Approximating the Othercell Interference Distribution in Inhomogeneous UMTS Networks

Dirk Staehle[1], Kenji Leibnitz[1], Klaus Heck[1], Bernd Schröder[2], Albert Weller[2], and Phuoc Tran-Gia[1]

[1] University of Würzburg,
Dept. of Computer Science
Am Hubland, 97074 Würzburg
Germany
staehle@informatik.uni-wuerzburg.de

[2] T-Mobile International,
Karl-Duwe-Straße 31,
53227 Bonn,
Germany,
Bernd.Schroeder@T-Mobil.de

Abstract—

In this paper we present an analytical model for computing the othercell interference distribution in a third generation UMTS network with inhomogeneous user distribution. Our proposed model is based on an iterative calculation of a fixed-point equation which describes the interdependence of the interference levels at neighboring base stations. Furthermore, we develop an efficient algorithm based on Lognormal approximations to compute the mean and standard deviation of the othercell interference. We will show that our model is accurate and fast enough to be used efficiently in the planning process of large UMTS networks.

I. Introduction

The *Universal Mobile Telecommunication System* (UMTS) is the proposal for third generation wireless networks in Europe. Contrary to conventional second generation systems, like GSM, which focus primarily on voice and short message services, UMTS will provide a vast range of data services with bit rates of up to 2Mbps and varying quality of service requirements. This will be achieved by operating with *Wideband Code Division Multiple Access* (WCDMA) over the air interface.

With the forthcoming introduction of UMTS in Europe a sophisticated planning of the network is required. The use of WCDMA, however, requires also new paradigms in wireless network planning. While in GSM capacity is a fixed term, it is influenced in WCDMA by the interference caused by all mobile stations (MS) on the uplink, as well as the transmit powers of the base stations (BS) or NodeB on the downlink. Due to the power control mechanisms in both link directions, the signals are transmitted with such powers that they are received with nearly equal strength. Therefore, the distribution of the user locations must be taken into account in order to perform a thorough network planning including both the uplink and the downlink. While the downlink primarily limits the capacity of the system, the uplink determines the coverage of the network, see [1]. The prediction of the coverage requires the knowledge of interference distributions at all BS to compute the outage probabilities for every point in the considered area.

A detailed examination of the interference on the uplink, however, is not a very straightforward task. Due to the universal frequency reuse in UMTS, all users both in the considered cell and in the neighboring cells will contribute to the total interference, thus influencing the link quality in terms of received bit-energy-to-noise ratio (E_b/N_0). Apart from the previously mentioned direct influence, there is also an indirect effect in the system. Since an increase in interference results in a higher required transmission power of the MS, there is a feedback behavior on the other cells as well. It is obvious that in order to model interference adequately it is necessary to capture this feedback behavior by performing an iterative computation.

Most studies on interference found in the literature do not fully take these interactions between cells into account. Among the first papers in this field, [2] and later [3] introduced a relative othercell interference factor f as the ratio between othercell interference to the interference due to users in the same cell. A closed form expression of the f-factor can be found in [4], when both BS and MS are assumed to be distributed according to a spatial Poisson process. Similar simple approximations with a fixed interference factor can be found in [1] and [5]. A more sophisticated model is given in [6] and later extended in [7]. Contrary to the prior studies, these models derive distributions for othercell interference which are used to calculate capacity bounds.

In this paper we present an analytical model for the computation of the othercell interference. Based on a spatial traffic distribution and given BS positions we use iterative fixed-point equations to determine the distribution of the othercell interference. This iterative approach allows us to include the interdependence between the interferences of neighboring cells in our model which is not fully considered in previous work. By using Lognormal approximations, this method proves to be superior in computation speed compared to the exact computation, which requires multiple convolutions. Furthermore, our model includes the possibility to investigate the influence of different service mixes on the othercell interference.

The paper is organized as follows. Section II describes the system model and gives a basic idea about the iterative approach. In Section III the othercell interference is calculated for a given set of MS with fixed positions. This computation is extended in Section IV to a stochastic spatial user distribution. Furthermore, we will use Lognormal approximations to derive an algorithm for the efficient computation of the othercell interference distribution. The accuracy of the model is validated in Section V by means of an inhomogeneous example network. The paper is concluded in Section VI with a short outlook on future work.

II. System Model and Basic Approach

The focus of this paper is to derive a method to compute the othercell interferences in a large UMTS network. The network is defined by a set of BS positions, a spatial user distribution, and a pathloss model. The spatial user distribution is either defined by a grid map [8] with a traffic density for every square or by a spatial arrival process. The example in Section V uses a modified Matern process [9] to describe the traffic distribution and we will show that the transformation to a traffic density map is simple. The model for the signal attenuation between BS and MS is given by a map, as well, or by a pathloss formula.

With these input parameters we derive the othercell interference distribution at all BS using an iterative approach. In the first step transmit power and thus the power received at other BS is computed without considering othercell interference. In our model othercell interference comprises the interference of all MS which are not power controlled by the considered BS. The transmit strength of a MS is always controlled by the BS with least attenuation and thus soft handover is neglected. In the next iteration step we know the othercell interference from the previous step and include it in the calculation of the transmit powers and determine a new value for the othercell interference. The iteration finally converges since the othercell interference increases less in every step. In Section III the iteration is described for the deterministic case and in Section IV the stochastic model follows.

III. Deterministic Interference

In a WCDMA system the relation between the power $\hat{S}_t^R$ of a MS with service t received at its BS and the interference $\hat{I}_{own}$ produced by the other MS which are power-controlled by this BS is given by the power control equation:

$$\hat{\varepsilon}_t^* = \frac{\frac{\hat{S}_t^R}{R_t}}{\hat{N}_0 + \hat{I}^{other} + \hat{I}^{own} - \frac{\hat{S}_t^R \nu_t}{W}} \tag{1}$$

The othercell interference $\hat{I}^{other}$ corresponds to the sum of the powers received by the MS not power-controlled by the considered BS. Furthermore, $\hat{\varepsilon}_t^*$ denotes the target E_b/N_0, R_t the bitrate, and ν_t the activity factor of MS with service t. The thermal noise density is denoted by $\hat{N}_0$. Solving this equation for the received power yields

$$\hat{S}_t^R = W \frac{\hat{\varepsilon}_t^* R_t}{W + \hat{\varepsilon}_t^* R_t \nu_t} \left(\hat{N}_0 + \hat{I}^{other} + \hat{I}^{own} \right). \tag{2}$$

In the following α_t is an abbreviation for the term $\hat{\varepsilon}_t^* R_t \left(W + \hat{\varepsilon}_t^* R_t \nu_t\right)^{-1}$, $\bar{\alpha}$ is the vector $(\alpha_1, ..., \alpha_T)$ where T is the number of available services. Further, n_t denotes the number of MS power-controlled by the considered BS and $\bar{n}_\nu$ stands for the vector $(n_1\nu_1, ..., n_T\nu_T)$. Then, the intracell interference is given by

$$\begin{aligned} \hat{I}^{own} &= \frac{1}{W} \sum_t n_t \hat{S}_t^R \nu_t \\ &= \bar{n}_\nu \bar{\alpha}^T \left(\hat{N}_0 + \hat{I}^{other} + \hat{I}^{own} \right) \end{aligned} \tag{3}$$

and solving for $\hat{I}^{own}$ yields

$$\hat{I}^{own} = \frac{\bar{n}_\nu \bar{\alpha}^T}{1 - \bar{n}_\nu \bar{\alpha}^T} \left(\hat{N}_0 + \hat{I}^{other} \right) \tag{4}$$

Hence, the power received from a MS with service t is

$$\begin{aligned} \hat{S}_t^R &= W \alpha_t \left(\hat{N}_0 + \hat{I}^{other} + \hat{I}^{own} \right) \\ &= W \frac{\alpha_t}{1 - \bar{n}_\nu \bar{\alpha}^T} \left(\hat{N}_0 + \hat{I}^{other} \right) \end{aligned} \tag{5}$$

For the calculation of the othercell interference $\hat{I}_x^{other}$ at BS x we are first interested in the interference $\hat{I}_{y,x}^{out}$ caused by the MS power-controlled by BS y. The power received at BS x by such a MS k is

$$\hat{S}_{k,x}^R = \hat{S}_{k,y}^R \frac{\hat{d}_{k,x}}{\hat{d}_{k,y}}, \tag{6}$$

where $\hat{d}_{k,\ell}$ is the attenuation of MS k to BS ℓ. The sum of these powers divided by the total bandwidth yields the interference density at BS x caused by all MS of BS y

$$\begin{aligned} \hat{I}_{y,x}^{out} &= \sum_{k:BS(k)=y} \frac{\nu_k \hat{S}_{k,x}^R}{W} \\ &= \left(\hat{N}_0 + \hat{I}_y^{other} \right) F_{y,x}, \end{aligned} \tag{7}$$

where $F_{x,y}$ stands for

$$F_{y,x} = \sum_{k:BS(k)=y} \frac{\nu_k \alpha_k}{1 - \bar{n}_\nu \bar{\alpha}^T} \frac{\hat{d}_{k,x}}{\hat{d}_{k,y}}. \tag{8}$$

Hence, the othercell interference density $\hat{I}_x^{other}$ at BS x is given as

$$\hat{I}_x^{other} = \sum_{y \neq x} \hat{I}_{y,x}^{out}. \tag{9}$$

Obviously, the interference $\hat{I}_{x,y}^{out}$ produced by all MS of BS x at another BS y depends on the othercell interference at BS x and vice versa. However, the term $F_{x,y}$ is independent of the othercell interference and this can be used to iteratively calculate the othercell interference.

IV. Stochastic Interference Model

The model presented in the previous section was deterministic for a set of MS with fixed positions and a set of BS. Furthermore, the attenuations between MS and BS were known. In this section we extend this model to the stochastic case where both the number of the MS and their location with corresponding attenuations are random while the BS positions are arbitrary but fixed.

The idea behind the analysis is to compute the distribution of the othercell interference iteratively. Starting without any othercell interference, i.e. the random variable (r.v.) $\mathcal{I}_x^{other}$ is zero for all BS x, the distribution of the interference densities $\mathcal{I}_{x,y}^{out}$ are determined for all pairs of BS (x, y). Then, adding the r.v. $\mathcal{I}_{x,y}^{out}$ for all BS $x \neq y$ yields a new and higher distribution of the othercell interference at BS x. This computation is performed for all BS. In the next iteration step the othercell interference which was initially zero is replaced by the new r.v. $\mathcal{I}_x^{other}$ and the othercell interference is computed again. The r.v. $\mathcal{I}_x^{other}$ increase in every iteration step and finally converge when the mean and variance of $\mathcal{I}_x^{other}$ remain constant.

The iteration corresponds to the solution of the following fixed-point equation which describes the relation between the r.v. $\mathcal{I}_x^{other}$ and $\mathcal{I}_{x,y}^{out}$:

$$\mathcal{I}_{x,y}^{out} = \left(\hat{N}_0 + \mathcal{I}_x^{other}\right)\mathcal{F}_{x,y} \quad \text{and} \quad \mathcal{I}_x^{other} = \sum_{y \neq x} \mathcal{I}_{y,x}^{out} \quad (10)$$

The r.v. $\mathcal{F}_{x,y}$ is the stochastic representation of the variable $F_{x,y}$ in Eq. (7) which remains constant throughout the iteration. This r.v. describes all the stochastic influences of the underlying spatial distribution. According to the theorem of total probability $\mathcal{F}_{x,y}$ is given as

$$\mathcal{F}_{x,y} = \sum_{\bar{n}:\bar{n}\bar{\alpha}^T < 1} p(\bar{n}, x) \frac{1}{1 - \bar{n}\bar{\alpha}^T} \sum_{t=1}^{T} \alpha_t \sum_{i=1}^{n_t} \mathcal{D}_{x,y}, \quad (11)$$

where $p(\bar{n}, x)$ is the probability that n_t is the number of active MS with service t having the least attenuation to BS x. If N_x is the mean number of MS with least attenuation to x and q_t is the probability that a MS has service t then the probability $p(\bar{n}, x)$ is given according to the product form solution, see e.g. [10]

$$\tilde{p}(\bar{n}, x) = \prod_{t=1}^{T} \frac{(N_x q_t \nu_t)^{n_t}}{n_t!} \text{ and}$$
$$p(\bar{n}, x) = \frac{\tilde{p}(\bar{n}, x)}{\sum_{\bar{n}':\bar{n}'\bar{\alpha}^T < 1} \tilde{p}(\bar{n}', x)}. \quad (12)$$

The number of MS in a cell is limited by the pole capacity. If $\bar{n}\bar{\alpha}^T$ is greater or equal to 1 the A_{out}-case according to [5] occurs. The computation assumes that the arrival process of the MS belonging to one BS is Poisson which is valid for both methods used to model the traffic distribution.

The r.v. $\mathcal{D}_{x,y}$ describes the spatial component of the arrival process. It is a r.v. for the ratio between the attenuations $\hat{d}_{k,y}$ and $\hat{d}_{k,x}$ while the MS k is located randomly inside the cell of BS x. The distribution of this r.v. is not given in closed form but numerically.

The computation of the distribution of the r.v. $\mathcal{F}_{x,y}$ would require many convolutions and additionally discretizations to sum them up. Since these calculations have to be performed numerically they are very time consuming. However, in [11] we showed that the r.v. $\mathcal{F}_{x,y}$ is well approximated by a Lognormal distribution. Thus, it is not necessary to determine the whole distribution but the mean and variance of $\mathcal{F}_{x,y}$ are sufficient to describe the r.v. The calculation of the moments of $\mathcal{F}_{x,y}$ is again performed according to the theorem of total probabilities. The mean is given by

$$E[\mathcal{F}_{x,y}] = \sum_{\bar{n}:\bar{n}\bar{\alpha}^T < 1} p(\bar{n}) E[\mathcal{F}_{x,y}(\bar{n})] \quad (13)$$
$$= \sum_{\bar{n}:\bar{n}\bar{\alpha}^T < 1} p(\bar{n}) \frac{\bar{n}\bar{\alpha}^T E[\mathcal{D}_{x,y}]}{1 - \bar{n}\bar{\alpha}^T} \quad (14)$$

and the second moment of $\mathcal{F}_{x,y}$ is

$$E[\mathcal{F}_{x,y}^2] = \sum_{\bar{n}:\bar{n}\bar{\alpha}^T < 1} p(\bar{n}) E\left[\mathcal{F}_{x,y}(\bar{n})^2\right], \quad (15)$$

where $\mathcal{F}_{x,y}(\bar{n})$ denotes the r.v. $\mathcal{F}_{x,y}$ under the condition that $\bar{n}$ users are active in cell x. The second moment of $\mathcal{F}_{x,y}(\bar{n})$ is determined by

$$E\left[\mathcal{F}_{x,y}(\bar{n})^2\right] = \left(VAR\left[\mathcal{F}_{x,y}(\bar{n})\right] + E\left[\mathcal{F}_{x,y}(\bar{n})\right]^2\right) \quad (16)$$

with the variance given as

$$VAR\left[\mathcal{F}_{x,y}(\bar{n})\right] = \sum_{t=1}^{T} n_t \left(\frac{\alpha_t^2 \cdot VAR\left[\mathcal{D}_{x,y}\right]}{\left(1 - \bar{n}\bar{\alpha}^T\right)^2}\right). \quad (17)$$

Finally, the variance of $\mathcal{F}_{x,y}$ is calculated as

$$VAR\left[\mathcal{F}_{x,y}\right] = E\left[\mathcal{F}_{x,y}^2\right] - E\left[\mathcal{F}_{x,y}\right]^2. \quad (18)$$

Note, that the sum over all user combinations $\bar{n}$ is performed only once since in each summation step the first and the second moment of all r.v. $\mathcal{F}_{x,y}(\bar{n})$ are calculated.

Altogether, the input parameters required to compute the mean and variance of a r.v. $\mathcal{F}_{x,y}$ are the traffic density at all BS x and the mean and the variance of the attenuation ratio $\mathcal{D}_{x,y}$ for all pairs of BS x and y. These values may be determined by two methods. The first one is to generate a set of MS scenarios according to the arrival process and then calculate the desired values from them. In the second method the plane is partitioned into a grid. For each of the resulting squares the traffic density and the attenuation ratio is determined. From these values the mean and variance of $\mathcal{D}_{x,y}$ are calculated.

Now we know the mean and variance of $\mathcal{F}_{x,y}$ for all BS x and y and can start the iteration to solve the fixed-point equation given in Eq. (10). The calculation of the distribution of

$\mathcal{I}_{x,y}^{out}$ comprises the multiplication of two r.v. which requires a numerically expensive computation. Again, we use the property that $\mathcal{F}_{x,y}$ approximately follows a Lognormal distribution to simplify the calculation considerably.

Starting with no othercell interference at all, i.e. $\mathcal{I}_{x,y}^{other} = 0$ for all BS x we obtain according to Eq. (10):

$$\mathcal{I}_{x,y}^{out} = \hat{N}_0 \mathcal{F}_{x,y} \tag{19}$$

which follows a Lognormal distribution, as well. The mean and variance are given as

$$\begin{aligned} E\left[\mathcal{I}_{x,y}^{out}\right] &= \hat{N}_0 \cdot E\left[\mathcal{F}_{x,y}\right] \quad \text{and} \\ VAR\left[\mathcal{I}_{x,y}^{out}\right] &= \hat{N}_0^2 \cdot VAR\left[\mathcal{F}_{x,y}\right]. \end{aligned} \tag{20}$$

Assuming that the r.v. $\mathcal{I}_{x,y}^{out}$ are independent for all $x \neq y$, the othercell interference at BS x is the sum of Lognormal distributions which is again approximately Lognormal. The moments of $\mathcal{I}_{y}^{other}$ are calculated by:

$$\begin{aligned} E\left[\mathcal{I}_{y}^{other}\right] &= \sum_{x \neq y} E\left[\mathcal{I}_{x,y}^{out}\right] \quad \text{and} \\ VAR\left[\mathcal{I}_{y}^{other}\right] &= \sum_{x \neq y} VAR\left[\mathcal{I}_{x,y}^{out}\right]. \end{aligned} \tag{21}$$

Hence, in the next and all further iterations the othercell interference at BS x approximately follows a Lognormal distribution and thus the sum $(\hat{N}_0 + \mathcal{I}_{other,x})$, as well. Accordingly, in each iteration we have to multiply two Lognormal distributed r.v. $(\hat{N}_0 + \mathcal{I}_{other,x})$ and $\mathcal{F}_{x,y}$ to determine $\mathcal{I}_{x,y}^{out}$. The multiplication is performed by summing up the parameters of the two Lognormal distributions:

$$\begin{aligned} \mu_{\mathcal{I}_{x,y}^{out}} &= \mu_{(N_0 + \mathcal{I}_{other,x})} + \mu_{\mathcal{F}_{x,y}} \quad \text{and} \\ \sigma^2_{\mathcal{I}_{x,y}^{out}} &= \sigma^2_{(N_0 + \mathcal{I}_x^{other})} + \sigma^2_{\mathcal{F}_{x,y}}. \end{aligned} \tag{22}$$

The parameters μ_Z and σ_Z^2 of a Lognormal distributed r.v. Z are calculated from the mean and variance by

$$\sigma_Z^2 = \log\left(\frac{VAR[Z]}{E[Z]^2} + 1\right) \text{ and } \mu_Z = \log\left(E[Z]\right) - \frac{\sigma_Z^2}{2}. \tag{23}$$

Next, the mean and the variance of the othercell interference is determined again according to Eq. (21). Therefore, the mean and variance of the r.v. $\mathcal{I}_{x,y}^{out}$ have to be determined for all pairs of BS x and y. For a r.v. Z the mean and variance are derived from the parameters as

$$E\left[Z\right] = e^{\mu_Z + \frac{\sigma_Z^2}{2}} \text{ and } VAR\left[Z\right] = E\left[Z\right]^2 \left(e^{\sigma_Z^2} - 1\right). \tag{24}$$

To summarize, one iteration comprises the calculation of the moments of the othercell interference given the mean and the variance of the previous iteration as well as the parameters of the r.v. $\mathcal{F}_{x,y}$. The following calculations are performed in each iteration:

1. determine parameters of $\mathcal{I}_x^{other}$ for all BS x according to Eq. (23)
2. determine parameters of $\mathcal{I}_{x,y}^{out}$ for all BS x and y according to Eq. (22)
3. determine mean and variance of $\mathcal{I}_{x,y}^{out}$ for all BS x and y according to Eq. (24)
4. determine mean and variance of $\mathcal{I}_x^{other}$ for all BS x according to Eq. (21)

The iteration converges if the relative change of the mean and the standard deviation fall below a certain threshold.

V. Numerical Results

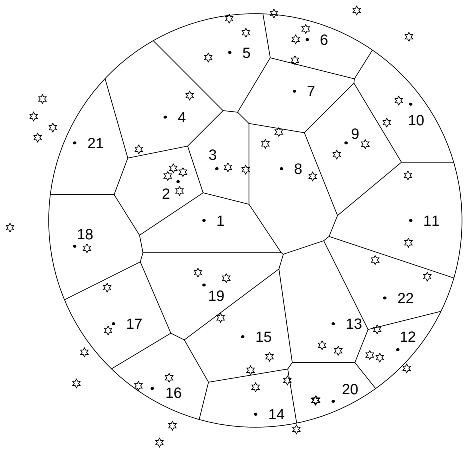
In the following, numerical results will be shown for the example UMTS network which is depicted in Fig. 1(a). The network consists of 22 base stations which are marked by black dots. In the example we model the attenuation of the radio signals due to propagation loss by the vehicular test environment model in [12]

$$d_{k,\ell} = -128.1 - 37.6 \log_{10}(dist_{k,\ell}), \tag{25}$$

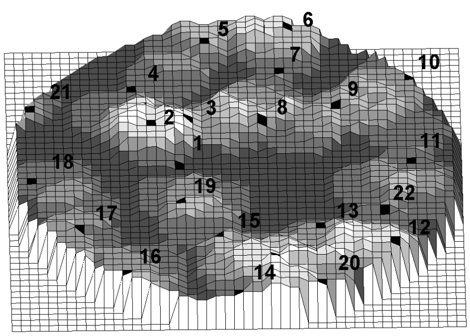
with $dist_{k,\ell}$ being the distance between MS k and BS ℓ in km. The graphic shows the regions in which the base stations control the power of the MS.

Furthermore, the spatial traffic distribution is modeled according to a modified Matern process. Generally, in the Matern process cluster centers are determined according to a homogeneous Poisson process. Then, the number of points around each center is again Poisson distributed and each of these points is uniformly distributed within a predefined radius around the center. In our example we focus on one instance of cluster centers which are marked by stars in Fig. 1(a) and generate the MS within a radius of 1.5km. A grid with the resulting traffic densities is presented in Fig. 1(b) where brighter colors correspond to higher traffic densities. Note that the traffic is only considered in a circle with a diameter of 16km. The traffic density in this example results in a mean of 10 active MS per base station with a maximum of 15.2 MS for BS 2 in average and a minimum of 2.9 MS for BS 21 in average. We considered three services with different probabilities. Voice users with 12.2kbps and a target-E_b/N_0 of 5.5dB are generated with 75%, data users with 64kbps and 144 kbps are taken with 20% and 5%, respectively. They have a target-E_b/N_0 of 4.0dB and 3.5dB.

In Fig. 2 the results for the example scenario are illustrated. The mean and the standard deviation of the othercell interference for the different base stations are marked by stars. The analytic results have been verified by using a point pattern simulation which is described in [13]. The mean and the standard deviation obtained by this method are depicted as circles. We can see that both the first and the second moment of the point pattern simulation match well with the analytic results. In particular, the mean values are calculated exactly. The iterative method slightly undervalues the standard deviations which is



(a) Example UMTS network



(b) Spatial traffic distribution

Fig. 1. Graphical presentation of the example network

a consequence of the independence assumptions. This effect increases for higher loads such that the standard deviations for cells in the neighborhood of a strongly loaded base station are underestimated. However, Fig. 2 shows that the maximum relative error for the standard deviation is 6.2% and for the mean even only 1.2%. Furthermore, the good match of both the first and the second moment elucidates that the othercell interference in fact follows a Lognormal distribution.

VI. Conclusion and Outlook

In this paper we presented an analytical model for computing the othercell interference in a UMTS system with multiple services. Our approach is based on solving a fixed-point equation which describes the interdependence between the interferences at neighboring BS. An efficient algorithm is used to solve these equations using Lognormal approximations such

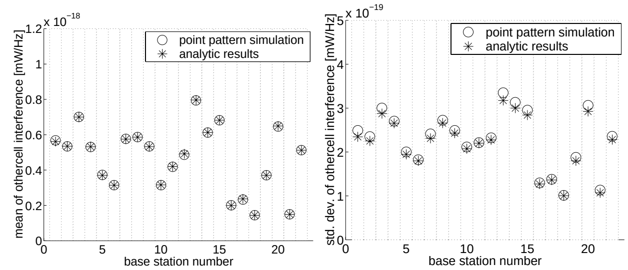


Fig. 2. Mean and standard deviation of the othercell interference

that the model can be implemented in network planning tools for large UMTS networks like T-Mobile's *Pegasos*, see [14]. Our future work consists of an extension of our model to soft handover. Furthermore, we will include a model for the downlink as well.

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