Optimizing the Location of Base Transceiver Stations in Mobile Communication Network Planning: Case study of the Nairobi Central Business District, Kenya

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Abstract

Optimal signal coverage has always been a fundamental issue for cellular network operators. Other issues related to capacity, quality of service and cost efficiency are also rapidly gaining prominence. In order to determine signal coverage, network engineers usually rely mainly on two dimensional (2D) terrain maps and rather simple empirical propagation-prediction models. In this study a framework which provides a more efficient and cost effective network coverage optimization for a dense urban environment was investigated. 3D Geographic Information System (GIS) of the study area was developed. The signal propagation-prediction tool based on ray-tracing coupled with the 3D geo-information was used to model the radio signal coverage for the Base Transceiver Stations for one of the mobile phone operators licensed to provide mobile phone services in Kenya. To determine the best locations of the BTSs for optimal signal coverage of the study area, spatial analysis tools in GIS were employed. Comparing the proposed methodology with classical methods demonstrates that this spatial analysis approach can be used to optimize mobile signal coverage in any dense urban environment without resorting to lengthy field measurements thus minimizing on costs of wireless network planning.

Key words: signal coverage, wireless network optimization, ray-tracing, GIS, BTS
1. INTRODUCTION

Wireless communication is one of the most rapidly growing industries worldwide. Whether it’s the ubiquitous cellular phones, pagers, or the more traditional systems such as radio and television broadcasting, wireless communication has become a fundamental infrastructure rivaling other traditional infrastructures such as transportation, electric and water systems. Indeed, many developing countries have put the deployment of two-way communication systems at a higher priority than other traditional infrastructures.

With millions of dollars being spent on building wireless communication systems there is significant incentive to develop engineering tools that can be used in the accurate and efficient designing and planning of such systems. Considering that a single cell system base transceiver station (BTS) requires colossal amounts of money to set up, an efficient system design, which eliminates just one such station, can easily justify the expense of the design tool and the effort of using it. As the wireless system grows to meet increasing and changing demands for service, the design tool is again a valuable asset in planning optimum modifications to the system to accommodate growth.

Of fundamental importance to the wireless system design tool, is the ability to accurately predict the strength of radio signals from the various transmitters in the system. The mathematical algorithms used for prediction are generally known as propagation models. Traditionally, propagation models have relied on terrain elevation data as the major environment parameter on which to base computations. Consequently, substantial effort has been invested over the past several years in developing accurate digital terrain models (DTMs).

While terrain has a profound effect on the propagation of radio signals (especially at higher frequencies), more localized features of the environment, whether natural or man-made, such as structures (e.g. buildings) and trees can also have a substantial impact on propagation. Thus it is expected that in rural areas the signal propagation is mostly affected by the terrain, while in highly built-up urban areas this is largely influenced by local obstructions especially buildings.

Man-made structures, such as buildings, exert a decisive influence on mobile communication, particularly in urban environments where the size of structures is greater. In rural environments, features such as isolated trees or groups of trees may have similar effects. These environmental features may both block and scatter radio signals, causing specular and/or diffuse reflections (Stamm, 2001). These contributions may reach the mobile receiver via multiple paths in addition to that of the direct signal. Thus two extreme propagation channel scenarios may be distinguished; LOS (Line-Of-Sight) and NLOS (No-Line-Of-Sight).

In LOS scenarios, a strong direct signal is available together with a number of weaker multi-path echoes. This case occurs mostly in open land or in very specific spots in city centers, e.g. public parks or open parking lots, with good visibility of the transmitter. In this case the received signal is strong and quite steady, with small, slow and fast fading due to shadowing and multi-path effects. For NLOS scenarios, a number of weak multi-path echoes are received. This case is typically found in highly built-up urban areas. This is the worst of all situations, because the received signal is weak and subject to marked variations due to shadowing and multi-path effects. This kind of situation may also occur in rural areas where trees and forests obstruct the signal.
Based on these two extreme scenarios, several different wave propagation prediction models have been developed which when combined with 3D-GIS (Geographic Information Systems) techniques for visualization, provide an invaluable tool to aid in predicting and ultimately optimizing cellular signal phone coverage within any area of interest. According to (Longley et al., 2005), a GIS is a spatial decision support system that can be used to input, retrieve, process, analyze, and output geographically referenced data or spatial data in order to support decision making for planning and management of natural resources and the environment.

The use of mobile phones has a direct impact on the deployment of BTSs. To serve an increasing number of users requires an increasing number of BTSs which requires enormous capital investment. This means that mobile cellular communication companies must carefully plan the deployment and configurations of BTSs in order to optimize signal coverage and thus support voice and data traffic at a level of Quality of Service (QoS) expected by customers and specified by the network regulator, while at the same time minimizing the cost.

In the early days of microwave tower placement, initial installations were often handled by sending technicians into the field and onto rooftops to physically check line of sight connections between antennas (Ledner, 2005). This approach nevertheless proved to be too time consuming and costly. Thus computer-based planning tools were gradually developed to help radio network planning engineers in the difficult task of balancing requirements of radio coverage and quality with economic and other aspects. These planning tools mostly make extensive use of terrain databases and visualization tools based on 2D geospatial information. They mostly make use of 2D maps as information basis which among their many shortcomings, limit the data visualization to an orthographic map view.

Furthermore, because radio communication between base stations and users is crucial, all computations in a planning tool are based on the use of radio-propagation predictions. Until recently, empirical propagation prediction seemed sufficient. However, more efficient planning and the need to plan for non-voice services (the so-called value-added-services e.g. SMS, internet etc) or of a mixture of voice and non-voice services, require more accurate propagation-prediction models. These models must of necessity be based on the computation of the physical interaction of radio waves and the environment. This calls for more detailed geo-databases, especially in highly built-up urban environments where most users are located.

The overall objective of this research is to optimize cellular phone signal coverage in a densely built-up urban environment, with part of Nairobi City CBD as the study area. The Airtel mobile phone network was used for demonstration purposes. Airtel Kenya (formerly Celtel Kenya Ltd), founded in the year 2000, is the second mobile telephony company to be licensed to operate the Global System for Mobile communication (GSM) technology in Kenya.

The specific objectives of the research were to:
   a) Develop 3D-GIS for the study area
   b) Map Airtel’s BTSs network covering the study area and generate a signal coverage map for the BTSs using an appropriate propagation model
   c) Generate signal coverage map for the Airtel’s BTSs using data acquired through field measurements of signal strength
d) Determine best BTSs location that provide optimal signal coverage using 3D geo-information and GIS analysis techniques

In dense urban environments, man-made structures (buildings, street furniture, street lighting posts etc), terrain and trees, exert influence on mobile communications. In this research however, only buildings and the terrain were considered since they offer the greatest influence on signal propagation. In order to achieve the desired QoS objectives in cellular network design, two of the most important issues which must be considered are BTS siting and frequency assignment. In this research, only BTS siting was considered since it has a direct correlation with signal coverage.

2. PROPAGATION MODELS AND WIRELESS NETWORK OPTIMIZATION

A propagation model is a set of mathematical expressions and algorithms used to predict radio channel characteristics for a given environment. Prediction models can be empirical (statistical), deterministic (physical), or a combination of the two (semi-deterministic). To implement a mobile radio system, wave propagation models are necessary to determine propagation characteristics for any arbitrary BTS installation. The predictions are required for a proper coverage planning, determination of multi-path effects as well as interference and cell calculations, which are the basis for the high level network planning process. The environments where BTSs are intended to cover range from in-house areas up to large rural areas.

Deterministic models provide the most accurate and site specific coverage information but are restricted by the computational resources. Two different deterministic approaches exist; one based on simplifying the electromagnetic formulas (Maxwell’s equations) and one based on the ray-tracing methods (Hjelt, 2001). Radio propagation models derived from Maxwell’s equations have however been found impractical in real environments. Ray-tracing is the method adopted for almost all deterministic models. It takes into account diverse physical phenomena including reflections, diffractions, and diffuse scattering.

Ray-tracing is quite complex since it attempts to follow possible ray path routes from source point (transmitter) to the receiver. These ray paths may undergo multiple reflections, diffractions and/or scattering effects incurring long processing times. Consequently, ray-tracing based models are computationally expensive even for moderately complex geographic environments. For the ray-tracing results to be accurate, the propagation environment has to be described in much more detail and much more accurately (see e.g. Anderson, 1993, Catedra et. al., 1998, Stamm, 2001, Rappaport, 2004 etc.).

The aim of optimizing a network is to achieve certain quality of service (QoS) objectives. An optimized design usually results in substantial savings in the cost of equipment, and in an improvement in the reliability of the overall network. Researchers have in recent years been exploring some of the most difficult optimization problems arising in the design of cellular networks, namely, base transceiver station siting and frequency assignment. In this study, only the first optimization problem was considered. One of the key issues mobile phone companies must face when deploying a mobile phone network is the selection of a good set of sites for installing BTSs. The optimization problem hence comes down to serving a maximum surface of a geographical area with a minimum number of BTSs. The set of sites where BTSs may be installed is taken as an input, and the goal is to find a minimum subset of sites that allows optimal coverage of the service area.
In order to tackle this problem, researchers have employed various optimization techniques (see e.g., Calegari et al., 1999, Stamm, 2001, Mathar and Niessen, 2001, Hurley, 2002, Oliver, 2004 etc.). Some of the techniques commonly studied by researchers include: Greedy algorithms, exact algorithms, Genetic algorithms, hill climbing algorithms, simulated annealing, Tabu search etc.

The deployment of these algorithms in the telecommunications industry has been rather slow however. This is primarily due to the fact that they are very complex and computationally intensive. In highly built up urban areas, the potential locations for BTSs will be on top of the existing building rooftops. Due to the spatial nature of the problem, Geographic Information Systems (GIS) can be considered as a potential tool for solving this particular problem. With its powerful functionalities in spatial data management and analysis, GIS has been effectively applied in solving the problem of BTSs siting in a dense urban area characterized with high-rise buildings.

3. METHODOLOGY

3.1 Description of the Study Area

The study area for this study comprised part of the Central Business District (CBD) of the City of Nairobi, Kenya (see Figure 1). This area is enclosed by the following streets; Moi Avenue to the east, University Way to the north, Uhuru Highway to the west, and City Hall Way to the south. The area was chosen because of its high concentration of skyscrapers and thus would be expected to provide maximum challenge for wireless signal coverage prediction. The signal coverage prediction methodology implemented for the study area can thus be applied to other parts of the City, as well as other Cities.

Figure 1: The study area
3.2 Preparation of Propagation Environment

For implementation of the ray-tracing model, the most important geospatial data are the clutter data i.e. buildings, trees and any obstacles within the environment which influences radio wave propagation, and the BTSs data. This clutter data was extracted from a topographical base map of Nairobi City which was acquired in hard-copy format from Survey of Kenya (SOK), the national mapping agency.

Using a digital photogrammetric workstation 3D coordinates of the buildings rooftops were obtained and stored in a tab delimited text format. During the process of extracting the building heights, it was discovered that most of the buildings had very irregular roofs. This necessitated heights to be obtained for a number of points within the roof. These heights were subsequently averaged to obtain the average roof level for each building. As indicated in (Wagen and Rizk, 2003), for typical urban environments, accuracy in the order of 1m for building heights is acceptable. The average height of each BTS antenna was provided as 2.5m above the roof level.

To prepare and ultimately visualize the physical propagation environment ArcGIS software was used. The base map of the study area was first scanned and saved in jpeg format. Using ArcMap the scanned image was geo-referenced. Buildings, roads, trees and spot heights were then digitized using on-screen digitizing method. For each class of digitized features, attribute information was also added. Some of the attributes added for buildings included; building name, building user, average building height and the parcel registration number. Using ArcScene, the propagation environment could be viewed in 3D (Figure 2). The buildings were extruded using their average building heights obtained by subtracting the ground level of the building from the average roof level. All the above spatial and attribute data were stored in a 3D-GIS geodatabase.

![Figure 2: 3D visualization of the study area](image)

3.3 Signal Strength Measurement

To aid in validating the prediction model used in this study, actual signal strengths were measured at different locations within the study area using an Alcatel mobile phone similar to the one used by Airtel-
Kenya field crew. 2D UTM coordinates of the sampled areas were simultaneously recorded using handheld GPS (Global Positioning System) equipment. These measurements were downloaded on a computer and stored in a Microsoft Excel file format. To compute the signal attenuation (in decibels) from the measured signal strength Equation 1 was employed. Table 1 shows the optimal signal reception ranges adopted by Airtel-Kenya Ltd.

\[
\text{Signal Attenuation (dB)} = \text{measured signal strength} - 110 \quad \ldots \ldots \text{Equation 1}
\]

Table 1: Optimum signal reception ranges

<table>
<thead>
<tr>
<th>Signal Attenuation (dB)</th>
<th>Quality of Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; -85 dB</td>
<td>Good</td>
</tr>
<tr>
<td>-85 to -95 dB</td>
<td>Marginal</td>
</tr>
<tr>
<td>-95 to -110 dB</td>
<td>Poor (potential loss of signal)</td>
</tr>
</tbody>
</table>

4. RESULTS

4.1 Signal Coverage Prediction for Existing BTSs

For signal propagation modeling, the propagation environment data (mainly buildings & terrain), the BTSs data, and mobile receivers’ data was input into appropriate software. The ray-tracing engine in this software was used to generate the signal coverage area. This coverage area could be displayed in both 2D and 3D. The prediction of signal coverage in this research was implemented using the student version of RPS (Radio Propagation Simulator) software.

Figure 3: Propagation area covered by 2 BTSs.
To import the propagation environment data into *RPS*, the data was first converted to the dxf file format using the ArcToolbox software in ArcMap. The resulting dxf file was then imported into *RPS*. Due to the software limitations indicated above, the area to be used for signal coverage prediction is shaded in green (see Figure 3). In order to accommodate all the buildings in the area in *RPS*, the shapes of some buildings were simplified. The buildings’ roofs were then added to each building. The buildings were all assumed to have flat roofs.

To perform accurate wave propagation prediction in *RPS*, the materials properties of the buildings walls and roofs had to be defined. The buildings walls were defined to be made of stone while the roofs were of concrete. The BTSs antenna parameters i.e. type, frequency, power and height above building top (or altitude) were then defined. Before starting the signal prediction for the BTSs, mobile receivers were placed in the propagation environment and their height above the ground defined to be 1.5m. The propagation simulation was then done using the 3D ray-tracing engine in *RPS*, first using each BTS separately and then using both BTSs at the same time. The results obtained when both BTSs were employed are shown in Figure 4.

![Figure 4: Signal coverage for both BTSs](image)

In order to verify the accuracy of the prediction model, the signal strength values obtained through field measurements were compared with those obtained through the use of the ray-tracing prediction model. In ArcMap, the signal attenuation values obtained from the actual signal measurements of the study area were used to generate a TIN (Triangulated Irregular Network) surface model. Regardless of their complexity all buildings could be accommodated in ArcMap and thus there was no need to generalize building shapes as is required in *RPS*.

Using the signal coverage map derived from the ray-tracing model, signal attenuation values were extracted for some points at which actual signal strengths had been measured. The points chosen were those well within the study area to prevent getting erroneous readings as a result of the influence of BTSs in other areas.
neighboring cells. The results are shown in Figure 5. To further assess the accuracy of the ray-tracing propagation prediction model, a statistical analysis was performed. In this case the hypothesis to be tested was whether the means of the attenuation values obtained from the ray tracing and field measurements were statistically different. The test scheme employed is outlined in Table 2.

![Figure 5: Comparison of signal attenuation values](image)

**Table 2: T test scheme for assessing accuracy of ray-tracing model**

<table>
<thead>
<tr>
<th>Null hypothesis:</th>
<th>$H_0 : \mu_{FM} = \mu_{RT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative hypothesis:</td>
<td>$H_A : \mu_{FM} \neq \mu_{RT}$</td>
</tr>
<tr>
<td>Test statistic:</td>
<td>$T = \frac{\mu_{FM} - \mu_{RT}}{\sqrt{\frac{S_{FM}^2}{N_{FM}} + \frac{S_{RT}^2}{N_{RT}}}} = 0.759; (v = 80)$</td>
</tr>
<tr>
<td>Test value:</td>
<td>$t_{(0.025,80)} = 1.99$</td>
</tr>
<tr>
<td>Test decision:</td>
<td>$H_0 : t_{(0.025,80)} \neq T; H_A : t_{(0.025,80)} \neq T$</td>
</tr>
</tbody>
</table>

Where $\mu_{FM}$ and $\mu_{RT}$ are the sample means, $S_{FM}$ and $S_{RT}$ are the sample standard deviations, whereas $N_{FM}$ and $N_{RT}$ are the sample sizes. The null hypothesis was accepted. It was thus inferred that within 95% confidence interval the two means were statistically equal.

### 4.2 Signal Coverage Optimization

The algorithms currently employed in network optimization are extremely complex and computationally intensive. To achieve the study objectives in a fast and effective way, the problem was considered as a spatial analysis problem and GIS techniques adopted (Munene, 2009). The best locations for BTSs were determined in a two stage process, namely:

a) selecting the potential sites, and

b) determining the best locations using optimization
4.2.1 Potential BTS Sites Selection

Selecting the potential sites for the BTSs was achieved by applying a constraint-based pre-processing phase on the spatial data within the propagation environment in order to filter out unsuitable locations. Thus the potential sites needed to satisfy the following criteria:

a) Building-use constraint: Some buildings are not suitable simply because of their use. These include restricted buildings such as state security buildings; media houses; fuel stations; national monuments; bus stops, and public toilets. In ArcMap, all buildings being used for the purposes listed above were selected on the basis of their building-user attributes. These buildings were subsequently eliminated as potential sites (see Figure 6). The remaining potential sites were then subjected to the next constraint.

![Figure 6: Applying building-use constraint](image)

b) Building-height constraint: In order to increase signal spatial coverage, it would seem logical to select the highest buildings within the coverage area as the best BTS location. However, due to various other considerations such as physical planning (visual impact), effects of wind pressure on the BTS antenna, safety of aircrafts, and accessibility (for maintenance purposes), the tallest buildings were not considered as potential sites. Very low buildings were also not considered as suitable BTS sites since ray paths emanating from such buildings would be prone to more obstacles and therefore contribute to low spatial coverage of the signals.

To resolve this problem an interval assessment was done with a threshold value for building height constraint first identified. In doing this it was reasoned that it would not be logical to site BTSs on buildings
whose height is below the average roof level of all the buildings within the study area. The average building height of all the buildings in the study area was calculated and found to be 20.79m. In ArcMap, any building whose height is below 20.79m was selected using the buildings height attributes and subsequently eliminated as a potential BTS site.

The upper threshold of suitable building height is mostly dictated by physical planning guidelines. In this particular case, the two most important considerations were that the BTS should not be sited where it results in significant adverse visual impact from the nearby streets or where it would be dangerous for flying aircraft. As stipulated in Bracknell Forest Borough Council (2002), it is required that a BTS should not exceed 10m in height and thus to meet the above requirements, it would not be logical to site BTSs on buildings whose heights are within 10m of the tallest building in the study area. The tallest building in the study area had a height of 103m. In ArcMap, any building whose height is above 93m was selected using the buildings height attributes and consequently eliminated as potential BTS site. The buildings eliminated as potential sites after applying the building-height constraint are shown in Figure 7.

Figure 7: Applying building-height constraint

### 4.2.2 Determining the Best BTS Sites
Path loss in the NLOS case is composed of the terms free space path loss $L_0$, multiple screen diffraction loss $L_{msd}$, and roof-top-to street diffraction and scatter loss $L_{rts}$ (Kürner, 1999):

$$
L_p = \begin{cases} 
L_0 + L_{rts} + L_{msd} & \text{for } L_{rts} + L_{msd} > 0 \\
L_0 & \text{for } L_{rts} + L_{msd} \leq 0
\end{cases}
$$

……..Equation 2
With
\[ L_0 = 32.44 + 20 \log_{10} (d) + 20 \log_{10} (f) \]

\[ L_{ets} = -16.9 - 10 \log_{10} (w) + 10 \log_{10} (f) + 20 \log_{10} (\Delta h_{mobile}) + L_{ori} \]

\[ L_{ori} = \begin{cases} 
-10 + 0.354 \varphi & \text{for } 0^\circ \leq \varphi < 35^\circ \\
2.5 + 0.075 (\varphi - 35) & \text{for } 35^\circ \leq \varphi < 55^\circ \\
4.0 - 0.114 (\varphi - 55) & \text{for } 55^\circ \leq \varphi < 90^\circ 
\end{cases} \]

\[ \Delta h_{mobile} = h_{roof} - h_{Rx} \]
\[ \Delta h_{Tx} = h_{Tx} - h_{roof} \]

Figure 8: Coverage area divided into circular cells

The model works best when \( h_{Tx} >> h_{roof} \). When \( h_{Tx} \) nears \( h_{roof} \), large errors can be expected. In order to determine the best BTS site for optimal signal coverage, the coverage area was first divided into cells. For simplicity, these cells were considered to be circular. The radius of each cell is equal to the maximum transmission distance of the signal. Using Equation 2 this distance was computed as 236m. In order to find the centre of each cell, the coverage area was divided into square grids whose diagonals equal twice the maximum transmission distance. Using ArcToolbox, the grids centroids which define the cell’s centre were
extracted. In ArcMap, buffers whose radius is equal to the maximum transmission distance to the grids centre points were applied. These buffers define the circular cells and were overlaid on the remaining potential BTS sites identified from the first two constraints (see Figure 8).

![Figure 8: Best locations for BTSs](image)

Figure 9: Best locations for BTSs

It is apparent from Figure 8 that the cells intersect. The intersection areas are useful since this is where the calls *handover* from one cell to another takes place. Thus it would not be logical to site the BTSs on buildings within the handover areas. In ArcMap, all buildings which are partially or wholly within the handover areas were selected as unsuitable BTS locations. After eliminating the buildings within the handover area, only buildings which are potential BTS sites were left. In order to determine the buildings offering the best location for optimal signal coverage of each cell, proximity analysis in ArcMap was used to find the buildings nearest to each cell centre. This step gave the final solution which is shown in Figure 9. Cell 6 was not considered since its centre is outside the study area.

5 CONCLUSIONS

Wireless network planning is a complicated task for network engineers. The most important consideration, particularly at the beginning of the wireless network design process, is optimizing the radio signals’ spatial coverage of the target area. Dense urban environments characterized by high-rise buildings are particularly challenging to the network engineer owing to the numerous factors which affect the signals and which must
be modeled as accurately as possible. As demonstrated in this study, the 3D ray-tracing model, when used with 3D geodatabases of the target area, is the most accurate method of modeling signal coverage.

The location of BTSs plays a crucial role in ensuring optimal signal coverage. Thus in wireless network design the determination of the best BTS sites that offer optimal signal coverage is a very important consideration, which must be handled with utmost seriousness. This is particularly important due to the fact that setting up of a single BTS requires colossal amounts of money and thus elimination of any redundant BTS(s) would result in significant savings for the network operator.

The problem of optimum BTSs siting is a target of much research work with various algorithms being employed. However, most of these algorithms are very complex and computationally intensive. This research has demonstrated that the powerful spatial analysis tools available in Geographic Information Systems (GIS) can be used to tackle this problem in a much more efficient and simpler way, particularly for dense urban environments where the BTSs must be located on building rooftops.

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