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MASTER'S THESIS

Optimized Backhaul Planning for the Case of Small Cell Deployment in Addis Ababa Region of ethio telecom

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Thesis Title

Optimized Backhaul Planning for the Case of Addis Ababa Region of Ethio Telecom

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Abstract

Operators are deploying small cells to complement their macro cells to increase the coverage and capacity of their mobile networks. Backhauling the small cells traffic to the core network is a challenge to operators as they are usually placed in difficult to access locations. To overcome this challenge, wireless solutions have been proposed as a cost-effective alternative to wired solutions. There are, however, many wireless technologies to realize this: point-to-point/point-to-multipoint, line-of-sight/non-line-of-sight (NLOS) and millimeter wave/microwave bands. This research studies practical wireless configurations of this technologies, and proposes a planning method an operator can determine which technology to use on each link of the small cell backhaul network so that the total cost of ownership (TCO) is minimized. To this end, a mixed integer linear programming (MILP) is formulated with a range of constraints for wireless technologies and backhaul requirements.

To demonstrate the effectiveness of the method, the MILP was used to plan a small cell backhaul network for different scenarios, in a relatively built up area of Addis Ababa. The scenarios were created based on different small cell demands, and on whether NLOS links are allowed in the network. The path loss values were predicted by ray tracing to determine the feasibility of a link configuration of each technology between nodes of the backhaul network. The results showed the reduction of TCO by inclusion of more technologies as can be seen with the need for more new aggregation nodes when NLOS was not considered. By accepting an optimality gap of 5 %, the computation time was also reduced to less than two hours which is acceptable for the purpose of planning. Using this method, an operator can plan a cost-effective backhaul from available practical wireless technologies.

Keywords: Backhaul network, optimization, small cells, microwave, millimeter wave, point-to-multipoint, non-line-of-sight, MILP

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Contents

List of Figures

List of Tables

List of Abbreviations

3G	**T**hird **G**eneration
AN	**A**ggregation **N**ode
AP	**A**ccess **P**oint
BER	**B**it **E**rror **R**ate
CAPEX	**Cap**ital **Ex**penditure
GO	**G**eometrical **O**ptics
GTD	**G**eometrical **T**heory of **D**iffraction
ILP	**I**nteger **L**inear **P**rogramming
IRT	**I**nteligent **R**ay **T**racing
LOS	**L**ine **o**f **S**ight
LTE	**L**ong **T**erm **E**volution
MC	**M**acro **C**ell
MINLP	**M**ixed **I**nteger **N**on**l**inear **P**rogramming
NLOS	**N**one **L**ine **o**f **S**ight
OPEX	**Op**erational **Ex**penditure
PoP	**P**oint of **P**resence
PTMP	**P**oint **t**o **M**ulti**p**oint
PTP	**P**oint **t**o **P**oint
QoE	**Q**uality **o**f **E**xperience
RNP	**R**adio **N**etwork **P**lanning
RT	**R**ay **T**racing
SBR	**S**hoot and **B**ounce **R**ay
SC	**S**mall **C**ell
TCO	**T**otal **C**ost of **O**wnership
UTD	**U**niform **T**heory of **D**iffraction

1 Introduction

1.1 Background

Mobile networks, throughout the world, are experiencing an increase in traffic load. This is mainly due to user data generated from the wireless devices which are equipped with bandwidth intensive applications [1]. In order to deal with this high traffic demand, cellular networks are using small cells together with the conventional macro cells. Small cells are low power, low cost and small form factor base stations. Small cells enable improvements in network coverage and capacity. Small cells can, usually, be used to provide a second layer of coverage in Third Generation (3G) and Long Term Evolution (LTE) mobile networks [2]. This results in higher throughput and data rates for the end user, and improved performance at cell edge. They are usually placed in the clutter, below rooftop level, where traditional mobile backhaul solutions may not be applicable. Due to their large number and inconvenient locations, backhauling, which is connecting the access portion of the network to the core network, cost efficiently will be a big challenge for operators.

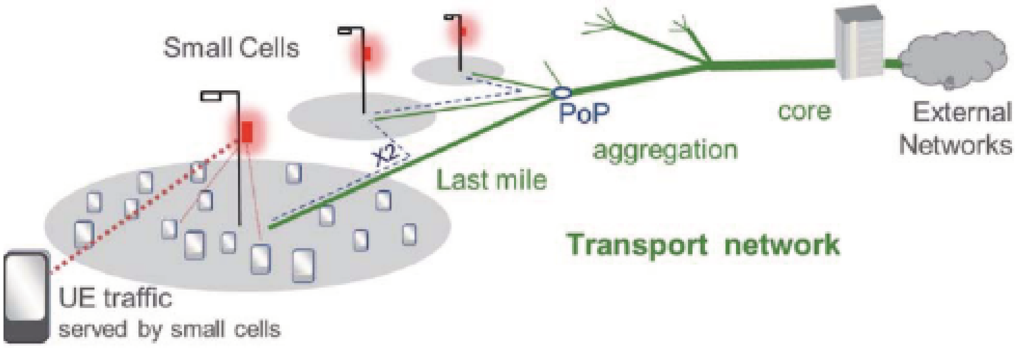

FIGURE 1.1: Backhaul Network Architecture (from [2]).

The small cell backhaul network architecture is shown in Figure 1.1. The topology of backhaul will usually be dictated by the location of the small cells from the radio network planning (RNP) output, i.e. the small cell network architecture, and the existing macro cells backhaul. Ring, daisy chain, hub and spoke are the topologies used for small cells. The technology to employ depends on the traffic forecasts, performance requirements, required resilience and deployment time [2]. The technology options are wired and wireless. The coverage of a wired solution greatly depends on the availability of existing infrastructure since deploying new ones is costly and time consuming. Wireless solutions give a good alternative to the wired solution in that they are flexible and cost-efficient. A wireless solution is defined by the propagation environment, spectrum used and topology formed by the nodes. The connectivity between a point of presence (PoP) and a small cell could be line-of-sight (LOS) or a non-line-of-sight (NLOS) utilizing either of sub-6 GHz, microwave or millimeter wave bands in point-to-point (PTP), point-to-multipoint (PTMP) or multihop topology. These factors affect the coverage, capacity and latency performance of the wireless solution [3].

The purpose of the small cell will also impact the backhaul choice. For the case of filling a coverage hole in order to provide seamless services, both the small cell and the backhaul need to have availability in the order of the macro cell. This will require a highly reliable backhaul end-to-end. Whereas, if the small cells are augmenting capacity of a macro cell, the small cell availability requirement may not be stringent. The subscriber access can fall gracefully to the macro cell, at a cost of the subscriber's QoE (Quality of Experience) [2]. The traffic distribution in space and time also has an impact on the backhaul dimensioning. Different small cell scenarios impose different quality of service requirements on the backhaul. It is possible to plan a cost optimal backhaul based on all available, practical wireless technologies by taking into consideration the requirements of each small cell. The research will help determine the optimal topology and technology for a given scenario.

Ethio telecom, the sole operator in Ethiopia, has been carrying out expansion projects to make telecom services available throughout the country. Addis Ababa, being the economic hub of the country, has seen the deployment of LTE together with 3G mobile networks to provide better mobile broadband services. Many international organizations, and companies are headquartered in the city. Various services, such as banking, hotel and tourism, are relying ever in the availability of mobile services. So, the company will have to go for small cells to alleviate congestion in hot spots to meet the expectations of its customers. And this has to be done cost efficiently. This can be achieved if the company has a planning method which is tailored to overcome small cell backhaul challenges.

1.2 Statement of the Problem

Mobile networks nowadays can support high data rates due to advances in the air interface. This is made possible by the availability of a cost-efficient backhaul that matches the air interface capabilities. Macro cell sites, with their base stations on rooftops, can get backhaul using high capacity LOS microwave links, fiber and copper. The location of the base stations can also be moved to within several meters of the optimal radio network planning output so that the deployment time and cost associated with the backhaul is reduced. Small cells, however, present a significant backhaul challenge to operators. They are usually positioned in difficult to access locations below rooftop at street levels. NLOS connectivity in sub-6 GHz bands has been a good option and widely deployed but capacity is limited. Millimeter wave and microwave bands, which are proven in LOS conditions, has been proposed for NLOS to provide high capacity. The commonly used topologies are PTP, PTMP and chain. Chain and PTMP have inferior capacity and latency performance. Besides, the technologies have different total cost of ownership (TCO).

In planning a wireless small cell backhaul an operator has to consider all available technologies in order to have a viable mobile network. Different small cell deployments impose different performance requirements on the backhaul which can be implemented using technologies which have different cost and capabilities. The lack of a method to select which technology to use between nodes makes the planning time consuming, and the resulting network costly. To this end, studies have been done on the feasibilities of individual technologies and, planning on some combination of them. But, to the best of my knowledge, there has not been a study that considers all practical wireless technologies available to an operator. Thus, there is a need to develop a planning method based on an optimization formulation that helps in choosing the cost optimal wireless backhauling solution for small cell deployment.

1.3 Related Work

With the advent of 5G (Fifth Generation) cellular networks , many works have been done on the challenges of small cell backhauling as densification is among the enabling technologies of the envisioned higher data rate. Microwave line-of-sight (LOS) and non-line-of-sight

(NLOS), millimeter wave, sub-6 GHz point to multipoint were among the wireless technologies researched by many as backhauling options for small cells. The merits and demerits of different technologies and topologies were studied.

Coldrey et al. [4] investigated the feasibility of using microwave frequencies for fixed non-line-of-sight wireless backhauling: connecting small-cell radio base stations below rooftop with an aggregation node above rooftop. They studied the possibility of using NLOS links for the relaxed backhauling requirements of a small cell associated with a macro cell; traditional line of sight microwave works between 6 GHZ and 42 GHz with very high availability requirements. The NLOS propagation model used for path loss prediction is based on multiple (knife-edge) diffraction over buildings. Using system level simulations, they established the effects of interference, antenna height, rain, and antenna alignment errors, on data rate at different carrier frequencies. The carrier frequencies were 2.3, 10, 24, 60 and 73 GHz. The 2.3 GHz is chosen as a representative for sub 6 GHz band where NLOS deployment is common. They found that there were trade-offs between different higher and lower frequencies. The higher frequencies gave higher bandwidth and antenna gain. But they were found to be intolerant to rain and antenna alignment errors. They recommended the mid-range frequencies between 15 GHz and 30 GHz which provide acceptable performances of capacity and robustness.

Islam et al. [5] proposed a two-tier small cell architecture using aggregation nodes. The aggregation nodes on the rooftops of tall buildings were connected by using NLOS paths, in either microwave or sub 6 GHz bands, to multiple small cells in the surrounding area. The aggregation nodes were then connected by LOS paths to the gateway nodes using millimeter wave bands. In both tiers, PTMP technology with time/frequency division multiple access is used. In order to optimize the backhaul network they performed on multiple objectives of cost optimal aggregator node placement, power allocation, channel scheduling and routing. They formulated mixed integer nonlinear programs (MINLP) to capture the different interference and multiplexing patterns at sub-6 GHz and microwave band applied it to an example network. To solve the optimization problem, they used linear relaxation to the MINLP problem and applied a heuristic algorithm to the resulting mixed integer linear programming (MILP). Their work did not consider practical aspects such as antenna alignment, material reflectivity, etc. The algorithm used in solving the problem assumes an ideal scenario of unlimited number of channels.

Li et al. [6] developed an integer linear programming (ILP) model and proposed a heuristic algorithm to plan for a microwave backhaul network to be deployed in a tree topology which minimizes (i) the number of hops, (ii) the sum of link distances, (iii) the number of long links, (iv) the number of small angles and (v) the number of link crosses in the topology. Even though tree topologies are cost effective, they are not resilient in case of a failure. Besides they only considered line of sight (LOS) microwave links in their topologies, which may not suit the practical operating environments of small cells.

Jafari et al. [7] made a survey of small cell backhaul challenges and identified the most important ones as physical design, coverage, capacity, synchronization and cost. Wired and wireless backhaul solutions were investigated. As a planning tool for a small cell backhaul which is based on wireless technologies, they proposed an optimization model that targets to find a minimum cost hop-constrained Steiner tree rooted at a PoP. The technologies allowed in the backhaul are: PTMP NLOS in sub 6 GHz band, PTMP LOS at microwave frequencies, PTP LOS millimeter wave frequencies. The small cells were first associated to PoPs based on availability of LOS and closest distance to PoP. They applied the model on an example network in downtown Paris for four backhaul scenarios, and solved the Steiner tree problem using a meta-heuristic method called simulated annealing. The three scenarios were for the three technologies and the fourth for a combination of them. The results showed that the hybrid solution containing a combination of the backhaul technologies was the most cost-effective.

Grondalen et al. [8] provided methods that can be used by operators in planning cost effective backhaul for small cells. The methods use computer based optimization models to determine which nodes to connect by what technology. They considered two types of backhaul solutions: fiber only and multi-technology. For fiber only solutions, minimum weight spanning tree algorithm was used to find a backhaul with tree topology, and traveling salesman problem algorithm was used to find an optimal backhaul with ring technology. They formulated the multi-technology backhaul problem as a MILP and provided techniques to lower the computation time needed for solving it. They applied the tool for planning small cell backhaul on a real network. Ring based fiber only solution was found to cost 27% more as compared to tree topology. The multi technology backhaul solution constituted all the technologies considered: PTMP NLOS and PTP LOS in microwave bands, and fiber. The computation time was lowered by accepting solutions that are within a given percentage of the true optimum. The case study assumed path losses for NLOS PTMP technology which are not realistic in urban areas to draw definitive conclusions.

A planning method that uses a more comprehensive optimization model will help in choosing the best solution. It will be in an operator's best interest to use the available technologies for small cell backhauling so that customer experience is guaranteed with the least expense.

1.4 Objectives

1.4.1 General Objective

The main aim of this research is to propose a small cell backhaul planning method based on optimization formulation and use it to evaluate different deployment scenarios.

1.4.2 Specific Objectives

The specific objectives of this research are:

1. To identify the practical configurations and associated costs of available wireless backhaul technologies
2. To propose an optimization formulation for small cell backhaul planning that allows for inclusion of a range of technological constraints and requirements
3. To analyze the performance of wireless technologies for providing backhaul connectivity for small cells using a suitable propagation model
4. To analyze the performance of wireless solutions in different scenarios by applying the formulation for planning small cell backhaul

1.5 Scope

The scope of this research is limited to proposing a planning method to provide cost optimal backhaul using available practical wireless technologies in the deployment of small cells. The last mile section of the transport network which connects the small cells to the nearest PoPs was considered. The problem was formulated with the assumption that the backhaul requirements are already in place as an output of RNP. The technologies included were LOS/NLOS, PTP/PTMP for traditional microwave band (6 - 42 GHz) and LOS/NLOS, PTP for millimeter wave band (70 - 80 GH). For demonstration, a relatively built up part of Addis Ababa was chosen for propagation analysis of the wireless technologies and for planning small cell backhaul under different scenarios. Existing macro cell locations were used as PoPs but small cells were synthetically placed as RNP is beyond the scope of this work.

1.6 Methodology

Practical configurations of wireless technologies that can be used to build small cell backhaul were identified from literature. As a planning method, a MILP was formulated that allows for the inclusion of the constraints of the identified technologies, and the requirements of the backhaul. For demonstrating the effectiveness of the method, planning under different scenarios was done on a selected area of Addis Ababa by taking existing macro cell locations as a basis for the backhaul network. The small cells were synthetically placed in the area. Candidate sites for aggregation node locations were selected in case the macro cell sites do not offer feasible paths to all small cells. Once the backhaul nodes were identified, path loss values were predicted using ray tracing (RT) tool. These values would be used to analyze the performance of each technology with regard to giving feasible links. Finally, the MILP was applied on different backhaul scenarios. The scenarios were created for different backhaul demands and on whether NLOS links are allowed in the network.

1.7 Contributions

The contribution of this thesis is an optimization formulation based planning method that an operator can use to decide which nodes to connect by what technology for the purpose of building a cost effective small cell backhaul network. For this, the optimization formulation has two constraints not found in other works that account for different requirements and constraints. The first one is for the purpose of selecting the direction of the sector antenna of a PTMP access point located at the root nodes. The second constraint is added to specify the number of directions allowed at a node since different devices have different number of ports and there is a limit to the number of antennas at the same location. Besides, for the case of existing PoPs not satisfiynig the connectivity requirements of all small cells in the area, new aggregation nodes are needed and selecting their optimal placement on rooftops of a set of candidate buildings is also included in this work.

1.8 Thesis Organization

Chapter 2 discusses microwave link design in urban environment. In Chapter 3, the problem of planning cost optimal backhaul network is formulated using graph theoretic approach. Chapter 4 presents the details of the methods used in applying the optimization model to plan a backhaul network for small cell deployment in a selected area in Addis Ababa city. The results of this network planning under different scenarios are presented and discussed in Chapter 5. Finally, Chapter 6 presents the conclusions of the research work.

2 Design of Short Haul Microwave Links in Urban Environment

Wireless backhaul network planning involves path loss calculations of possible links between nodes and optimization formulation to select the cost effective feasible links of the network. Path loss calculations will determine the feasibility of links with regards to availability and capacity. After identifying the feasible links, the network topology and types of link configurations will be identified through the use of network design problem formulations. A typical backhaul scenario is shown in Figure 2.1 [9].

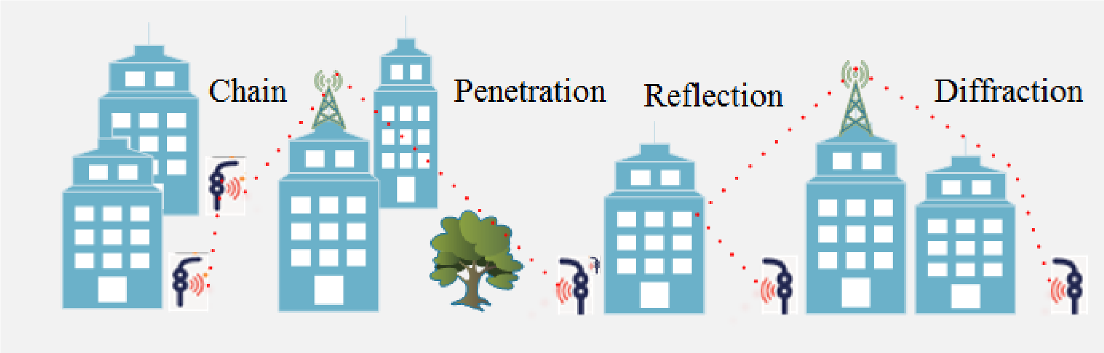

FIGURE 2.1: Wireless Backhaul for Small Cell Deployment(from[9])

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2.1 Radio Propagation

Wireless communication from one point to another requires a transmitter and an antenna at one end to create electromagnetic waves that are modified in some way in response to the information being communicated, and a receiver and an antenna at the other end to recreate the original information as accurately as possible . The environment between these points in which the wave travels determines the link performance. The mechanisms by which a wave travels are free space propagation, reflection, diffraction and scattering.

Free space propagation. A primary consideration in wireless communication is free space transmission which occurs when the radio wave travels through free space and meets no obstacles along its path.This propagation is characterized by Friis' transmission equation:

$$\frac{P_R}{P_T} = G_T G_R (\frac{\lambda}{4\pi d})^2 \tag{2.1}$$

where P_R is the power received at the output of an antenna with G_R gain, located at a distance of d from a transmitter which is radiating with a wavelength of λ and output power of P_T and antenna gain of G_T [10].

Reflection. Reflection occurs when a propagating electromagnetic wave hits an object that has very large dimensions compared to the wavelength of the propagating wave. The wave continues propagating in a path defined by the angle of reflection and may interfere constructively or destructively at the receiver. Reflection occurs from the surface of the ground, from walls, and from furniture. When a wave strikes such a surface, the wave may also be partially refracted. The coefficients of reflection and refraction are functions of the material properties of the medium. The power of the reflected wave depends on the wave polarization, the angle of incidence, and the frequency of the propagating wave.

Diffraction. Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp edges. The waves produced by the obstructing surface are present throughout space and even behind the obstacle, giving rise to the bending of waves around the obstacle, even when a line of sight (LOS) path does not exist between the transmitter and receiver. Diffraction depends on the geometry of the object, as well as on the amplitude, phase, frequency, and polarization of the incident wave at the point of diffraction. Knowledge of the terrain of a microwave path is important because diffraction will take place if the path clearance is small. This will reduce the received signal strength as can be explained with the concept of Fresnel zone.

The locus of points where the diffracted path length is multiples of 180 degrees ($\pi/2$) different from the direct path length are called the Fresnel zones. If there is an obstruction in these zones, the diffracted wave may add constructively or destructively at the receiver. For a path length much greater than r, the nth Fresnel zone radius in meter can be calculated by

$$r_n = 17.3 \sqrt[2]{\frac{n d_1 d_2}{f(d_1 + d_2)}}, \tag{2.2}$$

where d_1 and d_2 are distances in kilometers from transmitter and receiver, the frequency f is in GHz, and the radius r_n is in meters [11].

Scattering. Scattering occurs when the propagation medium contains objects whose dimensions are approximately the same as or smaller than the propagating wavelength. Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel. As frequencies increase, the wavelengths become shorter, and the reflective surface appears rougher, thus resulting in more diffused reflections as opposed to specular reflections. In urban areas, foliage, street signs, and lampposts, can induce scattering for wireless systems which require accurate modeling.

2.2 Propagation Models

In designing a wireless system, accurate estimation of its signal parameters is needed to predict the system's performance in the area it is to be deployed. Path loss and time-delay spread are two of these parameters. A propagation model predicts these parameters. For microwave short haul link planning in urban areas, the most important parameter is path loss.

Path loss - The link budget is determined by the amount of received power that may be expected at a particular distance or location from a transmitter. Path loss is a measure of the average RF attenuation suffered by a transmitted signal when it arrives at the receiver, after traversing a path of several wavelengths. It is defined by

$$PL(dB) = 10\log\frac{P_T}{P_R} \tag{2.3}$$

where P_r and P_t are transmitted and received powers, respectively.

For free space, path loss is derived from Friis transmission equation and is given by

$$PL(dB) = 20\log d + 20\log f + 92.44, \tag{2.4}$$

where f is frequency in GHz and d is distance in kilometers. The free space path loss cannot be applied to many practical cases. A simplified path loss model, that uses a parameter n for power-law relationship of distance d and the power received, is formulated for these situations by [12]

$$PL(dB) = PL(d_o) + 10n\log\frac{d}{d_o} + X_\sigma, \tag{2.5}$$

where d_o is the reference point distance which is in the far field of the transmitting antenna; typical values are 1 km for large urban cells, 100 m for microcell and 1 m for indoor . X_σ denotes a zero-mean Gaussian random variable of standard deviation σ, which reflects the variation, on average, of the received power that naturally occurs when a PL model of this type is used. No site-specific information about the propagation environment is included in this model.

There are two main models for predicting path loss in a given system: empirical (or statistical) models, and site-specific (or deterministic) models. The former relies on the statistical characterization of the received signal while the later has a physical basis. They differ also on the amount of information required; the deterministic ones requiring more data such as terrain profile and building data.

2.2.1 Empirical Models

These models are mainly based on empirical measurements over a given distance in a given frequency range and a particular geographical area or building. Empirical models predict path loss for typical wireless environments such as large urban, suburban, rural and indoor. When applying them to generalized areas, the accuracy of the prediction lowers.

Okumura Model. This is one of the most common models for propagation in urban macrocells. This model is applicable for distances of 1 - 100 km and frequency ranges of 100 – 1500 MHz. The model is given as

$$L_{50}(dB) = L_F + A_{mu}(f,d) - G(h_{te}) - G(hre) - G_{AREA} \tag{2.6}$$

where L_{50} is the median value of the propagation path loss, L_F is the free-space propagation loss, A_{mu} is the median attenuation in the medium relative to free space at frequency f, and d corresponds to the distance between the base and the mobile unit. $G(h_{te})$ and $G(h_{re})$ are the gain factors for the antennas at the base-station and mobile which are located at effective heights of h_{te} and $h-re$, respectively. G_{AREA} is the gain due to the propagation environment. Both $A_{mu}(f,d)$ and G_{AREA} can be found from empirical curves [13].

Okumura-Hata Model. The Hata model is an empirical formulation of the graphical path loss data provided by Okumura's model [14]. The formula for the median path loss in urban areas is given by

$$L_{50,urban}(dB) = 69.55 + 26.16\log f - 13.82\log h_{te} - a(h_{re}) + (44.9 - 6.55\log h_{te})\log d \tag{2.7}$$

where f, the, h_{re} and d are the same parameters from Okumura model. $a(h_{re})$ is the correction factor for the effective antenna height of the mobile unit, which is a function of the size of the area of coverage. For small- to medium-sized cities, the mobile-antenna correction factor is given by

$$a(h_{re}) = (1.1\log f - 0.7)h_{re} - 1.56\log f - 0.8dB \tag{2.8}$$

For a large city, it is given by

$$a(h_{re}) = 8.29\log(1.54h_{re})^2 - 1.1dB \qquad forf \leq 300MHz \tag{2.9}$$

$$a(h_{re}) = 3.2\log(11.75h_{re})^2 - 4.97dB \qquad forf \geq 300MHz \tag{2.10}$$

The standard Hata formula is modified for suburban and open rural areas as follows:

$$L_{50,suburban}(dB) = L_{50,urban} - 2(\log f/28)^2 - 5.4 \tag{2.11}$$

$$L_{50,suburban}(dB) = L_{50,urban} - 4.78(\log f/28)^2 - -18.33\log f - 40.98 \tag{2.12}$$

This model is quite suitable for large-cell mobile systems, but not for small cells, since its working range is the same as Okumura model.

COST-231-Walfisch-lkegami Model. This model utilizes the theoretical Walfisch-Bertoni model and is composed of three terms [13]:

$$L_b = \begin{cases} L_o + L_{rts} + L_{msd}, & \text{for } L_{rts} + L_{msd} > 0. \\ L_o, & \text{for } L_{rts} + L_{msd} \leq 0. \end{cases} \tag{2.13}$$

where L_o represents the free-space loss.L_{rts} is the "roof-top-to-street diffraction and scattering loss." L_{msd} is the "multi-screen diffraction loss."

2.2.2 Deterministic

Deterministic models are based on the theory of electromagnetic-wave propagation. With greater knowledge on the detail of the environment, they can provide accurate predictions of the signal propagation. They can be broadly classified as numerical and ray tracing. The numerical methods consist of calculating the time varying electromagnetic field, described by Maxwell's equations in every location in the area under study. Since these calculations are time consuming for large scale modeling, ray tracing methods are more practical for outdoor propagation environment.

Ray tracing is a technique based on Geometrical Optics (GO) which assumes that energy of high frequency electromagnetic waves to be to be radiated as rays. In GO, a ray undergoes reflection or transmission depending on the nature of objects it interacts in the propagation environment. These interactions can be described using the theory of refraction and reflection. To incorporate diffraction, the Geometrical Theory of Diffraction (GTD) and its uniform extension, the Uniform GTD (UTD), complement the GO theory by introducing a new type of rays, known as the diffracted rays. The purpose of these rays to is account for the energy found in the zero-field regions predicted by GO. The Fermat principle, which states that a ray follows the shortest path from source to a field point, is an important concept used in ray tracing models [13]. The image method and the shoot and bounce ray (SBR) method are generally used in ray tracing.

In the image method, possible paths between transmitter and receiver are found by constructing images of the transmitter at all planes of interactions. An image point is computed so that the distance from the source to relevant face is always equal to the distance between that face and image point. This is shown for a source S placed between two reflecting mirrors A and B in Figure 2.2. If the source is found to be visible at the receiver point, the ray will be traced to calculate the reflection attenuation from its interactions to the walls. In SBR method, finite sample of possible directions of the propagation from the transmitter is chosen and a ray is launched for each direction as shown in Figure 2.3. A sphere is placed at the receiver and all the valid rays arriving at the sphere are used to compute the total field at the receiver location. There are two kinds of methods to obtain the rays at the source point. One is a two-dimensional (2D) approach; the other is a three-dimensional (3D) method.

Ray based deterministic propagation models give realistic path loss predictions which is important in the design and optimization of wireless backhaul networks in urban areas. The computation time of these models can be minimized by database preprocessing which refers

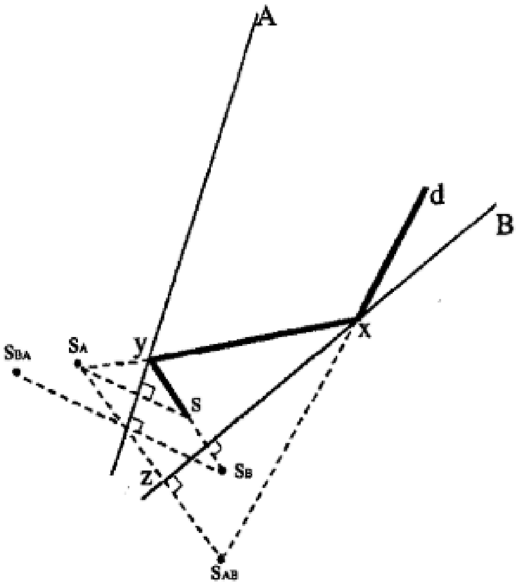

FIGURE 2.2: Images due to a source placed between two mirrors, A and B (from[13])

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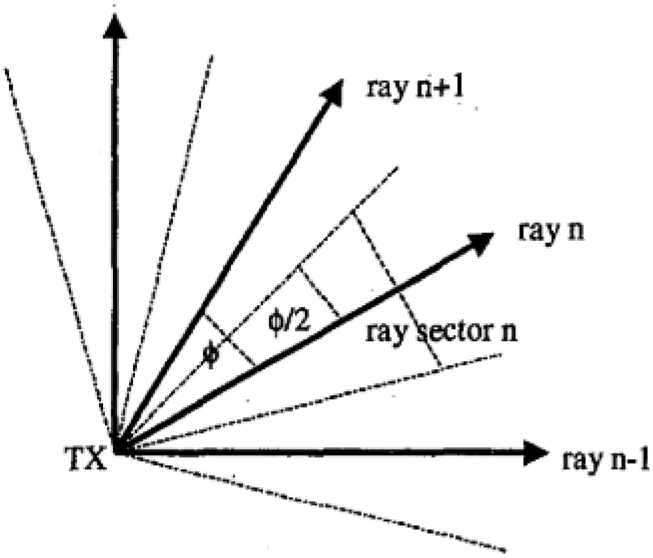

FIGURE 2.3: Rays generated from source in 2 dimensions (from[13])

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to the division of building walls into tiles, building edges into horizontal and vertical segments, and the prediction plane into a grid of receiving points. Visibility relations will be determined between these element i.e. centers of tiles and walls, and receiving points using ray tracing to determine incidence angles and distances between them. Since the visibility relations are independent of transmitter location, the preprocessed database can be used for different transmitter locations. At prediction time, only the relation to the first element needs determination. Computation time can further be reduced by using empirical interaction losses instead of Fresnel equation (for reflection losses) and UTD (for diffraction losses). Empirical interaction losses use the angles of incidence and diffraction together with predefined reflection and diffraction losses to calculate these losses [15].

2.3 Link Budget Calculation

The link budget is a listing of all the gains and losses for the wireless link that are added in order to arrive at the received mean signal level. This number can be used to assess the availability of the link under a variety of fading mechanisms. The link availability is the percent of time averaged over a month or a year when the link performance in terms of bit error rate (BER) meets or exceeds an acceptance criterion. For example, a BER of 10^{-03} is acceptable for voice service but a more stringent BER of 10^{-06} is required in packet networks. For a microwave link, the link budget equation is typically given by:

$$P_{RX} = P_{TX} - L_{TX} - L_P - L_{RX} + G_{TX} + G_{RX}, \tag{2.14}$$

where P_{RX} = received signal level(dBm)
P_{TX} = transmitter output power(dBm)
L_{TX} = transmitter losses (circulator, line, connectors, radome) (dB)
L_P = total path loss (free space, absorption) (dB)
L_{RX} = receiver losses (circulator, line, connectors, radome) (dB)
G_{TX} = transmitter antenna gain (dBi) and
G_{RX} = receiver antenna gain (dBi)

The path loss L_P depends on whether the link is LOS or NLOS. For a properly designed LOS link, only the distance dependent free space path loss is considered. For NLOS links which dominate small cell backhaul networks, additional losses from buildings and foliage are considered. Using propagation models described in section 2.2 is necessary to determine the path losses of NLOS links in planning for dense deployment of small cells.

The direct outcome of the link budget calculation is the fade margin which is the difference between received signal level and the receiver sensitivity. Receiver sensitivity is the minimum received power required at the receiver input to get the required signal to noise ratio (SNR) at the output of the receiver. The SNR value is the main design objective which tells the maximum modulation order that can be used for a specified BER. The fade margin FM can be obtained from the receiver noise threshold N, the required SNR and received power by:

$$FM = P_{RX} - (SNR + N), \tag{2.15}$$

The fade margin determines the availability of a link against a fading channel. For a link to be in outage, i.e. for the BER to fall below the design target, the fade depth should exceed the available margin. The antenna gains at both ends can be changed to achieve the required margin.

In microwave links, two types of fading may occur: multipath fading and rain fading. Multipath fading, which is a result of multiple components of a signal arriving at a receiver to add constructively or destructively, is dominant in long-range low-frequency links. In high-frequency short-haul links, the main reason for outage is rain.

2.4 Rain Attenuation

Rain attenuates radio waves in three ways: absorption by raindrops smaller than the radio wavelength, scattering by raindrops in the order of radio wavelength, and depolarization by scattering of the surface of the rain drops. Rain size distribution, orientation and rain intensity determine the amount of rain attenuation. Only rain intensity is available for a particular area. The primarily used models to predict the fade from rain are Crane and ITU-R rain models; the later one being widely used worldwide. Both use only rain intensity or rain rate for prediction.

The rain attenuation, in ITU-R model, is given in Rec. ITU-R P.838-3 [16] as:

$$\gamma_R = kR^{\alpha}, \tag{2.16}$$

where γ_R is specific attenuation in dB/km, and R is the rain rate in mm/hr for a given percentage of time for a given rain region of the world. The rain rate is found for each rain region in Rec. ITU-R PN.837-1 maps [17]. The coefficients k and α are a function of operating frequency f and are given, for any radio wave with circular or linear polarization, by the following equations:

$$k = \frac{\left[k_H + k_V + (k_H - k_V)\cos^2\theta\cos 2\tau\right]}{2}, \tag{2.17}$$

$$\alpha = \frac{\left[k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta\cos 2\tau\right]}{2k}, \tag{2.18}$$

where θ is the path elevation angle and τ is the polarization tilt angle relative to the horizontal (τ = 45° for circular polarization). k_H, k_V, α_H and α_V are given in Rec. ITU-R P.838-3 for a frequency in the range from 1 to 1000 GHz.

The outage from rain fading can be calculated by first identifying the rain region in which the link is to be constructed and calculating the specific attenuation for a rain rate that corresponds to the percentage of time of interest. For example, a rain rate that is exceeded 0.001 percentage of time can be used to calculate the fade margin needed for 99.999 % availability.

2.5 Wireless Backhaul TCO Model

Cost is one of the criteria, besides capacity, reliability and deployment time, with which operators select a backhaul technology. To estimate cost of a backhaul system, it is necessary to differentiate the different architectures of deployment. Regardless of topology, microwave links have two types of architectures: PTP and PTMP. The cost model of a point to point microwave link [18], which is based on TCO classification as shown in Figure 2.4, is discussed here.

2.5.1 CAPEX

CAPEX refers to all the expenses related to having the backhaul network in place, and is divided into two: equipment and infrastructure costs.

Equipment cost. Equipment cost includes the purchasing and installation of equipment. The purchasing cost of the equipment (Eq_{pur}) is given by:

$$Eq_{pur} = 2N_{link}Pr_{ant} + N_{sw}Pr_{sw}, \tag{2.19}$$

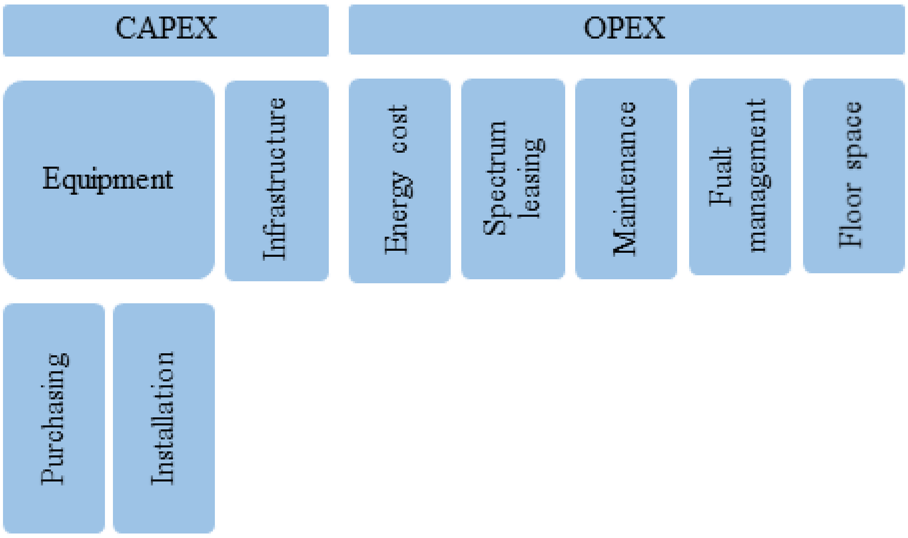

FIGURE 2.4: Cost Classification of TCO Model of Backhaul. (from[18])

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where N_{link} and Pr_{ant} represent the total number of microwave links, and the price of each antenna, respectively. N_{sw} and Pr_{sw} denote the number of aggregation switches and the price of each switch connected to microwave antennas.

Installation cost is given by:

$$Eq_{inst} = \left[\sum_{i=1}^{N_{link}} \left(T_i^{antIn} + 2T_i^{tra} \right) N_t N_{team}^{tech} + T_{swIn} N_{sw} \right] Tech_{sal}, \tag{2.20}$$

N_{link}, N_t and N_{team}^{tech}denote the number of microwave links, the number of teams (i.e., two in case of a PTP microwave link to ensure the correct antenna alignment) needed per each link, and the number of technicians per team, respectively. The time to install a microwave antenna and the traveling time to its location are represented by T_i^{antIn} and, T_i^{tra} respectively. The installation time for the switches connected to the microwave links is calculated by multiplying the installation time of a switch (T_{swIn}) by total number of switches (N_{sw}) used in the backhaul network. Multiplying the total time required for the installation of all links by the hourly technician rate, $Tech_{sal}$, gives the total installation cost, Eq_{inst}

Infrastructure cost. This cost, denoted by Inf, includes all the expenses needed for hub installation and is given by:

$$Inf = N_{hub} + Pr_{hub}^{in}, \tag{2.21}$$

where N_{hub} and Pr^{in}_{hub} represent the number of hubs in the backhaul and cost of installing each one.

2.5.2 OPEX

OPEX refers to all the expenses incurred in operating the network in a specified interval of time. These expenses are defined on a yearly basis by the following equations.

Spectrum licensing. For a licensed microwave link, the yearly cost of leasing a spectrum, denoted by Pr^{link}_{ci}, varies by channel capacity and frequency band. Spectrum licensing cost L is given by:

$$L = \sum_{i=1}^{N_{cc}} \left(N^{link}_{c_i} Pr^{link}_{c_i} \right), \tag{2.22}$$

where N_{cc} and $N^{link}_{c_i}$ denote the number of capacity classes of the microwave links used in the backhaul (e.g., 100 Mbps, 500 Mbps), and the number of microwave links belonging to capacity class i, respectively.

Energy cost. The energy cost, E, is given by:

$$E = a \sum_{i=1}^{N_{site}} S^{E}_{i} Pr_{Kwh}, \tag{2.23}$$

where N_{site}, S^{E}_{i} and Pr_{Kwh} represent the number of microwave sites where antennas are located, the energy consumed in each site and price per Kwh of energy, respectively. The coefficient a accounts for the cooling expenses of a site.

Maintenance cost. The maintenance of microwave links includes the monitoring and testing the equipment, updating the software and renewal of power supply components. The yearly cost of maintenance M is given by:

$$M = \sum_{i=1}^{N_{ant}} \left(N^{Mh}_{ant} + 2T^{trav}_{ant_i} \right) Tech_{sal} + SW_{li}, \tag{2.24}$$

where N^{Mh}_{ant} and $T^{trav}_{ant_i}$ represent yearly man-hours required for the maintenance of each microwave antenna and the traveling time to its location, respectively. $Tech_{sal}$ and SW_{li} denote the hourly rate of technician and software yearly licensing fee.

Fault management cost. Fault management refers to the expenses related to the reparation of the failures that might occur in a backhaul network. The average number of failures per year of each component type i (ANF_i) can be calculated based on the component failure rate. ANF_i multiplied by the number of equipment of type i (N_i^{eq}) in the backhaul network gives the expected number of failed components of type i during one year. The average total yearly reparation cost (FM) for the backhaul network as the sum of the reparation cost of each failure occurring during the year is defined by:

$$FM = \sum_{i=1}^{N_{type}^{eq}} \left((MTTR_i + 2T_{trav}) N_{tech} Tech_{sal} + Eq_i^{cost} \right) ANF_i N_i^{eq} \tag{2.25}$$

The reparation cost depends on the cost of purchasing new component when needed (Eq_i), mean time to repair ($MTTR_i$) of each device/network segment i, and the traveling time to the location of failure (T_{trav}). N_{tech} and $Tech_{sal}$ denote the number of technicians required to repair a failure and the hourly rate of technician, respectively.

Floor space cost. The outdoor floor space cost is a yearly rental fee paid by an operator to house its equipment, i.e. for the area required to house microwave hub and remote equipment. The cost can be calculated by:

$$FlSp = (A_{hub} N_{hub} + A_{site} N_{site}) Pr_{m^2} \tag{2.26}$$

where A_{hub} and A_{site} denote the areas required for microwave hub and remote sites respectively. The number of hubs and remote sites in the network are indicated by N_{hub} and N_{site}. The total floor space cost $FlSp$ is found by multiplying the total floor space by the yearly rental fee per meter square (Pr_{m^2}).

3 Cost Optimal Wireless Backhaul Planning

3.1 Network Model

This research considers a wireless backhaul network whose nodes are located at the sites of existing macro cells, small cells and new aggregation devices, see Figure 3.1. The existing macro cell and aggregation nodes are designated as the root nodes of the backhaul network. The traffic from(to) small cells is carried to(from) the core network through root nodes by a wireless link, either directly or through other small cells. The root nodes are assumed to be connected to the core network with a transport network of sufficient capacity to accommodate the additional small cell traffic. For the newly built aggregation nodes which will be located above rooftop level, a high capacity PTP link will be built; the cost of which will be included in the problem formulation. The wireless links could be LOS/NLOS, PTMP/PTP in microwave/millimeter wave. The feasibility of the link depends on the propagation environment and the selected system configurations of each technology. The wireless links have an associated TCO the summation of which this work desires to minimize.

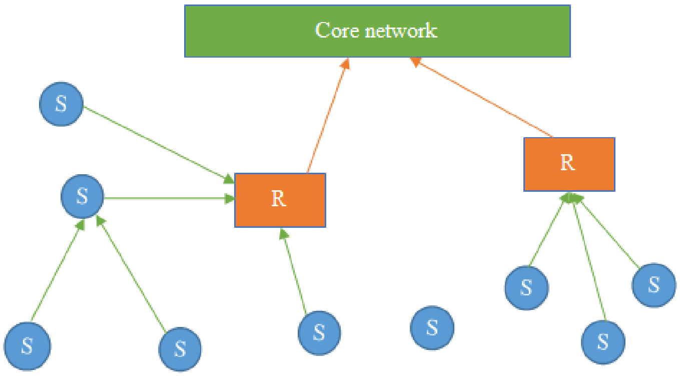

FIGURE 3.1: Backhaul Network Model: the connections among small cells (S) and root nodes (R) could be of any of the considered wireless technologies

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TABLE 3.1: Description of Notations

Notation	Description
N	A set of nodes in the backhaul, $R \cup S$
M	A set of macro cell base stations in the area
G	A set of new aggregation nodes
R	A set of root nodes,
S	A set of small cell base stations
W	A set of wireless technologies
W_m	A set of PTMP wireless technologies, $W_m \subseteq W$
c_{ij}^k	Capacity of link $\{i,j\}$ when technology k is used
d_i	Demand of small cell i
$C_i^{k_o}$	Capacity of access point (AP) of wireless PTMP technology k_o
q_i	Number of allowable directions at node i
$v_i^{k_o}$	Sector angle of wireless PTMP technology of k_o
v_{jil}	Angle subtended by link $\{i,j\}$ at node i
p_{ij}^k	Cost of link $\{i,j\}$ when using technology k
$m_i^{k_o}$	Cost AP of wireless PTMP technology k_o at node i
g_i	Cost of new aggregation node i
y_{ij}^k	Decision variable on using technology k for link $\{i,j\}$
f_{ij}^k	Amount of flow on link $\{i,j\}$ when using technology k
$z_i^{k_o}$	Decision variable on the placement of AP of PTMP technology k_o at node i
x_i	Decision variable on using new aggregation node i

3.2 MILP Formulation of the Backhaul Network

The problem is formulated using graph theoretic approach: given a multigraph $G(N,E)$, find a minimum cost forest F that spans S. The trees of F are rooted at R'. R' is a subset of R. The non-root nodes of the trees of F contain disjoint subsets of S. Many types of formulations are given for optimal tree in [19]. The single commodity flow model is modified to find an optimal forest, from an initial topology of a multigraph. The nodes of the backhaul network are initially connected by multiple edges that represent different wireless technologies. These edges have a capacity limit and TCO that is related to their specified system configuration. The formulation also includes constraints related to technology like capacity, sector antenna and number of directions at a node. Eq. 3.1 - 3.15 give the proposed MILP that minimizes the TCO of the backhaul network. The variables, sets and parameters of the MILP are given in Table 3.1.

$$\text{minimize} \sum_{k\in W,\{i,j\}\in E} p_{ij}^{k} y_{ij}^{k} + \sum_{k\in W_m, i\in E} m_i^{k_o} z_i^{k_o} + \sum_{i\in G} g_i x_i \tag{3.1}$$

$$\text{subject to} \sum_{k\in W,\{i,j\}\in E} f_{ji}^{k} - \sum_{k\in W,\{i,j\}\in E} f_{ij}^{k} = d_i \qquad \forall i \in S \tag{3.2}$$

$$\sum_{r\in R} \sum_{k\in W,\{i,j\}\in E} f_{ri}^{k} - \sum_{r\in R} \sum_{k\in W,\{i,j\}\in E} f_{ir}^{k} = \sum_{i\in S} d_i \tag{3.3}$$

$$\sum_{k\in W,\{i,j\}\in E} y_{ij}^{k} = |S| \tag{3.4}$$

$$f_{ij}^{k} \le (\sum_{i\in S} d_i) y_{ij}^{k} \qquad \forall i \in S, k \in W \tag{3.5}$$

$$f_{ji}^{k} \le (\sum_{i\in S} d_i) y_{ij}^{k} \qquad \forall i \in S, k \in W \tag{3.6}$$

$$f_{ij}^{k} \le c_{ij}^{k} y_{ij}^{k} \qquad \forall i \in S, k \in W \tag{3.7}$$

$$f_{ji}^{k} \le c_{ij}^{k} y_{ij}^{k} \qquad \forall i \in S, k \in W \tag{3.8}$$

$$\sum_{j\neq i, j\in N} y_{ij}^{k_o} \le |S| z_i^{k_o} \qquad \forall i \in N, k_o \in W_m \tag{3.9}$$

$$\sum_{j\neq i, j\in N} y_{ij}^{k} \le |S| x_i \qquad \forall i \in G, k \in W \tag{3.10}$$

$$\sum_{j\in N} f_{ij}^{k_o} \le C_i^{k_o} z_i^{k_o} \qquad \forall i \in N, k_o \in W_m \tag{3.11}$$

$$y_{ijo}^{k} + y_{il}^{k_o} \le 2v_i^{k_o}/v_{jil} \qquad \forall i \in N, \{i,j\} \in E, \{i,l\} \in E \tag{3.12}$$

$$\sum_{\{i,j\}\in E, k\in W} y_{ij}^{k} \le q_i \qquad \forall i \in N \tag{3.13}$$

$$y_{ij}^{k}, z_i^{k_o}, x_i \in 0,1 \tag{3.14}$$

$$f_{ij} \ge 0 \tag{3.15}$$

Equation 3.1 represents the objective function that minimizes the backhaul deployment cost. For PTMP technologies, the cost per link is the cost of terminal at the small cell site. The second term of the objective function accounts for the AP placement that serves these PTMP terminals. The last term is the cost of placing an aggregation node at a new site. Eq. 3.2 and 3.3 are flow conservation constraints at small cell nodes and root nodes, respectively. The demand of a small cell is satisfied if the difference between the incoming flows to outgoing flows equals that node's demand. The supply at root nodes is constrained to be equal to the sum of the demands of small cells. Eq. 3.4 states that the number of links defined by any solution is equal to the number of small cells; a condition for a spanning forest. Eq. 3.5 and 3.6 force the flow on an edge, in both directions, to be zero if the edge is not in the solution, and not be greater than the total demand of the small cells if it is selected. Eq. 3.7 and 3.8 represent the capacity constraint of links. Eq.3.9 forces the number of PTMP links from a node to be zero if an AP is not placed there, and not to be greater than the number of small cells if an AP is placed. Eq. 3.10 states that the number of links incident on a new aggregation node not to be greater than the number of small cells if it is in the solution, and zero if it is not. Eq. 3.11 states that the sum of flows from an AP of particular PTMP technology should not be greater than the capacity of the AP. Eq. 3.12 represents that for any two nodes to be connected to the same AP , the angle subtended by the line connecting them at the PTMP node cannot be greater than the sector angle of the AP. Eq. 3.13 describes the number of radio directions a node can support, which is determined by the switch capability and interference requirements. Eq. 3.14 limits the decision variables to be binary. The last equation states the nonnegativity of flow on links.

4 Case Study

To apply the MILP formulated in the previous section, an area in Addis Ababa city was chosen on the basis of presumed difficulty in backhauling posed by the presence of buildings that minimize the probability of getting LOS links among the nodes of the backhaul network. Optimal backhaul planning for small cell deployment in the selected area involved three main tasks. First, representative system configurations of the three wireless backhaul technologies were determined and their TCO calculated. Next, for each technology, path loss values and the existence of LOS between the nodes were predicted using ray tracing techniques. These predictions would determine the feasibility of a link of a particular technology between the nodes of the network, and whether it is LOS or not. Finally, scenarios were created based on types of technologies used in the backhaul solution and different demands of small cells. The MILP was solved for the different scenarios to get the respective wireless backhaul solutions that minimize TCO. The procedure is elaborated in the following sections.

4.1 System Configurations and TCO of Wireless Backhaul Solutions

4.1.1 System Configurations

Three wireless technologies are considered: microwave PTP, millimeter wave PTP and microwave PTMP. A PTP technology is defined by a symmetric link between nodes whereas a PTMP technology requires an AP that connects to multiple remote nodes. The difference in the PTP technologies is the band they operate in and the available bandwidth to use in these bands. PTMP technologies also differ for these same reasons and additionally by the access mechanism they use. Microwave PTMP is chosen because the other options are either not mature enough like millimeter wave PTMP, or found in a crowded band like sub-6 GHz. A more common sector angle of 90° is chosen; the other sector options being 30° and

60°. The parameters chosen for the wireless systems are given in Table 4.1 and are based on current availability of equipment and deployment trends [8][20][1][21][3] . The antenna diameters are, for example, chosen to be smaller to meet the aesthetic requirements of equipment mounted at street level. Also in this table are given the performance requirements like modulation order and availability of link. Availability requirements may range from 99 % - 99.99 % depending on the reason for the small cell deployment, i.e, whether for capacity or coverage [2] In short-haul links operating in microwave and millimeter wave bands, the most important unavailability contributor is rain fading. To achieve 99.99% availability, the required margins are calculated using ITU-R rain models (eq. 2.4) and rain regions described in section 2.

TABLE 4.1: System Parameters

Parameter	**Microwave PTP**	**Millimeter Wave PTP**	**Microwave PTMP**
Antenna Type	0.2 m reflector at both ends	0.2 m reflector at both ends	90°sector at hub site and 0.2 m reflector at remote site
Antenna Gain	34 dB	42 dB	sector: 20 dB and remote: 26 dB
Antenna Half Power Beam Width	3.6°	1.4°	65°
Transmit Power	21 dBm	10 dBm	21 dBm
Frequency	28 GHz	73 GHz	28 GHz
Bandwidth	56 MHz	250 MHz	56 MHz
Rain Fade Margins for 99.99 % Availability	2 dB	5 dB	2 dB
Noise Figure	3 dB	3 dB	3 dB
Modulation Order	256-QAM	256-QAM	256-QAM
SNR for 10^{-6} BER	32 dB	32 dB	32 dB
Capacity	370 Mbps	1.6 Gbps	370 Mbps
Multiple Access	Not applicable	Not applicable	TDMA uplink/ TDM downlink

4.1.2 TCO Calculations

The costs are based on [22], and modified to the requirements of this work as shown in Table 4.2. These costs are used in the equations of the TCO model described in section 2 to calculate TCOs of each technology. The first year TCO of microwave PTP link, millimeter wave PTP link, microwave PTMP terminal and access point are calculated from these costs and found to be \$35,050, \$40,890, \$15,135 and \$25,646, respectively. For a new site, the additional cost is assumed to be that of a microwave PTP link cost which is required to create connectivity to the core network. These values are used in the objective function of the optimization problem.

TABLE 4.2: TCO Assumptions

	Cost Type	**Microwave PTP per Link**	**Millimeter Wave PTP per Link**	**Microwave PTMP**	
				Terminal	**AP**
CAPEX	Equipment cost	\$7,950)	\$15,400	\$3,985	\$10,500
	Network planning and installation	\$8,700	\$8,700	\$3,650	\$5,950
OPEX	Site rental fees per year	\$8,500	\$8,500	\$3,500	\$5,000
	Spectrum licensing fees per year	\$1,900	\$290	0	\$196
	Power and maintenance	\$8,000	\$8,000	\$4,000	\$4,000

4.1.3 Link Feasibility Criterion

A wireless link of a particular technology is deemed feasible between two nodes if it can support the capacity and availability requirement with the given system configuration as described in Table 4.1. In the three wireless solutions under consideration, the minimum highest modulation level required is 256-QAM which requires an SNR of 32 dB at the output of the receiver for a BER of 10^{-6}. Thus, the received power at the receiver input should be greater than the receiver sensitivity, which is the sum of the receiver noise threshold and SNR requirement. The receiver noise threshold is calculated by:

$$N = 10\log(kTB) + NF, \tag{4.1}$$

where k is Boltzmann's constant(1.37×10^{-23} J/K), T is room temperature in Kelvin and B is the bandwidth of the system in Hertz. NF is noise figure of the receiver and can be found from datasheet of the receiver. Inserting the corresponding parameters for microwave PTP, millimeter wave PTP and microwave PTMP in eq. 4.1 will give noise powers of -93.5 dBm, -87 dBm and -93.5 dBm, respectively.

The minimum required received powers for 256-QAM ($SNR = 32$ dB) demodulation are calculated for each system by

$$P_{RX,min} = N + SNR, \tag{4.2}$$

and found to be -61.5 dBm, -55 dBm and -61.5 dBm, respectively.

The maximum allowable path loss $L_{P,max}$ of a link can be calculated by letting the transmitter radiate at its maximum power P_{TX} and taking into account margins for rain fading as:

$$L_{P,max} = P_{TX} + G_{TX} + G_{RX} - P_{RX,min} - FM, \tag{4.3}$$

where G_{TX} and G_{RX} are the respective antenna gains at the transmitter and receiver. The fade margin (FM) for rain is calculated for 99.99 % availability target by applying the model described in section 2.4.

Using eq. 4.3 and Table 4.1, the allowable path losses for microwave PTP, millimeter wave PTP and microwave PTMP are calculated to be 148.5, 144 and 126.5, respectively. If path loss of a link is less than these maximum values while operating in the corresponding configurations, it can have a feasible link of that technology. Between any two nodes, there may be three, two or no feasible wireless link technologies one can select from while planning the backhaul network.

4.2 Numerical Study

For demonstration, a 2.41 km^2 area was selected in a relatively built-up part of Addis Ababa city. It contains 9 macro cell sites already serving 2G, 3G and 4G networks. All macro cell sites are located above roof top level with height range of 25 to 46 m. These will be used as possible points of presences through which the traffic from the 28 synthetically placed small cells is to be transported to the core network. The small cells are placed below rooftop level at a height of 6 m [23], by physical inspection and a help of a map. Additionally, 4 locations are selected in the area as candidate sites for the placement of aggregation nodes if the need arises. These aggregation nodes together with the macro cell sites are the root nodes of the trees which are part of the forest that represent the backhaul topology. The area of study along with the site locations is shown in Figure 4.1. First, the path losses for the three wireless technologies are obtained for any two node pair using propagation modeling. Then, these will be analyzed for feasibility and LOS/NLOS determination of the link. Finally, using these parameters scenarios will be created for backhaul planning of the case study.

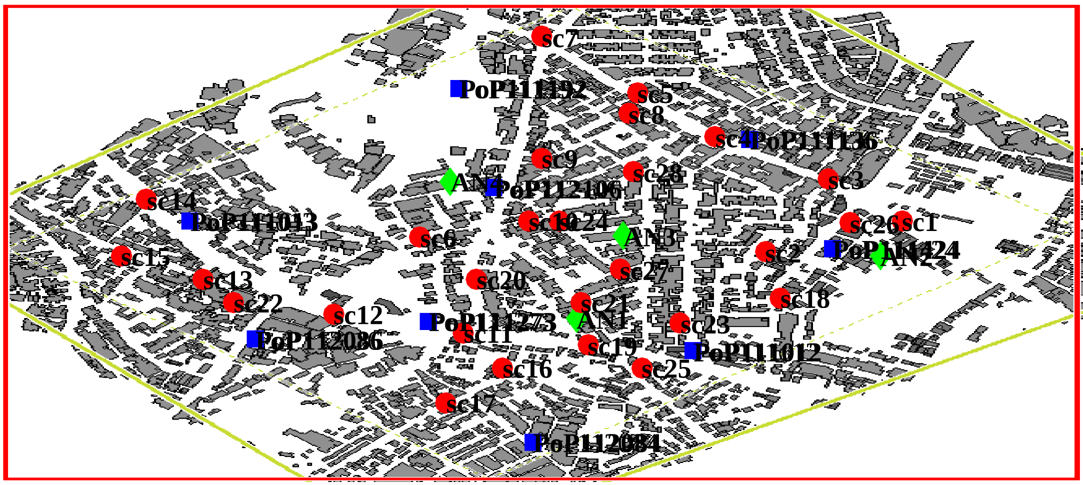


FIGURE 4.1: Backhaul Planning Area. Red circles represent small cells, blue squares macro cells and green diamonds new aggregation nodes.

4.2.1 Path Loss Predictions using IRT

Intelligent ray tracing (IRT) is a ray tracing model that uses preprocessing techniques to decrease computation time. Winprop's Wallman and Proman tools were used for path loss prediction using IRT. The former is a building database editing tool and the latter a propagation modelling tool.

A building map of Addis Ababa was first preprocessed to specify propagation and prediction areas to be used in IRT. The prediction area was matched to the area selected for the case study and the prediction height was set to 6 m, which was the height of the small cells. The IRT settings used are listed in Table 4.3. Only one ray path is considered and the ray should take no more than one diffraction interaction. This is chosen in accordance with the expected deployment which uses directional antennas aligned to the direction of one diffracted ray for the case of NLOS links [4]. For material properties, empirical parameters are used as physical parameter settings need identification of the electrical properties of all the walls in the propagation area. Propagation modeling was then done using these configurations for the three wireless technologies: microwave PTP, millimeter wave PTP, and microwave PTMP. The resulting output data was exported to text files to be used in the analysis of link feasibility and LOS availability between nodes.

The analysis on the results of the propagation modeling were done in Matlab. For each technology, path loss and LOS (whether a LOS exists or not) values from all nodes to all grid points that correspond to node locations in the propagation area were extracted from the text files. These values were, then, analyzed to determine how many small cells had feasible links to macro cell sites, and whether theses links were LOS/NLOS. The number of feasible links small cells had to other small cells were also calculated. Finally, the total number of feasible links each small cell has to all other nodes in the network is determined.

TABLE 4.3: IRT Parameters

IRT Parameter	**Value**
Number of interactions	1
Type of interaction	Diffraction
Number of ray paths	1
Material Properties	Empirical

4.2.2 Backhaul Planning Scenarios

Matlab's optimization toolbox is used to solve the optimization under different scenarios. Scenarios are defined by the wireless technologies used, and the demand of the small cells in the network as shown in Table 4.4. The first demand is chosen to be 75 Mbps on the reflection of a single sector 20 MHz LTE macro cells currently deployed in the city. Backhaul capacity demand at a node is dependent on the traffic demands of the small cells it is planned to transport. Hence, a backhaul node may serve one or more small cells which use similar or different radio access technologies. The rest of the demands were chosen on this basis and to find out their impact on the backhaul solution.

For all planning scenarios, the other parameters of the optimization are shown in Table 4.5. Nodal degree was restricted to 6 at root nodes and 3 at non root nodes to decrease the level of interference. In microwave PTMP solution, 90° sector was chosen and it was only to be deployed at root nodes, i.e at AN and MC locations above rooftop level.

TABLE 4.4: Backhaul Planning Scenarios

Scenario	**Demand of SC (Mbps)**	**Wireless Solutions**
1	75	PTP microwave, PTP millimeter wave and PTMP micrwave LOS links
2	150	
3	350	
4	75	PTP microwave, PTP millimeter wave and PTMP microwave LOS/NLOS links
5	150	
6	350	

TABLE 4.5: Parameters Used in the Scenarios

Parameter	**Value**
Capacity of microwave PTP link	370 Mbps
Capacity of millimeter wave PTP link	1.6 Gbps
Capacity of microwave PTMP link	370 Mbps
Sector of AP	90°
Cost of microwave PTP link	\$35,050
Cost of millimeter wave PTP link	\$40,890
Cost of microwave PTMP terminal	\$15,135
Cost of microwave PTMP AP	\$25,641
Cost of new AN	\$35,050
Nodal degree of root nodes	6
Nodal degree of nonroot nodes	3

Another important consideration in solving MILP problems is the computation time. Matlab's linprog uses branch and bound algorithm to solve MILPs and this algorithm suffers from exponential worst case complexity. Finding a solution is, thus, time consuming except for a backhaul of few nodes. To get a solution in a reasonable amount of time, the optimality gap option of the tool can be used. Optimality gap, in branch and bound algorithm, is defined as the difference between the upper and lower bands. A tolerable 5 % is chosen in all scenarios, to minimize the computation time.

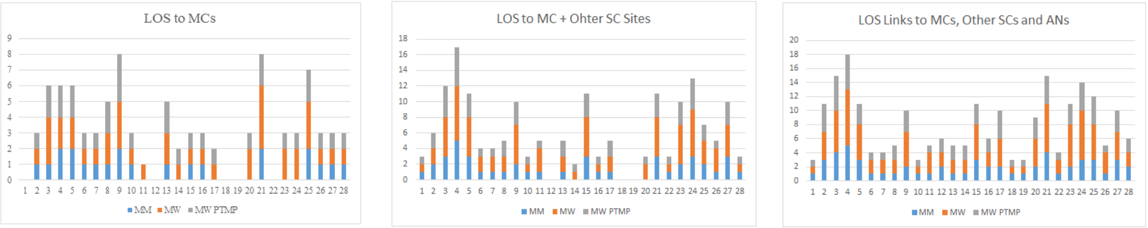
5 Results and Discussion

5.1 Link Feasibility

For each small cell, connectivity status to other backhaul nodes i.e. MC, other SC and AN, is identified using the result of RT path loss predictions and the maximum path loss criterion described in Chapter 4. The connectivity status with LOS links and LOS/NLOS links for the three wireless technologies is shown in Figure 5.1 and Figure 5.2, respectively. Here, connectivity status means the number of links the 28 small cells have to other nodes in the network and what technologies are feasible.

For only LOS case, 23 of the 28 small cells have feasible microwave PTP links to either of the 9 macrocells, see Figure 5.1a. This number decreases to 17 for millimeter wave links due to the frequency dependency of the path loss. For the microwave PTMP LOS case, the observed difference is in average number of macrocells a small cell has feasible links to; 1.1 macrocells as compared to 1.4 to that of PTP. This could be attributed to the 14 dB lower gain of the sector antennas used at PTMP AP. As can be seen in Figure 5.1c, 3 of the 4 candidate AN are needed to provide connectivity to the 3 small cells which have no LOS connectivity to either existing macrocells or other small cells. The numbers here are larger as compared to [7]. This maybe mainly due to the higher ratio of macrocell to small cell in this work; 9:28 as compared to 2:23 in [7]. The areas used for planning also contribute to the difference.

With both LOS and NLOS allowed in the network, the number of small cells with feasible microwave PTP links to macrocells increased to 25 from 23 when only LOS links were allowed. There is also an increase in the average number of macrocells a small cell has feasible links to: from 1.4 to 1.8. The associated higher path loss in millimeter wave propagation and the lower gain of microwave PTMP decreased the performance of these technologies in these scenarios too. Only one of the candidate aggregation nodes was needed to create connectivity to the only unconnected small cell in the backhaul; the other 27 small cells have



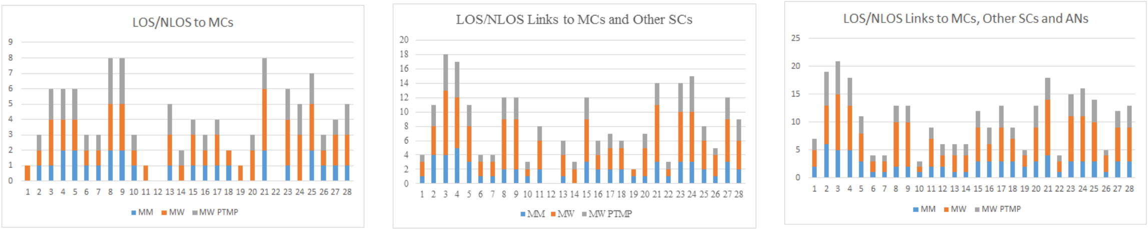
(a) LOS Availability to MC Locations.

(b) LOS Availability to MC and other SC Locations.

(c) LOS Availability to MC, other SC and AN Locations.

FIGURE 5.1: LOS Links from SC to MC, other SC Locations and AN.

feasible LOS/NLOS links either a macrocell or other small cells in the network as is shown in Figure 5.2.



(a) LOS/NLOS Availability to MC Locations.

(b) LOS/NLOS Availability to MC and other SC Locations.

(c) LOS/NLOS Availability to MC, other SC and AN Locations.

FIGURE 5.2: LOS/NLOS Links from SC to MC, other SC and AN Locations.

The details of link level simulation are presented from Tables 5.1 - 5.3 for LOS, NLOS and LOS/NLOS links. Microwave PTP technology outperforms both millimeter wave PTP and microwave PTMP technologies. The tables show that consideration of NLOS links increases the number of feasible links a network planner can choose from to achieve the planning objectives. This will be demonstrated in the following section.

TABLE 5.1: Small Cells with LOS Links to other Nodes in the Backhaul

Backhaul Nodes	Number of SC with Microwave PTP Links	Number of SC with Millimeter wave PTP Links	Number of SC with Microwave PTMP Links
MC	23	17	22
SC	17	13	13
AN	16	12	12
MC/SC	25	23	25
MC/AN	27	23	25
MC/SC/AN	28	28	28

TABLE 5.2: Small Cells with NLOS Links to other Nodes in the Backhaul

Backhaul Nodes	Number of SC with Microwave PTP Links	Number of SC with Millimeter wave PTP Links	Number of SC with Microwave PTMP Links
MC	10	4	4
SC	13	8	7
AN	8	2	2
MC/SC	20	11	10
MC/AN	14	6	6
MC/SC/AN	20	12	11

TABLE 5.3: Small Cells with LOS/NLOS Links to other Nodes in the Backhaul

Backhaul Nodes	Number of SC with Microwave PTP Links	Number of SC with Millimeter wave PTP Links	Number of SC with Microwave PTMP Links
MC	26	20	22
SC	25	18	17
AN	20	13	13
MC/SC	27	26	26
MC/AN	28	25	26
MC/SC/AN	28	28	28

5.2 Backhaul Network Planned under Different Scenarios

The results of backhaul planning scenarios under different small cell traffic demands, and inclusion and exclusion of NLOS links is presented here. The scenarios are given in Table 4.4. And additional parameters used in the optimization problem can be found in Table 4.5. The topologies of the resulting backhaul networks for scenarios 1, 2, 3, 4 and 6 are shown from Figures 5.3 to 5.7. No feasible set was found for scenario 5.

The summary of the wireless solutions is presented in Table 5.4. Scenarios 1 and 2 have the same small cell demands but due to the consideration of NLOS links in the later scenario there is a cost reduction by 7.92 % to the former. One can also see this trend for scenarios 3 and 4: they both have the same demand and only difference is the later allows NLOS links into the backhaul network. The resulting reduction in cost is 10.6%. Scenarios 5 and 6 are also of same small cell demand but no solution was found for the former one. Inclusion of NLOS is a necessary condition for this small cell demand to provide connectivity using the three wireless technologies and their corresponding system configurations.

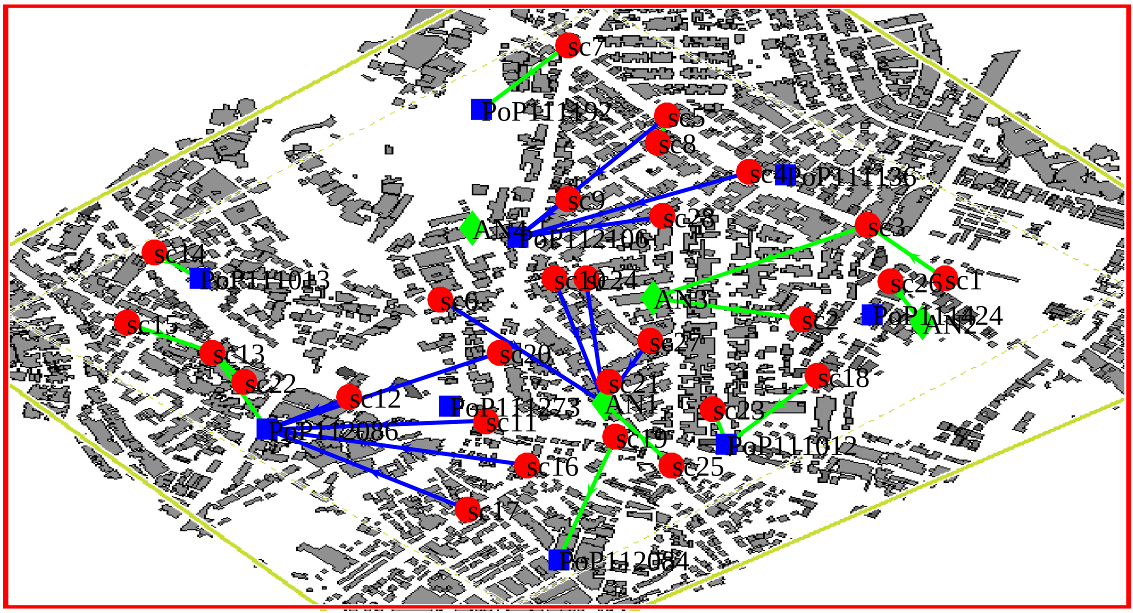


FIGURE 5.3: Planned Backhaul for Scenario 1. Red circles represent SCs, blue squares MCs and green diamonds new ANs. Green arrows are for microwave PTP links..

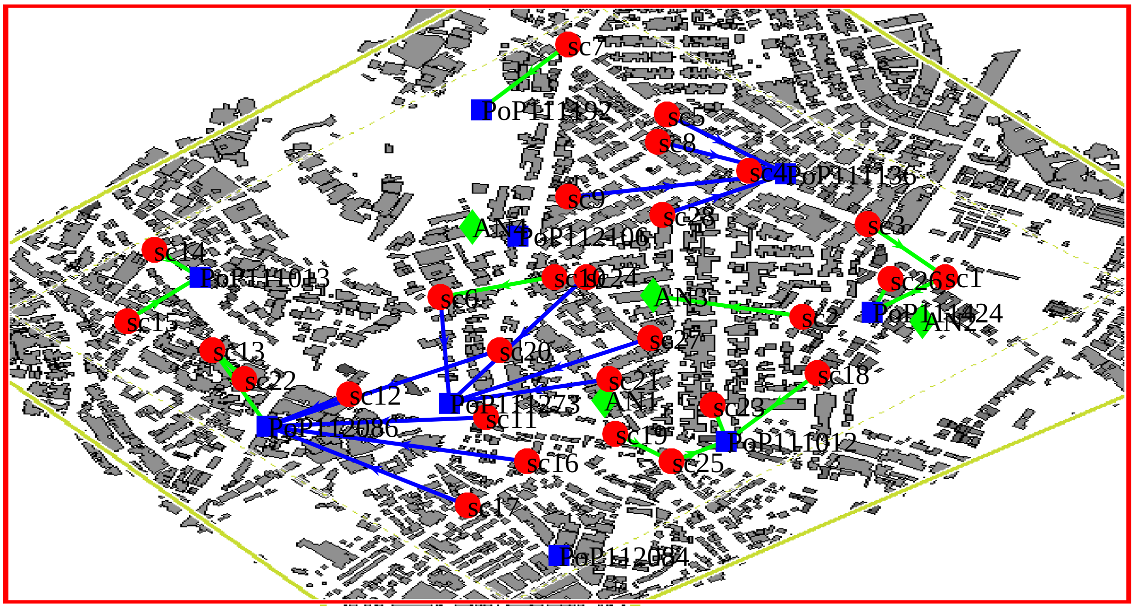


FIGURE 5.4: Planned Backhaul for Scenario 2. Red circles represent SCs, blue squares MCs and green diamonds new ANs. Green arrows are for microwave PTP links.

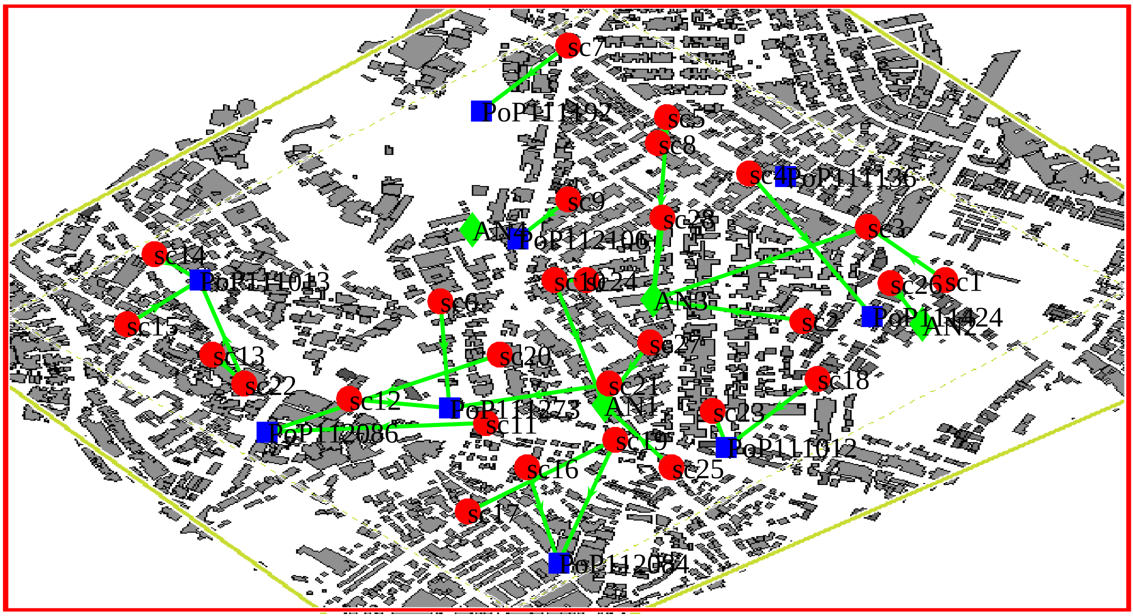


FIGURE 5.5: Planned Backhaul for Scenario 3. Red circles represent SCs, blue squares MCs and green diamonds new ANs. Green arrows are for microwave PTP links.

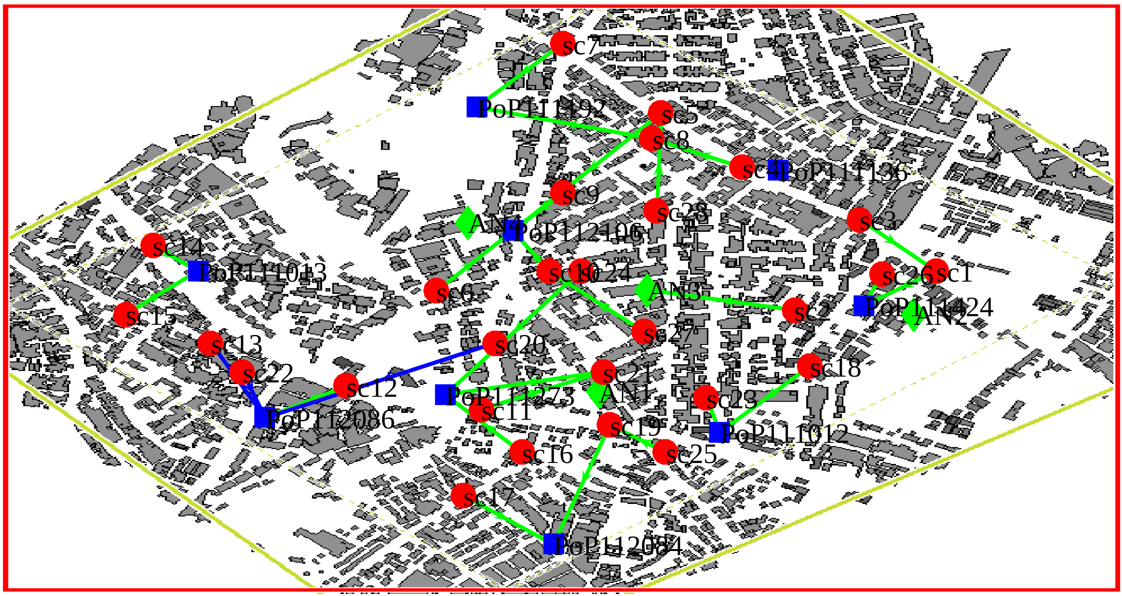


FIGURE 5.6: Planned Backhaul for Scenario 4. Red circles represent SCs, blue squares MCs and green diamonds new ANs. Green and blue arrows are for microwave PTP and PTMP links.

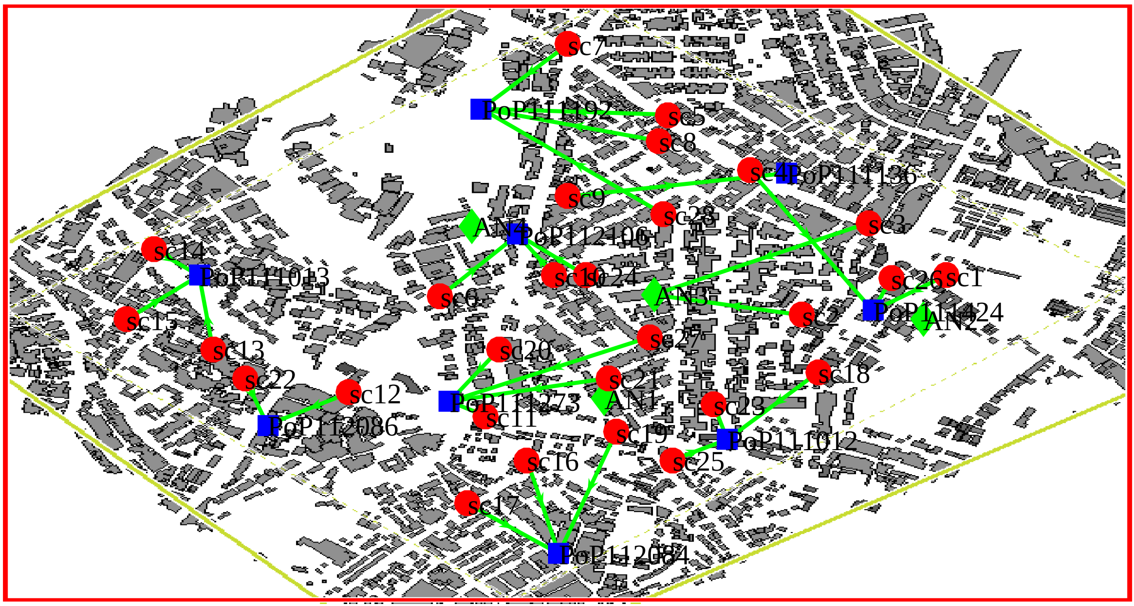


FIGURE 5.7: Planned Backhaul for Scenario 6. Red circles represent SCs, blue squares MCs and green diamonds new ANs. Green arrows are for microwave PTP links.

TABLE 5.4: Summary of Backhaul Solutions for Planning Scenarios

No.	Number of Links by Technology			Number of AP	Number of AN	TCO	Optimality Gap
	Microwave PTP	Microwave PTMP	Millimeter Wave PTP				
1	14	14	0	3	3	884678	1 %
2	14	14	0	3	1	814578	2.18 %
3	28	0	0	0	3	1086550	4.68 %
4	25	3	0	1	1	982351	5 %
5	-	-	-	-	-	-	-
6	28	0	0	0	1	1016450	0

Regarding practical aspects, solutions of 0 - 5 % optimality gap were found for the 5 scenarios in less than two hours, and they can be considered of good quality as compared to 10 % in [8], see Table 5.4. This computation time can be considered reasonable since the optimization problem is formulated for a planning purpose.

6 Conclusion and Future Works

6.1 Conclusion

To build a cost effective small cell backhual, operators need a planning method that leverages on practical wireless technologies. This work has analyzed the technical feasibility of microwave and millimeter wave band systems in providing connectivity to small cells located in the clutter, below rooftop level. Two configurations were considered: PTP/PTMP and LOS/NLOS. At relatively short distances (few hundreds of meters) which are typical of small cell backhaul, NLOS links can be feasible due to the higher antenna gain of microwave and millimeter wave bands. The selected NLOS model, single diffraction over vertical or horizontal wedges, has given a useful number of feasible links in all bands and configurations and thus should be considered in backhaul networks. The number of feasible PTMP links is found less as compared to PTP links due to the lesser antenna gain of sector antennas used at APs. Their applicability should be for low order modulation orders, or for shorter link distances.

A method based on MILP formulation is proposed for planning small cell wireless backhaul network of tree topology. The MILP includes technological constraints of the wireless solutions and the requirements of the backhaul. Instances of the MILP were created for six backhaul scenarios and solved using branch and bound algorithm. Whenever PTMP is available, it is found to be part of solution when demand is small, resulting in cost minimization. Consideration of only LOS links leads to the costly construction of new aggregation nodes. The case study was done for microwave PTP and PTMP, and millimeter wave PTP systems of one link configuration for each technology. Any variety of technologies based on PTP and PTMP are allowed in the formulation. Regarding the computation time for the 41 nodes network, all scenarios are solved within 2 hours with a tolerable optimality gap of less than 5%.

6.2 Future Work

This work used a propagation modeling tool made for radio access network simulation. A simpler RT modeling tool for path loss prediction would have made computation time less, and integrating the results into the proposed MILP a lot easier. Studying visibility algorithms and using them to build an RT tool tailored to planning small cell backhaul is important. Joint optimization of backhaul and small cell planning could also be done as an extension to this work.

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