# Antenna Tilt Control in CDMA Networks

## ABSTRACT

This paper presents a real-time utility based procedure for antenna tilt control in cellular networks. The method's convergence to Nash equilibrium is guaranteed by the concave dependence between utility function and tilt angle. The solution was verified using a CDMA motion simulator with real path-loss data collected in downtown Delhi. The simulations show a significant reduction in dropped calls when the tilt is adapted to changes in traffic. This solution can be realized on systems that install remote control antennas.

## Categories and Subject Descriptors

C.4 **[Performance of systems]** Design studies, Fault tolerance, Measurement techniques, Modeling techniques, Performance attributes, Reliability, availability, and serviceability

## General Terms

Algorithms, Measurement, Performance.

## Keywords

CDMA, Antenna tilt, Game theory.

## 1. INTRODUCTION

The initial deployment of a cellular system is based on extensive drive tests and computer simulations. Later on, the system parameters are fine tuned based on collected statistics and fault reports taken in the field. Unfortunately, this approach does not cope with real-time changes in traffic and propagation conditions. The effects of adjusting the antenna height and tilt in cellular networks are well known, in radio network planning and optimization. In [1] the authors show significant reductions in path-loss, delay spread, transmitted power, and system interference when suitable height and antenna tilt are selected for a static system. The tradeoff between coverage and capacity using dynamic optimization of an ideal four-cell model of a 3G cellular network is presented in [2]. The authors show that even with uniform traffic the optimization provides a set of network configurations with a larger capacity-coverage tradeoff. The effect of electrical and mechanical antenna down-tilting in UMTS networks is presented in [3]. In this paper the authors demonstrate the need for adapting antenna settings to the expected traffic distribution and cell size. Using simulations, the authors show that the smaller the cell size the larger the antenna down-tilt should be, and the higher the traffic load the higher the antenna down-tilt should be to improve performance. The analysis of antenna tilting in cellular networks is the subject of other recent papers [4-9]. Fewer papers though present algorithms for down-tilt control. In [10] the authors using real path-loss data, collected from urban and suburban environments, show through computer simulations that the capacity increases when an optimal tilt angle is used. They use a global optimization algorithm that finds the optimal tilt in a cell by maximizing network capacity while keeping the other antennas' tilt angle constant. The algorithm is stopped once all of the optimal tilts are found. Unfortunately, none of the above papers offer a real-time solution that adapts the antenna tilt based on the actual traffic and propagation conditions in the field. These conditions usually differ from the initial measurements and data used in computer simulation. Only a real-time adaptive control of antenna's tilt can provide an increase in capacity and a reduction in the number of call drops under large variations in traffic and channel propagation.

In this paper we propose a new approach for antenna tilt optimization based on real time data collected in a CDMA network. The proposed method is based on distributed optimization of cells' utility functions, and implements the tilt changes in a distributed asynchronous manner.

## 2. COVERAGE vs. PILOT POLLUTION

Interference and lack of coverage are the two main reasons for call failures (call drops). Co-channel interference in the cellular systems is usually associated with poor antenna design/orientation or improper pilot power levels. The optimum values for antenna tilt and orientation obtained through simulation or provided by local experts are implemented in the network and afterward rarely modified. This approach often degrades under daily traffic variations or seasonal changes in the propagation environment. These changes equate to an increased fraction of call failures or poor RF coverage. For instance, Figure 1 shows the normalized traffic and call drop variations during a day in a typical cellular system.

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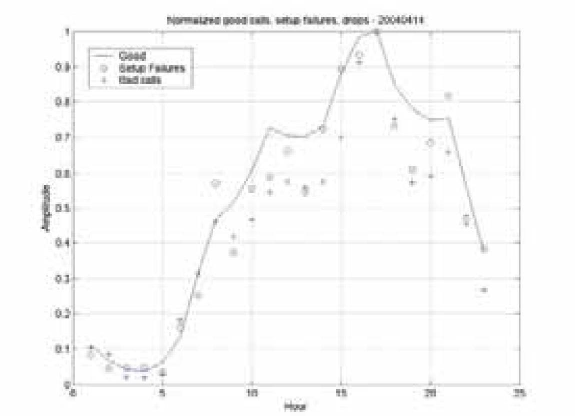

**Figure 1 - Hourly Normalized Traffic and Dropped Call Variations**

A poor antenna orientation causes additional inter-cell interference, which leads to call failures even in the area relatively close to the serving base station. A common form of inter-cell interference is the so called pilot pollution, when the number of pilots/cells seen at the mobile is larger than the number of rake receiver fingers. In these situations, there are a number of parasite pilots that do not contribute to successful signal decoding and act as interference. In other variations in pilot polluted areas candidate pilots so quickly pass active set that a saving handoff can not be performed. The pilot strength at a receiver in CDMA networks can be expressed as

$$\frac{E_c}{I_o} = \frac{P_{pil\,0}\,A_{G0}\,10^{-PL_0}}{h(P_{tr0} - P_{pil\,0})A_{G0}\,10^{-PL_0} + \sum P_{tr\,j}A_{G\,j}10^{-PL_j} + N}$$

where $P_{tr\,j}, P_{pil\,j}, A_{G0}, h, PL_j$ and N represent total transmitted power, the pilot power in cell j, antenna gain corresponding the receiver location, orthogonality factor, pathloss between the receiver and base station j, and respectively the noise. There are two main variables in the pilot strength formula pilot power and antenna gain. Both impact the cell radius (service area), the quality of coverage intra-cell and the level of extra-cell interference. Cell breathing represents the change of the cell radius under traffic load fluctuation. When number of active users increases the cell radius decreases and when the number of active users decreases the cell radius increases. This phenomenon reduces the sensitivity of the cell radius with respect to pilot power changes. Therefore the key parameters associated with antenna gain remain important control variables for interference reduction and capacity increase [2].

## 3. ANTENNA TILT

Antenna gain of base station for a specific user depends on antenna pattern, antenna orientation (azimuth and tilt) and user's coordinates with respect to base station.

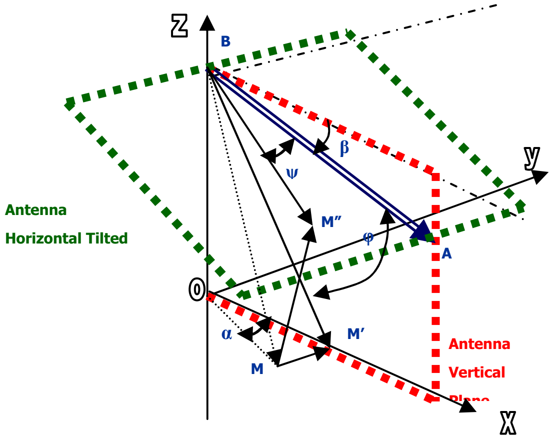

**Figure 2 Antenna orientation geometry**

In Figure 2 point M represents an arbitrary receiver, AB antenna boresight (minimum attenuation), $\alpha, \beta$ represent the angle of receiver location with respect to boresight and respectively the antenna tilt angle with respect to horizontal plane and $\psi, \varphi$ represent the horizontal and the vertical angles with respect to the boresight in the antenna reference system. The coordinates of the receiver in the antenna reference system are obtained by a simple translation along z axis and a rotation with tilt angle of the horizontal plane. If the user is located at the distance r from the origin and angle α from $x$ axis, and the base station antenna has a height h, the vertical and horizontal angles in antenna reference are:

$$\varphi = \arctan\left(\frac{\cos\alpha\sin\beta - \frac{h}{r}\cos\beta}{\cos\alpha\cos\beta + \frac{h}{r}\sin\beta}\right)$$

$$\psi = \arctan\left(\frac{\sin\beta}{\cos\alpha\cos\beta + \frac{h}{r}\sin\beta}\right)$$

The angles $\psi$ and $\varphi$ then can be used to estimate antenna attenuation $A(\psi,\varphi)$ from 3D antenna pattern. If only 2D projections of the antenna pattern are available, the antenna gain is obtained from the horizontal $H(\psi)$ and the vertical $V(\varphi)$ antenna patterns as:

$$A(\psi,\varphi)_{dB} = H(\psi) + V(\varphi)$$

Or from a parabolic approximation of the antenna's main lobe

$$A(\psi,\varphi)_{dB} = \min\left\{12\left(\left(\frac{\psi}{\psi_{3dB}}\right)^2 + \left(\frac{\varphi}{\varphi_{3dB}}\right)^2\right), A_{\max}\right\}$$

Where $\psi_{3dB}, \varphi_{3dB}$ are the angles in degrees from the antenna boresight for 3dB attenuation, and $A_{max}$ is the ultimate antenna attenuation.

Figure 3 show a typical antenna vertical pattern and Figure 4 shows the pilot strength signal at 500 m from the base station as a function of antenna tilt and user's azimuth angle when the base station's transmitted power is 20 dBm and the path-loss model is the Walfish–Ikegami model.

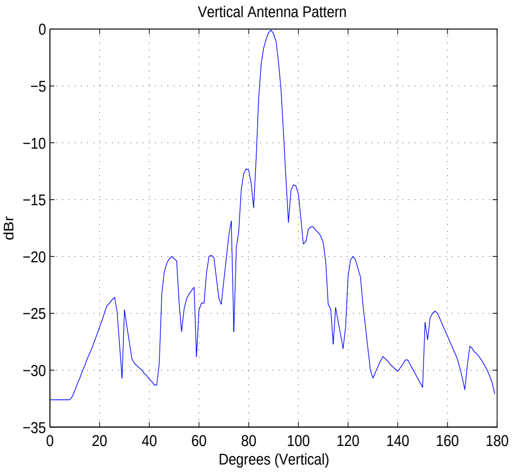

**Figure 3 Vertical antenna pattern**

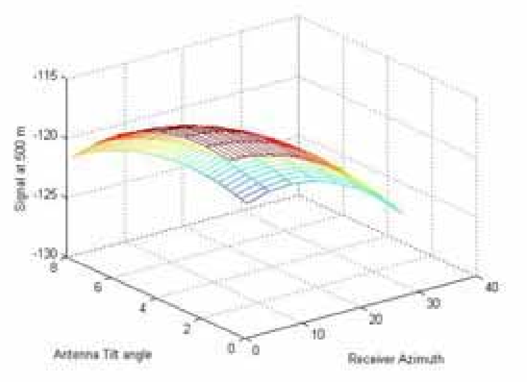

**Figure 4 Received Ec/Io at 500 m**

The cell coverage is defined by the geographical region around the base station where the received pilot strength (Ec/Io) is above the receiver sensitivity. The dependence between received Ec/Io for a single cell and antenna tilt angle is a concave function for a restricted range of antenna tilt angle [0,9] as shown in Figure 4. There are commercially available antenna's that can remotely change their down-tilt, azimuth and beamwidth [14].

## 4. PILOT POLLUTION GAME

Cellular operators want to increase capacity of their networks with a minimum number of call drops costs. This goal can be formulated as an utility function $U = vC - wD$, where C is the number of served users, D is the number of call failures and v , w are weighting factors. When the operator wants to enforce low call failures, the linear cost wD is replaced by a nonlinear cost g(D) where g(D) is a nonlinear convex function, for instance exponential or tangent functions. This utility function has a concave variation with service area and the service area has a concave dependence with tilt angle as it follows from Figure 4. Indeed, if the antenna tilt angle is too low the cell radius is too large and users near to the borders will experience call failures which leads to a small utility number. If the antenna down tilt is too large the number of active users is small which leads to a small utility number. Maximizing utility function using antenna tilt can be modeled as a non-cooperative game played by each cell against its neighbor cells. For instance, if a cell experiences low traffic in order to maximize the utility function the cell decreases the antenna tilt and therefore increases the interference in adjacent cells. These cells will experience more call failures and therefore they will react by increasing antenna tilt that reduces cell coverage. In this game, the utility function of a cell increases at the expense of utility functions of its neighbors. Concave dependencies between cell coverage and antenna tilt angle are reported in literature in [1], [15].

## 5. GAME THEORY

Game theory is a very promising tool for distributed control in wireless networks. The focus of game theory is [15] "interdependence, situations in which an entire group of people is affected by the choices made by every individual in that group". The application of game theory in power control (uplink and downlink), call admission, data rate control and scheduling are reported in [11] and [12]. One of game theory's advantages is that it provides conditions for stability and convergence to local optimum (Nash equilibrium) even when local decisions with limited information are used. A few concepts of the basic game theory are provided next. For more information one can consult [13].

**Definition:** A *game* is a triplet $\{I, A, U\}$, where $I = \{1,2,...,N\}$ is the set of players, $A = A_1 \times A_2 \times ...A_N$ denotes the space of all action profiles with $A_i$ the set of all possible actions of player *i*, and $U = \{u_1, u_2, ..., u_N\}$ is the set of utility (payoff) functions, each utility function mapping a player's actions to real numbers $u_i : A \rightarrow R, i \in I$.

In tilt control game the possible actions of a player (cell) are *increase/decrease tilt with x degrees,* where x is limited to a compact interval. The utility function is a linear increasing with successful calls and linearly (or nonlinearly) decreasing with call failures.

**Definition:** *Nash equilibrium* is an action profile $a \in A$ at which no user gains by unilaterally deviating. More precisely $a = \{a_1, a_2, ...., a_{i,} ...\} = \{a_i, a_{-i}\}$ is Nash equilibrium if

$$u(a_i, a_{-i}) \geq u(\widetilde{a}_i, a_{-i}), \quad \forall \widetilde{a}_i \in A_i, \ \forall i \in I,$$

where $a_{-i}$ denotes the action of players other than *i* player.

Consider a two cells scenario where each cell tries to increase its utility function u. When cell A, for instance, increases its tilt it maximizes its utility function and it forces cell B to decrease its tilt. The action pairs (increase x, decrease y) and respectively (decrease x, increase y) are Nash equilibrium points in our tilt game when the traffic conditions do not change.

**Theorem** [1] Compact, quasi-concave, and continuous strategic form games have a pure strategy equilibrium. In other words, if the payoff functions $u_i : A \to R, i \in I$ are quasi-concave and continuous and each $A_i$ is compact, the game has a pure strategy Nash equilibrium.

In the distributed tilt game the existence of Nash equilibrium results as corrolary of above theorem and the concavity of utility function with respect to tilt angle.

The existence of the Nash equilibrium does not guarantee the convergence of the game. In order to analyze the convergence of the game players' response function must be considered. In this paper the game of tilt control is a discrete-time gradient play [16]. Upon observing it own utility function each base station estimates at each stage (k) the gradient [16] of its own utility function U using an approximation of its gradient(W):

$$W(k+1) = W(k) + \frac{\lambda}{k+1}(U(k) - W(k)), \lambda > 0$$

The action (i.e. the tilt change) $\Delta\beta(k)$ at stage k is proportional to the logit function of the gradient [16] as follows:

$$\Delta\beta(k) = \sigma\left\{\frac{1}{\tau}(U(k) + \gamma\lambda(U(k) - W(k)),\right\}$$

$$\gamma > 0, \tau > 0$$

Theorem 4.1 in [16] guarantees the local stability of Nash equilibrium points when the gradient approach is used. In practice the change in tilt is limited by a fixed amount $\Delta\beta_0 > 0$ and the tilt angle is limited to a compact interval.

At each moment player's action consists in increase or decrease of its antenna tilt angle. In our method the utility function is estimated using call data reports from cell users over a finite time interval. The cell's active calls are those calls that report the cell in their active or candidate lists. The cell's call drops are the failed calls that recently reported the cell in one of their lists active, candidate, or neighbors. This definition of call drops captures better the pilot pollution effect in the neighboring cells. The utility function is evaluated for each cell from call data collected in the cell and its first tier of neighbors.

The tilt control algorithm proposed in this paper consists in the following steps:

a. For each cell, collect call data logs (CDL) over a time interval T1 (sliding window of time or amount of call activity).
b. For each cell, estimate the call traffic in the cell's cluster. A cluster cell is formed by a cell and its first tier neighbor cells.
c. Find the number of active reports and call failures in each cluster. The active reports keep track of how many times each cell was reported in the active list of the call in the last T1 second interval. A cell is reported in the active list when its Pilot Strength is above a fixed threshold. Normalize the active reports to the total number of occurrences of the cell in active, candidate, and neighbor list. Normalize the number of call failures to the total number of calls.
d. Estimate the utility function and its gradient.
e. Modify the tilt based on the utility's gradient using a tilt change limit (2 degree) and a total tilt limit of 9 degrees.
f. Evaluate the uplink and downlink quality and balance the links.
g. Repeat steps b to f until the utility function does not change significantly.

## 6. SIMULATION RESULTS

The proposed algorithm was tested in a simulated environment using the CDMA Motion Simulator (CMS) and path-loss data collected in New Delhi, India. The simulated system had 66 cells and it used real data for path-loss, antenna patterns, antenna heights, orientations, cell radius, and radiated power. Figure 4 shows the RF coverage data collected in drive test and used in the simulations.

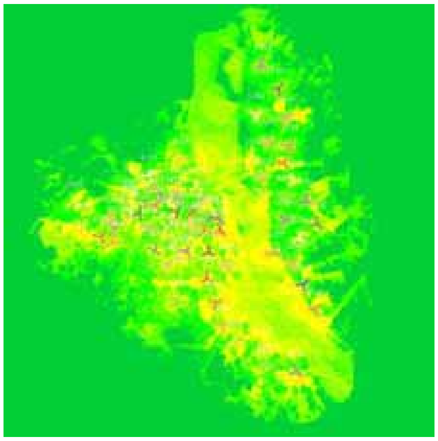

**Figure 5 RF coverage in downtown Delhi**

The scenarios considered had 300, 400 and 500 mobile users. The tilt angle of each antenna was constrained between 0 and 10 degrees in order to assure concavity. In our simulations we used $\gamma = 1, \tau = 1, \lambda = 1$ and the tilt step changes were limited to $\Delta\beta_0 = 2$ degree. The number of normalized active list reports was used as measure of served users for a particular base station. A base station is reported by a mobile phone in its active list if the received pilot strength is above a prescribed threshold. We then normalized the number of the active reports to the total number of base station's occurrences in active, candidate and neighbor lists. The tilt control in a particular cell was triggered by call drops change while the magnitude of change was computed using the gradient of the utility function. The reduction in dropped calls with respect to statistics collected from the operational network was obtained using various user densities and various random seeds. The results for each user density averaged over 10 random seeds are presented in Table 1.

| Number of mobiles | Dropped Call Reduction (Mean) | Dropped Call Reduction (Std Dev.) |
|---|---|---|
| 300 | 18.45% | 5.8% |
| 400 | 19.68% | 5.75% |
| 500 | 7.8% | 3.1% |

**Table 1 Calls dropped reduction after tilt control**

The algorithm shows a significant reduction in the calls dropped, which are normally at 1-2% of the total calls in the case of 300 and 400 users. Because in our simulations we used a mechanical down tilt, it is expected that an electrical tilt will provide even better results due to decreased inter-cell interference.

## 7. CONCLUSIONS

Our paper offers an iterative approach for antenna tilt control to reduce the interference and increase the RF coverage. Our approach removes the need for drive testing, which can involve expensive and time-consuming path-loss tuning; the algorithm does not need location accuracy or predictive SNR values. Using this approach the cellular network could adapt near real time to traffic variations and fluctuations in RF propagation conditions. The approach of remote control of antenna properties (azimuth and tilt) is a very cost effective solution to op-ex and capacity/coverage solution.

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