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Validation of Tilt Gain under Realistic Path Loss Model and Network Scenario

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Abstract

Despite being a simple and commonly-applied radio optimization technique, the impact on practical network performance from base station antenna downtilt is not well understood. Most published studies based on empirical path loss models report tilt angles and performance gains that are far higher than practical experience suggests. We motivate in this paper, based on a practical LTE scenario, that the discrepancy partly lies in the path loss model, and shows that a more detailed semi-deterministic model leads to both lower gains in terms of SINR, outage probability and downlink throughput and lower optimum tilt settings. Furthermore, we show that a simple geometrically based tilt optimization algorithm can outperform other tilt profiles, including the setting applied by the cellular operator in the specific case. In general, the network performance is not highly sensitive to the tilt settings, including the use of electrical and/or mechanical antenna downtilt, and therefore it is possible to find multiple optimum tilt profiles in a practical case. A broader implication of this study is that care must be taken when using the 3GPP model to evaluate advanced adaptive antenna techniques, especially those operating in the elevation dimension.

I. Introduction

The frequency reuse factor of one is utilized in the Third Generation Partnership Project (3GPP) Long-Term Evolution (LTE) air interface, which means that each cell reuses the full frequency band at the cost of higher inter-cell interference (ICI). Such a scheme reduces the cost of network planning, and also tends to increase the spectrum efficiency, since user equipment (UE) near the base station (BS) can enjoy high data rate due to larger bandwidth. However, UEs at the cell-edge typically suffer from high ICI, and therefore the achievable throughput is low.

As a result, mitigating the ICI is an important task in the LTE radio network planning process. Probably the simplest way to achieve this is by adjusting the BS antenna downtilt angle. The antenna usually has a high directivity in the vertical plane, and by pointing the vertical antenna pattern towards the ground in front of the BS, the signal strength within the cell coverage is maximized, while the interference level to adjacent cells is minimized. Antenna downtilt can be realized mechanically or electrically, or in a combination thereof [1]. Mechanical tilt implies that the antenna is physically rotated around the horizontal axis, while electrical tilt means that a phase taper is introduced in the aperture to tilt the beam. The electrical tilt is often controlled efficiently and flexibly with the help of remote electrical tilt (RET), without the need of sending technicians to the site. However, due to grating lobe effects, the RET antenna tilt interval is typically limited to around 10^o relative to a nominal tilt direction, which is insufficient in cell plans with dense site distribution and/or high antenna installations. Therefore, large tilt angle must be achieved by applying additional mechanical tilt [2].

In existing literature, the impact of mechanical and electrical antenna downtilt has been discussed in [3], [4], [5], [6] for the Wideband Code Division Multiple Access (WCDMA) system, and in [2], [7] for the LTE system. The tilt optimization algorithms are investigated in [8], [9], assuming that the performance curve, which is a measure of spectral efficiency, is a unimodal function, so that existing heuristic optimization algorithms can be utilized to find the best tilt angle. All these studies are based on regular networks with fixed inter-site distance (ISD), a simplified antenna model and an empirical path loss model. Since such a model is derived independent of the antenna pattern, the effect of the pattern is most commonly added linearly to the path loss. This model is not valid in practice, where the path loss and the tilt impact has a more complex relationship due to the fact that the signal often has to travel over the roof-top to get to the UE in dense urban scenarios. A typical outcome of studies based on this model is an overestimation of the network SINR gain from antenna tilting and too aggressive downtilting [2], [7].

In this paper our aim is to study the tilt gain in a more realistic evaluation. We investigate the tilt gain in a real-world network configuration based on actual BS locations, antenna patterns, urban environment and a 3D path loss model which takes the building structures into account. The performance in terms of Signal to Interference plus Noise Ratio (SINR) and throughput statistics is compared to similar performance numbers derived based on a 3GPP-specified empirical path loss model. The remainder of the paper is organized as follows: In Section II we discuss the impact of the path loss model and give details of the Urban Dominant Path Model (UDP) model applied in this study. Also, we describe a simplified approach to estimate the required downtilt. The system level simulator

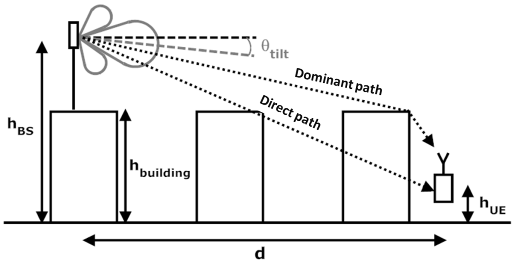

Fig. 1. Direct and dominant path between BS and UE

used to derive the network SINR statistics is described in Section III. The numerical results are shown in Section IV, and finally the conclusions are given in Section V.

II. Path loss model and tilt optimization

The path loss model used in this study is the UDP introduced in [10]. The UDP is a semi-deterministic 3D prediction model which besides the planar dimension takes the ground and flat top building heights into account. See the Appendix for a more detailed description of the UDP model.

In the UDP model, the antenna gain is included in the path loss by evaluating the antenna pattern at the Angle of Departure (AoD) seen by the *dominant path*, not the *direct path*, as is usually done when empirical path loss models are applied. Fig. 1 illustrates in the vertical plane the direct and dominant path between the BS and UE, assuming that the dominant signal path is elevated above the roof-top and then diffracted down into the street. Similar to ray-tracing, the AoD is computed from the transmitter to the first interaction point, in this case the roof-top. The position of the first interaction point is determined in such a way that the dominant path has minimum interaction angle and distance (or a combination of both). This method reflects better what is happening in reality, and therefore it can describe more accurately the impact of the antenna downtilting.

To verify the accuracy of the UDP model in predicting the effect of antenna tilting, a measurement campaign was carried out in a 2.6GHz LTE network in Aarhus, Denmark (See [11] for more detailed information about the campaign). The Reference Signal Received Power (RSRP) was measured from three cells of interest with similar deployment in terms of propagation environment, transmitted power, antenna height and type. The antenna type is Kathrein 800 10644, which has approximately 61^o and 5.4^o horizontal and vertical half-power beamwidth (HPBW), respectively. The antenna was set at 0^o mechanical tilt and measurements were repeated along the same drive-test routes for 6 different electrical tilt values: 0^o, 2^o, 4^o, 6^o, 8^o, and 10^o.

We also ran the UDP prediction for the three same cells of interest, according to the 3D city map and BS deployment, at each of the above-mentioned electrical tilt values. To increase the accuracy of the UDP prediction, half of the data set (tilt angles 0^o, 4^o and 10^o) were used to calibrate the prediction tool. Both measurement and prediction data for the three cells

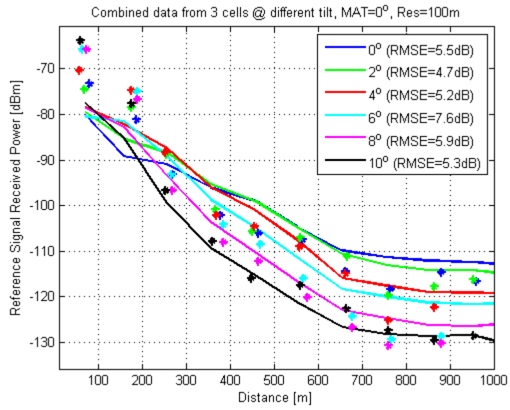

Fig. 2. UDP prediction (solid lines) vs measurement (dots) at various tilt angles.

were filtered to keep only those points located inside the HPBW of the respective cells, and averaged over distance intervals of 100m along the cells' main beam direction to remove fast fading and shadowing effects. Fig. 2 shows the averaged RSRP versus distance for different tilt angles. The UDP predictions agree quite well with the trend shown by the measurement. Overall the prediction error is relatively small with the maximum root mean square error (RMSE) being 7.6dB for 6^o tilt.

As we can see, the measurement data indicates that higher downtilt angles offer higher power close to the BS, while at the same time lowering the power at far distance. Making the right trade-off between interference and coverage in determining the downtilt of all cells collectively is a complicated optimization problem. In this paper, a simple geometric-based tilt optimization algorithm is used to obtain the *optimized tilt profile* for the given network layout. Assuming that the cell selection is based purely on the distance between the UE and the BS, a map of the cells dominance area can be drawn, in which the cell border to the neighboring cells can be identified. We refer to this as the *natural cell border*. If we focus only on the cell bearing direction, we can identify the *furthest point* on the natural cell border, to which the tilt angle must be adjusted to ensure sufficient coverage. Using a straightforward geometrical algorithm, the optimum tilt angle can be computed so that the upper 3dB point of the main lobe radiation pattern hits that point. Although this algorithm is simple and does not take into account neither the 3D building map nor the lognormal shadow fading, it is shown to outperform other tilt profiles in Section IV.

III. System model

The impact of antenna tilting is evaluated numerically under a static snap-shot network level LTE simulator. The scenario under study is a typical medium-size European city. A real-world network layout is loaded into the simulator, which consists of locations, antenna heights, bearing angles for 140 BSs (corresponding to 421 cells) at an average 1-neighbor ISD of 260m as shown in Fig. 3. The LTE network is assumed to be

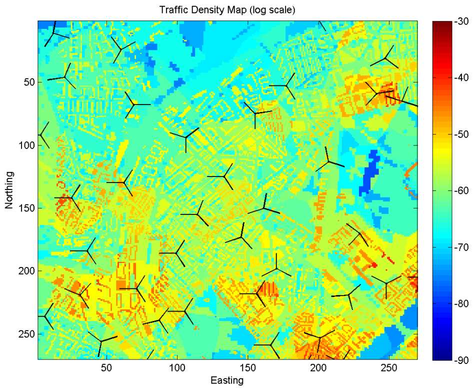

Fig. 3. A section of the study area, illustrating partially the network layout and the traffic density map (normalized logarithm-scale density, where hot color indicates hotspots and cool color marks areas with low user density)

TABLE I

SIMULATION PARAMETERS

Parameter	Value
Network Layout	140 BSs (with 421 cells)
Monitored Sites	75 BSs (with 225 cells)
Carrier Frequency	2600MHz
System Bandwidth	20MHz
Antenna Model	Kathrein 800 10644
No. of Antenna Branches	2
Transmit Power	46dBm per branch
Frequency Reuse Factor	1
UE Height	1.5m
Path Loss Models	UDP and 3GPP model
Penetration Loss	20dB
Indoor Attenuation	0.6dB / m
Shadowing STD	8 dB
Shadowing Corr. Distance	50m
Shadowing Correlation	0 (sites), 1 (cells)
Traffic Distribution	Realistic density map
Traffic Model	Full-buffer
Min. data rate Requirement	2Mbps
Scheduling	Outage-optimized

single-carrier operating at 2.6GHz, with 20MHz of bandwidth. Each cell has two antenna branches with a transmission power of 46dBm per branch, and the antenna model is Kathrein 800 10644. Users are dropped in the study area following a spatial traffic density map. The map is created according to the measured traffic load on each cell, and it is assumed to be dependent on clutter types (e.g. very low traffic on river or sea-covered regions and the ratio between indoor and outdoor traffic is 70/30). Simulation statistics are collected from 75 BSs (or 225 cells) located in the center of the map, so that there is at least 1-tier of interference. The system performance is based on computation of the downlink SINR distribution in a cell of interest, i.e. for all UEs served by a specific cell, in the presence of a number of interference sources, i.e. neighboring cells. Assuming that the network is fully loaded, such that all cells are transmitting at their maximum power P_{tx} in all Physical Resource Blocks (PRBs), we can simply calculate the SINR for the u^{th} UE in the system as follows:

$$\text{SINR}_u = \frac{P_{tx} V_{k,u}}{P_{tx} \sum_{i=1;i\neq k}^{K} V_{i,u} + N_0} \quad (1)$$

in which $V_{i,u}$ indicates the path gain from the i^{th} cell to the u^{th} UE. K is the total number of cells in the system, and N_0 is the thermal noise power per PRB. We assume that the cell selection is based on the strongest path gain, regardless of the actual UE position, and in this case the u^{th} UE is connected to the k^{th} cell. The path gain is determined by the distance dependent path loss and shadow fading. In our definition, we further compensate for the path gain by the antenna gain. Fast fading is not considered in this study because the coverage and capacity are evaluated on a very long timescale. Depending on the path loss model, the path gain is given in logarithm scale by:

$$V_{i,u}[dB] = \begin{cases} G(\varphi_{dp}, \theta_{dp}) - L_{\text{UDP}} & \text{for UDP} \\ G(\varphi_{dr}, \theta_{dr}) - L_{\text{3GPP}} - S & \text{for 3GPP} \end{cases} \quad (2)$$

L_{UDP} is the UDP path loss presented in the Appendix, which already includes the shadow variation introduced by the 3D building map. $L_{\text{3GPP}} = 128.1 + 37.6\log\big(d[km]\big)$ is the 3GPP path loss model [7], which is included in this paper for reference. This model assumes the BS antenna height is fixed at 15m above the average roof-top, and the carrier frequency is 2GHz. The 3GPP model is accompanied by a spatially-correlated lognormal shadow fading S with a decorrelation length of 50 m and a standard deviation of 8dB. $G(\varphi, \theta)$ is the antenna gain at a given azimuth and elevation angle (φ, θ). For the UDP model, this is the angle of the dominant path $(\varphi_{dp}, \theta_{dp})$, while the angle of the direct path $(\varphi_{dr}, \theta_{dr})$ is considered in the 3GPP path loss model. For indoor location, the path loss is computed similar to WINNER II recommendation [12], i.e. a outdoor-to-indoor penetration loss of 20dB, and linear indoor attenuation of 0.6dB/m is applied in addition to the closest outdoor path loss.

The user achievable throughput is calculated based on a SINR-to-throughput mapping curve, which includes the Adaptive Modulation and Coding (AMC), Hybrid Automatic Repeat Request (HARQ) and Multiple Input Multiple Output (MIMO) transmission up to 2x2 spatial multiplexing [13]. The scheduler in this simulation is "outage-optimized", and works in two phases: In the first phase, users served by a specific cell are sorted by their SINR, and available resources are allocated in such a way that, if possible, the *minimum data rate requirement* is met for all users. The minimum data rate requirement for each user is 2Mbps, and a user is said to be in *outage* if its achievable donwlink throughput is lower than this value. Users with higher SINR will be scheduled first, as they require the least amount of resources to obtain the required data rate. In the second phase, if there are remaining resources, they are distributed to each user in a round-robin fashion [13]. All important simulation parameters are summarized in Table I.

IV. NUMERICAL RESULTS

In this section, the tilt gain is measured in terms of 5%-tile and average SINR. The first represents the performance

TABLE II

SUMMARY OF TILT GAIN, RELATIVE TO ZERO TILT PROFILE

Profiles	**3GPP Model**						**UDP Model**					
	SINR [dB]		Outage [%]		Throughput [%]		SINR [dB]		Outage [%]		Throughput [%]	
	5%-tile	Average	Low	High	Low	High	5%-tile	Average	Low	High	Low	High
Operator Tilt (OPER)	2.9	3.0	82.3	17.2	28.3	17.3	1.1	3.2	67.0	23.4	45.3	28.6
Operator Tilt, blind+2 (OPER+2)	3.2	4.2	88.8	27.0	45.7	28.6	0.4	3.2	39.7	23.3	44.1	28.8
Operator Tilt, blind+4 (OPER+4)	2.6	4.2	86.1	30.2	52.3	32.5	-0.4	2.6	7.3	20.9	38.8	25.2
Operator Tilt, blind-2 (OPER-2)	1.8	1.3	58.1	5.5	9.4	5.1	1.2	2.3	61.7	17.1	33.2	20.1
Operator Tilt, blind-4 (OPER-4)	0.7	0.3	21.5	-1.0	-0.3	-0.5	0.6	1.1	38.2	8.7	16.0	9.0
Optimized Mechanical Tilt (OPTI-M)	3.5	4.7	92.4	32.5	57.0	35.6	1.1	3.6	49.4	26.4	52.5	32.9
Optimized Electrical Tilt (OPTI-E)	3.6	4.3	91.3	28.7	49.8	31.0	1.1	3.9	51.2	27.3	52.6	34.5

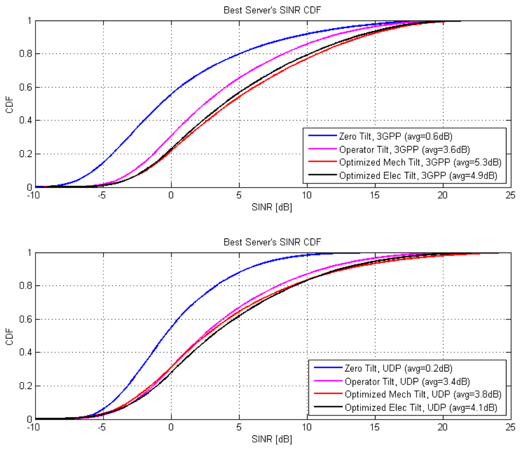

Fig. 4. Best server's SINR CDF for ZERO, OPER, OPTI-M and OPTI-E profile using (a) 3GPP and (b) UDP model.

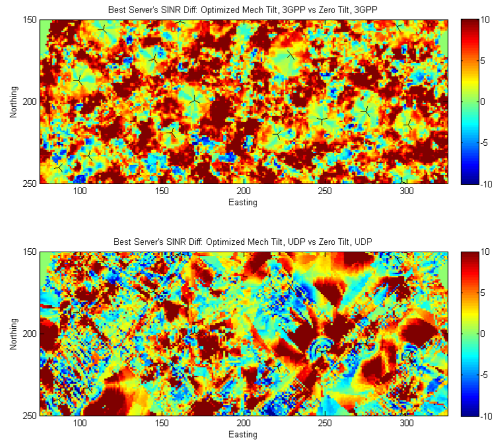

Fig. 5. SINR difference (in dB) between the OPTI-M and ZERO profile using (a) 3GPP and (b) UDP model.

of UEs at cell-edge, an indication of coverage, while the latter represents the average performance of all UEs in the cell as an indicator of overall capacity gain. We also look at the outage probability and average UE downlink throughput gain at two different load conditions: In the low load scenario there is approximately one UE per cell on average, while in the high load case representing a capacity-limited network, there is 7 UEs per cell on average. Table II summarizes the gain, relative to the Zero Tilt (ZERO) profile, for different tilt profiles. The ZERO profile means that 0^o of mechanical and electrical tilt is applied for all cells. The OPER sets the mechanical and electrical tilt according to the real-world value for the current network layout. These values result from a careful network planning process, including drive-tests and subsequent tuning of BS antenna tilts to ensure that the best network coverage is achieved. To study the sensitivity of the two path loss models against tilt change, we blindly add/subtract x degrees of mechanical tilt to/from the OPER, which is referred to as *Operator tilt, blind* $\pm x$ (OPER$\pm x$) for $x = [2, 4]$. Finally, the Optimized Tilt (OPTI) is the one obtained using the algorithm described in Section II. Two different methods are employed to realize the optimized tilt: The Optimized Mechanical Tilt (OPTI-M) keeps the electrical tilt unchanged at 4^o, where the highest antenna gain among available electrical patterns is achieved, and only modifies the mechanical tilt to obtain the required optimized tilt angle for a cell. In contrast, the Optimized Electrical Tilt (OPTI-E) varies the electrical tilt within a range of $[0 - 10^o]$ and leaves the mechanical tilt at 0^o whenever possible. The average tilt for the OPER profile is 6.13^o, while this value is 7.99^o for the OPTI. In other words, the tilt optimization algorithm suggests that the network should be tilted down more aggressively, approximately by 2^o.

The best server's SINR cumulative distribution function (CDF) for the ZERO, OPER, OPTI-M and OPTI-E profiles predicted by the 3GPP and UDP models are shown in Fig. 4. It is clear that antenna tilting improves both capacity and coverage. However, comparing the SINR performance of the OPTI-M and ZERO, we can see that the 3GPP model tends to overestimate such gain: It shows 3.5dB gain at the cell-edge and 4.7dB on average; these numbers are 1.1dB and 3.6dB for the UDP model, respectively. Fig. 5 illustrates the SINR gain per UE location for OPTI-M: Hot color (i.e. gain) can be seen almost everywhere for the 3GPP model. For UDP, downtilt may actually bring loss to certain UE locations, especially those shadowed by buildings or at the cell-edge.

Another problem with the 3GPP model is that it often suggests too aggressive downtilt. According to the 3GPP model, the OPER+2 preforms much better than OPER, in terms of both capacity and coverage. The situation is quite different for the UDP model, where it indicates that blindly adding mechanical tilt to the OPER profile results in degradation of the system performance, especially at the cell-edge. By comparing the performance of the OPER with the OPTI-M and OPTI-E profiles, we can say that the tilt optimization algorithm discussed in this paper is able to identify a close-to-optimum tilt profile for a practical scenario, even when the UDP model and the 3D building map is considered.

From the UDP results, it is also clear that the achievable tilt gain is most significant going from ZERO to OPER, whereafter it diminishes. The OPTI-E profile is able to improve the outage and throughput gain by 3.9 and 5.9%-point in high load scenario, compared to the OPER, respectively. In low load scenario, the more aggressive OPTI-E even results in lower outage gain: 51.2% compared to 67% in OPER. On the other hand, significant gain is still observed for the 3GPP model, when a more aggressive tilt profile is applied. For example, in the high load scenario, the outage and throughput gain between OPTI-E and OPER is improved by additional 11.5 and 13.7%, respectively. The difference between the OPTI-M and OPTI-E is insignificant in terms of both outage and throughput gain.

V. Conclusions

In this paper we investigated the gain of base station antenna tilt using two different propagation models - a semi-deterministic 3D dominant path model and an empirical-based 3GPP path loss model. The main difference between the two models in respect to tilt is that the former includes the complex interaction between path loss and tilt, whereas the latter does not. From network performance evaluation in a practical LTE scenario, the study shows that the empirical path loss model tends to overestimate the tilt gain, and suggests too aggressive downtilting. With the semi-deterministic model, the system performance is less affected by the tilting. As part of the study we proposed a simple geometric-based tilt optimization, which can be used to find close-to-optimum tilt settings for an operational network without a complex network planning process. Although this study is mainly about tilt gain, it also implies that the 3GPP model might not be reliable for evaluating other advanced adaptive antenna techniques operating in the elevation dimension, such as 3D MIMO or user-specific beamforming.

Appendix
Urban Dominant Path Model

The UDP algorithm consists of two prediction steps: The first step is to determine geometrically all available propagation paths between the transmitter and the receiver according to a site-specific environment, given in terms of transmitter height, bearing, antenna pattern, 3D vector building database and optional topographical data. In the second step, the loss along each propagation path is calculated based on the following equation:

$$L_{\text{UDP}} = 20\log\left(\frac{4\pi}{\lambda}\right) + 10p\log(d) + \sum_{i=1}^{N} f(\beta, i) - \Omega \qquad (3)$$

L_{UDP} is the path loss in dB of a path with length d, and wavelength λ. $f(\beta, i)$ is a function which determines the interaction loss in dB, i.e. the loss when changing the direction of propagation. The angle between the former direction and the new direction of propagation is β, and the loss increases linearly with the angle until a maximum interaction loss is reached [14]. N is the total number of the interaction along the propagation path. The factor p is the path loss exponent, which depends on the visibility situation between the current pixel and the transmitter and the breakpoint distance, similar to the two-ray path loss model. Ω is the waveguiding factor, which is set to zero in this study. From Eq. (3), we observe that the UDP does not take the reflection phenomenon into account, and therefore it is only valid for low frequency band, where the contribution to the received signal of reflection path is neglectable. Finally, the losses of the different paths are compared to each other to identify which propagation path is dominant, i.e. the path with the least loss. The loss of the dominant path determines the path loss between the transmitter and the receiver.

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