Field Trial Evaluation of UE Specific Antenna Downtilt in an LTE Downlink

Martin Danneberg†, Joerg Holfeld†, Michael Grieger†, Mohammad Amro∗ and Gerhard Fettweis†
†Vodafone Chair Mobile Communications Systems, TU-Dresden, Germany
∗Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Saudi Arabia
Email: {martin.danneberg; joerg.holfeld; michael.grieger; fettweis}@ifn.et.tu-dresden.de

Abstract—The benefits of horizontal beamforming in cellular networks are well understood, and the technology is already used in commercial products. Recently, vertical beamforming (basically a user specific downtilt (DT)) receives a lot of attention as well. However, available channel models do not allow for an accurate simulation of this transmission scheme. This publication investigates the impact of antenna DT in a typical urban area using field trials. Two models are presented and compared with measurement data in order to study their value and limitations for the evaluation of vertical beamforming, which is an important basis for planning and deploying of such schemes in order to increase cellular downlink (DL) throughput.

I. INTRODUCTION

It’s in the principal nature of wireless communications that transmitted energy is spread across large areas which is certainly a good property for broadcast applications like radio and TV. For cellular communications, however, it is a blessing and a curse at the same time: It enables for mobility of users, but it also results in a waste of transmit power and interference of other communication links. As a result, the spectral efficiency of today’s cellular systems is limited by inter-cell interference. Cellular networks are designed and optimized on different time scales in order to trade-off objectives such as maximum throughput, spectral efficiency, energy efficiency, and cost. Obviously, optimization of base station (BS) site locations can only happen on very long time scales. Other parameters like the antenna DT can be changed in order to follow, for example, the average user traffic that is changing rather slowly over the duration of a day.

Recent advancements, e.g. in computing, signal processing, antenna, and network design, facilitate the adaptation of radio properties on shorter time scales. An important achievement are smart antenna technologies that allow an almost instantaneous adaptation of the radiation pattern by using appropriate signal processing for antenna arrays. Thus, in a cellular context, signals can be transmitted in the direction of each user equipment (UE) individually, by adding the phases of the signals in this direction constructively. At the same time the radiation in other areas is reduced, or interference to other UE can even be avoided on purpose by nulling the pattern in their directions. The benefit of this approach is well investigated for the adaptation of the horizontal beam direction, and it is currently finding its way into cellular communication standards [1]. The system level performance of these schemes can be evaluated using the same channel models that are in common use today. The UE specific adaptation of the vertical beam direction or DT (the elevation angle corresponding to the highest directional antenna gain), however, is not exploited yet in the design of cellular systems. In a first publication, the authors of [2] present different design options for a UE specific DT in an orthogonal frequency division multiple access (OFDMA) system, and they show their potentials in system level simulations. However, a conclusive evaluation of the concept is not yet possible due to the lag of a reliable 3D channel model (to the best of the authors’ knowledge). From a practical perspective, vertical beamforming is motivated by the wish to apply a user specific DT in an OFDMA system that can be adapted taking for example the user location into account. In this publication, we investigate the impact of an UE specific DT in an OFDMA field trial (in the same test bed that was previously used for a study on DT in a coordinated uplink [3]). The field trial results are then compared to two models of different complexity. In particular, we are interested in the trade-off between an optimal DT for the served UE and the impact of DT on the interference power caused at UEs located in other cells. A UE specific DT could be realized by adapting the phases of a linear antenna array on a subcarrier basis. The measurement system that was available for our field trial does

Fig. 1: BS deployment setup and UE measurement locations.
not support this option due to the lack of a sufficient large number of RF outputs. However, since we are not interested in the realization of real time switching of the beam direction in this study, but in the impact of different DTs on the large scale fading in a representative urban scenario, we see the same effects by adapting the electrical DT using the provided mechanism of our antenna system.

### A. Outline of this Paper

We study UE specific BS antenna DT in cellular networks. Static measurements are performed and compared with simulation models. Two different such models that capture the impact of DT on channel characteristics are presented in Section 2. After that, in Section 3, the measurement methodology and physical environment of the test bed are described. In the following Section 4, field trial results are presented and interpreted. A comparison between modeling and field trial results is given in Section 5. Finally, Section 6 summarizes the results.

### II. Modeling the Impact of Antenna Downtilts

Models for wireless radio channels can be classified into three categories: deterministic, empirical, and stochastic models. The former are in the focus of this correspondence. The radio channel is affected by the antenna patterns and the physical surroundings. In the following, two models will be presented that differ in the accuracy in which these factors are considered. The first, ray tracing, gives a simplified solution of Maxwell’s equations for a modeled surrounding that is a very close representation of the actual physical environment. In the second simplified model a generic antenna pattern is assumed that is characterized by few parameters. The impact of the surroundings is not considered in this model at all.

#### A. The Ray-Tracing Approach

In ray tracing (RT), radio signal propagation is modeled by the principles of geometrical optics (GO) and uniform theory of diffraction (UTD) [4]. For an accurate prediction of real propagation, the environment should be modeled as close to reality as possible. In practice, engineers always have to trade-off accuracy and complexity when using RT. As a result, 3D maps are used that contain all major structures such as buildings and bridges, but ignore most details.

In the RT process, rays are launched at the transmitter and propagate in the modeled environment until they hit the targeted receiver, or fall below a pre-specified noise floor level [5]. This way, RT is capable of simulating actual multi-path propagation [5], [6]. As a result, a multidimensional characterization of the radio propagation environment, including time delay, angle of arrival, as well as angle of departure profiles is determined. In this work, the RT software Actix RPS 5.5 was used. The actual RT algorithm can be influenced by a large amount of parameters, again allowing a trade-off of accuracy and complexity. A key parameter is the angular step size which determines the number and the spacing between the rays that will be launched from a transmitter. Two dimensions are considered: a horizontal angle referred as (azimuth) and a vertical angle (elevation or tilt).

#### B. The Simplified Approach

A simple model for the impact of DT based on a universal antenna pattern that only depends on few antenna specific parameters is described in [7]. The model consists of two components, a horizontal and a vertical gain model: The horizontal (azimuth) gain model is parameterized with a maximum gain $G_{\text{max}}$ in [dB], half-power beamwidth (HPBW) $\text{HPBW}_h$, a front back ratio $\text{FRB}_h$ in [dB], and the angle between the antenna boresight and the direct link between transmitter and receiver $\phi$:

$$G_h(\phi) = -\min (12 \cdot (\phi/\text{HPBW}_h)^2, \text{FRB}_h) + G_{\text{max}}$$

(1)

The vertical model is parameterized using the vertical half-power beam width $\text{HPBW}_v$, a side lobe level $\text{SLL}_v$ in [dB], and the angle between the antenna boresight and the direct link between transmitter and receiver $\phi$:

$$G_v(\Phi_{\text{geo}}) = \max (12 \cdot (\Phi_{\text{geo}} - \Phi_{\text{th}})/\text{HPBW}_v)^2, \text{SLL}_v).$$

(2)

The antenna gain in a certain direction is given by the sum (1) and (2):

$$G(\phi, \Phi_{\text{geo}}) = G_h(\phi) + G_v(\Phi_{\text{geo}})$$

(3)

As described in [7] and as follows directly from the minimum of (1) and (2), the minimum antenna gain is $\text{SLL}_v + \text{FRB}_h + G_{\text{max}}$, all side lobes have the same power. Compared to RT, this simplified model does not consider any effects of the surroundings and can, thus, be expected to give a good representation only under line-of-sight (LOS) conditions, while not under non-line-of-sight (NLOS).

### III. Physical Environment and Measurement Methodology

The test bed consists of two BSs located at different sites in downtown Dresden as depicted in Figure 1. Buildings within the test bed area are mostly 4-5 story apartments of similar height between 15 m and 19 m. In contrast, the BSs themselves are located on buildings of about three times that height (two further buildings have that height as well). Many trees are planted along the streets which are laid out in a checked

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise floor</td>
<td>-100 dBm</td>
</tr>
<tr>
<td>Angular ray launching step size</td>
<td>1°</td>
</tr>
<tr>
<td>Max. number of reflections</td>
<td>infinite</td>
</tr>
<tr>
<td>Max. number of penetrations</td>
<td>4</td>
</tr>
<tr>
<td>Max. number of diffractions</td>
<td>3</td>
</tr>
<tr>
<td>Depolarization</td>
<td>mean</td>
</tr>
<tr>
<td>Buildings permittivity coefficient (real part)</td>
<td>5</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### TABLE I: Key parameters used in the ray tracing model.
TABLE II: Parameters of the BSs within the test bed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BS1</th>
<th>BS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna height over ground [m]</td>
<td>54.5</td>
<td>50.1</td>
</tr>
<tr>
<td>KATHREIN antenna type</td>
<td>800 10541</td>
<td>800 106 29</td>
</tr>
<tr>
<td>Antenna gain [dBi]</td>
<td>18</td>
<td>16.5</td>
</tr>
<tr>
<td>Downilt [°]</td>
<td>(0-12)+5</td>
<td>(0-10)+5</td>
</tr>
<tr>
<td>half-power beamwidths</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical [°]</td>
<td>6.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Horizontal [°]</td>
<td>58.0</td>
<td>80.0</td>
</tr>
<tr>
<td>Front to back ratio [dB]</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Side Lobe Level [dB]</td>
<td>-18.0</td>
<td>-18.0</td>
</tr>
</tbody>
</table>

pattern. So, whether a UE has NLOS or LOS to the BSs may change quickly within few meters.

Figure 1 depicts five different measurement locations each of which is characterized in Table III. The geometric DT \( \Phi_{geo}(i,j) \) for which the (vertical) antenna pattern of BS \( j \) is facing directly towards Location \( i \) is given by

\[
\Phi_{geo}(i,j) = \arctan\left(\frac{h_j}{d_{i,j}}\right),
\]

where \( d_{i,j} \) is the distance between the UE location and BS and \( h_j \) is the height of the BS antenna as given in Table II.

The objectives of the field trials are twofold: First, previously described models are tested and assessed regarding their limitations and potential development and, the second, possible gains of UE specific down tilt in the context of a 3D beamforming system should be shown.

IV. DESCRIPTION OF THE TRANSMISSION SYSTEM

Each BS is equipped with a cross-polarized antenna as described in Table II. These antennas provide an electrical mechanism for changing the DT, which is used in addition to a pre-configured mechanical DT of \( 5^\circ \). For the measurements, a modified (orthogonal frequency division multiplex (OFDM) based) Long Term Evolution (LTE) system was used, as described in [8], [9]. The system enables the estimation of the physical channel transfer functions (CTFs) via cell-specific CSI reference symbols (CSI-RSs) that are transmitted on the physical channel transfer functions (CTFs) via cell-specific described in [8], [9]. The system enables the estimation of the wideband channel power was determined via GPS-based synchronization with Meinberg GPS 170MP reference normals [10]. For a first set of measurements, the UE test equipment from the company Signalion was mounted on the roof top at a height of \( 2 \) m. An antenna rotation table was mounted on top of the rack. Two dipole antennas were used at the UE, placed in about \( 40 \) cm distance. A second set of measurements was conducted using the same UE carried on a bus. In these measurements, the same generally setup was used, including the rotating table which was mounted on the roof top at a height of \( 2.5 \) m, compared to \( 1.5 \) m on the rickshaw. In all measurements, a control notebook was used, running specific software to automate the measurements. To guarantee sufficient averaging of small scale fading, at every location, data from five different antenna positions was collected using the rotation table. The angle between the antenna positions was \( 72^\circ \), and each measurement was done for a duration of \( 30 \) ms. Since pilots are transmitted twice per ms, in total \( N_t = 300 \) measurements are taken per location.

The geometric DT of both BSs, both transmit antennas (\( N_t = 2 \)) and each slot \( N_s \) is estimated. The average channel power \( p_{i,j} \) is given by

\[
p_{i,j}(n) = \frac{1}{N_t \sum_{i=1}^{N_t} \sum_{r=1}^{N_t} \sum_{t=1}^{N_t} \sum_{s=1}^{N_s} |H_{s,t,r,i,j,\Phi_{geo}(n)}|},
\]

Of all measurements of the first field trial (using the rickshaw), the highest average channel power was observed at Location 5 and BS2 at a DT of \( 7^\circ \). In the following, all other results are expressed relative to this maximum value. Thus, the (average) channel power, can be considered as a relative path loss.

V. RESULTS

In this section, all field trial results are described in detail. First, we concentrate on the impact of the antenna DT on the SIR. We compare a system that allows for a UE specific DT through vertical beamforming with a conventional system with fixed DT per BS antenna. Afterwards, investigate the effect of DT on the multi-path channel, namely the delay spread. Finally, we explore the impact of location and DT on the channel power.

A. Impact on the SIR

At each location, the wide band channel power was determined for different DTs between \( \Phi_{lift} = 6^\circ \ldots 15^\circ \). For most measurements, the geometric DT of both BSs is in this adjustable range. The relative channel power to each BS and for each location is depicted in Figure 3. The DT of the maximum channel power was observed to be consistent with the geometric DT which is depicted by the asterisks. However, the sensitivity of channel power with respect to DT differs substantially across the measurements. DT can have an
effect between 3 dB and 21 dB on channel power. Thus, the surroundings have a great impact on the DT sensitivity.

The circles in Figure 3 indicate the optimal UE specific DT setting that would maximize the SIR. Depending on the user location, the achievable SIR varies between 12 dB and 17 dB, compared to an SIR between 2 dB and 12 dB for a system that would apply a fixed DT of 10° at all BS. However, achieving such gains would require a sufficient number of users for which different DTs are optimal, such that a coordinated scheduling algorithm could find compatible user groups. Compatible users would, for example, be at Location 2 and Location 3. In this case, BS2 would serve the user at Location 2 with a DT of about 8° and BS1 would serve the user at Location 3 with a DT of 15°. This way BS2 has its maximum power and BS1 has its minimum power at Location 2, and the situation is reversed at Location 3. At Location 1, the channel powers of BS1 and BS2 intersect at a certain DT, 9° in this case. The decision on the serving BS would, thus, depend on the DT as well. Clearly this could only be achieved in a system with a certain BS coordination.

Typically, a UE is served by the closest BS. However, in some specific cases, the UE should be served by a BS that is further away, because nearby obstacles can substantially raise the path loss to the closer BS. An example for this behavior can be found at Location 4 where the LOS to the BS1 ($d_{4,1} = 214$ m) is blocked by the roof-edge of BS building. Probably through reflections from the neighboring building, which has the same height as the BS antenna, the receive power is constant over all DTs. In comparison, the signal power from BS2 is up to 13 dB larger, at a distance of $d_{4,2} = 710$ m. At Location 2 a similar (but not so pronounced) effect can be observed. Here, the maximum channel powers differ by 7 dB.

### B. Impact on Multi-Path

With 20 MHz bandwidth of our field trial system, we are able to detect channel taps which differ in time by about 0.0326 µs. This corresponds to about 9.7 m. The multi-path propagation profile observed in the measurements and the RT simulation are partially consistent. The CIR for Location 2 and BS2 at a DT of 6° is shown in Figure 4a. Note that using our field trial system, we are not able to determine absolute path

---

**TABLE III:** The geometrical properties.

<table>
<thead>
<tr>
<th>Loc.</th>
<th>Distance [m]</th>
<th>Geom. DT [°]</th>
<th>$\phi$ [°]</th>
<th>LOS/NLOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS1</td>
<td>BS2</td>
<td>BS1</td>
<td>BS2</td>
<td>BS1</td>
</tr>
<tr>
<td>1</td>
<td>299</td>
<td>418</td>
<td>10.3</td>
<td>6.8</td>
</tr>
<tr>
<td>2</td>
<td>325</td>
<td>392</td>
<td>9.5</td>
<td>7.2</td>
</tr>
<tr>
<td>3</td>
<td>199</td>
<td>573</td>
<td>15.3</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>214</td>
<td>710</td>
<td>14.3</td>
<td>4.0</td>
</tr>
<tr>
<td>5</td>
<td>259</td>
<td>472</td>
<td>11.8</td>
<td>6.0</td>
</tr>
</tbody>
</table>

---

Fig. 3: Relative channel power at five different measurement locations. The circles indicate the optimal DT setting that would maximize the SIR in a system with UE specific vertical DT. The asterisks mark the geometrical DT.

Fig. 4: CIRs of BS2 at Location 2

Fig. 5: Environment modeled in the RT simulator for a DT of 6°
delays. Two significant taps are visible that are about 0.63 µs apart. These taps can also be identified in the RT simulation. As shown in Figure 5, the right building reflects the signal. The distance of the building from the measurement location is about 85 m, twice that distance accounts for a delay of 0.57 µs. Thus, the latter tap in the CIR is assumed to be reflected from the building and the former to be a fraction of the direct signal. The time difference between the two paths in measured in the RT simulation is 0.601 µs.

An interesting observation is that a third tap appears in the measured CIR at a higher DT as shown in Figure 4b. So, interestingly, the DT of the BS has an impact on multi-path propagation and, thus, on the delay spread as well. At this location the delay spread for BS2 is increasing with the DT as shown in Figure 6. The same behavior at location 2 was consistently seen during all measurements no matter if the UE was located on the rickshaw or the bus. We failed, however, to identify this third strong reflector using RT.

C. Impact of Location

As stated before, the impact of the DT on the channel depends on the location of the UE. To validate and extent the insight of this effect, the measurements described above were repeated at selected locations. However, in this second field trial the UE was carried on a bus. For practical reasons, the measurement were done at locations about 2 m away from the original ones. As shown in Figure 7, this can have a strong effect on the channel power (up to 8 dB) in certain scenarios. Even the DT for which the maximum received power was observed to shift slightly. The different UE antenna height had a great impact on the received power even under NLOS conditions, e.g. at Location 1 where the the rickshaw was placed behind a small garage (of about 2.6 m height), while the antennas on the bus were at the same height of this blocking obstacle resulting in a higher receive power. This explains the offset between the channel power in both measurements. Despite this effect, both curves follow the same trend. To investigate influence of the location on the channel, new locations were explored near BS2 in the second field trial as depicted in Figure 9. These Locations are about 25 m away from each other and at a distance of 450 m and 272 m to BS1 and BS2, respectively. All locations have NLOS to both BSs. However, at Location 7, 9, and 10 LOS to BS2 is only blocked by trees, not by concrete. In Figure 8 we observe that a similar DT dependency was observed at all locations, but the absolute values differ by up to 14 dB depending on the UE location. A noticeable observation is that for almost all measurements the DT with the maximal receive power is slightly smaller than the geometric DT.

VI. COMPARISON OF MEASUREMENTS AND MODELS

A. The Simplified Model

As shown in the Figure 10, the channel power obtained by the simplified model and the measurements match very well for LOS channels. However, as assumed, strong deviations are occur under NLOS conditions. E.g. at Location 4, the channel of BS2 can be modeled well, but the channel of BS1 cannot be predicted well because LOS is blocked by the roof-edge of the BS building. Location 3 is special in the sense that even though we have LOS to BS1 the measured channel power is higher the modeled power for lower DT. This can be explained by strong reflections from buildings nearby that are not considered by the model. In diffuse NLOS cases, where only parts of the Fresnel zone are blocked, the simple approach gives good predictions as long as the number of reflections is small, e.g. at Location 2 for BS2.

B. The Ray-Tracing Model

In this paper, RT is used to calculate the received signal power at each of the receivers locations for the purpose of comparing and verifying the RT results with the field measurements. Smaller details such as foliage and cars are
not considered in the 3D model, because they are difficult to model and supposed to give negligible gains in terms of accuracy [6]. In the Actix RPS RT simulator, overall similar settings as in [11] are used, including the 3D map of the environment and the use of a directive scattering model which steers the scattering lobe more into the direction of the specular reflection. However, some modifications have been done in order to reflect the scenario under study. The most important parameters are summarized in Table I. The results given by RT are matching the measurements very well at most locations and DTs, as depicted in Figure 11. They support the earlier argument that the geometric DT is not always the best choice for a maximum received power. Multi-path scattering can effect the optimal DT at NLOS locations. When RT simulation results are compared to the results of the simplified approach, RT matches the measurements better especially for NLOS situations.

It can be noticed that at high DT values for BS2 most of the locations in RT model receive different power level trends than in field measurements. One explanation for this observation could be the absence of small scattering details. Some of the measurement locations are located in vicinity of dense trees. A possible solution is to enhance the 3D map as described in [12] by various optimization techniques, e.g. by the pre-creation of different trees. Another reason for slight differences is that the RT simulator uses one LTE antenna pattern which is similar but not exactly the pattern of the antennas used in the testbed. Another improvement might be the use of spatial averaging technique as described in [6] to avoid the inaccuracy of receiving antenna positions.

A problem that could have occurred during the measurements is inter-carrier interference. An effect that is certainly not severe when channels to both BSs have similar power, but seems to impact the measurement accuracy they differ by about 15 dB. Where this is the case, e.g. BS2 at Location 3, the difference between RT and measurements is not due inaccuracy in the RT model but in the measurement. However, the effect of inter-carrier interference would also occur in practical system where it limits the benefit of vertical beamforming.

In order to improve the accuracy of the simulations, the ray launching step size was reduced from $1^\circ$ to $0.1^\circ$ which gave better results for the channel to BS2 at Location 1, 2, and 3, especially at higher DTs. The reason for this is that the transmit signal is exposed to less free space propagation and more to the details of the terrains. Therefore, a more accurate modeling of the signal propagation using a larger number of rays and achieved a more accurate channel propagation model which is significant at all locations where NLOS dominates.

Fig. 6: Delay spread over DT for Location 2

Fig. 7: Comparison between rickshaw and bus measurements

Fig. 10: Measured UE relative channel power compared to results of the simplified model. The plus sign marks the point where the powers of the model and the measurement were aligned.
such as between BS2 and Location 1, 2 and 3. Keeping in mind that the number of rays and the computation complexity increases 100 times when the step size is changed from 1° to 0.1°, this is another good example for the importance of the trade-off of accuracy and complexity in RT. Certainly, this required to find proper settings for each individual study.

VII. SUMMARY

In this publication, the benefit of a user specific DT was investigated through field trials in a urban cellular test bed. We have shown, for a set of UE locations, that vertical beamforming could increase SIR by about 5 – 10 dB. The measurement results were compared to two different models that describe the impact of DT on radio channels. Provided that appropriate simulation parameters are chosen, a task that can require a lot of calibration work, a very good match between measurement and RT model can be achieved. Under LOS condition, even when parts of the Fresnel zone are blocked, the impact of DT can even be modeled using a much simpler approach that only considers the impact of the antenna pattern. Future work could be done on further models that, in terms of complexity and accuracy, range between the approaches that are considered in this paper.

ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Commission’s seventh framework programme FP7-ICT-2009 under grant agreement no 247223 also referred to as ARTIST4G. The authors would like to thank the German Ministry for Education and Research (BMBF) for funding the test equipment that is essential for the field trials presented. Further, this work would not have been possible without support from Ainoa Navarro Caldevilla, Sven-Einar Breuer, Vincent Kotzsch, and Eckhard Ohlmer.

REFERENCES