A Cell Focused Approach to Propagation Prediction Modelling

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Abstract - **The design of cellular networks that are optimal in coverage as well as cost-effective requires the accurate prediction of the coverage of the radio frequency signal. To improve the accuracy of signal strength prediction, localised environmental features of the area under consideration have to be modelled to closely represent the real environment. The main problem in a selected area in the north of Pretoria that is characterized by a rolling hill terrain with mixed structures and trees is the estimation of the effect of all these localized features on the total path loss between a transmitter and a receiver. While terrain has a profound effect on the propagation of radio signals (especially at higher frequencies), more localized features of the environment such as trees and structures (buildings, houses, etc.) can also have a substantial impact on propagation. To cater for the effects of these localized features for a selected area, data from selected cells were obtained and analyzed to identify trends and errors. Based on this analysis, problematic cells were identified. The area was then analysed to establish whether it is rural, suburban or urban. The topology and morphology of the area was analysed. The contribution of each of the localized features to the path loss was established. Based on these factors, a conclusive correction factor for each feature was obtained. The defined correctional factors may be used to characterize new cells where no real data for the new region is available. This work attempts to model localized features of environment, for modifying, testing and optimizing a radio propagation model that takes into consideration the effect of rolling hill terrain with mixed structures and trees within the environment using a selected region as a test case.**

Index Terms — Cellular networks, Radio Propagation, Propagation Models, Model Tuning.

I. INTRODUCTION

Mobile telecommunication systems have experienced tremendous growth since they were put into operation in the early 1990s **[1]** and has since encroached almost every country in the world. Mobile systems have become one of the successful communication infrastructures in Africa primarily due to their ease of deployment. This has led to the expansion of mobile networks to accommodate the growing number of the subscribers. As a result, mobile system networks have to be designed accurately to allow for this expansion. Predictions of signal strength and propagation coverage area **[2]** are vital aspects in the design of wireless communication networks. The mathematical algorithms used for prediction are generally known as propagation models. Model tuning **[2, 3]** is a process in which a theoretical propagation model is "trained" with the help of measured data. The aim is to get the predicted field strength as close as possible to the measured field strength. This paper attempts to model the localized environmental features and then use them to tune the propagation model for optimal predictions.

II. MODEL TUNING APPROACHES

Model tuning starts with the selection of a propagation model **[3]**. There is several correction methods applied to the basic path loss based on morphology, topology, etc. **[2].** There are three basic approaches utilized in the prediction of signal strength and propagation coverage area namely statistical tuning, deterministic tuning and semi-statistical tuning.

A. *Statistical Tuning Approach*

This method uses "predictors" in general statistical modelling theory **[3]**. These are parameters that have been found through statistical analysis to bear relationship to the quantity that is to be predicted. First, the appropriate statistical model is selected. Then, the model is used to predict the field strength of a given network. Next, drive tests are carried out to collect measurement data of the network. The data is then analysed to identify trends and errors before converting it into a suitable format to calibrate the predictor's coefficients. The iterations are repeated several times to minimize the error between the predicted and the measured field strength **[2, 3]**. In the statistical tuning approach, all environmental influences are implicitly taken into account regardless of whether they can be separately recognized. Thus, the accuracy of this approach depends not only on the accuracy of the measurements, but also on the similarities between the environment to be analyzed and the environment where the measurements are carried out **[4]**.

B. *Deterministic Tuning Approach*

In this method physical laws governing the interaction of electromagnetic waves with the physical elements of the propagation environment are focused on. It begins with the selection of a propagation model. Detailed data on morphology, topology, street orientation, **[2]** etc. are used to

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model the physical environment to adjust the coefficients of the model chosen. This is repeated to minimize the errors in the model approximating the real physical environment. The physical environment model is simplified by the use of path loss approximation models for diffraction, reflection, refraction, and absorption **[3, 5]**.

C. Semi-Statistical Tuning Approach

The semi-statistical approach is based on the application of deterministic methods to generic rural or urban models. It uses calibrations to improve the agreement of the model with measurement data. It requires more information than the statistical approach, but less than that of the deterministic approach. It is a compromise between the two approaches discussed above. It tends to have both the advantages of the statistical and deterministic approaches. The inclusion of deterministic correction factors improves the accuracy of the statistical models as a result of the model considering environmental factors influencing propagation in a more detailed form and facilitates the statistical propagation model to simulate the real environment as close as possible.

III. INFORMATION RICH RADIO-WAVE TUNING APPROACH

Predictions can be carried out on an individual cell or for groups of cells (cluster approach) intended to cover a given area **[3]**. Information rich radio-wave tuning stems from this statement. This approach is based on the three approaches discussed earlier. The principle used is to establish a method of being able to tune propagation models for a *single cell* based on a well established correction factor as opposed to the cluster tuning approach. The approach is of great importance to network operators in situations where only particular cells experience problems or morphology and topology of the cells are varied. Many factors are included in the determination of signal path loss to a specific point within the cell. The three main considerations are transmission of the signals, the environment, and losses due to multiple signal paths causing self-destructive interference **[3]**.

To determine the signal path loss from the cell site to a specific point within the cell, propagation models take into account transmission losses, environmental losses, and power margins to account for multi-path fading and environmental shadowing **[2]**. Once selected, the propagation models must be calibrated to accurately model a specific cell site. Typical calibrations include calculation of values for geographical environment parameters to account for factors such as the morphology, height differences between the transmitter and remote receiver, and the density and height of terrain features between the transmitter and receiver.

The calibration process involves modifying the model parameters to accurately approximate relevant measurement data **[3]**. Propagation measurement data is used to calibrate these propagation models. Propagation measurement data is obtained through field measurements taken at various locations throughout the cell. Once the raw data is collected, it is converted to appropriate format and used to characterize the cell site to its location. The calibration process uses the field data collected to define parameters, variable coefficients and constants of equations used to model cell coverage. The advantage of this model is that it focuses on a small area and therefore models the real environment closely. However it is tedious and time consuming if performed on a larger area.

IV. MODELLING OF PREDICTION ALGORITHM

If we assume isotropic conditions, the power flux density for a base transceiver station (BTS) in a given cell is given by:

$$\Phi_R = [P_T / 4\pi d^2] \qquad (1)$$

$4\pi d^2$ is the surface area of the sphere, P_T is the power of the transmitter and d is the distance between BTS and MS. The power captured by the mobile station (MS) in a given cell is:

$$P_R = [\lambda / 4\pi d]^2 P_T = P_T / L_p \qquad (2)$$

Where $[\lambda^2 / 4\pi]$ is the absorption cross section and $L_p = 1 / [\lambda / 4\pi d]^2$ is the free space path loss between the BTS and MS in a cell. But real BTS and MS are not isotropic, thus the aspect of antenna gains for both BTS and MS antennas **[2, 3]** are considered. Thus,

$$P_R = P_T G_T G_R L_p \qquad (3)$$

Where G_T and G_R are BTS and MS antenna gain respectively. Equation (3) can be represented in dB as follows.

$$P_R (dB) = P_T (dB) + G_T (dB) + G_R (dB) - L_p (dB) \qquad (4)$$

Where $X (dB) = 10 \log_{10} (X)$. This model only accounts for the transmission loss.

Multi-path modelling predicts the effects of multiple signal paths and resultant destructive interference at the received location, namely multi-path fading **[3]**. Multi-path fading results from multiple paths taken by a signal from the BTS to a specific point within a cell. When two or more signal components arrive at a particular MS point in space after travelling different distances, the resultant signals may no longer be in phase. Thus, when these signals are combined, the difference in the phase shifts may combine destructively and produce a degraded sum signal at the specific point. Accordingly, for system planning purposes, power margins are normally included in path loss predictions to account for the effects of multi-path fading. Thus equation (4) can be represented as follows.

$$P_R = P_T G_T G_R h_T^2 h_R^2 [1 / d]^2 \qquad (5)$$

Where h_T and h_R are BTS and MS antenna heights in *m*. Environment modelling involves determining the effects of the terrain features between the BTS and the specific position within the cell. Modelling of the environment includes the signal reduction due to the distance from the BTS as well as diffraction losses caused by buildings or other terrain features between the BTS and specific points within the cell. Furthermore, since radio propagation conditions vary significantly in typical operating environments, signal path loss models normally account for the statistical variability of the received signal by incorporating suitable power margins for the purpose of cell planning. The equation used to approximate the prediction model in dB can be represented as follows.

$$P_R = P_T + C_{CT} + C_d \log d + C_{dh} \log d \log h_T + C_h \log h_T + C_{dk} K_{dk} + C_{dr} K_{dr} + C_{CI} K_{CI} + G_T + G_R \qquad (6)$$

Where C_{CT} is a fixed correction term, C_d is the distance correction term, d is the distance in meters, C_{dh} is distance and BTS height correction factor, C_{dk} is knife-edge correction term, K_{dk} is knife-edge diffraction loss factor, C_{dr} is a rounded hill correction term, K_{dr} is a rounded-hill diffraction loss factor, C_{CI} is clutter correction term, K_{CI} is the clutter factor.

The Okumura-Hata path loss propagation model was selected as a testing model before taking into account other models. This is due to its popularity, simplicity and ease of use. The algorithm is as follows.

$$L_{dB} = 69.55 + 26.16 \lg_{10} f - 13.82 \lg_{10} h_T - \beta + (C - 6.55 \lg_{10} h_T) \lg_{10} d \qquad (7)$$

Where C = 44.9, β is the environmental correction factor, and f is frequency (MHz).

V. MODELLING OF THE CORRECTION FACTORS

The study was carried out in a Northern suburb of Pretoria. The scanned map and the digital terrain map are shown in figures 1 and 2 respectively.

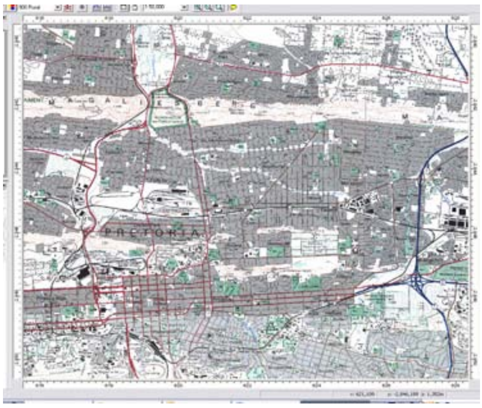

Figure 1: *Scanned Map of Area Studied*

Every physical entity that the radio signal encounters after it leaves the transmitting antenna affects the strength and direction of the signal **[6]**. The physical entities that impact the signal can be grouped into four broad categories

(i). The atmosphere (or other gaseous media) which refracts (bends) and diffracts (scatters) the radio waves.
(ii). Terrain features (hills and mountains) that block the radio waves, requiring them to diffract over the top or around the sides, weakening the signal on the other side.
(iii). Like terrain, structures such as buildings, houses, towers, etc. block the radio waves.
(iv). Leaves and branches of trees weaken radio waves by scattering them.

The atmosphere and terrain have been included for many decades in the propagation models which are designed to predict the strength of radio signals. Only recently has propagation modelling attempted to incorporate information about structures and foliage and their impact on transmitted signals.

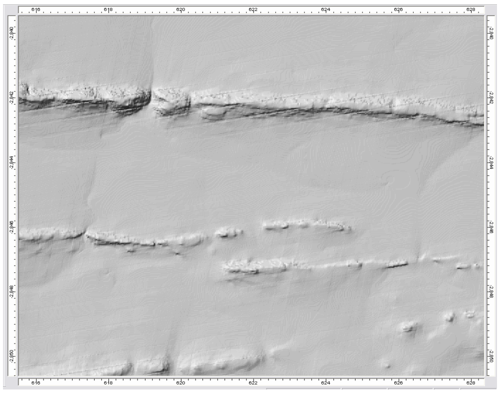

Figure 2: *Digital Terrain Map of Area Studied.*

The measurement data was obtained through drive test in the area under study. Predictions were carried out using MATLAB based on the Okumura-Hata model. The data was analyzed and cells with conflicting results were identified. The result obtained from a studied cell is depicted in figure 3 below. Usually in the Okumura-Hata model, the slope C can be changed which amounts to the tuning of the slope **[2]**. In rural areas C is lower and higher in urban areas. The optimum value of C for this case was 34.9.

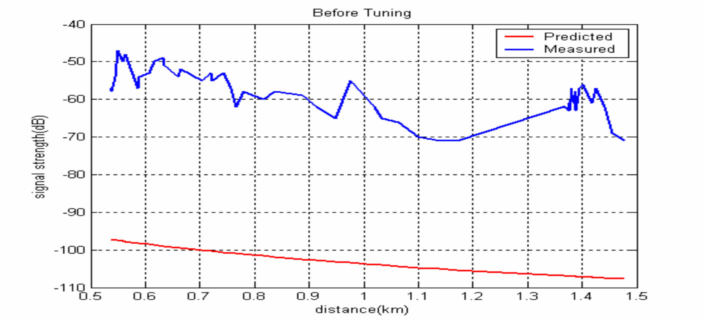

Figure 3: *Measured and Predicted Results*

The Clutter and the Digital terrain map of the area were used to characterize the particular cell. First, it was established that it is a suburban region and hence, the use of suburban correction factor in addition to urban areas correction factor was used **[6]**.

$$\beta_{urban} = 3.2(\lg_{10}(11.75\, h_R))^2 - 4.97 \qquad (8)$$

$$\beta_{suburban} = \beta_{urban} - 2(\lg_{10}(f/28))^2 - 5.4 \qquad (9)$$

The MS height chosen was 2m. The terrain height of the area was then analyzed and the path to every measurement point studied carefully. The RF planning tool, ATOLL, **[10]** was used to give the loss attributed to each terrain obstacle with reference to the measurement point. Based on point analysis, (figure 4) values for the diffraction factor corresponding to each terrain obstacle were noted. From these, the correction factor for each path was used to alter the predicted value.

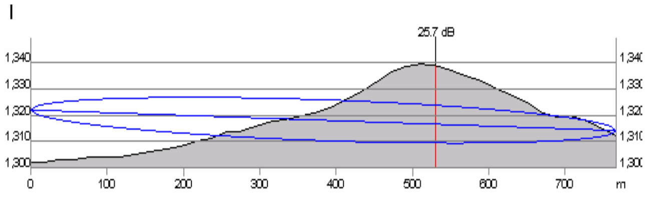

Figure 4: *Point Analysis Window Estimation*

The last correction factor to be considered was land use / land cover (LULC) data of this region. Morphology correction for the various morphology classes was considered. The radio path to each measurement and prediction point was analyzed and the morphology classes traversed noted. The distance covered by each morphology class was recorded and then taken as a ratio of the total path distance.

From this, the most encountered morphology type was buildings. On average, the buildings were found to be 5m tall. As in outdoor environments, radio propagation inside buildings is governed by mechanisms such as reflection, diffraction, and scattering from various objects. The field distribution inside building is therefore dependent on specific features of its internal structure (e.g., layout, construction materials). As no knowledge is available about these features, it is impossible to predict the exact internal field distribution. Instead, in an attempt to capture the global behaviour of the internal and transmitted fields, the building interior is treated as a homogeneous medium in which the excess propagation loss (the path loss relative to the free-space loss) can be described by a specific attenuation factor α_b, expressed in decibels per meter, and the propagation velocity is equal to that in free space.

If we let a point r_0 be the reflection point, we can then have a reflection coefficient $R(r_0)$ which relates the complex amplitude of the reflected field to that of the incident field and is dependent on the permittivity ε_r and the incidence angle $\theta_{i,0}$, which is defined as the angle that the incident electromagnetic wave makes with respect to wall of the building. $R(r_0)$ can then be represented as follows.

$$R(r_0) = \frac{\sin\theta_{i,0} - \sqrt{\varepsilon_r - \cos^2\theta_{i,0}}}{\sin\theta_{i,0} + \sqrt{\varepsilon_r - \cos^2\theta_{i,0}}} \qquad (10)$$

This reflection coefficient, in combination with values of the complex permittivity within a range that applies to most common building materials, is well known to provide an accurate approximation of the fields reflected from buildings and is used in most ray-based propagation models. A permittivity equal to 5 was shown to be an optimum choice in two independent studies **[7]**, **[8]** and will be used in this study. Since not all of the incident power is reflected, the rest is transmitted through the wall and thus we have the transmission coefficient $T(r_0)$. Because total power is conserved at the building surface, the part of the incident power that is not reflected back must be transmitted into the building interior, and is represented as follows.

$$|R(r_0)|^2 + |T(r_0)|^2 = 1 \qquad (11)$$

Neglecting a possible phase jump of the transmitted field at wall of the building, which is not important for the present application in any case, $T(r_0)$ can therefore be written as follows.

$$T(r_0) = \sqrt{1 - |R(r_0)|^2} \qquad (12)$$

The losses inside the exterior wall are not included in the transmission coefficient. Together with the other losses inside the building, they are accounted for by the attenuation coefficient $\alpha_b$as in figure 5 below.

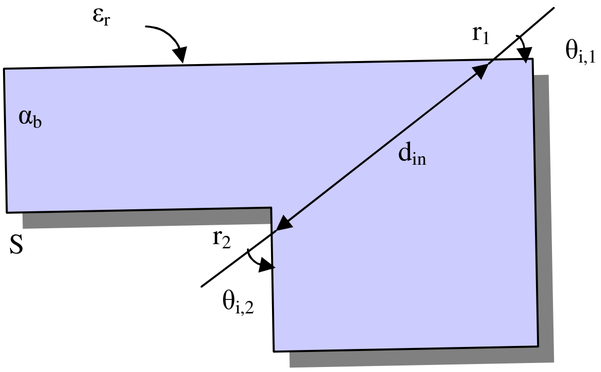

Figure 5: *Illustration of the Building Model (top view).*

The transmission points mentioned above are found with the aid of the generalized Fermat's principle, which states that the optical path length of each transmitted ray must be an extremum—a minimum in the present case—with respect to movement of the transmission point over the building wall. In practice, this means that transmitted rays can be traced straight through building walls, as if none were present. The excess attenuation due to the building, which we will call the building-transmission loss, is then found to be follows.

$$L_b = \alpha_b * \sum_{i=1}^{M} d_{x_j}^{i} - 20\log_{10} T(r_1) - 20\log_{10} T(r_2) \qquad (13)$$

Where $d_{x_j}^{i}$ is the distance covered by single i th occurrence of a particular clutter type along a given radio path. The distance covered by buildings on the radio path over the distance of the radio path multiplied by the building transmission loss gave the total contribution of the buildings to the loss due to morphology **[9]**.

Another class considered was the foliage due to trees in the area. It is known that vegetation produces a constant loss independent of distance as long as the radio path is over one km which increases as the fourth power of the frequency [9]. Buildings are the main source of attenuation but vegetation elements such as trees and large bushes can also have some reducing effects on the propagated radio signal. In the case of attenuation by trees and bushes, the incident electromagnetic field mainly interacts with leaves and branches. The tree trunk does have some influence on the attenuation, but since the volume occupied by the trunk is much smaller than the total volume of a tree, these effects can be considered as negligible.

The attenuation of the leaves and branches increases with increasing frequency. When the wavelength is much less than the scattering body no resonance effects occur and the attenuation will be purely exponential **[9]**. It is also assumed that the attenuation does not vary with depression angle. The diffraction over the vegetation is modelled with the ideal knife-edge diffraction. An additional loss is added for penetration through vegetation in the empirical form as follows.

$$L_{Veg} = \alpha_v * \sum_{i=1}^{M} d_{x_j}^{i} \qquad (14)$$

Again, this was multiplied by the distance covered by foliage on the radio path over the total distance of the radio path to give the total contribution of foliage to the path loss.

The remaining morphology classes were found to have negligible effect since there are no large water bodies or open fields. All these LULC factors accounted for a morphological correction factor and together with the terrain height, slope and environmental type correction factors yielded the figure 9 above.

Based on all these correction factors for each point of measurement, the Okumura-Hata model was modified to account for clutter and terrain. Let's assume a BTS with various measurement points as in the figure 6 below.

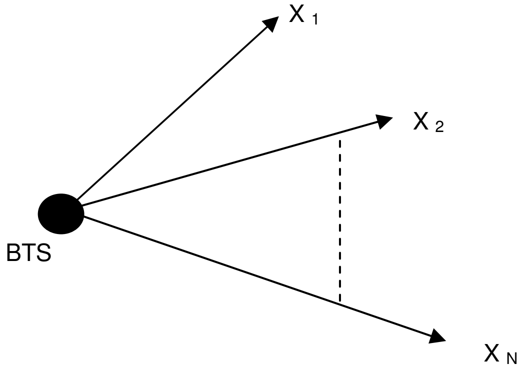

Figure 6: *BTS and MS Points*

If we assume N measurement points with path length d_1, d_2… d_N respectively, then we can establish the distance covered by each clutter type along the radio path. Lets call the distance covered by single i th occurrence of a particular clutter type along a given radio path as $d_{x_j}^{i}$.

Thus the total distance covered by the particular clutter over the radio path to each measurement point will be given as follows.

$$\begin{aligned} I_{x_1} &= \sum_{i=1}^{n} d_{x_1}^{i} \\ I_{x_2} &= \sum_{i=1}^{m} d_{x_2}^{i} \\ &\vdots \\ I_{x_N} &= \sum_{i=1}^{z} d_{x_N}^{i} \end{aligned} \qquad (15)$$

The path loss due to buildings to each of the measurement points then becomes the following.

$$\begin{aligned} L_{x_1} &= \sum_{i=1}^{n} (d_{x_1}^{i}) * L_b / d_1 \\ L_{x_2} &= \sum_{i=1}^{m} (d_{x_2}^{i}) * L_b / d_2 \\ &\vdots \\ L_{x_N} &= \sum_{i=1}^{z} (d_{x_N}^{i}) * L_b / d_N \end{aligned} \qquad (16)$$

This can be written generally as follows.

$$L_{x_{jb}} = I_{x_j}(b) * L_b / d_j \qquad (17)$$

Where j = 1, 2, 3… N

Similarly we can derive the path loss due to vegetation to each of the measurement points as follows.

$$L_{x_{jVeg}} = I_{x_j}(Veg) * L_{Veg} / d_j \qquad (18)$$

Where j = 1, 2, 3… N

Hence, the Okumura-Hata model is modified as follows.

$$\begin{aligned} L_{dB} &= 69.55 + 26.16 \log_{10} f - 13.82 \log_{10} h_T - 3.2 \\ &(\log_{10}(11.75 h_R))^2 + 2(\log_{10}(f/28))^2 + 5.4 + (34.9 \\ &- 6.55 \log_{10} h_T) \log_{10} d + L_{x_{jb}} + L_{x_{jVeg}} \end{aligned} \qquad (19)$$

VI. RESULTS AND DISCUSSIONS

The terrain height correctional factor was read directly from the ATOLL planning tool point analysis window **[10]** for each of the measurement points. Using slope tuning, the environmental correction factor and terrain height correction factor was obtained as shown in figure 7 below.

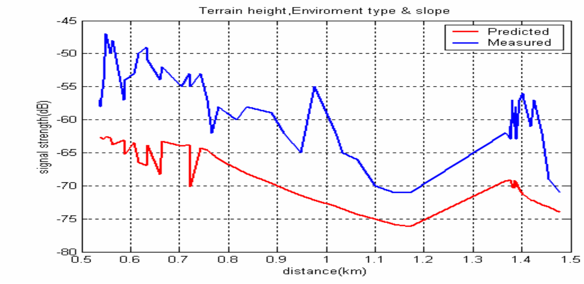

Figure 7: *Terrain Height, Environment and Slope Correction Effect.*

To determine the reflection coefficient, $\theta_{i,1}$ and $\theta_{i,2}$ are assumed to be equal and the reflection coefficient was averaged over the values of θ ranging between (0, π). This means that the transmission coefficients $T(r_1)$ and $T(r_2)$ are the same. The specific attenuation factor α_b is chosen such that the root-mean-square (rms) error of the theoretical L_b with respect to the averaged measured data is minimized. For the example under consideration, α_b equals 1.30dB/m (for $\varepsilon_r = 5$) and the rms error is 6.58dB. The overall correction factor for the buildings ranged from 5 to 30 dB. The correction factor due to buildings yielded figure 8 below.

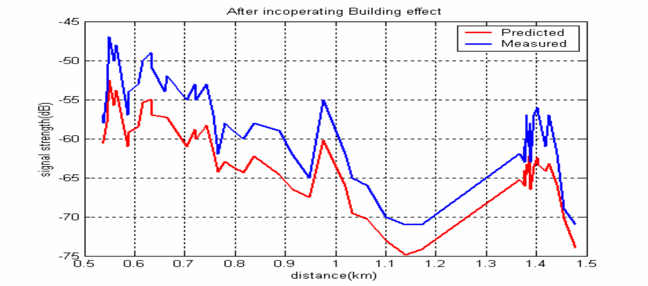

Figure 8: *Building Correction Effect.*

To establish the attenuation factor due to vegetation, measurement was carried out in the field for various tree species using the TEMS Cell planner **[11]**. An average attenuation factor for the trees was found to be 0.34dB/m. The overall correction factor for the trees ranged from 5 to 20dB.

The total correction factor for each point of measurement and prediction was then computed. From this, it was found that the correction factor for each point varied. To be able to arrive at a conclusive correction factor for this cell, the loss due to each of the factors for all points was multiplied by the distance occupied by each of the localised features. The graph corresponding to incorporation of vegetation correctional factor is shown in figure 9.

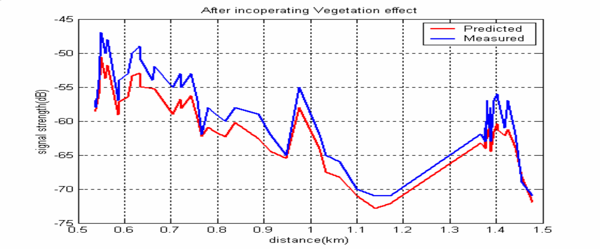

Figure 9: *Vegetation Correction Effect*

If the normal generic tuning procedure is applied, most points did not correlate well, though a few points did correspond well. Figure 10 below shows the effect of this average correctional factor on the predicted results. Thus, it is evident that information rich radio-wave tuning method yields a close approximation to the real environment than the usual generic tuning.

Based on localised environmental features, correctional factors can be used to tune propagation models for other similar cells in different locations if the characteristics are as the studied cell.

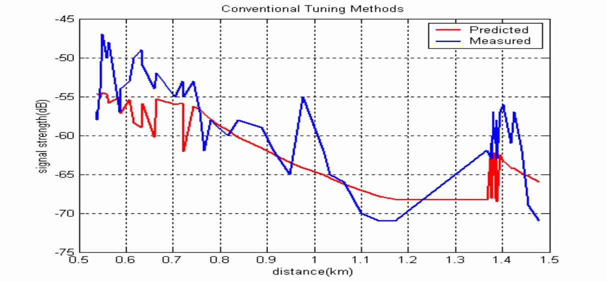

Figure 10: *Average Correction Factor*

Currently, similar areas on the outskirts of Pretoria are being examined to apply the methodology to problematic cells which have similar characteristics that resemble the studied region. In essence, the model is to be adapted for areas with similar environmental features.

VII.CONCLUSION

It can be shown that propagation prediction is a vital step in network design and has to be accurate to achieve effective network coverage. The importance of tuning propagation prediction models is vital to achieve high levels of accuracy. Various approaches of tuning can be used depending on the type of propagation model used. Of all these approaches, the information rich radio-wave tuning approach emphasizes accuracy since it considers a small section of the network allowing for detailed modelling of the physical environment. This detailed modelling of the environment improves the propagation model to closely approximate the real field strength as shown in this study.

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