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A Geometrical-based Vertical Gain Correction for Signal Strength Prediction of Downtilted Base Station Antennas in Urban Areas

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***Abstract*— Base station antenna downtilt is one of the most important parameters for optimizing a cellular network with tight frequency reuse. By downtilting, inter-site interference is reduced, which leads to an improved performance of the network. In this study we show that a simple geometrical-based extension to standard empirical path loss prediction models can give quite reasonable accuracy in predicting the signal strength from tilted base station antennas in small urban macro-cells. Our evaluation is based on measurements on several sectors in a 2.6 GHz Long Term Evolution (LTE) cellular network, with electrical antenna downtilt in the range from 0 to 10 degrees, as well as predictions based on ray-tracing and 3D building databases covering the measurement area. Although the calibrated ray-tracing predictions are highly accurate compared with the measured data, the combined LOS/NLOS COST-WI model with downtilt correction performs similarly for distances above a few hundred meters. Generally, predicting the effect of base station antenna tilt close to the base station is difficult due to multiple vertical sidelobes.**

I. Introduction

Base station antenna downtilting is a common technique used by wireless network operators to optimize cell coverage and capacity, since by adjusting tilt, inter-site interference is reduced while signal strength increases in the cell dominance area [1–3]. Antenna downtilt is by far the most commonly applied technique, but in some special cases antenna uptilt is used. Similarly, antenna tilting can be done both mechanically and electrically [1], however remote electrical tilt is preferred among network operators due to the fact that the sidelobes of the horizontal radiation pattern are also tilted and the reduced operational costs. In this paper, we are concerned about electrical downtilt only.

The impact of antenna tilting has been the topic for several simulation studies covering Global System for Mobile Communications (GSM), Wideband Code Division Multiple Access (WCDMA) and Long Term Evolution (LTE), but not much experimental investigation has been done in real network deployments. Some of the recent simulation studies concerning antenna tilting in LTE networks show that the throughput and coverage are significantly affected by tilting, and are sensitive to the actual setting [3]. Most simulation studies predict quite large optimum tilt angles, e.g. 10 degrees and above [1][3], whereas commonly applied tilting angles in practical deployment are well below 10 degrees. Part of the discrepancy is due to concerns about coverage in practical deployment where too much downtilting may lead to coverage holes and dissatisfied customers, despite that there might be potential cell throughput gains with larger tilts.

A great deal of trial-and-error (drive testing) is involved in adjusting the antenna tilt since typically applied empirical Path Loss (PL) models have no good account of antenna tilt. In the first place, there is a need to extend these models to enable sufficiently accurate predictions so that network performance with tilt can be evaluated. On a somewhat longer run there is a need to verify whether the cell Signal-to-Interference-and-Noise-Ratio (SINR) and throughput gains resemble those predicted by simulations studies. In general, practical tilt optimizations, e.g. drive-test based, suggest that the experienced gains are smaller, even considering that gains in synthetic test networks with uniform inter-site distance are believed to be smaller than in practical networks with varying inter-site distance [3].

With this motivation, we set out to investigate, based on measurements in a realistic urban scenario, how the signal strength predictions provided by empirical path loss models can be compensated to include antenna tilt, and to compare these results with a more advanced prediction method based on ray-tracing. Since the ray-tracing method can account for the specific environment effects, we use these predictions as a reference for the achievable prediction accuracy. We consider two well-known empirical models which often form the basis for network planning tools, namely the COST-Hata (HATA) and the COST-Walfisch-Ikegami (WI) model for Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS). Although the proposed compensation is not new, we identify through experiments how to apply the compensation with existing path loss models to obtain the best prediction accuracy. Further details on the measurement campaign are provided in Section II. The path loss models are reviewed in Section III, and Section IV explains how vertical gain correction is combined with the

path loss to compute the received power at different antenna downtilt angles. In Section V, the model predictions are compared with the measurements, and finally, Section VI provides a conclusion.

II. Measurement campaign

The measurement campaign was performed in the city centre of Aarhus, Denmark. The environment is a typical urban medium city where average building height and street width are about 15-18 m (4-5 floors) and 20 m, respectively. Measurements were made on the 2600 MHz LTE network of the telecommunications operator Telenor. The LTE signal bandwidth available at this frequency was 20 MHz.

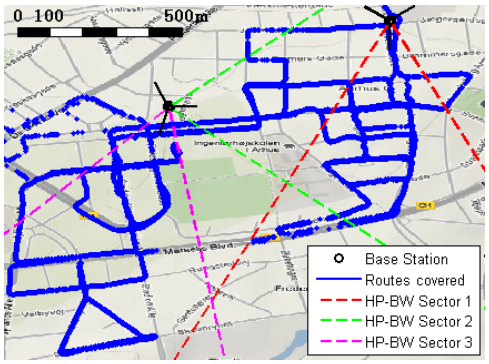

Fig. 1: Measurement area. Base station locations and routes covered.

For this campaign, 3 sectors from the 2 different sites indicated in Fig. 1, and placed above rooftop at 23 m height, were selected with the aim to include propagation environments with approximately the same characteristics in terms of building density, height and composition. The distance between these two sites was 687 m. Transmit antennas were typical sectorial with 60° half-power beamwidth (HP-BW) in azimuth and 5° in elevation. Maximum gain was 16 dBi. Each sector was set to a mechanical downtilt of 0° and equipped with two antenna branches transmitting a maximum power of 2x46 dBm.

At the reception end, an omnidirectional antenna with ground plane and 5 dBi of gain was mounted on a van at 2.5 m height.

Measurements consisted of driving different routes located inside of the half-power horizontal beam of the respective sectors (Fig. 1), collecting data up to around 1 km of distance from the base station. Reference Signal Received Power (RSRP) was measured with a network scanner and subsequently normalized to full LTE bandwidth. The average driving speed was 15 km/h and the sampling rate 50 samples/s. The routes were repeated for 6 different electrical downtilts: 0, 2, 4, 6, 8 and 10 degrees.

A. Measurement processing

Effectively, there were around 5500 samples available along the measurement routes for each electrical downtilt angle. These samples were subsequently averaged over distance intervals of 50 m along the sector's main beam to remove fast-fading, and the mid-point of each interval was taken to represent the average value. As the propagation environment is similar for the 3 selected sectors (same antenna type, antenna height, and average building height), the different data was combined and treated as one sample with improved representation of the shadowing variability.

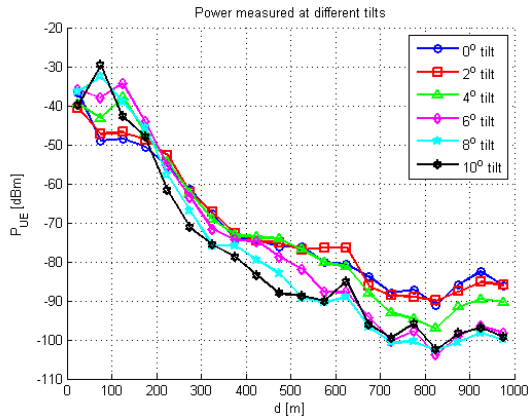

Fig. 2: Average received power as function of distance from the base station for different electrical downtilt angles.

As it can be seen in Fig. 2, different downtilt angles have a distinct effect to the average received power. In general, higher downtilt angles provide higher power close to the base station and lower power for farther locations.

III. Path loss prediction models

In this section, we shortly review the characteristics of the two well-known path loss models that are considered in this paper. They both originate from empirical studies and are commonly applied for statistical path loss prediction assuming that the model prediction determines the overall average path loss value for a range of similar environment types and that any local mean variation from this average follows a log-normal statistical distribution. They require only a few environment specific parameters and are therefore generally applicable. All the values of the different terms and constants in the equations can be directly calculated from the environment-specific values previously detailed in Section II. In contrast, the ray-tracing based prediction model requires a site-specific description and makes deterministic predictions for a given environment. The specific implementation of ray-tracing used for this evaluation is described at the end of the section.

A. Empirical models

1) COST-Hata-Model: The Hata model is an empirical model based on Okumura's correction functions [4]. It was designed to predict path loss where land cover is known roughly. It is valid for macrocells with base station antennas above rooftop, and for frequencies below 1500 MHz, so an extension of the model was proposed in the COST 231 action [5] for higher frequencies. The path loss is calculated according to Eq. (1) based on frequency (f), distance between base station and user equipment (d), base station height (h_{BS}), and correction factors for user equipment height ($a(h_{UE})$) and clutter (C_m).

$$PL = 46.3 + 33.9\,log_{10}(f) - 13.82\,log_{10}(h_{BS}) - a(h_{UE}) + \\ + \{44.9 - 6.55\,log_{10}(h_{BS})\}\,log_{10}(d) + C_m \quad (1)$$

2) COST-Walfisch-Ikegami-Model: The COST 231 action also proposed a combination of the Walfisch and Ikegami models [5]. It is a semi-empirical model which includes different parameters to characterize the urban environment. This model distinguishes between two different scenarios:

- Line-of-Sight (LOS): Simple propagation along a street canyon. In this case, path loss is calculated based on frequency (f) and distance between base station and user equipment (d) as indicated in Eq. (2).

$$PL_{LOS} = 42.6 + 26\,log_{10}(d) + 20\,log_{10}(f) \quad (2)$$

- Non-Line-of-Sight (NLOS): Originally, Walfisch and Bertoni approximated the solution for multi-screen diffraction for base station antennas above rooftops, but COST 231 extended the model to below rooftops based on measurements. In this case, the basic transmission loss defined in Eq. (3) is composed of the free space loss (L_0), the multiple screen diffraction loss (L_{msd}) and the rooftop-to-street diffraction and scatter loss (L_{rts}); L_{msd} depends on distance (d), frequency (f), average building separation (b), base station height (h_{BS}) and average building height ($h_{building}$). L_{rts} is function of the average street width (w), the loss related to street orientation (L_{ori}), average building height ($h_{building}$) and user equipment height (h_{UE}).

$$PL_{NLOS} = \begin{cases} L_0 + L_{rts} + L_{msd} & L_{rts} + L_{msd} > 0 \\ L_0 & L_{rts} + L_{msd} \leq 0 \end{cases} \quad (3)$$

This paper also considers a combined LOS/NLOS version of the model. A probability of LOS is defined in Eq. (4) as a function of distance between the base station and the user equipment. As it will be explained in the following sections, it was found that, when tilt is considered, a good prediction can be achieved by applying the LOS function probability defined in [6] for the Macro to UE scenario. The resultant model in Eq. (5) changes the path loss prediction from LOS close to the base station to NLOS for long distances.

$$p_{LOS}(d) = e^{-d/0.2} \quad (4)$$

$$PL_{combined} = PL_{LOS} \cdot p_{LOS}(d) + PL_{NLOS} \cdot (1 - p_{LOS}(d)) \quad (5)$$

Although the COST 231 action [5] limits the two models to frequencies below 2 GHz, they are applied with approximation at the slightly higher frequency of 2.6 GHz.

B. Semi-deterministic models

1) Dominant Path Model (DPM): The DPM is based on a site-specific description of the environment in terms of 3D vector building databases and topographical information. The dominant path model prediction is a reduced complexity implementation of standard ray-tracing where only the paths carrying the dominant part of the power are included [7]. It allows predictions for large network areas within a reasonable computational effort and without compromising the accuracy of the tool. First of all, all the different complete paths are calculated and then the total loss of each path is computed as indicated in Eq. (6) to decide which is the dominant path. In this case, the prediction is based on wavelength (λ), length of the path (d), path loss exponent (p) which adapts to the current situation (LOS or NLOS areas), a function $\alpha(\varphi, i)$ which determines the loss due to changes in the direction of propagation, and a waveguiding factor (w_k) which takes into account reflection loss on the walls.

$$PL_{path} = 20\,log_{10}\left(\frac{4\pi}{\lambda}\right) + 20\,p\,log_{10}(d) + \\ + \sum_{i=1}^{n} \alpha(\varphi, i) - \frac{1}{c}\sum_{k=0}^{c} w_k \quad (6)$$

IV. Including antenna tilt in power prediction

A straightforward extension to the previous empirical models is to introduce a compensation factor for the vertical antenna gain seen from the elevated base station in the direction towards the user equipment. The vertical gain can be calculated from the available antenna patterns provided by the manufacturer, and the average received power can be estimated as indicated in Eq. (7), at least within a restricted range of distances as it will be seen later.

$$P_{UE} = P_{BS} + G_{BS}(\theta) - PL + G_{UE} \quad (7)$$

P_{UE} is the received power at the user equipment, PL is the path loss according to one of the previous models, P_{BS} is the base station transmit power, G_{UE} is the antenna gain of the user equipment (assumed 0 dBi) and $G_{BS}(\theta)$ is the vertical gain pattern in the broadside direction (*planar cut* at $\phi = 0$). For simplicity, only the broadside direction will be considered in this paper, but extensions to the full azimuth direction can be based on e.g. the pattern multiplication model often used in simulation studies [1]. From now on, $G_{BS}(\theta)$ will be referred as the Vertical Gain Correction (VGC).

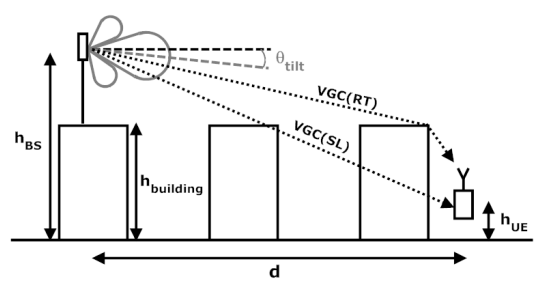

Fig. 3: Vertical antenna gain compensation for 1) Street level (SL) geometry and 2) Rooftop (RT) geometry.

In this paper, VGC is applied by considering the geometry in the vertical plane connecting base station and user equipment according to the geometries illustrated in Fig. 3.

- Street level (SL): Gain seen by the user equipment at street level. In this case the gain is a function of downtilt angle (θ_{tilt}), distance from base station to user equipment (d), base station height (h_{BS}) and user equipment height (h_{UE}).

$$VGC(SL) \rightarrow G_{BS}(\theta) = G_{BS}(\theta_{tilt}, d, h_{BS}, h_{UE}) \quad (8)$$

- Rooftop level (RT): Gain seen at the rooftop of the last building just before the user equipment. Implicitly diffraction over the rooftop is assumed as the main contributor to the received signal at the user equipment in line with the observations in [8]. In this case instead of user equipment height, the average building height ($h_{building}$) is considered.

$$VGC(RT) \rightarrow G_{BS}(\theta) = G_{BS}(\theta_{tilt}, d, h_{BS}, h_{building}) \quad (9)$$

Analysis of 900 MHz tilt measurements in [9] gave some credibility to the RT geometry when considered along with a simple propagation model. However, both of the previous empirical models, and especially the COST-WI, account for over the rooftop propagation in their predictions.

Fig. 4 shows the two different VGC, parametrized according to the measurement area in Fig. 1, and calculated directly from Eq. (8) and Eq. (9) with the actual base station antenna patterns applied for two different downtilts (0 and 10 degrees).

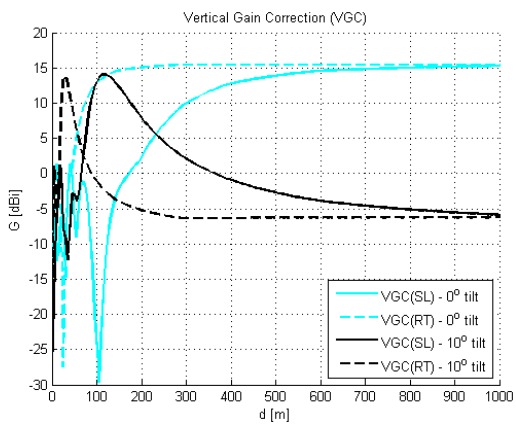

Fig. 4: Vertical Gain Correction (VGC) as a function of distance for 1) SL geometry and 2) RT geometry.

In VGC(SL), the effect from the secondary lobes of the vertical pattern is very clear, while in VGC(RT) the gain curve is compressed in distance as smaller angles are seen from over the buildings. This effect is observed for all the different downtilted patterns considered. It is clear already from this plot that accurate compensation for the area close to the base station is very difficult due to the large and rapid variations with distance below approximately 100 m distance.

Differently from the empirical path loss models, the DPM applies the directional gain for the strongest path between base station and user equipment, including the respective space angles in azimuth and elevation, to calculate the appropriate base station antenna gain.

V. Comparison between model predictions and measurements

To compare the different models with the measurements, the root mean square error (RMSE) is considered. This metric, defined in Eq. (10), considers both bias and variability from the measured samples ($P_{UE,1...n}$) to the samples predicted by the model ($P_{model,1...n}$).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_{UE,i} - P_{model,i})^2}{n}} \quad (10)$$

The considered models are evaluated for different distance (d) ranges: short distance ($d \leq 200\,m$), intermediate distance ($200\,m < d \leq 400\,m$), long distance ($400\,m < d \leq 1000\,m$) and full range corresponding to the measurement range.

Although the analysis is presented on distance intervals of 50 m, the same conclusions were obtained with 25 m and 100 m, but the average over 50 m was found to be the clearest way to represent the data. The RMSE values for most relevant cases are summarized in Table I.

A. Empirical models with and without VGC

For a base station antenna with zero downtilt, and no VGC applied to the propagation models, which means $G_{BS}(\theta) = max\{G_{BS}\}$ in Eq. (7), the NLOS COST-WI gives the best prediction accuracy with an RMSE of 4.9 dB. HATA is worse in predicting the signal level in this urban environment with an RMSE of 9.5 dB. Also in this case, without applying the antenna pattern to predict other downtilt angles, the combined LOS/NLOS COST-WI achieves an RMSE of 8.1 dB. The prediction from the different models without VGC applied can be seen in Fig. 5 compared to the zero tilt measurements.

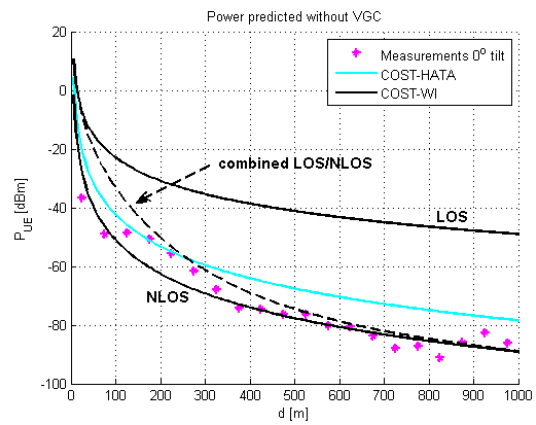

Fig. 5: Power predicted by the COST-Hata and the COST-WI models with no VGC applied.

For a base station antenna with downtilt and with VGC applied to the propagation models, the combined LOS/NLOS COST-WI + VGC(SL) achieves the lowest RMSE at the different distance intervals (8.7 dB for short distance, 3.6 dB for intermediate distance and 4.8 dB for long distance), as well as for the full range (overall RMSE of 5.9 dB). This model reduces significantly the overall error, especially for larger downtilt angles.

The best downtilt prediction with the HATA model was achieved by applying VGC(RT) with an overall RMSE of 9.3 dB which is higher than the one obtained with the combined LOS/NLOS COST-WI. The fact that the HATA model gives better prediction with VGC(RT), and COST-WI with VGC(SL), can be partly motivated by assumptions behind

the models: The COST-WI model explicitly includes multi-screen diffraction, and therefore it makes no sense to account for it twice.

B. Empirical models compared to DPM

The DPM prediction is used as an accurate reference of the achievable RMSE. Half of the data set (0, 4 and 10 degrees) was used to calibrate the ray-tracing tool. DPM predicts with different RMSE values of 9.0 dB for short distance, 4.0 dB for intermediate distance and 5.3 dB for long distance. This prediction achieves an RMSE of 6.3 dB for the full range.

A comparison between predictions from different models HATA + VGC(RT), NLOS COST-WI with no VGC, combined LOS/NLOS COST-WI + VGC(SL) and DPM, is shown in Fig. 6 for two downtilt angles (0 and 10 degrees), and Table I summarizes the accuracy of the models for the different distance ranges for all the downtilt angles considered (0, 2, 4, 6, 8 and 10 degrees).

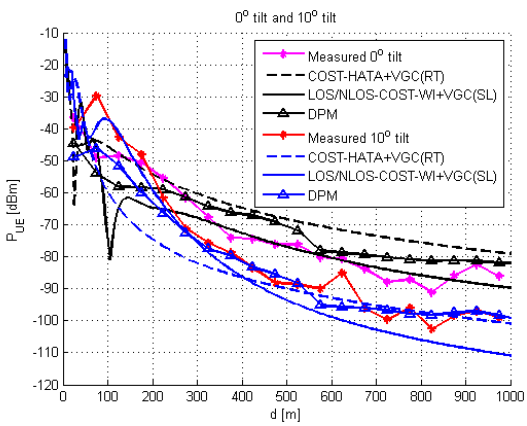

Fig. 6: Comparison between model predictions and measurements for two different downtilt angles (0 and 10 degrees).

Both Table I and Fig. 6 reveal that the combined LOS/NLOS COST-WI with VGC gives overall best prediction accuracy, and for distances above 200 m even in comparison with DPM. It is also clearly seen that when no VGC is applied (i.e. with NLOS COST-WI), a worse prediction accuracy is obtained, especially for large downtilt angles.

VI. Conclusions

This study analyzed the impact of antenna downtilt in an urban scenario. A comparison between measurements and predictions from different path loss models has been carried out. The analysis shows that the predictions from the existing COST-WI path loss model can be compensated by a simple geometrical-based vertical gain correction (VGC) applied for an user at the street level (SL). Specifically, our evaluation shows that the combination of COST-WI LOS and NLOS models with VGC gives the lowest RMSE for the considered urban environment with base station antennas above the average rooftop level. The RMSE is in the range of the prediction accuracy achieved by highly-accurate site-specific prediction models based on ray-tracing. For ranges beyond 200 m the RMSE (bias and variability) is 4.5 dB compared to the 5.0 dB based on calibrated ray-tracing. As future work we are considering further refinements of the VGC as a function of downtilt angle as well as a network level evaluation of the SINR and throughput gains from network-wide downtilting in LTE networks based on the derived model which outcome could have particular interest from the tilt optimization point of view.

TABLE I: RMSE in dB for the different models.

Distance to BS	Downtilt [°]	HATA VGC(RT)	WI NLOS no VGC	WI LOS/NLOS VGC(SL)	DPM
Short d≤200m	**0**	12.7	8.0	10.5	7.1
	2	10.3	10.3	11.0	5.5
	4	6.8	12.3	8.1	7.6
	6	12.2	13.9	8.5	10.9
	8	17.0	12.9	7.2	10.8
	10	20.3	12.4	5.8	10.9
	ALL	13.9	11.8	***8.7***	9.0
Intermediate 200m<d≤400m	**0**	6.7	5.7	5.1	5.2
	2	6.2	6.6	3.8	5.3
	4	3.3	5.7	3.5	4.6
	6	6.3	5.0	2.7	3.4
	8	9.6	4.4	2.3	2.4
	10	9.3	5.0	3.7	2.3
	ALL	7.2	5.4	***3.6***	4.0
Long 400m<d≤1000m	**0**	10.0	2.9	2.8	5.7
	2	9.4	3.3	3.4	5.2
	4	7.9	5.2	4.0	4.8
	6	6.5	9.8	3.8	7.2
	8	4.0	11.4	4.0	4.7
	10	3.5	10.7	8.6	3.8
	ALL	7.3	8.0	***4.8***	5.3
Full Range	**0**	10.4	***4.9***	5.8	5.9
	2	9.2	6.0	6.2	5.2
	4	7.0	7.5	5.4	5.7
	6	8.1	10.4	5.4	7.9
	8	9.6	11.0	4.8	6.6
	10	11.0	10.5	7.4	6.2
	ALL	9.3	8.7	***5.9***	***6.3***

References

[1] F. Athley and M. N. Johansson, *Impact of Electrical and Mechanical Antenna Tilt on LTE Downlink System Performance*, 71st IEEE Vehicular Technology Conference, Spring 2010.

[2] J. Niemelä, T. Isotalo and J. Lempiäinen, *Optimum Antenna Downtilt Angles for Macrocellular WCDMA Networks*, EURASIP Journal on Wireless Communications and Networking, no. 5, 2005.

[3] O. N. C. Yilmaz, S. Hamalainen and J. Hamalainen, *Analysis of Antenna Parameter Optimization Space for 3GPP LTE*, 70th IEEE Vehicular Technology Conference, Fall 2009.

[4] M. Hata, *Empirical Formula for Propagation Loss in Land Mobile Radio Services*, IEEE Transactions on Vehicular Technology, vol. 29, August 1980.

[5] COST 231, Final Report, Digital Mobile Radio, *COST 231 View on the Evolution Towards Future Generation Systems*, Commission of the European Communities and COST Telecommunications, 1999.

[6] 3GPP TR36.814 V.9.0.0, *Technical Specification - Group Radio Access Network. Further advancements for E-UTRA Physical Layer Aspects (Release 9)*, March 2010.

[7] R. Wahl, G. Wölfle, P. Wertz, P. Wildbolz and F. Landstorfer, *Dominant Path Prediction Model for Urban Scenarios*, 14th IST Mobile and Wireless Communications Summit, June 2005.

[8] A. Kuchar, J. P. Rossi and E. Bonek, *Directional Macro-cell Channel Characterization from Urban Measurements*, IEEE Transactions on Antennas and Propagation, vol. 48, February 2000.

[9] H. Asplund, J. E. Berg, T. B. Sørensen, *The Influence of Base Station Antenna Tilt on Path Loss*, Antennen och dess omvärld, kopplingen mellan antenn och radiosystem, Nordiskt Radioseminarium, Lunds Tekniska Högskola, November 1999.