustration of the decision logic in the implementation of the model

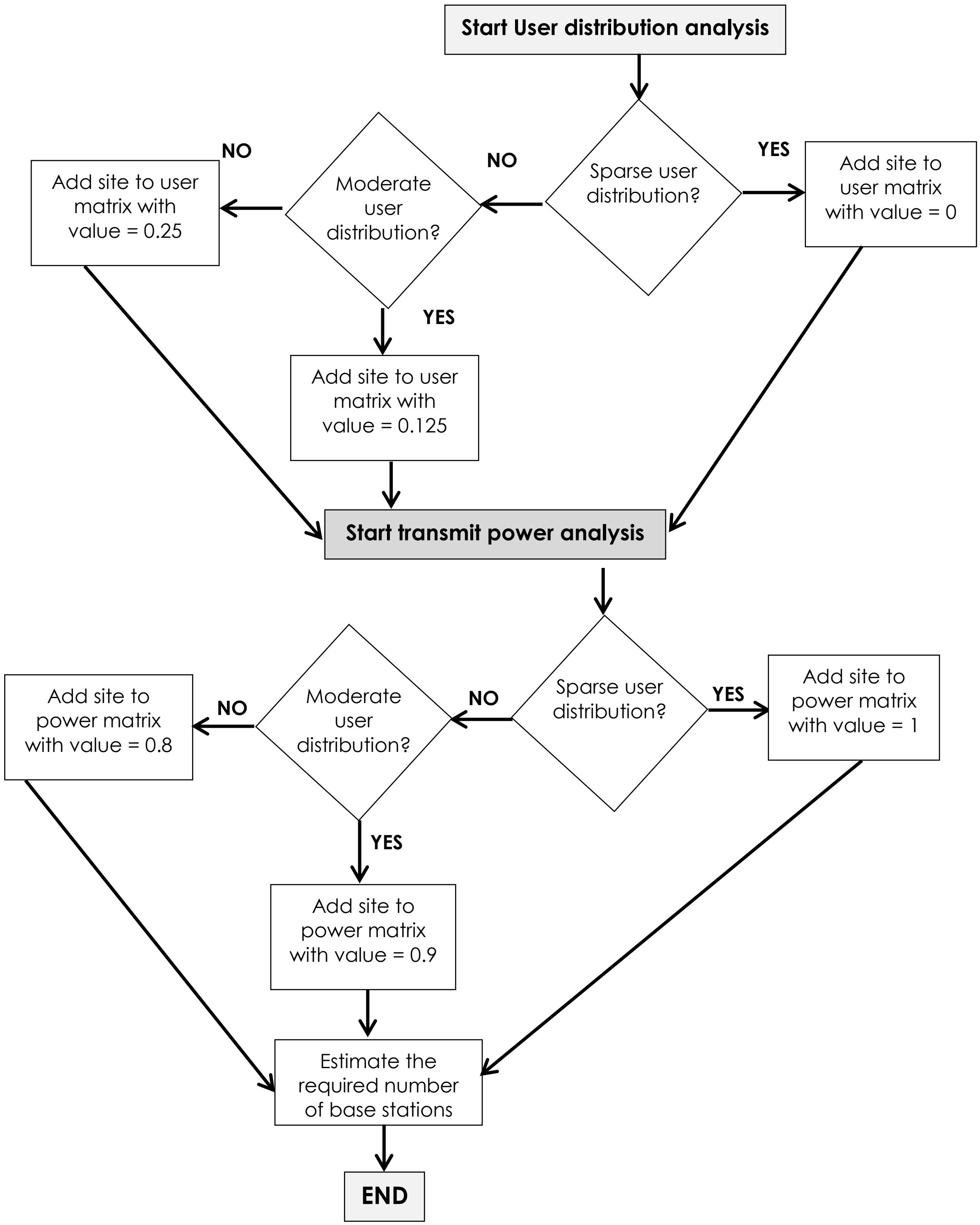


Figure 8: User distribution and transmit power analysis

The reality however, is that the 27 permutations of system configurations considered represent the extreme scenarios that may not be adequately provided for on a real network. These scenarios on the other hand, represent the bounds within which networks can be optimally configured for specified system targets. The flow charts in figures 7 and 8 illustrate the decision flow for the implementation of the model. Considering the fact that the antenna height contributes largest to the objective function, it is the first decision made.

The described system was implemented using MATLAB for all the 27 permutations of the system configuration. A uniform arrangement of site groupings was maintained for each category to allow for a level comparison of the results. Calculations for site quantities from 10 to 200 were made and the results found are discussed in Chapter 4 – Results and Analysis.

IV: RESULTS AND ANALYSIS

This chapter presents the results and analysis of the numerical study coded in MATLAB based on the flow charts illustrated in Figures 7 and 8. The results and analysis are presented in three categories of the antenna height requirement – minimum, medium and maximum. The analyses of the results emphasize the interplay between the different permutations of user distribution and transmit power for a fixed antenna height requirement. A general upward incremental trend for the number of estimated site count is observed for all three categories of antenna height.

A uniform count of input sites is applied to all categories ranging from ten (10) input sites to two hundred (200) input sites. The results from each of the system configurations are presented in reference to the antenna height category under consideration. The results obtained are tabulated below following the "XyzXyz" convention with each set of three letters representing the user distribution and transmit power category respectively, for a specified category of antenna height. As earlier discussed, the requirement of any of the categories of antenna heights translates into a site count of one. The final result of estimated site requirement is the ceiling of the formulation output.

4.1 Minimum Antenna Height

Table 9 captures the first portion of the estimates made for all the system configurations considered with minimum antenna height requirements. Considering that the cost of the site is inferred from the antenna height required to provide the target coverage, it is not surprising that the results obtained for the first three columns of table 9 are equivalent to those values used as the number of input sites. This clearly implies that for the lowest category of users, while the variation of transmit power from the minimum setting to the maximum setting may increase the area of coverage, its effectiveness remains the same for the same minimum value of user distribution.

This trend however, is not cascaded to all the other mixes of minimum antenna height for different combinations of user distribution and transmit power. Table 9 shows a slow growth of the required number of sites for the different permutations for the input number of sites. This is not surprising since the minimum antenna height requirement is the reference point for site count translating into a count of one site. The lowest growth is seen with the low categories of input sites at an average of 5% while the high categories are seen to grow at an average of 6%. The highest growth however is at 11.5%. It is logical that the highest growth is seen with the maximum user distribution permuted with the minimum transmit power at minimum antenna height. This effectively implies that multiples of minimum transmit powers are required to sufficiently cover the maximum user distribution, and thus the high number of estimated required sites. Compared to the configuration that combines minimum user distribution with maximum transmit power, the results clearly show no additional benefit. Such a configuration would instead be counterproductive on the network since it would contribute to the interference on the network thereby degrading the network services unnecessarily.

Table 9: Results for all permutations involving minimum antenna height

Input Sites	Estimated Number of Sites: Minimum Antenna Height								
	MinMin	MinMdm	MinMax	MdmMin	MdmMdm	MdmMax	MaxMin	MaxMdm	MaxMax
10	10	10	10	11	11	11	12	12	11
20	20	20	20	22	22	22	23	23	23
60	60	60	60	64	64	63	67	67	67
100	100	100	100	106	106	105	112	111	110
140	140	140	140	148	148	147	156	155	154
200	200	200	200	212	211	211	223	222	220

The lowest growth is seen with the MdmMdm combination representing a moderate user distribution covered with moderate transmit power for minimum antenna height. This configuration seems to strike a balance between the cost factors that make up the modeled network. Generally, the medium user distribution with any combination of transmit power presents a small growth in the required number of sites. Notice that the growth of the permutations involving a maximum user distribution consistently grow at a rate centered around 10%. Such a consistent growth can be appropriately exploited for large input site counts when the effects of interference from the maximum transmit power considered negligible for a given network configuration. Similarly, if the costs of the effects of transmit power are considered to be much lower than those costs incurred for a high site count, the maximum user distribution configurations can be applied appropriately. It can thus be inferred that this configuration may result into the most optimum for large networks since it maximizes the user distribution thereby maximizing revenues. The results obtained are graphically illustrated in a histogram as shown in figure 9 below. The trend line shows a steady growth of the additional number of sites required. The additional number of site from the estimates grows from 1% of the input number of sites to 11.5% with increasing number of input sites.

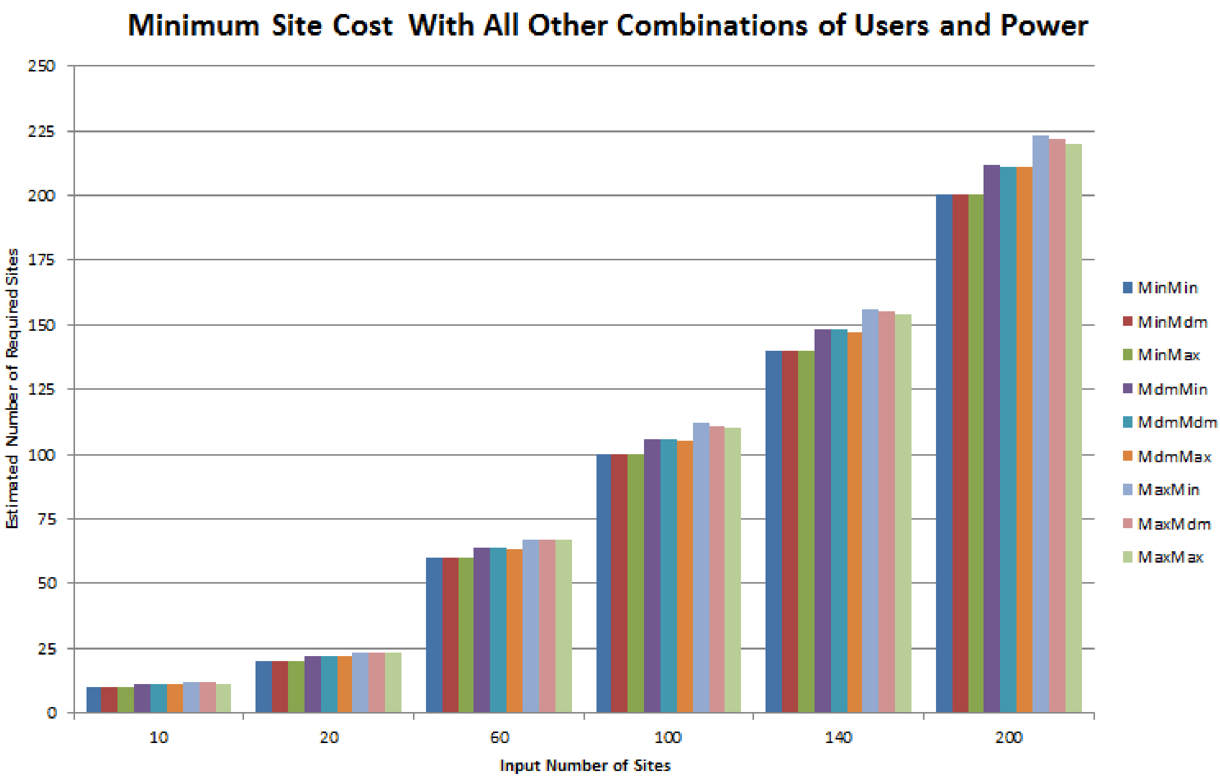


Figure 9: Results of the different permutations of user distribution and transmit power for minimum antenna height

4.2 Medium Antenna Height

A similar upward growth trend is observed for the medium antenna system configurations as was observed in the minimum antenna heights. Here too, configurations incorporating the minimum user distribution category of users return the same number of estimated site count as the initial input sites. However, the growth of the estimated number of sites from the input sites is much higher than that obtained with the previous category of minimum antenna height.

The lowest average growth is calculated to be at 25% while the highest is at 31.5%. This jump from the previous category is mainly as a result of the cost of the additional height requirement that was factored into the formulation. It is important to note that this additional site cost was considered at 20% over the minimum value for each higher subcategory.

Table 10: Results of formulations for all system permutations for medium antenna height

Input Sites	**Estimated Number of Sites for User-power permutation**								
	MinMin	**MinMdm**	**MinMax**	**MdmMin**	**MdmMdm**	**MdmMax**	**MaxMin**	**MaxMdm**	**MaxMax**
10	10	10	10	13	13	13	14	14	14
20	20	20	20	25	26	26	27	27	27
60	60	60	60	75	76	76	78	79	79
100	100	100	100	125	126	126	130	131	132
140	140	140	140	175	176	176	183	183	184
200	200	200	200	250	251	252	261	262	263

In this category however, the distinction between the inappropriate applications of minimum transmit power with the medium and maximum user distributions becomes blurred. Such a configuration in the minimum antenna height category resulted in a significant difference between the configuration incorporating minimum transmit power for both medium and maximum user distributions. In the medium antenna height category, results show that there is a small difference between the estimated numbers of sites for all permutations of these two categories. The results imply that it would cost almost the same to build a network for all the categories of transmit power within the same category of user distribution. Clearly in this category, the user distribution drives the estimated number of sites required. As a result, it would be most prudent to exploit those configurations that require the lowest transmit power to further minimize the effects of interference on the network. Compared to the graph from the minimum antenna height configurations, this category results in a trend that promises a quick exponential growth for a large number of input sites.

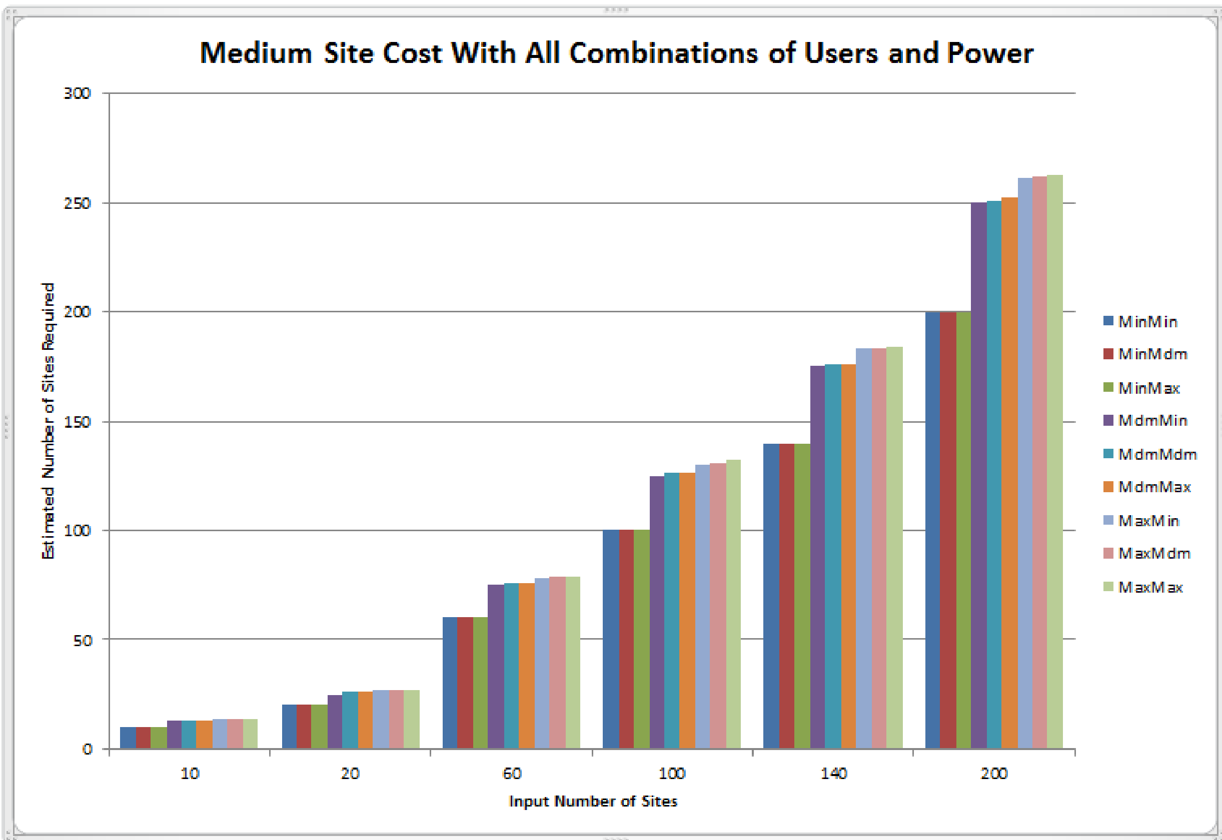


Figure 10: Results of the medium antenna height with different permutations of user distribution and transmit power

4.3 Maximum Antenna Height

As expected, the combination of maximum antenna height with any other permutation of user distribution and transmit power, presented the highest growth rate averaged at 50%. This is mainly due to the fact that the antenna height requirement is modeled for the highest tower and site construction costs. This is in line with the industry practice where a tall tower would cost significantly more than its shorter counterpart, notwithstanding the geographic formation of the actual site location on which the tower is to be erected and the expected loading on it. MdmMdm and MaxMin have growth rates closely related to the lowest growth rate. This is similar to the trend witnessed in the minimum antenna height category. The MdmMax permutation maintains its steady growth that hints at becoming more optimal with large input site values. Like with all the other cases considered, the permutations that are configured for the minimum user distribution still return the input number of sites as the estimated required number of sites. These results are tabulated in table 11 below and graphically illustrated in a histogram in figure 11. The additional number of site from the estimates grows from 6% of the input number of sites to 51.5% with increasing number of input sites.

Table 11: Results of estimations for maximum antenna height with all system configuration permutations

Input Sites	Estimated Number of Sites for User-power permutation								
	MinMin	MinMdm	MinMax	MdmMin	MdmMdm	MdmMax	MaxMin	MaxMdm	MaxMax
10	10	10	10	16	15	15	15	16	15
20	20	20	20	31	30	29	30	31	30
60	60	60	60	91	88	88	88	91	90
100	100	100	100	152	146	146	146	151	150
140	140	140	140	212	204	203	204	211	210
200	200	200	200	303	291	290	292	302	300

From the numerical analysis of the 27 permutations possible, the maximum additional number of sites was found to be 51.5% of the initial input sites, while the lowest was at 1% and the average was at 29.3%. Typically, a slow growth is witnessed for a small number of input sites. The additional number of sites required dramatically increases from input sites of 100 onward. Section 4.4 below presents the results of varying the values of the set categories for each parameter to achieve a predefined limit on the acceptable additional sites returned by the formulation.

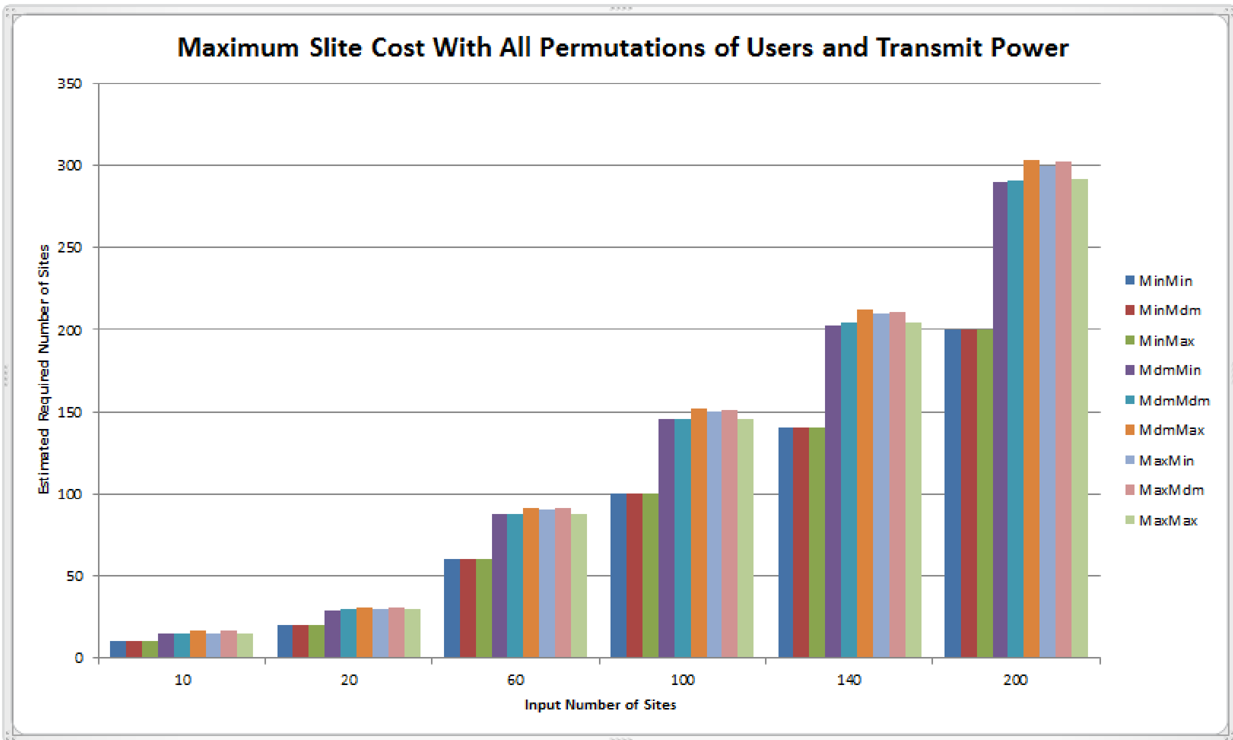


Figure 11: Results of the maximum antenna height with different permutations of user distribution and transmit power

Such deviations can be logically thought to be due to the contribution of both the user distribution and the transmit power to the site count. However, investigations show that the value associated to the antenna height makes the most significant contribution to the total site count. While such deviations can be expected, it is important to manage their magnitude to ensure economic feasibility of the designs. A discussion of the possible variations for each parameter and their impact is made in section 4.4. The associated numerical studies are also carried out and the results presented in the same section.

4.4 Predefining Maximum Additional Count

Given known values of site construction pricing and budgetary allocations, this model can be appropriately applied to allow for a predefined limit on the additional sites acceptable. This would require the downward varying of the three network considerations made – antenna height, user distribution and transmit power. Such variations were made in this numerical study. The following results show the model output for different variations in the values of antenna height to allow a maximum of 10% increase in the total number of sites require.

The minimum and maximum antenna height categories were varied to determine the bounds that would give a maximum of 10% additional sites. The results are tabulated in Table 12 and 13, and illustrated in the following graphs. The graphs compared the new results obtained using the new bounds to those that were originally obtained using the earlier set boundaries. It was found that the minimum antenna height category could be varied as low as 0.95 to result in a maximum of 10% extra sites and a minimum of -5%. The highest antenna height that would maintain the 10% addition sites was found to be 1.

All system permutations are well within the 10% limit for the 0.95 minimum antenna height value. Deviations from the 10% target on the maximum antenna height value are generally observed starting at the input site count of 60. Considering that there is a significant gap between its predecessor input site count of 20, it is possible the model deviates before the count of 60. This effectively implies that for this 10% maximum additional site count target, the range between the lowest and highest antenna height is less than 0.5 with the lowest being 0.95. This therefore insinuates that the boundaries between the different categories of the antenna heights may be more finely grained than was earlier postulated and modeled.

Table 12: Comparison of minimum antenna height value of 0.95 against 1

System Permutation	Minimum Antenna Height	Input Sites: Minimum Antenna Height = 0.95 and 1					
		10	**20**	**60**	**100**	**140**	**200**
MinMin	0.95	9.5	19	57	93	133	190
	1.00	10	20	60	100	140	200
MinMdm	0.95	9.5	19	57	93	133	190
	1.00	10	20	60	100	140	200
MinMax	0.95	9.5	19	57	93	133	190
	1.00	10	20	60	100	140	200
MdmMin	0.95	11	21	61	101	141	202
	1.00	11	22	64	106	148	212
MdmMdm	0.95	11	21	61	101	141	201
	1.00	11	22	64	106	148	211
MdmMax	0.95	10	20	60	100	140	200
	1.00	11	22	63	105	147	211
MaxMin	0.95	11	22	64	107	149	213
	1.00	12	23	67	112	156	223
MaxMdm	0.95	11	21	62	103	144	206
	1.00	12	23	67	111	155	222
MaxMax	0.95	11	22	63	105	147	211
	1.00	11	23	67	110	154	220

Table 13 is intended to contrast the results of the model with both the old and new antenna height bounds. Notice that while the antenna height value of 1 was found to be the maximum applicable value to give 10% maximum additional sites, it was previously modeled as the minimum antenna height. The results show a minimum of deviation between the two sets of results of 10% and a maximum of 46% comparing the results incorporating only the medium and maximum user distributions.

Table 13: Comparison of maximum antenna height of 1 against 1.4

System Permutation	Minimum Antenna Height	Input Sites: Minimum Antenna Height = 0.95 and 1					
		10	**20**	**60**	**100**	**140**	**200**
MinMin	1.0	10	20	60	100	140	200
	1.4	10	20	60	100	140	200
MinMdm	1.0	10	20	60	100	140	200
	1.4	10	20	60	100	140	200
MinMax	1.0	10	20	60	100	140	200
	1.4	10	20	60	100	140	200
MdmMin	1.0	11	22	64	106	148	212
	1.4	16	31	91	152	212	303
MdmMdm	1.0	11	22	64	106	148	211
	1.4	13	30	88	146	204	291
MdmMax	1.0	11	22	63	105	147	211
	1.4	15	22	88	146	203	291
MaxMin	1.0	12	23	67	112	156	223
	1.4	15	30	88	146	204	292
MaxMdm	1.0	12	23	67	111	155	222
	1.4	16	31	91	151	211	302
MaxMax	1.0	11	23	67	110	154	220
	1.4	15	30	90	150	210	300

Evidently, the antenna height and its associated value in the model significantly determine the output. This is very logical considering that the presence of a mounting structure loaded with one or more antennas at a location defines a cellular site within the boundaries of a cellular operator's network. If available, knowledge of the actual site construction pricing could be used to determine the exact values to be associated to this design parameter.

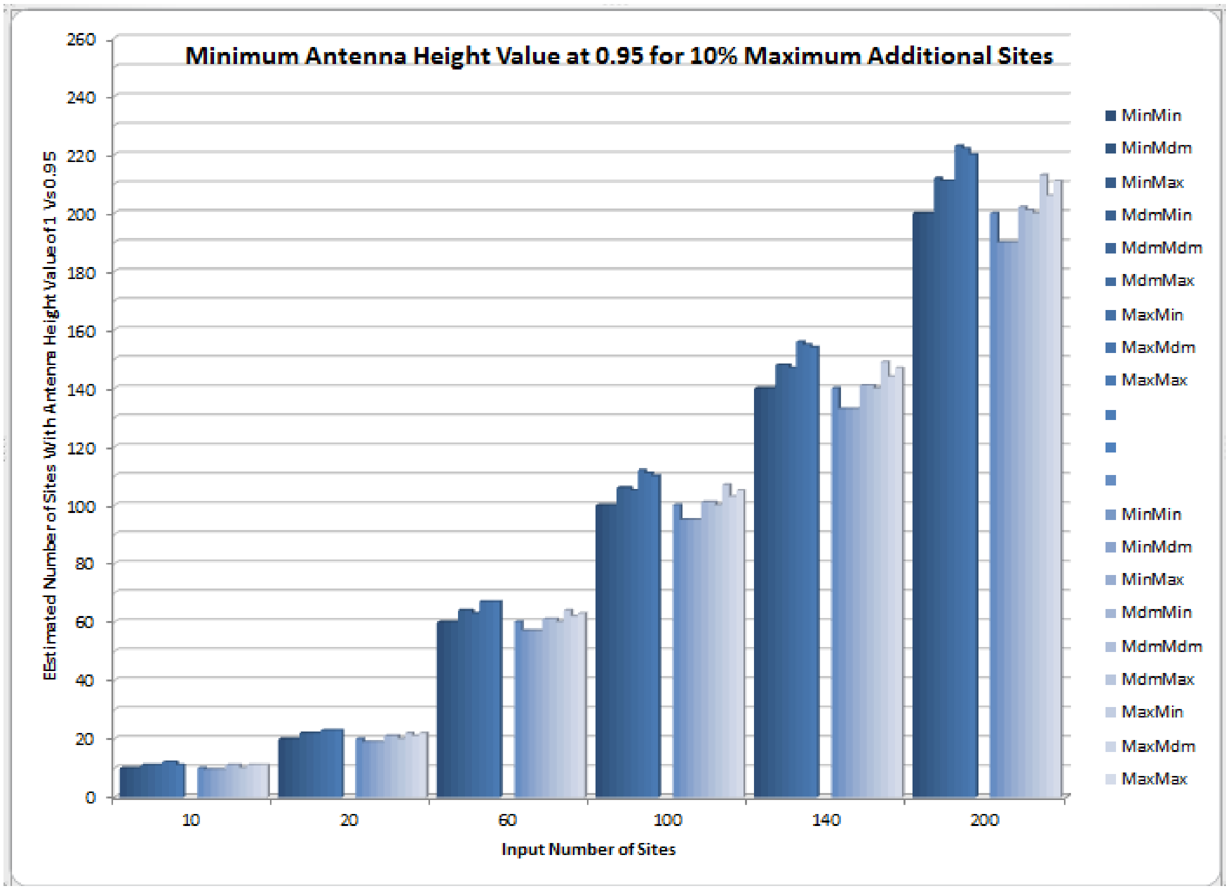
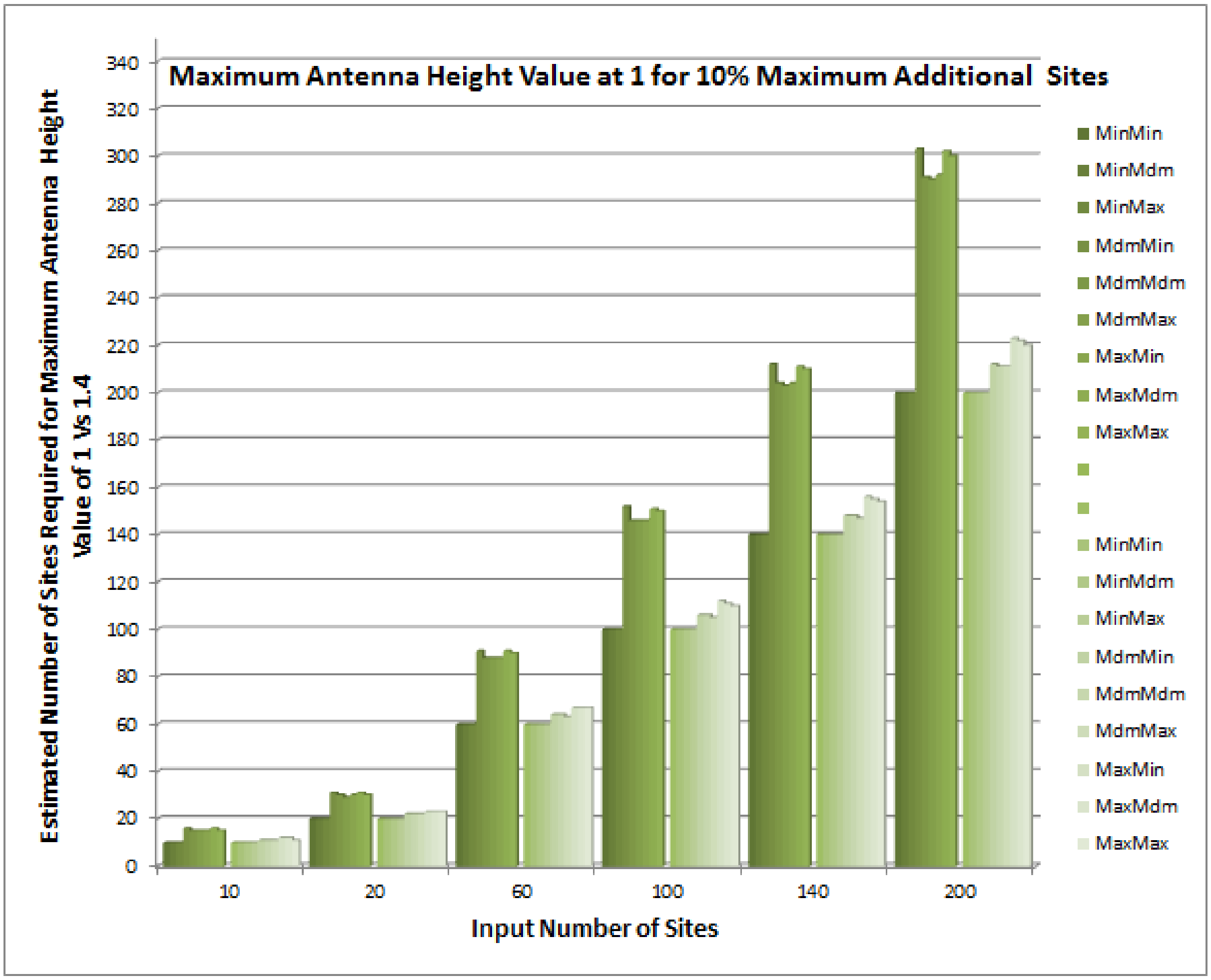


Figure 12: Minimum antenna height set at 0.95 for all permutations of system configurations

Figures 12 and 13 graphically represent the comparisons for the minimum and maximum categories respectively with the application of the new and old antenna height values. Notice the high difference between the model outputs when the two maximum bounds are compared.

Similar variations were tested for both the values associated to user distribution and transmit power. It was found that a significant reduction in the estimated number of required sites needed a significant downward variation of their respective associated values to produce a meaningful difference in the estimated site count. Such results, however, could be easily attained by slight variations in the values associated to the antenna height. This further emphasized the fact that the antenna height significantly drives the output of the model. It is important to note however, that this trend of events is partly supported by the weight factor associated to the problem formulation to incorporate the user distribution and the transmit power. The choice of a higher value for this weight factor would see a bigger contribution to the model output from both the user distribution and the transmit power.



<u>Figure 13: Maximum antenna height set at 1 for all permutations of system configurations</u>

4.5 Mixed Antenna Height Inputs

In a bid to present a more realistic network design scenario, the inputs to the formulation were mixed up in two cases of 33% and 50% combinations of the input parameters. This was done considering the fact that it is difficult to find an actual network configuration comprised of just one specific category of system parameter, say minimum antenna heights, for the complete network. Numerical studies were made to accommodate an equal mix of all three categories of each system parameter in an equal measure of 33%. Similarly, numerical studies comprised of just two categories of each system parameter in a 50% total measure were carried out and the results are as discussed below.

The original antenna height values are considered in the 33% case. These results are compared against the 33% case using the new antenna height value bounds of 0.95 as lowest and 1 as the height. A new maximum value for antenna heights of 1.1 is also introduced in this mix to determine its impact on the system with mixed values. Three cases of 50% mixes are made for the new values of minimum and maximum antenna height, together with the 1.1 value. All these considerations are made for a target of a maximum of 10% additional site count.

Table 14: Results from using mixed antenna height values

Input Sites	Estimated Number of Sites for Mixed Antenna Height Values				
	33% - Original	33% - New	50% - NewMinMax	50% - NewMinMax2	50% - NewMaxMax2
10	13	12	11	12	12
20	26	23	22	23	23
60	77	68	65	68	70
100	128	113	108	113	116
140	180	158	151	158	161
200	257	225	215	225	230

Table 14 and Figure 14 show the results from these numerical studies. Results show that the 30% mix of the original antenna height highly exceeds 10% target. It returns estimates of site counts that require 30% additional sites for all cases of input sites. The uses of the new values of antenna heights in the 50% cases return results with a minimum of 7.5% and a maximum of 10% additional sites. Notice that the maximum additional site requirement is only in the low count of input sites. As the count of input sites increases beyond 60, the maximum additional sites required significantly falls to 7.5%. The 50% combinations involving the new maximum value of 1.1 for antenna heights exceeds that 10% target by a minimum of 2.5% for the cases considered. Again, this minimum value is only realized in the high cases studied.

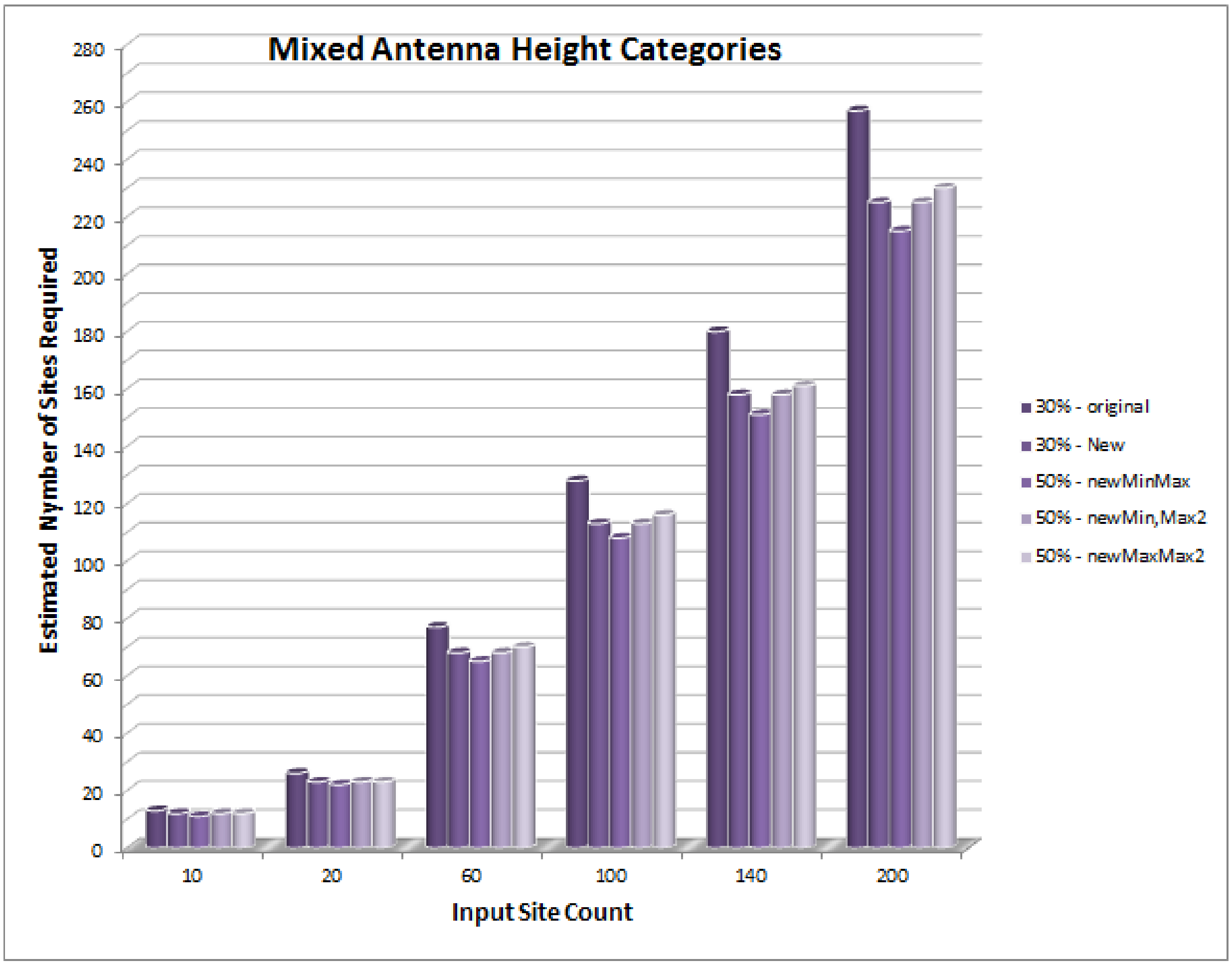


Figure 14: Mixed antenna heights for 33% and 50% cases

4.6 Incremental Design: Applying Model on Live Network

Network data providing coverage in Kampala – Uganda was applied on this formulation. Kampala is the capital of the Republic of Uganda. It is also a district in the central region of the country and serves as the main central business district of the country. Kampala is home to 24% of the country's population of thirty eight million people.

Figure 15: Map of Uganda - Eastern Africa

The central business district is heavily built with high rise buildings. It is surrounded by residential neighborhoods place on seven hills. The rest of the suburbs surrounding Kampala are placed on plateau-like terrain.

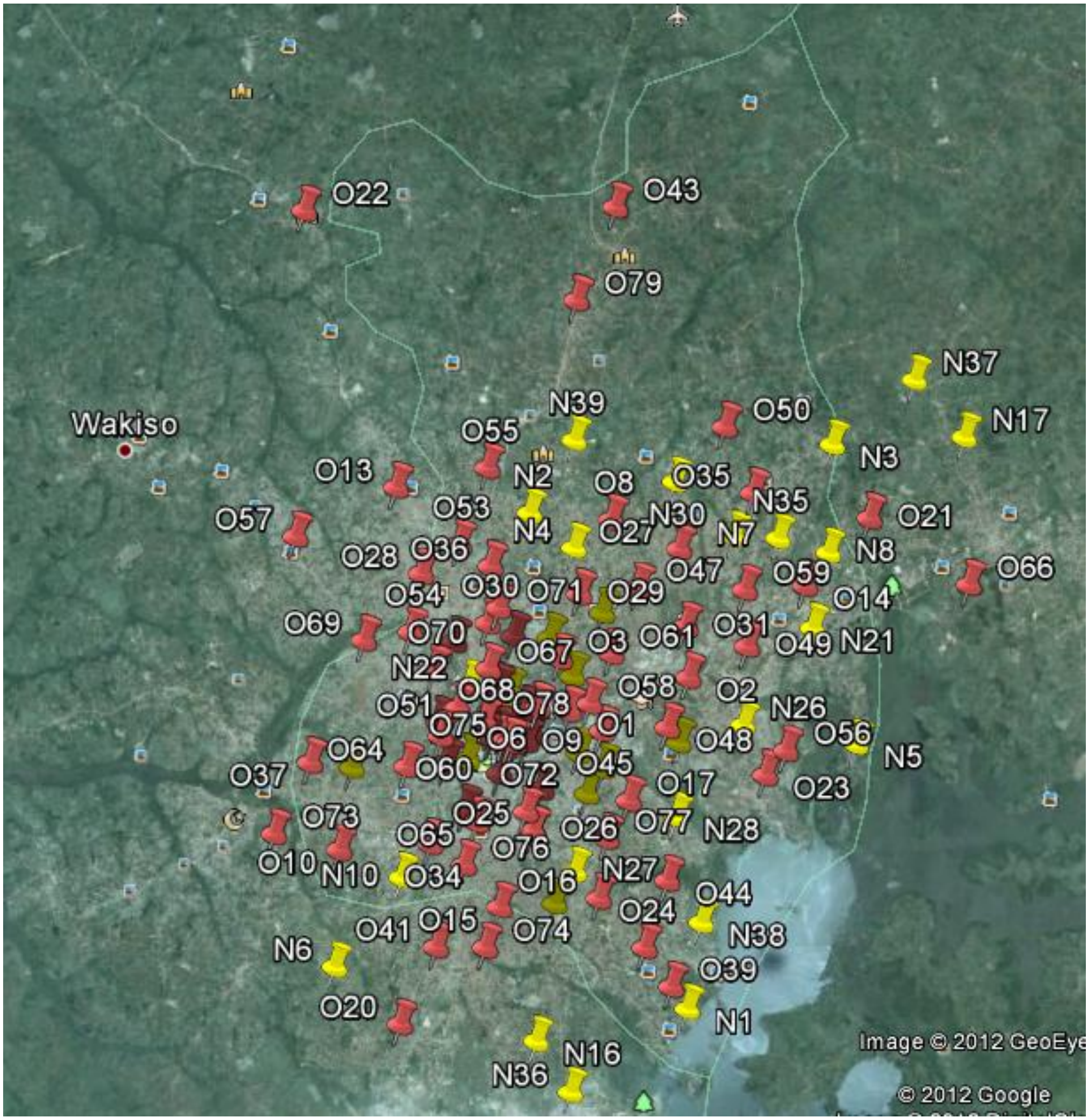


Figure 16: Plot of existing sites (red pins) and proposed sites (yellow pins) to serve Kampala City (Uganda)

The telecommunications needs of the people of Uganda are met by a total of five cellular network operators. The teledensity in Kampala has grown significantly to 35% within ten years. Figure 15 is a map of Uganda as placed in the Eastern Africa. The boarders of Uganda's capital city Kampala are as shown in figure 16. Also inserted in figure 16 are a set of two site categories. The red pins mark the locations of the existing sites on the network proposed for the provision of 3G telecommunication services. The yellow pins mark the locations of the proposed new additional sites to supplement the 3G coverage from the already on air sites. The network operator is assigned two carriers that can be applied to each base station. Tables 15, 16 and 17 show the modeling configurations that were made for the on-air sites and the new proposed sites. Notice that the new bounds of antenna height values were applied to all the site configurations. A total of 80 existing sites and 34 new proposed sites are shown in the tables.

Table 15: Modeling of an air sites using the new bounds of antenna height values - 1

Site ID	Antenna Height	User Distribution	Transmit Power
O1	0.95	0.15	1.3
O2	0.95	0.25	1.3
O3	0.95	0.125	1.2
O4	0.95	0.25	1.2
O5	1.00	0.25	1.2
O6	1.00	0.25	1.2
O7	1.00	0.25	1.2
O8	1.00	0.25	1.2
O9	1.00	0.25	1.2
O10	1.00	0.25	1.2
O11	1.00	0.25	1.2
O12	1.00	0.25	1.2
O13	0.95	0.25	1.2
O14	0.95	0.25	1.2
O15	0.95	0.25	1.2
O16	0.95	0.25	1.2
O17	1.00	0.25	1.2
O18	1.00	0.25	1.2
O19	0.95	0.25	1.2
O20	1.00	0.25	1.2

Site ID	Antenna Height	User Distribution	Transmit Power
O21	0.95	0.125	1.2
O22	1.10	0.25	1.2
O23	0.95	0.125	1.2
O24	0.95	0.25	1.2
O25	1.00	0.25	1.2
O26	1.00	0.125	1.2
O27	1.00	0.125	1.2
O28	1.00	0.125	1.2
O29	1.00	0.125	1.2
O30	1.00	0.125	1.2
O31	1.00	0.25	1.2
O32	1.00	0.25	1.2
O33	0.95	0.125	1.2
O34	1.00	0.25	1.2
O35	1.00	0.25	1.2
O36	1.00	0.125	1.2
O37	1.00	0.25	1.2
O38	0.95	0.25	1.2
O39	1.00	0.25	1.2
O40	0.95	0.25	1.2

Table 16: Modeling of on-air sites using the new bounds of antenna height values - 2

Site ID	Antenna Height	User Distribution	Transmit Power
O41	1.00	0.250	1.2
O42	0.95	0.125	1.2
O43	1.10	0.125	1.2
O44	1.00	0.125	1.2
O45	0.95	0.250	1.2
O46	1.00	0.250	1.2
O47	1.00	0.125	1.2
O48	1.00	0.250	1.2
O49	1.00	0.250	1.2
O50	1.00	0.125	1.2
O51	1.00	0.125	1.2
O52	0.95	0.125	1.2
O53	1.00	0.125	1.2
O54	0.95	0.250	1.0
O55	1.00	0.250	1.0
O56	1.00	0.125	1.2
O57	1.00	0.250	1.2
O58	1.00	0.125	1.2
O59	1.00	0.125	1.2
O60	0.95	0.125	1.2

Site ID	Antenna Height	User Distribution	Transmit Power
O61	0.95	0.250	1.2
O62	0.95	0.250	1.2
O63	1.00	0.250	1.2
O64	1.00	0.250	1.2
O65	0.95	0.125	1.2
O66	1.00	0.250	1.2
O67	0.95	0.125	1.2
O68	0.95	0.125	1.2
O69	0.95	0.125	1.2
O70	1.00	0.125	1.2
O71	1.00	0.125	1.2
O72	0.95	0.125	1.2
O73	0.95	0.125	1.2
O74	0.95	0.125	1.2
O75	1.00	0.125	1.2
O76	0.95	0.125	1.2
O77	0.95	0.125	1.2
O78	0.95	0.125	1.2
O79	0.95	0.125	1.2
O80	0.95	0.125	1.2

Notice that five new site locations, N6, N16, N17, N36 and N37, were excluded from the numerical study because they were found to be located more than 3km outside the boundaries of Kampala district. The foregoing site configuration data was fed into the formulation and returned a total of 157 sites as the required estimated number of sites. Compared to the 166 sites actually used to provide this coverage, it can be said that the new values of antenna height are pretty accurate.

Table 17: Modeling new proposed additional sites using the new bounds of antenna height values

Site Name	Antenna Height	User Distribution	Transmit Power
N1	1.00	0.125	1.2
N2	1.00	0.000	1.0
N3	1.00	0.000	1.0
N4	1.00	0.000	1.0
N5	1.00	0.125	1.0
N6	1.00	0.250	1.2
N7	1.00	0.125	1.0
N8	0.95	0.125	1.0
N9	0.95	0.125	1.0
N10	1.00	0.125	1.0
N11	0.95	0.125	1.0
N12	1.00	0.125	1.2
N13	1.00	0.125	1.2
N14	0.95	0.125	1.2
N15	1.00	0.250	1.2
N16	0.95	0.125	1.2
N17	0.95	0.125	1.2
N18	1.00	0.125	1.2
N19	1.00	0.25	1.2
N20	0.95	0.125	1.2
N21	1.00	0.125	1.2
N22	1.00	0.25	1.2
N23	0.95	0.25	1.2
N24	0.95	0.125	1.2
N25	1.00	0.125	1.2
N26	1.00	0.125	1.2
N27	0.95	0.125	1.2
N28	0.95	0.125	1.2
N29	0.95	0.25	1.2
N30	1.00	0.125	1.2
N31	1.00	0.125	1.2
N32	1.00	0.25	1.2
N33	1.00	0.25	1.2
N34	0.95	0.25	1.2
N35	1.00	0.125	1.2
N36	0.95	0.125	1.2
N37	0.95	0.125	1.2
N38	1.00	0.25	1.2
N39	1.00	0.25	1.2

V: SUMMARY AND FUTURE WORK

5.1 Summary

A modified model was proposed that was simplified through the elimination of the automatic selection and placement of sites. Instead, this action was left to the discretion of the network planner. Numerical studies of the application of the model were carried out for each of the specified parameter categories for three extreme cases.

- Minimum antenna height category specified at a value of 1.
- Medium antenna height category specified at of 1.2
- Maximum antenna height category specified at 1.4

Each of the above three categories was permuted with the three categories of user distribution and transmit power. This resulted into a total of 27 cases whose numerical results have been included. However, the results show a great deviation of up to 51.5% additional sites to the initial input number of sites.

The reality however, is that the above system configurations represent the extreme cases of network design that may not be the design of choice. In this work however, these cases serve to set bounds within which optimal system performance and configuration can be achieved. While the minimum user distributions return the lowest count of required base stations, it is by no means the best system design mainly because it restricts network growth. In terms of initial investment, this configuration has the capacity to require the lowest cost and may be ideal for startup networks or network expansion into new areas. In the long run, such a design would crumble in the presence of high user distribution. In addition, reconfiguring system parameters from this minimum user case to accommodate increase number of users may turn out to be more complex.

In contrast, the design that maximizes the system configurations from the start would require a huge initial cost. Such a design however, allows the system to evolve without restraint. In addition, such a system can be dynamically tuned to respond to network growth and expansion. This therefore lives the combinations that mix the three categories – antenna heights, user distribution and transmit power – moderately as the most optimal. Such systems guard against a degraded user experience that would result if the system were minimally designed. They also allow the network operators time to maximize the investment made.

Variation of the set bounds of the three system parameter category values was also numerically studied. Variation of the antenna heights was found to have the most significant impact on the reduction of the maximum allowable additional sites for a predefined target. The user distribution and transmit power were also varied and their impact was found to be very small. New bounds were established for the values associated to the antenna heights with 0.95 as being the lowest and 1 as the highest. An additional new maximum value of 1.1 for antenna heights was included to determine their interplay in the mixed antenna heights network configuration.

The 33% and 50% mix of antenna height values were numerically studied. The 33% category was applied to both the original values of antenna heights and the new established bounds for a maximum of 10% maximum additional sites. It was found that the network configuration that mixed the three antenna height categories equally still exceeded the predefined target of 10%. The new bounds applied in a 33% mix also exceeded the maximum by 2.5%. However, the 50% mix of the two new antenna height bounds returned a maximum of 7.5%, well below the target. The 50% combinations that involved the additional maximum value of 1.1 returned values that exceeded that target 10%.

The new antenna height bounds - 0.95 for the lowest, 1 for the medium and 1.1 for the maximum values - were applied to a live network configuration. Results showed that the estimated required number of sites were well below the actual network installation by 5%.

This work emphasizes the tremendous role that the network planner’s knowledge of the system plays in the optimal design of the network. While a lot of work has been done in automating the location of UMTS base stations, little has been done to allow user intervention for planning and decision making. As a result, the output from this tool cannot be compared to the available results.

5.2 Future Work

Further simplification of this model is planned to more accurately support the selection of antenna heights based on three new considerations:

- Number of carriers assigned to the operator
- Altitude of the proposed site location
- Vegetation of the surrounding area
- Clutter of the area.

The choice of this direction is mainly based on the fact that a more detailed consideration of the combination of factors that determine the antenna height required would significantly increase the accuracy of the model and reduce the impact of the lack of pricing information for site construction.

BIBLIOGRAPHY

[1] Lingyang Song and Jia Shen: "Evolved Cellular Network Planning and Optimization for UMTS and LTE", CRC Press, First edition, 2010

[2] C. Smith and D. Collins: "3G Wireless Networks", McGraw Hill Communications, Second edition, 2007.

[3] Erik Dahlman, Stefan Parkvall, Johan Skold and Per Beming – 3G Evolution: "HSPA and LTE for Mobile Broadband", Academic Press, 2007

[4] Joseph C. S.Cheung, Mark A. Beach and Joseph P. McGeehan: "Network Planning for third generation mobile radio systems", IEEE Communication magazines, Vol. 32, Issue 11, 1994

[5] CEC/RACE deliverable R2007/ATT/8/81/DS/P/06/b0: Quality of service requirements. Nov 1992

[6] Raffaele Menoascino, Marta Pizarroso, Chiara Lepschy, Bartolome Salas: "Third Generation Mobile Systems Planning Issues", IEEE Vehicular Technology Conference, VTC 98. 48^{th}, 1998

[7] The LTE Network: http://www.interphase.com/products/lte_about.cfm

[8] Ville Eerola, Helsinki University of Technology: "LTE Network Architecture Evolution" – http://www.cse.tkk.fi/fi/opinnot/T-109.7510/2009/luennot-files/LTENetworkArchitectureEvolution.pdf

[9] Amin Abdel Khalek, Lina Al-Kanj, Zaher Dawy and George Turkiyyah: "Optimization models and algorithms for joint uplink/ downlink UMTS radio network planning with SIR-based power control", IEEE transactions of vehicular technology, Vol. 60, No. 4, May 2011.

[10] *Giovanni Colombo, Hans Hegeman:* "Network architectures and functionality in UMTS", 5^{th} IEEE International Symposium on "Catching the mobile Future", Vol. 3, 1994.

[11] Ermanno Berruto, Mikael Gudmundson, Werner Mohr, Marta Pizarroso: "Research activities on UMTS Radio interface, network architectures and planning", IEEE Communications magazine, Vol. 36, 1998.

[12] Edoardo Amaldi, Antonio Capone, Federico Malucelli: "Planning UMTS base station location: Optimization models with power control algorithms. IEEE transactions on wireless communications, Vol. 2, No. 5, September 2003.

[13] A. Molina, G. E. Athanasiadou, A. R. Nix: "The automatic location of base stations for optimized cellular coverage – a new combinatorial approach", 49th IEEE Vehicular Technology Conference, Vol. 1, 1999

[14] Yufei Wu and Samuel Pierre: "Base station positioning in third generation mobile networks", IEEE CCECE Canadian Conference on Electrical and Computer Engineering, Vol. 1, 2003 .

[15] Hsin-Piao, Rong-Terng Juang, Shiann-Shiuu Jeng, Chen-Wan Tsung "A cell planning scheme for WCDMA systems using genetic algorithm and performance simulation platform", 15th IEEE Symposium on Personal Indoor and Mobile Radio Communications, Vol 4, 2004.

[16] *Amin Abdel Khalek, Lina Al-Kanj, Zaher Dawy and George Turkiyyah: "* Site placement and site selection algorithms for UMTS radio planning with quality constraints", 17th IEEE International conference on Digital Object Identifier, 2010.

[17] Jie Zhang, Liang Guo and Joyce Y. Wu: "An integrated approach for UTRAN planning and optimization", 59th IEEE Vehicular Technology Conference, Vol. 4, 2004.

[18] C. Esposito and C. Willard: "PLATON", Universal Personal Communications, 2nd International

[19] R. D. Galvao: "Uncapacitated Facility Location Problems: Contriubutions", Pesquisa Operacional, V.24, N.1, P.7-38, Janeiro a abril de 2004

[20] M. R. Pasandideh: "Automatic Planning of UMTS All-IP Release 4 Networks with Realistic Traffic", Masters thesis, Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada 2011.

[21] Z. Drezner, H. W. Hamacher et al: "Facility Location – Applications and Theory", Springer, First edition, 2002.

[22] R. Johnson and M. Schaefer: "Algorithms", First edition, Pearson Education, 2004

[23] E. Dahlman et all: "The 3G Long-Term Evolution Radio Interface Concepts and Performance Evaluation", IEEE 2006

[24] A. Abdel et al: " Optimization Models and Algorithms for Joint Uplink/Downlink UMTS Radio Network Planning With SIR-Based Power Control", IEEE Transactions on Vehicular Technology, Vol. 60, No. 4, May 2011