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Impact of Electrical and Mechanical Antenna Downtilt on the Uplink of a WiMAX System with Soft Frequency Reuse

Florian Wamser, David Mittelstädt, Dirk Staehle, and Phuoc Tran-Gia

Abstract – In an interference-limited mobile WiMAX network, efficient cell planning and tuning is an essential task to ensure a functioning network. This includes the selection of the optimal settings for the antenna to on the one hand, provide a good coverage and on the other hand achieve cell isolation. Two different antenna tilting methods are examined in this article, namely the mechanical and the electrical vertical downtilt. The evaluation is done with an advanced WiMAX IEEE 802.16e simulator. In particular, the impact of the antenna configuration on WiMAX soft frequency reuse (SFR) is studied. The results show a high dependency of SFR to the downtilt configuration, since the inter-cell interference level changes significantly with different settings.

Index Terms – Mechanical Antenna Downtilt, Electrical Antenna Downtilt, OFDMA, WiMAX, Soft Frequency Reuse

1 Introduction

The necessity of a highly efficient mobile communication network arises from the ever increasing traffic demand of the users. Such a network requires better radio systems, better radio transmission techniques but also a more efficient network planning and tuning.

Cell and frequency planning has always been a prerequisite for an efficient functioning network. In GSM, for instance, frequency planning was used in such a way that neighboring cells use different frequencies in order to avoid inter-cell interference. These systems can cope with a certain coverage overlap of the different cells since it does not cause significant interference. Newer systems like UMTS utilize the entire system bandwidth in all cells resulting in a much higher spectral efficiency but also in inter-cell interference. These systems are usually interference-limited which means that a large cell overlap considerably affects the system performance.

In next generation mobile communication systems like WiMAX and LTE, a high utilization of the frequencies is essential due to the ambitious requirements and performance objectives. Advanced inter-cell interference mitigation techniques are planned for LTE and already defined in WiMAX in release 2. However, these techniques do rely on a reasonable antenna configuration. The configuration has the purpose to on the one hand, support all the users in the cell which means it should provide sufficient cell coverage. However on the other hand, it has to avoid the cell overlap and in turn, provide good cell isolation.

A WiMAX mobile network with soft frequency reuse (SFR) as inter-cell interference mitigation technique is investigated in this work. In particular, we evaluate the direct influence of the antenna configuration on the uplink of such a mobile network. The focus thereby lies on the impact on the performance of the soft frequency reuse.

The antenna configuration consists of several different components. Therefore, the static base station antenna gain, the horizontal antenna gain, and the vertical antenna gain which is either modeled by the electrical downtilt or the mechanical downtilt, are considered. A large and sophisticated WiMAX IEEE 802.16e simulation of the resource allocation was used which considers 75 sectors with wrap around and 1–26 users per sector on average. The results show the diverse performance outcomes of the WiMAX SFR system at different loads.

The rest of this article is structured as follows. In the second chapter, related work and previous publications are reviewed and summarized to give an overview over existing literature. In the third chapter, a system model for the resource allocation of a WiMAX network is introduced. In chapter 4, the simulation is described and results are shown in chapter 5. Finally, chapter 6 gives concluding remarks. The references are listed in chapter 7.

2 Related Work

Antenna downtiliting has always been regarded as an effective means to reduce inter-cell interference and hence, to increase the system capacity [1–6]. There are two different mechanisms available. Either the antenna can be tilted as a whole or the antenna tilt can be achieved by electrically changing the phases of antennas which are closely together in an antenna array. The first method is called *mechanical downtilt.* The second method is called *electrical downtilt.* The electrical downtilt is more complex but also more easy to adapt.

In [1] a vertical electrical downtilt antenna radiation model is given. It is verified with measured data of real networks. The vertical deviation from antenna boresight is calculated as

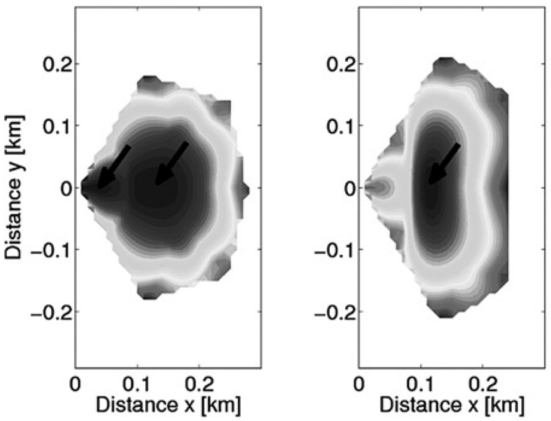

Fig. 1: Spatial distribution of the emitted interference under electrical and mechanical downtilt

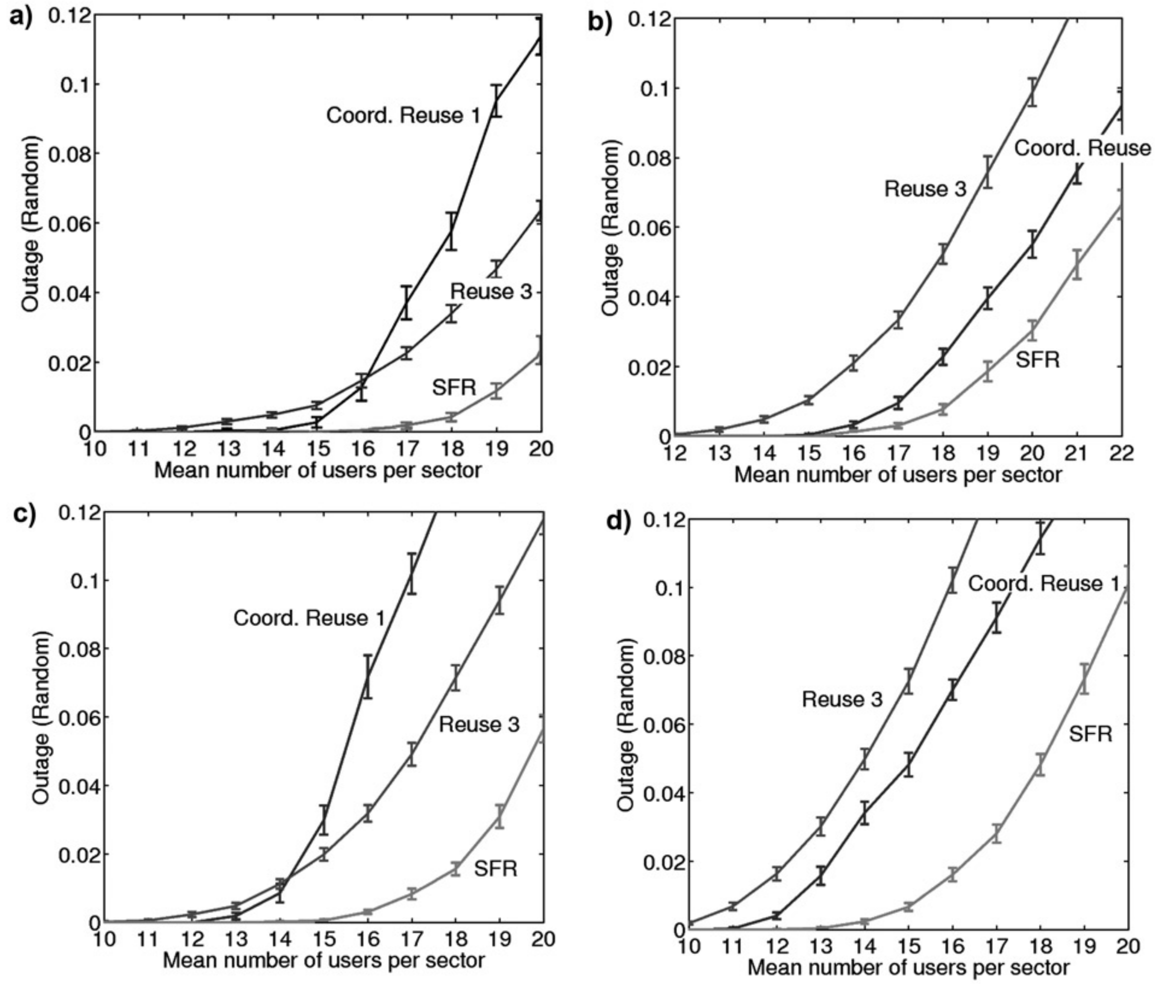

Fig. 2: Frequency reuse schemes under different downtilt configurations: a) Electrical downtilt, $\theta_{3dB} = 6.2$, b) Mechanical downtilt, $\theta_{3dB} = 6.2$, c) Electrical downtilt, $\theta_{3dB} = 15$, d) Mechanical downtilt, $\theta_{3dB} = 15$

illustrated in Figure 4a). Angle β is calculated as the difference between the downtilt angle and the vertical angle of the direct line between the mobile and the sector antenna. Angle θ_{tilt} describes the vertical tilt of the base station antenna while θ_{3dB} defines the angle between an attenuation of 3dB when deviating from the tilt direction into both directions. Here, the vertical antenna gain is independent of a horizontal angle α between the mobile and the base station. This may have an impact on the performance of a system as users in the center of a neighboring sector may become interference critical. The electrical downtilt pattern is given by

$$G_{el.}(\beta) = -\min\left\{12 \cdot \left(\frac{\beta - \theta_{tilt}}{\theta_{3dB}}\right)^2, \varphi_{SLL}\right\}, \tag{1}$$

where $\phi_{SSL} = 20$dB is the side lope level, relative to the maximal gain of the main beam. Figure 4b) shows the attenuation of the electrical downtilt as a function of the mobile's distance from the base station. In this figure the base station antenna height h_b is assumed to be 30 m. The height of the user antenna h_m is assumed to be 1.5 m. The three curves each represent a different angle θ_{tilt}. The value of θ_{3dB} is 6.2°.

The mechanical downtilt in contrast considers the effect of mechanically tilting the base station antenna by an angle θ_{tilt}. The vertical attenuation depends on the angle α between horizontal antenna direction and user direction. It is given by

$$G_{me.}(\alpha, \beta) = -\min\left\{12 \cdot \left(\frac{\beta - \theta_{tilt} \cdot \cos(\alpha)}{\theta_{3dB}}\right)^2, \varphi_{SLL}\right\}. \tag{2}$$

Additionally to the vertical downtilt, an antenna has also got a horizontal radiation pattern. The directivity in the horizontal plane (azimuth) for the antenna model is proposed by many system evaluation documents to simulate a realistic scenario [7, 8]. [1, 7] recommend the following model:

$$G_{horiz.}(\alpha) = -\min\left\{12 \cdot \left(\frac{\alpha}{\alpha_{3dB}}\right)^2, \varphi_{FRB}\right\} \tag{3}$$

where the angle in which a user will experience an attenuation of 3dB is defined as α_{3dB}. Furthermore, = -18dB is the front back ratio of the antenna. Figure 4c) shows the attenuation of a signal in dB as a function of the horizontal angle between the base station antenna and the mobile as defined in (3). The value of α_{3dB} is 70°. This results in a gain of -3dB at an angle α of ±35°.

Gunnarsson et al. [1] describe in their work the impact of the horizontal and the electrical pattern for LTE and UMTS High-speed Packet Access (HSPA). They examine the system performance with 8° and 10° downtilt angle at a base station height of 30 m. 10° electrical downtilt is in both cases the best

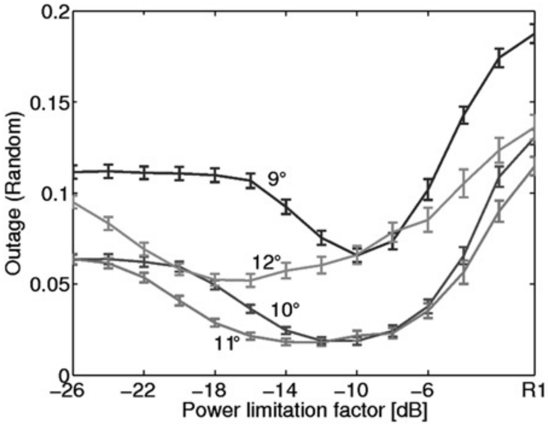

Fig. 3: SFR power mask parameter study under different varying downtilt angles

performing setting. However, a load dependent investigation is not done. Forkel et al. [4] present a simulation with different user loads but consider a single cell only. The users are homogenously spread across a grid and move along the grid with a speed of 30 km/h. They simulate a UMTS system and use a basic speech traffic model. The best performance is achieved at a mechanical downtilt of 6° for a base station height of 25 m. The authors recommend an adaption of the antenna settings according to the expected traffic situation and cell size. The most comprehensive investigation of the downtilts is done by Nimelä [2, 3]. He studied the impact of different electrical and mechanical downtilt values on the performance of a WCDMA network. Several traffic and mobile profiles are evaluated in conjunction with different antenna heights, cell sizes, and sectoring schemes (3-sectored or 6-sectored). One outcome is that the traffic mix does not much change the optimal downtilt parameter whereas it is heavily dependent on the number of users and their location distribution within the cell. Finally, among the different papers that consider multi-array beamforming approaches like [9], Calcev and Dillon [5] have to be mentioned since they propose a real-time procedure for antenna tilt control in cellular networks. Results are verified by a motion simulator in a large city and show a significant reduction in dropped calls when the downtilt is adapted.

Most of the studies focus on the downlink like [10]. However, in this work the performance of the uplink is investigated. Moreover, SFR is used in the uplink of the system which is proposed for WiMAX Release 2.

3 System Model

We consider the uplink of a WiMAX IEEE 802.16e mobile communication system where frequency partitioning and an interference mitigation scheme are used. The interference mitigation scheme is based on common transmit power masks [10, 11]. In the following, we first describe soft frequency reuse (SFR) which is a well-performing variant of fractional frequency reuse. Afterwards, the system model for the simulation is described with focus on the resource allocation.

Consider a sector x of a trisectorized network. The available frequency band of the network is divided in 3 distinctive frequency bands A, B, C. Frequency band A is exclusively assigned to the sector i. The principle of SFR now is to allocate resources of the frequency band A to mobiles in the outer area of the sector. Mobiles in the outer area of the sector are more interference critical since they are close to the next sector and use high power to reach their own base station. Additionally, resources of frequency B and C are allocated for mobiles in the inner area of the sector although the frequencies are actually assigned to other sectors. Mobiles in the cell center must not transmit at high power since they are not far away from the base station. Normally, SFR is achieved with frequency partitioning in conjunction with defining a cell-specific SFR power mask over the system bandwidth [10] which works as follows. Depending on the frequency, the power profile defines the fraction of the maximum transmit power which is allowed for transmission. Obviously, power factor p_A is normally 1 for the exclusive sector band, in the following called home sector band, and higher than 1 in the frequency partition which is shared with other sectors to keep the inter-cell interference at a certain limit.

Let us review the terminology of the IEEE 802.16e standard. A subchannel is a group of subcarriers of an OFDMA symbol. A subchannel consists of a number of $N_{subca.}$ subcarriers. A slot is the minimum resource allocation unit and spans over one subchannel and three symbols. Each slot carries a number of N_{data} data subcarriers and N_{pilot} pilot subcarriers. The frame is subdivided into subchannels in one dimension and slots in the second dimension. Users are successively assigned to slots in the resource allocation. Additional optional symbol structure for PUSC is used as underlying symbol structure. In contrast to IEEE 802.16e, subcarrier permutation is done per frequency partition like in IEEE 802.16 m Advanced Air Interface due to the SFR.

We consider the uplink of a mobile network with a set of users M which wants to transmit V bits of data. Consider a mobile $i \in M$ in sector x. Both, power control and adaptive modulation and coding (AMC) are used in conjunction with an interference mitigation strategy. If i has to transmit V_i bits with modulation and coding scheme (MCS) k, it requires $S_k (V_i)$ slots. Now, the power P_i that a mobile i can spend per slot depends first, on the interference mitigation scheme and

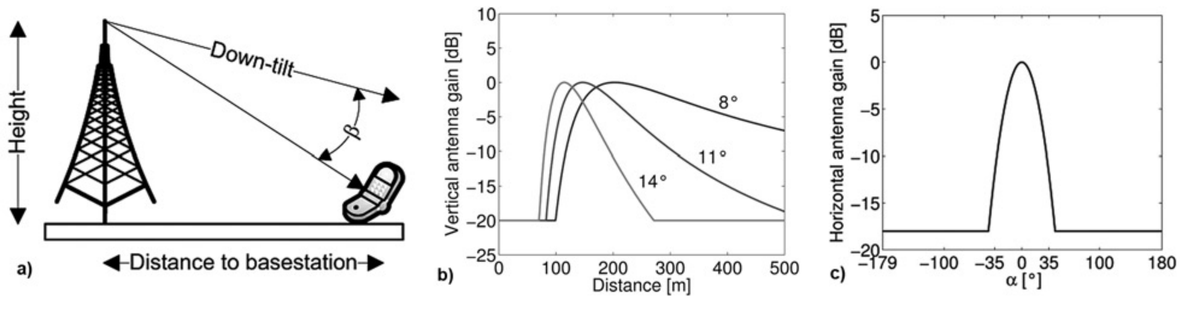

Fig. 4: Downtilt angle, vertical and horizontal antenna pattern
a) Downtilt angle, b) Vertical electrical antenna pattern under different downtilts, c) Horizontal antenna pattern

second, on the number of subchannels that the $S_k(V_i)$ slots occupy and that we denote as $C_k(V_i)$. The total power P_{tot} for the whole transmission is restricted according to power factor p_A for frequency band A. Thus, the total power is defined as $P_{tot}= P_{max} / p_A$ where P_{max} is the maximum sending power of a mobile for the whole transmission. Now, the power per subchannel is $P_k^{SubCh}(V_i)=P_{tot}/C_k(V_i)$, and the power per slot is $P_k^{slot}(V_i)= P_k^{SubCh}(V_i)/18$ since a subchannel occupies 6 tiles or 18 subcarriers in parallel.

We consider an IEEE 802.16e open loop power control. That means it adjusts the desired transmit power in order to achieve a target carrier to interference and noise ratio (CINR) that is sufficient to guarantee the desired frame error rate (FER). The target CINR is MCS specific and denoted as γ_k*. The propagation loss $L = G_{path}+G_A+G_{horiz.}+G_{vert.}$ includes the static base station gain G_A, the horizontal antenna gain $G_{horiz.}$ and the vertical antenna gain $G_{vert.}$ which is either modeled by the electrical downtilt G_{el} or the mechanical downtilt G_{me}. Now, if I is the average per slot interference at the receiver and N_0 is the per slot thermal noise power, then the target power is $P_k^*(I,L)= \gamma_k^*,(N_0+I),L$.

The MCS $k^*(i)$ that mobile i uses is the MCS consuming the least resources while requiring less than $P_k^*(I_x^A,L_{i,x})$ power, where I_x^A is the average per slot interference for sector x on frequency A and $L_{i,x}$ is the path loss from mobile i to sector x. Let us assume that MCS 1 is the most robust MCS and MCS k_{max} is the least robust MCS, then $k^*(i)=max\{ k \mid P_k^*(I_x^A,L_{i,x}) \leq P_k^{slot}(V_i)\}$. If $P_k^{slot}(V_i)$ is too small due to for instance, the power mask or the propagation loss, then $k^*(i)$ could result into an empty set which means that the mobile cannot send at all.

Consequently, mobile i occupies $s_i = S_{k(i\,)}\,(V_i)$ slots and the per slot transmit power is $p_i^A = P_{k(i)}^*(I_x^A,L_{i,x})$ assuming that i transmits on frequency A in sector x. The per slot interference $I_{i,y}^A$ that mobile i produces at sector y is $I_{i,y}^A = p_i^A\,,\rho_{i,A}/L_{i,y}$ where $\rho_{i,A}$ is 1 if i uses frequency A and 0 otherwise.

The task of the resource allocation is now to decide which user i should be considered for the home frequency band A (and which to the side bands) with respect to the interference $I_{i,y}^A$ to other sectors to support as many users as possible. The interference $I_{i,y}^A$ depends on the transmission power which in turn depends on the antenna configuration.

The resource allocation works as follows. The first decision that has to be made is which users have to be allocated to which bands. The idea is to allocate interference critical users to the home band. To do this the users within a sector are made comparable by defining a metric $O(i)$ that estimates the interference criticalness of a user i [11]. Higher values of $O(i)$ indicate less critical users. Note, choosing the right metric has a large influence on the interference and thus, on the overall performance of the system,too. The function $c(i,k,A)$ checks if enough resources are available on frequency A to allocate user i with MCS k. Now, the mobiles i are allocated to the home band A in ascending order of $O(i)$ if $c(i,k^*(i),A)$ is true. If the home band is fully utilized, the remaining users are either assigned to one of the side bands or they are not assigned to any resources at all depending on $k^*(i)$ is empty or not. In the latter case there are insufficient resources to allocate all users. If this is the case, a user must be selected whose transmission is delayed or denied in this frame. Due to fairness reasons random outage selection is assumed. With random outage selection, each mobile i has the same probability to experience outage.

4 Simulation

The simulation of the resource allocation of the OFDMA uplink is carried out using a time-invariant WiMAX Monte Carlo simulator. It is based on fundamentals of the IEEE 802.16 m Evaluation Methodology Document [7]. The used order $O(i)$ can be found in [11]. One transmission frame is simulated with a fixed traffic demand of all users. In contrast to a full buffer simulation, this means that every user constantly tries to send v bits and the simulation calculates a feasible resource allocation according to the power and resource allocation algorithms. The cell simulation considers a 5x5 deployment with hexagonal 3-sector sites. In order to avoid bounding effects and thus, an overestimation of the system performance, wrap around is applied which ensures that all cells experience the same interference characteristics. Table 1 provides central modeling parameters and assumptions. The simulator is able to process non-MIMO antenna configurations including different downtilts, diverse antenna patterns, and different user traffic volumes. In all simulations, error free feedback from the MS to the BS is assumed. For the simulations, frequencies in the 3.5 GHz band are chosen. We consider an OFDMA system with FFT size of 512 subcarriers. After eliminating the guard subcarriers, we effectively use 432 data subcarriers. G_{path} is modeled with the urban macrocell path-loss model [7]. The user antenna is considered to be omni-directional with a gain of 0dB. The horizontal 3dB attenuation threshold is set to $\alpha_{3dB} = 70^\circ$. Hybrid ARQ (HARQ) and shadow fading is not included in this evaluation. Especially, the first one can provide an interference benefit. However, due to the type of simulation, HARQ is not applied.

For the system evaluation, several parameters are used which are enumerated for completeness. The results are generated with 1 to 22 users per sector. The users transmit 1024 bits per frame. We consider the average cell outage percentage as performance measure. It is calculated per cell sector and afterwards, the mean is derived of all 75 sectors to get the average outage. The outage percentage is equivalent to the throughput in the sector due to a fixed transmission rate of the mobiles. Each curve shown in the results correspond to the average of at least 20 samples. Additionally, the 95 % confidence intervals are drawn to ensure the reliability of the stochastic results.

5 Impact of Different Downtilt Configurations

The goal of the article is to examine the impact of the downtilt settings on SFR in a WiMAX mobile network. First, the intercell interference of a sector under mechanical and electrical downtilt is investigated. Afterwards, the performance of SFR compared to two other frequency reuse schemes is presented. Finally, the optimal power mask parameter of SFR is determined under different downtilts.

Table 1: Simulation Parameters

Cellular layout	25 hexagonal, trisectorized cells
Site-to-site distance	0.5 km
BS/UE antenna height	30 m, 1.5 m
Carrier freq. f, Bandwidth	3.5GHz, 5MHz
FFT size, # subchannels	512, 24
Frame length	5ms
Subchannel mode	Additional optional symbol structure for PUSC
Antenna configuration	Single-Input-Single-Output
BS/UE antenna gain	14dBi / 0dBi
Path loss model	$G_{path}[dB] = 35.2 + 35\ log10(d) + 26\ log10(f/2)$
UE thermal noise density	-174dBm/Hz
UE maximal transmit power	200mW
Channel state information (CSI)	Perfect CSI

In SFR, the resource allocation has to decide which user should be considered for the sector exclusive home band and which is considered for the side bands. This is done after the uplink power control and with respect to the interference criticalness *O(i)*. Fig. 1 shows the spatial distribution of the emitted inter-cell interference. The electrical downtilt is depicted in the left figure of Fig. 1 with $\theta_{3dB} = 6.2^\circ$. The right figure shows the interference distribution at mechanical downtilt, again with $\theta_{3dB} = 6.2^\circ$. The positions in dark color which are marked with an arrow have low values of emitted interference whereas the dark areas at the border indicate high ones. Therefore, the areas at the border show interference critical positions in a sector. When comparing the two figures, it can be seen that the sector inter-cell interference is changing significantly with the downtilt type. Therefore, the performance of SFR is evaluated in the following in detail.

SFR is evaluated in conjunction with coordinated reuse 1 which is a reuse 1 that makes use of the home sector frequency partitions [11]. Furthermore, a simple frequency reuse 3 is also included the figure. The optimal downtilt parameter for this cell size and base station height is previously determined to 11° with 1 to 19 users.

Fig. 2a) contains a comparison of the reuse schemes for electrical and mechanical downtilt with θ_{3dB} at either 6.2° or 15°. The best downtilt configuration supporting the most users in a sector is electrical downtilt at $\theta_{3dB} = 6.2^\circ$. The random outage of the reuse 1 intersects reuse 3 at an average load of 16 users. For $\theta_{3dB} = 15^\circ$ this is the case at an average load of 14 users. The users experience outage more earlier since the inter-cell interference is higher for this configuration. For mechanical downtilt, reuse 1 always performs better than reuse 3. All evaluated reuse schemes perform better under θ_{3dB} of 6.2° than under $\theta_{3dB} = 15^\circ$. With electrical downtilt and $\theta_{3dB} = 6.2^\circ$, a gain of about 3 users per sector on average is achieved by SFR compared to coordinated reuse 1 at 1 % outage. This is a gain of 15 % in terms of allocated users. For mechanical downtilt the gain is lower at $\theta_{3dB} = 6.2^\circ$. These results underline the fact that it is essential to choose a suitable downtilt configuration for WiMAX SFR.

To evaluate the impact of the downtilt on SFR in detail, several downtilt angles are compared under varying transmit power limitation factors p_A. p_A denotes the fraction of the maximum transmit power which is allowed for transmission. The average number of users per sector is 24. Fig. 3 shows the random outage of the network. Four curves represent the outage under a downtilt of 9° to 12°. The optimal parameters and the achieved outage vary strongly for the four downtilt angles. This indicates that an optimization of the downtilt angle in conjunction with SFR is necessary to achieve optimal performance.

6 Conclusion

By adapting the antenna downtilt the signal level within a cell can be improved and interference to other sectors can be avoided due to the focused beam direction. The determination of the optimum downtilt angle with respect to the area around the antenna is essential for a smooth network operation. However, there are two different downtilt antenna configurations: mechanical and electrical downtilt.

We showed in this article the impact of the mechanical and electrical downtilt on a WiMAX SFR mobile communication system. The results are evaluated by simulating the resource allocation of a WiMAX SFR system with a large and sophisticated simulation with up to 26 users per sector in 25 cells. Results show that by changing the antenna configuration the inter-cell interference is varying. This in turn results in a different behavior of the individual frequency reuse patterns. With a cell size of 0.5 km and a base station height of 30 m the best performing antenna configuration is determined to 11° electrical downtilt. However, the results are dependent on the load of the sector. The angle in which a user will experience an attenuation of 3dB is determined to 6.2dB. Furthermore, this evaluation revealed that the optimum SFR power mask factor is highly dependent on the downtilt angle which in turn is a result from the varying inter-cell interference in case of different downtilts.

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First Author:
Florian Wamser
University of Würzburg
Institute of Computer Science, Chair of Communication Networks
Würzburg, Germany
E-mail: florian.wamser@informatik.uni-wuerzburg.de

Other authors: David Mittelstädt, Dirk Staehle, Phuoc Tran-Gia,
University of Würzburg, Institute of Computer Science, Chair of
Communication Networks, Würzburg, Germany

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