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**Abstract**

**Abstract -** Soft handover is one of the key features in UMTS networks. For a sophisticated network planning it is necessary to understand the influence of soft handover on the capacity and coverage of UMTS systems which is expressed by the soft handover gain. In this paper we derive a method for computing interference distributions for UMTS networks with and without soft handover. Thus, we are able to show the benefit of soft handover resulting in an increased coverage area. Furthermore, the soft handover gain is characterized for both homogeneous and inhomogeneous UMTS networks with hexagonal as well as with irregular BS layouts. In particular, it is shown that the soft handover gain is increasing with the degree of inhomogeneity of the traffic intensity.

## 1 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 operating 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.

The use of WCDMA, however, requires also new paradigms in wireless network planning [2]. While capacity in GSM is a fixed quantity, it is influenced in WCDMA by the interference caused by all mobile stations (MS) on the uplink, as well as the transmission 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 an accurate network planning [3].

Another important difference is the behavior of WCDMA compared to GSM during handovers. While GSM supports only hard handovers where the connection to the new cell is established after terminating the one to the old cell ("break before make"), *soft handover* is performed in WCDMA. Here, the mobile assists in the handover process by measuring the pilot signals from the neighboring BS and storing those BS with the strongest received signals in the Active Set. The mobile then communicates with all BS in the Active Set simultaneously ("make before break"). As a consequence, the MS receives multiple power control commands and adapts its transmission power on the uplink to the BS with the least requirement. From previous studies on IS-95 systems it was shown that the use of soft handover has a beneficial effect on the coverage area and capacity of the cells [4, 5].

The influence of soft handover on coverage and capacity was also investigated in [6]. The authors derived from simulations that soft handover requires a lower shadow fade margin than in the case of hard handover. This gain due to soft handover was, however, computed without any consideration of the interference from other cells. In [7] an alternative algorithm for the combination of power control commands under soft handover is presented. Especially in the case when there are errors in the power control commands this scheme improved capacity by reducing the interference. The authors of [8] investigate the correlations between the multiple links in soft handover. The previously mentioned studies considered an IS-95 CDMA system with only a single class of users. In [9] the soft handover gain for the slightly differing mechanism used in WCDMA was evaluated by simulation. The authors focused on the effects that the specific parameters *handover delay* and *enter threshold* have. However, in their simulations they considered only voice users.

In this paper, we will present an analytical model for the computation of the interference when taking soft handover and maximum MS transmission power into account. We will focus on the uplink direction and investigate the effects of the user density, inter-BS distance, and traffic mix on the interference and transmission powers of the MS in homogeneous UMTS networks. This leads to a characterization of outage probability which can be used for network planning. Furthermore, the soft handover gain will be subject to sophisticated investigations in both homogeneous and inhomogeneous networks. We will show how the soft handover gain changes when the inhomogeneity of the spatial MS distribution increases.

The paper is organized as follows. Section 2 describes the basic model and the derivation of interference and transmission power in a multi-cell and multi-user scenario. This is extended to include the combination of power control signals from multiple base stations and the case with maximum MS transmission power boundaries. In Section 3 we will present numerical results from the analysis. The paper is concluded in Section 4 with an outlook on future work.

## 2 Model Description

### 2.1 Basic Model

The capacity of a UMTS system is limited on the uplink by the interference at the BS. This interference level corresponds to the sum of the powers received from all MS within a certain distance to this BS. In the following, the interference level at BS $\ell$ is denoted by $\hat{I}_\ell$, $\hat{S}_k$ and $\nu_k$ define the transmission power and the activity of MS $k$, and the path loss from MS $k$ to BS $\ell$ is given by $\hat{d}_{k,\ell}$. The interference level is computed as

$$\hat{I}_\ell = \frac{1}{W} \sum_{k=1}^{K} \hat{S}_k \hat{d}_{k,\ell} \nu_k. \tag{1}$$

The variables $\hat{\alpha}$ written with a hat are always linear and the corresponding values $\alpha$ are in decibels with $\hat{\alpha} = 10^{\alpha/10}$. $K$ denotes the number of considered MS and $W$ is the frequency bandwidth. The transmission power of each user is defined by the power control equation, see e.g. [10],

$$\hat{\epsilon}_k^* = \frac{\frac{\hat{S}_k \hat{d}_{k,\ell}}{R_k}}{\hat{N}_0 + \sum_{i \neq k} \frac{\hat{S}_i \hat{d}_{i,\ell} \nu_i}{W}} \tag{2}$$

with the target $E_b/N_0$ $\hat{\epsilon}_k^*$, the bit rate $R_k$, and the activity $\nu_k$ specifying the service of user $k$. Note that in this case $\ell$ is the BS which controls the power of MS $k$. This BS is determined by the minimum attenuation only, thus soft handover is not included, yet. These $K$ power control equations are equivalent to the following $K$ equations together with Eqn. (1) for each of the $L$ considered BS.

$$\hat{\epsilon}_k^* = \frac{\frac{\hat{S}_k \hat{d}_{k,\ell}}{R_k}}{\hat{N}_0 + \hat{I}_\ell - \frac{\hat{S}_k \hat{d}_{k,\ell} \nu_k}{W}} \tag{3}$$

Solving each of these equations for $\hat{S}_k$ yields

$$\hat{S}_k = \frac{W}{\hat{d}_{k,\ell}} \left(\hat{N}_0 + \hat{I}_\ell\right) \frac{\beta_k}{W + \beta_k \nu_k}, \tag{4}$$

where $\beta_k = \hat{\epsilon}_k^* R_k$ is an abbreviation for the "bit rate"×"target $E_b/N_0$"-product of MS $k$. These $K$ equations are merged into a single matrix equation to compute the transmission power vector $\hat{S}$ which comprises the transmission powers $\hat{S}_k$ of all users.

$$\begin{aligned} \hat{S} &= W\left(\hat{N}_0 + \hat{I}\right) Q \qquad (5) \\ Q_{k,\ell} &= \begin{cases} \frac{\beta_k}{(W+\beta_k\nu_k)\hat{d}_{k,BS(k)}} & \text{if} \quad \ell = BS(k) \\ 0 & \text{otherwise} \end{cases}, \end{aligned}$$

where $BS(k)$ is the BS which controls the power of MS $k$. Note that $\hat{N}_0$ in matrix equations denotes an $L$-vector with identical entries. This equation also contains the variable $\hat{I}$ which denotes a vector of the interference levels at the BS defined in Eqn. (1). These $L$ equations are also written as matrix equation

$$\hat{I} = \frac{1}{W} \hat{S} \tilde{\nu} \hat{d}, \tag{6}$$

where $\tilde{\nu}$ is a $K \times K$ diagonal matrix with $\tilde{\nu}_{k,k} = \nu_k$ and $\hat{d}$ is a $K \times L$-matrix containing the attenuations. Now substituting the vector $\hat{S}$ in Eqn. (6) by Eqn. (5) and solving for $\hat{I}$ yields after some transformations

$$\begin{aligned} \hat{I} &= \hat{N}_0 A \left(E - A\right)^{-1}, \qquad (7) \\ A &= Q \tilde{\nu} \hat{d}. \end{aligned}$$

The matrix $E$ is the $L \times L$ identity matrix. Similar to the $A_{out}$ case defined in [10] when the pole capacity of a single cell is exceeded, the capacity in the multi BS case is sufficient only if the inverse of matrix $(E - A)$ is positive. Finally, the transmission power $\hat{S}_k$ of MS $k$ can be calculated using Eqn. (5). A more detailed description of the model can be found in [11]. Two important features of UMTS, soft handover and transmission power limitations, are not considered so far. In the following sections the model is extended accordingly.

### 2.2 Soft Handover

In CDMA systems, MS in soft handover can be connected not only to a single but to several BS. An MS moving in an area with several BS has an Active Set which changes dynamically.

This Active Set of an MS is defined by the pilot signal which is transmitted by every BS with 30dBm. An MS detects the BS with the strongest received pilot signal and also those BS with a signal strength less than the reporting range lower than the strongest signal, see [12]. All these BS form the Active Set of an MS.

On the uplink, all BS in the Active Set receive the frames transmitted by the MS and transfer them to the RNC (radio network controller). There, all frames are checked for errors and only if all of them are erroneous a frame error occurs. The RNC evaluates the resulting frame error rate and adapts the target $E_b/N_0$ in the outer loop power control. This target $E_b/N_0$ is signaled to all BS in the Active Set and they try to adjust the transmission power of the MS to this value according to the inner loop power control. Hence, the MS receives power control signals from all BS in the Active Set and combines them in the way that it increases its power only if all BS signal *power up*. Otherwise, if one or more BS signal *power down* the MS obeys that command. Thus, assuming perfect power control, the MS is always controlled by the BS with the largest $E_b/N_0$ and only the target $E_b/N_0$ is decreased by soft handover. Our model focuses on the combination of power control commands from all BS in the active set by selecting the BS with the largest $E_b/N_0$.

In the basic model the BS with the least attenuation controls the MS independent of the interference levels at the different BS. Once this solution, i.e. the values for $\hat{I}$ and $\hat{S}$, is known, the $E_b/N_0$ values $\hat{\epsilon}_{k,\ell}$ at other BS $\ell$ in the Active Set are computed according to Eqn. (3). In the case that one of these $\hat{\epsilon}_{k,\ell}$ is larger than the target $E_b/N_0$ $\hat{\epsilon}_k^*$, the MS is controlled by the "wrong" BS and the assignment has to be changed. Instead of calculating the $E_b/N_0$ for every MS at every BS, the conditions are simplified as follows. The controlling BS $\ell$ of an MS $k$ has to be changed if for another BS $j$

$$\hat{\epsilon}_k^* = \hat{\epsilon}_{k,\ell} < \hat{\epsilon}_{k,j} \quad \Leftrightarrow \quad \frac{\hat{d}_{k,\ell}}{\hat{d}_{k,j}} < \frac{\left(N_0 + \hat{I}_\ell\right)}{\left(N_0 + \hat{I}_j\right)}. \tag{8}$$

In the case that this condition is true for multiple BS the one with the largest $E_b/N_0$ is chosen. The change of the controlling BS for MS $k$ affects only the matrix Q, i.e.

$$Q_{k,j} = Q_{k,\ell}\frac{\hat{d}_{k,\ell}}{\hat{d}_{k,j}}, \quad Q_{k,\ell} = 0. \tag{9}$$

After the matrix Q is changed for all MS with a new assignment, the computation of $\hat{I}$ according to the basic model is performed again and if necessary the matrix Q is updated. This iteration finally converges since any change in Q leads to a reduction of the interference level at each BS.

### 2.3 Maximum Transmission Power

The other approximation, both in the basic model and in the model including soft handover, is that the MS are allowed to transmit with unlimited power. A real MS $k$, however, has a maximum transmission power $\hat{S}_k^{max}$. Hence, assuming unlimited power for an MS leads to an overestimation of the interference. These MS which are not capable to fulfill their power requirement are called *outage MS* from now on. In the following, two different ways are considered to deal with an outage MS $k$. The first possibility, from now on called "fixed power", is to retain it in the system and fix its transmission power to $\hat{S}_k^{max}$. The other possible approach is to remove the MS from the system due to outage ("removal").

For both methods, a diagonal matrix $F$ is defined which indicates MS which are either not considered any more or are transmitting with maximum power. Given the results of the basic or soft handover model, $F$ is defined as

$$F_{k,k} = \begin{cases} 0 & \text{if} \quad \hat{S}_k > \hat{S}_k^{max} \\ 1 & \text{else} \end{cases} \tag{10}$$

and the matrix $A$ of Eqn. (7) changes to $A = QF\tilde{\nu}\hat{d}$. In the case of "fixed power", the interference $\hat{I}$ is

$$\hat{I} = \left(\hat{N}_0 A + (E - F)\,\hat{S}^{max}\tilde{\nu}\hat{d}\right)(E - A)^{-1} \tag{11}$$

and in the case of "removal", $\hat{I}$ follows according to Eqn. (7).

Like in the model for soft handover, iterations are necessary for the power limit model. Due to the reduced power of the outage MS, either to $0$ ("removal") or to $\hat{S}^{max}$ ("fixed power"), the interference levels at the BS decrease. Therefore, some of the former outage MS may now fulfill their power requirements. The new values for $\hat{S}$ are determined according to Eqn. (5) and if now for a former outage MS $k$ the condition $\hat{S}_k < \hat{S}_k^{max}$ holds, the entry in $F$ is reset to $0$. In the case of "fixed power", the iteration converges since setting a value in $F$ back to $0$ always reduces the interference level at each BS. If the "removal" approach is used, taking a former outage MS into account again leads to an increase in interference. Thus, the outage MS are reentered into the system one by one and after each MS the power requirements have to be checked again. If soft handover is included, as well, the iterations of the soft handover model have to be performed before every iteration step of the power limitations model as soft handover decreases the power requirements and thus the set of outage MS.

# 3 Numerical Results

## 3.1 Homogeneous User Distribution

### 3.1.1 System description

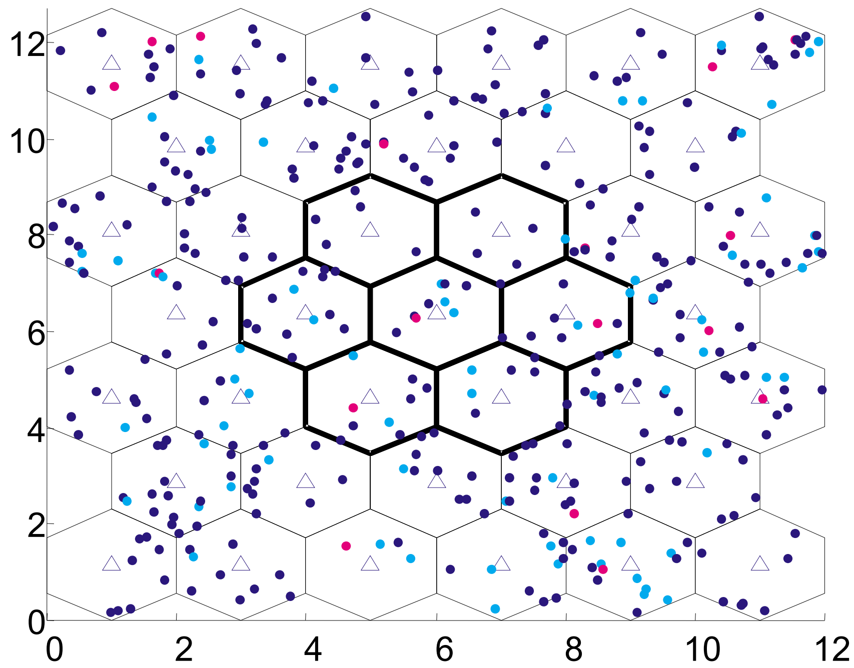


Figure 1: Hexagonal cell layout

Let us consider the hexagonal cell layout with $L = 39$ base stations and a random number of $K$ mobile stations given in Fig. 1. The user distributions are generated randomly according to a spatial homogeneous Poisson process [13]. Such a process is characterized with an intensity $\lambda$, giving the mean number of users per unit area size. This results in the number of users in the cell, denoted as $N$, also being a random variable. In order to relate $\lambda$ to $E[N]$, the following equation is used:

$$\lambda = \frac{E[N]}{\text{coverage area of BS}} = \frac{E[N]}{0.5\sqrt{3}D^2}, \tag{12}$$

where $E[\cdot]$ denotes the mean of a random variable.

We model the attenuation of the radio signals due to propagation loss by the vehicular test environment model in [14]

$$d_{k,\ell} = -128.1 - 37.6 \log_{10}(dist_{k,\ell}), \tag{13}$$

with $dist_{k,\ell}$ being the distance between MS $k$ and BS $\ell$ in km. In order to capture the effects of the user distribution, we concentrate on a flat earth environment without shadow fading. An inclusion of shadowing and multipath fading, however, can easily be performed.

The types of service we consider are given in Tab. 1 and consist of the typical target $E_b/N_0$ values for each bit rate. In particular we selected combinations of services, denoted as traffic mix 1-3, which we will focus on in the following. The other parameters used in the model are

| bit rate [kbps] | 12.2 | 64 | 144 |
|---|---|---|---|
| target $E_b/N_0$ [dB] | 5.5 | 4.0 | 3.5 |
| traffic mix 1 | 75% | 20% | 5% |
| traffic mix 2 | 50% | 25% | 25% |
| traffic mix 3 | | 50% | 50% |

Table 1: Model parameters of services

as follows: frequency bandwidth is $W = 3.84$ MHz, thermal noise power density $N_0 = -174$ dBm, maximum MS transmission power $S^{max} = 24$ dBm, and activity factor $\nu = 1$.

In the following sections we will investigate the influence of the average number of MS per cell $E[N]$ and the inter-BS distance $D$ on the total interference and the received signal strength under the condition that the call admission control eliminates $A_{out}$-cases, cf. Eqn. (7). This is realized by considering only point patterns generated by the spatial Poisson process not leading to an $A_{out}$-event.

#### 3.1.2 Results

In this section, the interference level at the BS according to the basic model is compared to the results from the various extensions. In Fig. 2, 5, and 6 the terms in the legend correspond to the following methods:

| | |
|---|---|
| standard | basic model |
| soft handover | soft handover without power limitation |
| fixed power | “fixed power” without soft handover |
| removal | “removal” without soft handover |
| soft+fixed | soft handover and “fixed power” |
| soft+removal | soft handover and “removal” |

Fig. 2 shows the mean interference for traffic mix 1 depending on the traffic density where only the inner 7 cells marked in Fig. 1 are considered. The BS distance was set to 2km, the error bars in the figure mark the 95% confidence intervals. For traffic densities below 20 MS per BS the 6 curves are almost identical, only the interferences are slightly smaller when soft handover is considered. This gap increases with the number of MS. For more than 25 users the curves without soft handover diverge while those with soft handover still coincide. We can see that “removal” and “fixed power” reduce the mean interference, i.e. outage occurs. This effect is compensated by soft handover, since the curves “soft handover” and “soft+removal” do not differ.

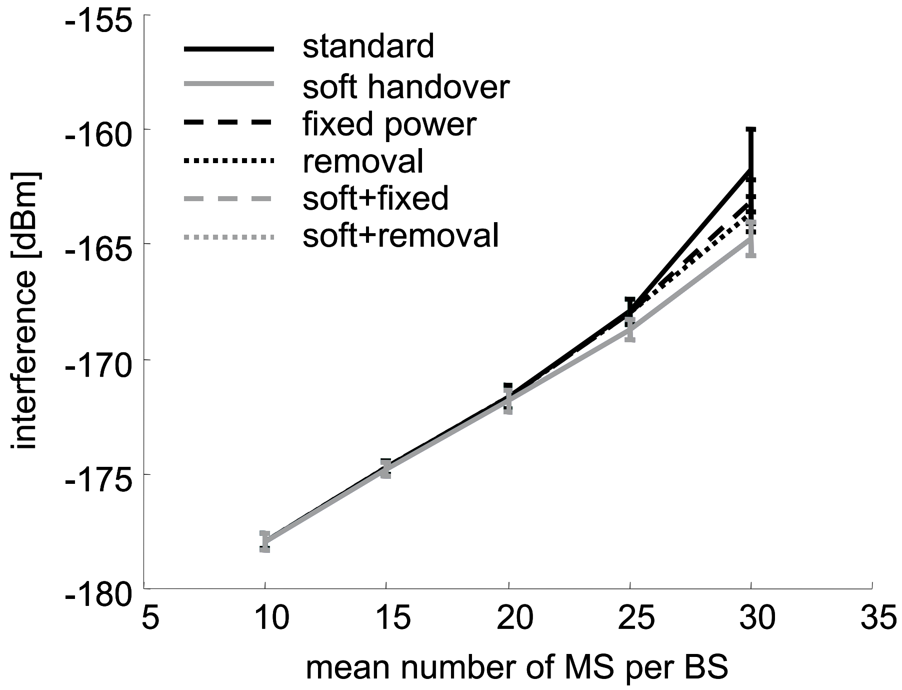


Figure 2: Mean interference depending on the user density

We define *soft handover gain* as the difference between the interference resulting from the basic model and that from the soft handover model. The power limitations are excluded from this definition since they make a comparison of interference levels impossible either due to the different effective number of MS in the system or due to MS received with too low signal strength. In Fig. 3 the soft handover gain for different traffic mixes depending on the mean number of users is illustrated. All curves have the same shape with a soft handover gain starting at 0dB for low traffic densities and increasing exponentially up to approximately 3dB. Higher soft handover gains are not achieved due to $A_{out}$-cases.

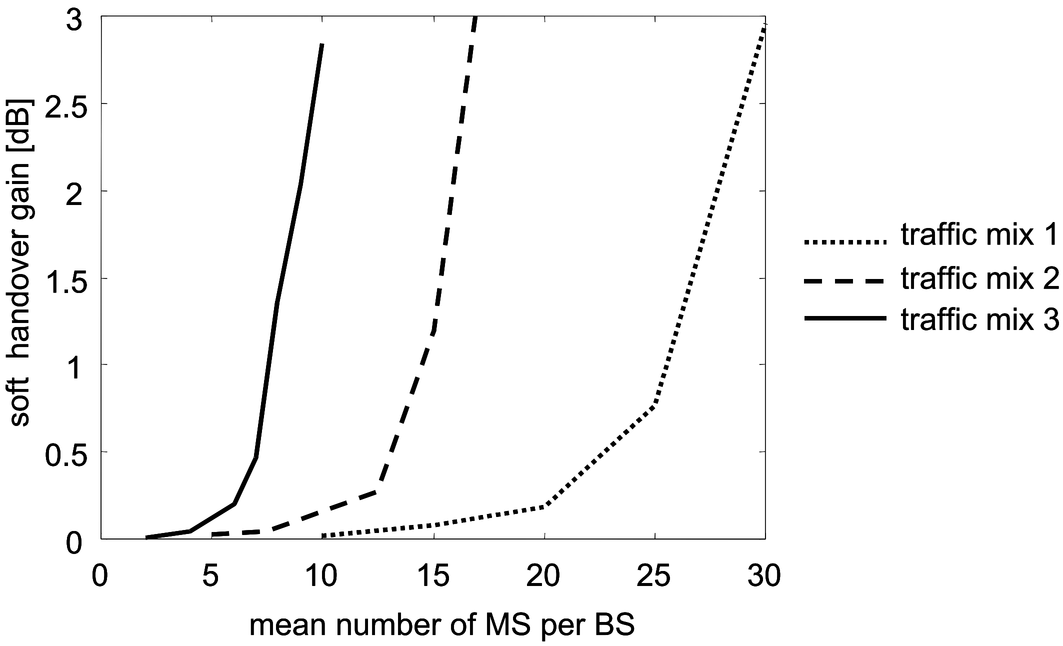


Figure 3: Soft handover gain

The similar shape of the curves is further emphasized by Fig. 4. The results plotted in this figure are equal to those of Fig. 3, however, the scale of the x-axis is different. We can see in Fig. 3 that the curve for traffic mix 3 increases much faster than the curve of traffic mix 1. This is due to the higher mean load produced by a user of traffic mix 3. Generally, the mean load $\alpha_m$ caused by a user of traffic mix $m$ with probabilities $p_{m,t}$ for service $t$ is defined as

$$\alpha_m = \sum_{t=1}^{T} p_{m,t} \frac{\beta_t}{W + \beta_t}. \tag{14}$$

The mean total load produced by the users of traffic mix $m$ is the mean number of MS per BS multiplied by $\alpha_m$ and this parameter is used on the x-axis of Fig. 4. Tab. 2 gives an overview of the mean loads per user for the considered traffic mixes. In this normalized representation the curves roughly coincide. Therefore, we can conclude that the mean soft handover gain in a homogeneous environment depends only on the mean load of the considered traffic mix.

|  | $p_{m,1}$ | $p_{m,2}$ | $p_{m,3}$ | $\alpha_m$ |
|---|---|---|---|---|
| traffic mix 1 | 0.75 | 0.2 | 0.05 | $\approx 0.011$ |
| traffic mix 2 | 0.5 | 0.25 | 0.25 | $\approx 0.040$ |
| traffic mix 3 | 0 | 0.5 | 0.5 | $\approx 0.077$ |

Table 2: Mean load per user of considered services

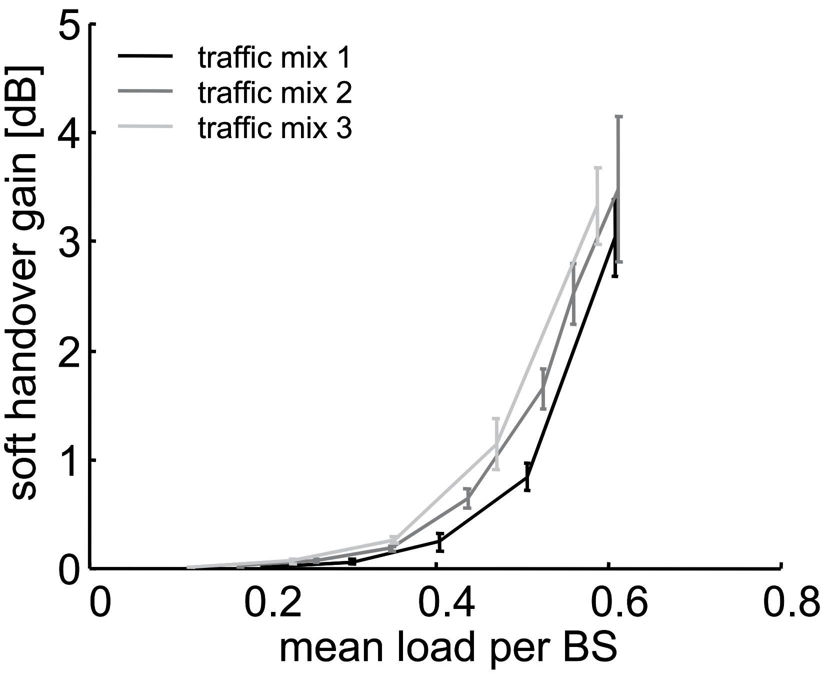


Figure 4: Soft handover gain versus BS load

Another item of interest is how the BS density influences the results. Therefore, the BS distance is varied for a fixed traffic density of 25 MS per BS. The mean interferences with confidence intervals are depicted in Fig. 5. For BS distances up to the already familiar 2km, the soft handover effects are the same as previously described. The difference between "standard" and "removal" diminishes since with decreasing maximum path loss the effect of outage disappears. For greater distances the curves considering soft handover diverge, as well. MS in soft handover reside in the middle between two or more BS. When the BS distance increases these mobiles are affected by outage first. Thus, the curves "soft+fixed" and "fixed power" converge for high BS distances as well as the curves "soft+removal" and "removal". The soft handover gain, i.e. the gap between "standard" and "soft handover" is almost independent of the BS distance if outage is not considered.

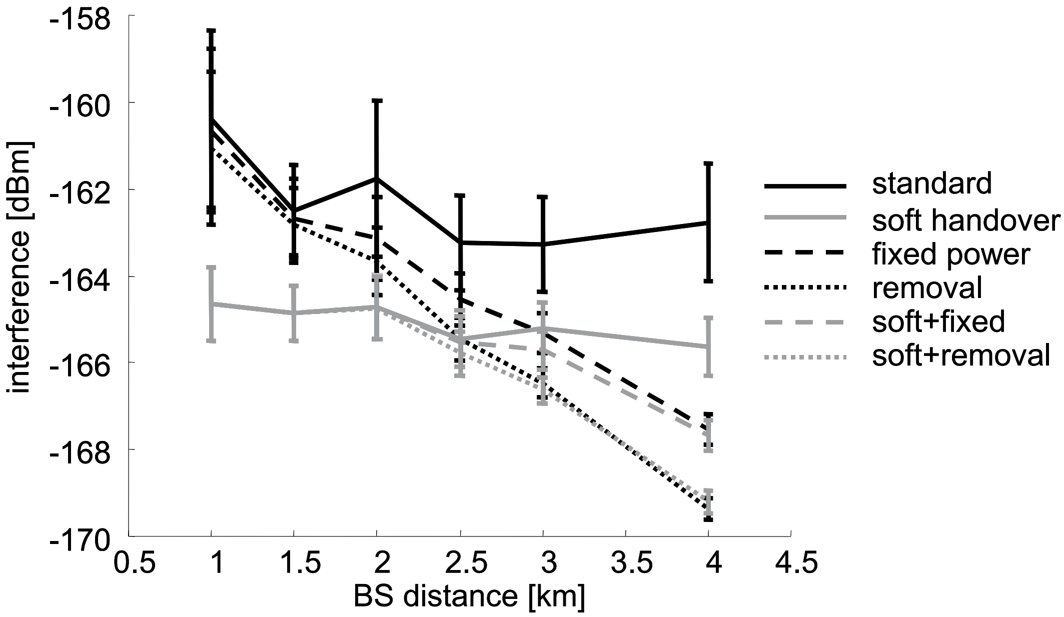


Figure 5: Mean interference depending on the BS distance

In the last figures we recognized that soft handover helps to reduce the effect of outage, however without quantifying the reduction of outage probability. For the planning of large UMTS networks it is necessary to determine the BS density such that an upper bound for the outage probability is maintained. Fig. 6 shows the CDF of the interference for traffic mix 1 with 30 MS per BS and a BS distance of 2km. Here, we can recognize the soft handover gain, as well. The 3 curves including soft handover lie upon each other and are the leftmost, i.e. those with the least interference. Furthermore, these curves are steeper than the others indicating a smaller variance. The variance for the basic model is the largest. Power limitations reduce the interference level at BS with high load and thus reduce the variance. Soft handover additionally shifts the load from BS with many MS to those with few MS and thus balances the interferences.

Fig. 6 can also be used to determine the coverage areas. Let the upper bound for the outage probability be 5%. In Fig. 6 the 95%-quantiles for "standard" and "soft handover" can be seen as -154.14dBm and -162.31dBm, respectively. Thus, a signal strength

$$S_k^R = W \left(\hat{N}_0 + \hat{I}_{BS(k)}\right) \beta_k \left(W + \beta_k \nu_k\right)^{-1} \tag{15}$$

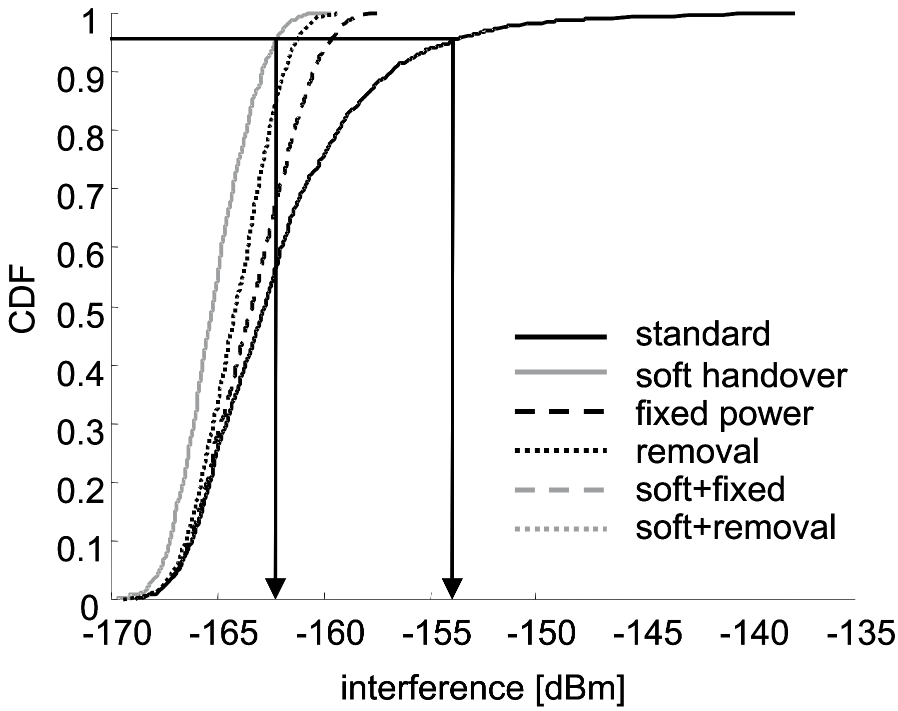


Figure 6: CDF of the interference for different methods

of -99.36dBm and -107.30dBm is required for MS with 144kbps. For a maximum transmission power of 24dBm and considering the path loss formula, cf. Eqn. (13), the coverage radius of the cells results in 0.88km and 1.08km, respectively.

### 3.2 Inhomogeneous User Distribution and Irregular Base Station Layout

In the last section we analyzed the influence of the traffic load and the base station distance in a homogeneous environment with a hexagonal BS layout. In the following we will extend these results to inhomogeneous user distributions and irregular cell layouts. Contrary to the homogeneous case, the difficulty arises for the inhomogeneous case to define a reference scenario suited to make general statements about the soft handover gain. In particular, we tried to demonstrate how the degree of inhomogeneity influences the soft handover gain. Therefore, two studies are conducted; one considers only a single BS with a load different to the one of the other cells and another study uses cell-wise varying user densities. Furthermore, a scenario with an irregular BS layout and a user distribution according to a clustered spatial process is considered.

#### 3.2.1 Single Base Station with Different Load

The first inhomogeneous scenario considered relies on the BS layout shown in Fig. 1. Basically, the traffic is still homogeneous except for the central cell. Within this cell the traffic is also homogeneous, however, with a different intensity. The following results are produced for traffic mix 1 and a traffic density of 20 MS per BS. The mean number of users in the central cell is varied from 20 users less than in the other cells to 30 users more. This corresponds to user densities from zero to forty MS in the central cell.

Fig. 7 shows the mean interference versus the load difference of the central BS. The interferences at the seven inner BS were taken into account for computing the mean. We can see that similar to Fig. 2 no outage occurs for equal or less traffic in the central cell. In the case that the central BS has more than ten additional users outage occurs if soft handover is neglected. Under the consideration of soft handover the three curves with and without outage coincide, since soft handover is capable to decrease the required transmission powers enough to avoid outage.

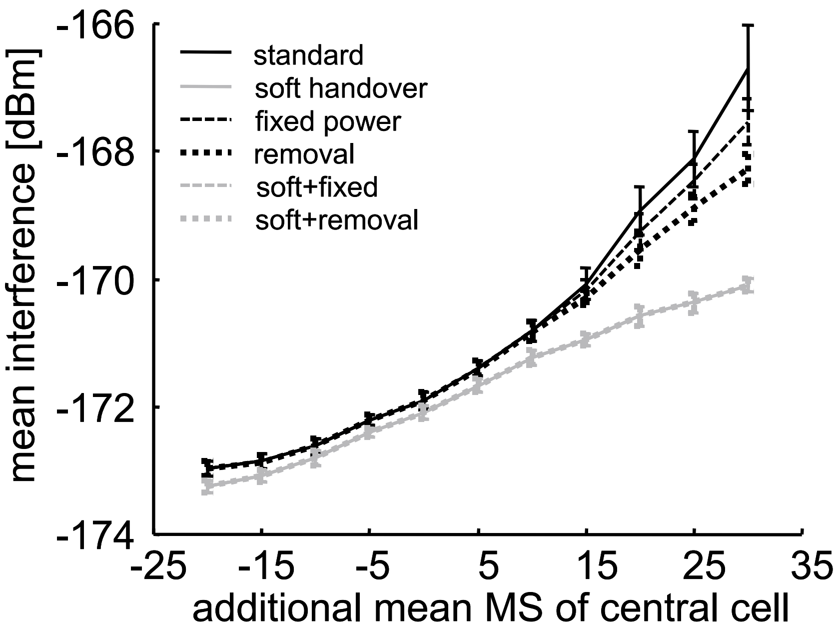


Figure 7: Mean interference for inhomogeneous load at central BS

Fig. 8 shows the soft handover gain depending on the user density difference of the central cell. The black curve represents the soft handover gain in the seven cells surrounding the central cell; the grey curve depicts the soft handover gain in the central cell. The first observation we can make is that the minimum soft handover gain is achieved for a homogeneous user density in all cells. For both cases a higher as well as a lower traffic intensity in the central cell soft handover shows a greater benefit. In particular, it is remarkable that for lower densities when the total interference decreases the soft handover gain nevertheless increases. Secondly, the mean soft handover gain exceeds the maximum possible value of 3dB in homogeneous networks. For a user density increased by 30 in the central cell a soft handover gain of about 4dB is achieved.

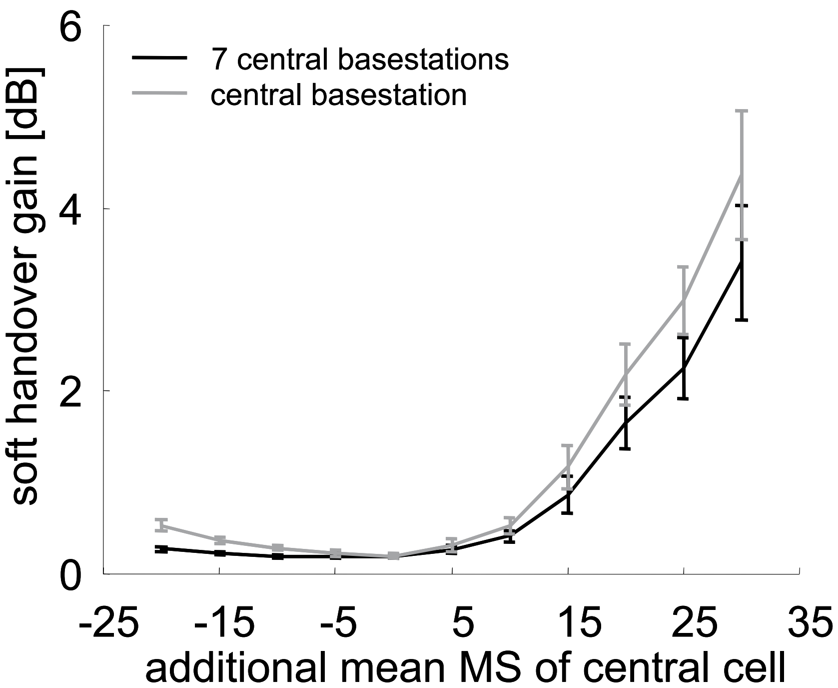


Figure 8: Soft handover gain for inhomogeneous load at central BS

### 3.2.2 Hexagonal Base Station Layout with Cell-Wise Inhomogeneous User Density

In this section we define a measure for the inhomogeneity of a user distribution. The scenario is still based on a hexagonal BS layout. However, the traffic density is now cell-wise inhomogeneous as in [15]. This means that within each cell the traffic follows a spatial Poisson process whereas each cell can have an arbitrarily chosen user density. This traffic density is generated according to a truncated Normal distribution with mean $\mu$ and standard deviation $\sigma$. This distribution is of course truncated at $0$ since negative user densities make no sense. To keep the mean constant the distribution is also cut off at $2\mu$. The grade of inhomogeneity is then characterized by the standard deviation $\sigma$.

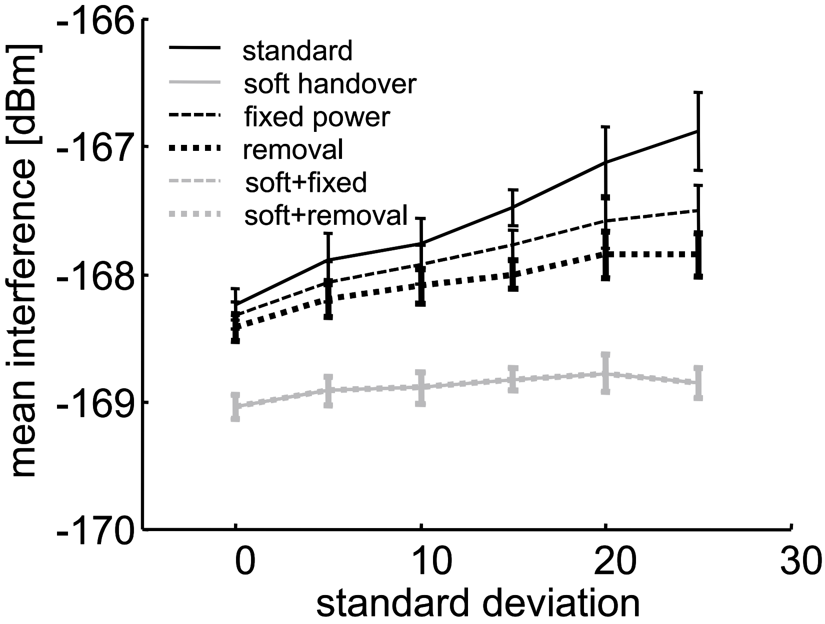


Figure 9: Mean interference for cell-wise inhomogeneous user density

In Fig. 9 the mean interference is given for traffic mix 1 with $\mu = 25$ MS per BS and an increasing standard deviation. For $\sigma = 0$ the traffic distribution is homogeneous, i.e. these values correspond to the values in Fig. 2 with 25 MS per BS. For growing standard deviations, i.e. if the traffic gets more inhomogeneous, the interference increases if no soft handover is considered while the curves including soft handover are roughly parallel to the x-axis. This shows that soft handover is capable to balance cell load variations. As a consequence outage increases with growing $\sigma$ if soft handover is neglected which can be recognized by the increasing gap between the standard and the removal curve. All three curves considering soft handover coincide, thus outage is completely compensated.

Another feature is that the standard curve and the soft handover curve diverge, i.e. the soft handover gain increases. This soft handover gain together with the soft handover gain for $\mu = 20$ MS per BS is illustrated in Fig. 10. In both cases the soft handover gain increases with growing $\sigma$. In particular, the two curves are roughly linear which indicates that the soft handover gain and the degree of inhomogeneity are proportional.

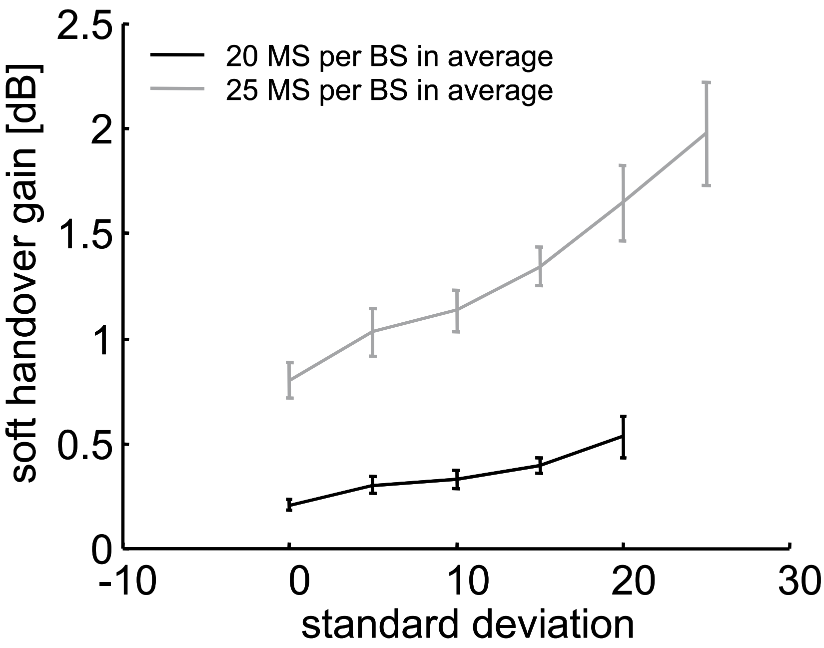


Figure 10: Soft handover gain for cell-wise inhomogeneous user density

#### 3.2.3 Clustered User Distribution

The previous inhomogeneous scenarios are all based on a regular hexagonal layout of the base stations and the MS within one cell always follow a homogeneous distribution. Now, a scenario is investigated which is completely inhomogeneous, i.e. the base stations are not arranged on a hexagonal grid and, furthermore, a clustered spatial process, the Matern process [16], is used to generate the MS.

In the Matern process point patterns are generated as follows. First, cluster centers are generated according to a spatial Poisson process with a given cluster density. Then, for each cluster center the number of points within the area of this cluster is generated according to a simple Poisson process with a given mean number of points per cluster. The cluster size is defined by a constant radius $R$. The location of the points within the cluster is generated using polar coordinates. The angle is distributed uniformly between 0 and $2\pi$. The distance $r$ to the cluster center follows the distribution function

$$A(r) = \frac{r^2}{R^2}. \tag{16}$$

In Fig. 11 a realization of a Matern process is depicted. The cluster centers are generated within the largest circle and are marked by black stars. The radius of the clusters is 1.5km. The users generated for each cluster are only accepted if they are located in the second largest ring. The users are plotted as dots and their color corresponds to the service.

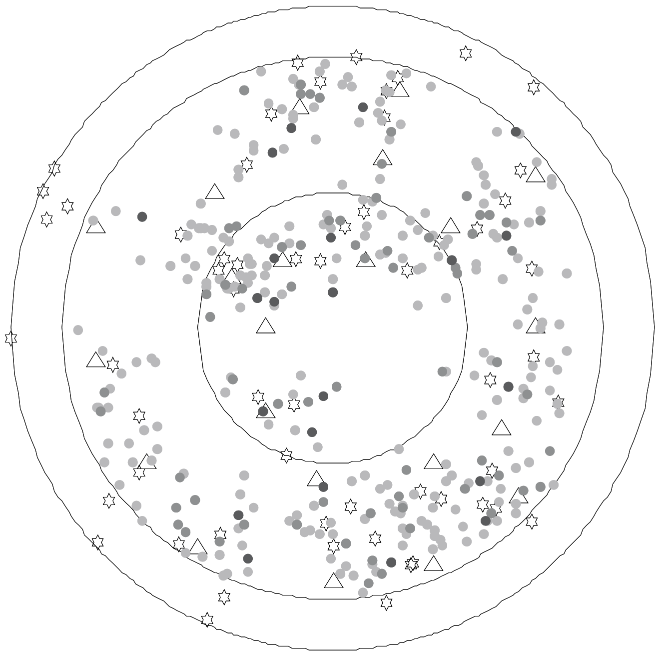

Figure 11: Inhomogeneous user distribution and irregular BS layout

For the characterization of the soft handover gain in an inhomogeneous scenario only the realization of the cluster centers depicted in Fig. 11 is chosen. According to the location of these clusters 21 BS are distributed manually such that most of the clusters are covered. The BS are marked by triangles in Fig. 11. In Fig. 3 the soft handover gain is investigated for a homogeneous traffic distribution with different user densities. To compare the effect of soft handover in the homogeneous scenario and in the Matern scenario, the load, i.e. the mean number of users per BS, has to be equivalent. Therefore, the mean number of users per cluster is adapted to the mean number of users per BS. The difficulty is that for some clusters only a part of their surface is located inside the considered area, i.e. within the second largest ring in Fig. 11 which has a diameter of 16km. Thus, not all users which are generated for these clusters are accepted. This has to be taken into account when determining the mean number of users per cluster. Let $L$ be the number of BS, $C$ the number of clusters, and $p_c$ the percentage of cluster $c$ within the considered area. Then, for a mean number of $K_{BS}$ MS per BS the number $K_C$ of MS per cluster is calculated as

$$K_C = \frac{K_{BS} L}{\sum_{c=1}^{C} p_c}. \tag{17}$$

For this value $K_C$ the MS are generated for each cluster and for each of these realization the interferences are calculated. To avoid border effects, i.e. missing othercell interferences at BS located near the border of the considered area, only interferences at those BS inside the inner ring with a diameter of 8km are considered. Fig. 12 shows the comparison of the soft handover gain in the homogeneous scenario and in the Matern scenario for traffic mix 1. We can see that in the inhomogeneous case the soft handover gain is larger and furthermore, the curve increases faster. For a load of 20MS per BS the soft handover gain is almost 2dB higher in the inhomogeneous scenario than in the homogeneous case.

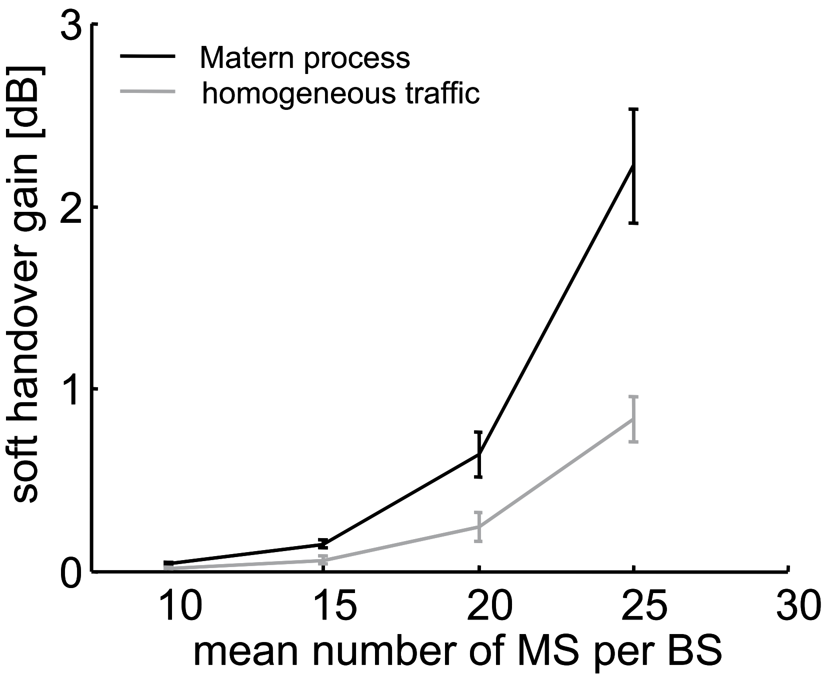


Figure 12: Comparison of the soft handover gain for homogeneous and inhomogeneous user distributions

# 4 Conclusion and Outlook

In this paper we derived a model to determine the interference levels at the BS in a UMTS network with irregular BS layout. Furthermore, the transmission powers of the MS which may belong to different services are determined. These calculations can be performed with or without soft handover which allows to characterize its benefits, in particular the soft handover gain. Three methods how to deal with outage users not capable of fulfilling their power requirement can be included. The first one allows unlimited power, the second one adjusts the power to the maximum possible power, and the third one removes these MS from the system.

We showed the effects of soft handover on the interference level and on the coverage area for different traffic mixes, user densities, and BS distances. A soft handover gain of up to 3dB for highly loaded cells was found for a homogeneous traffic distribution and a hexagonal BS layout. For inhomogeneous traffic we investigated three scenarios. Two of them still assume a hexagonal layout. The first one considers one cell with a different load than the other cells and in the second one the traffic intensity of each cell is independent and distributed according to a Normal distribution, i.e. the traffic is cell-wise inhomogeneous. For these two scenarios we showed that the soft handover gain increases if the traffic distribution becomes more inhomogeneous. The third scenario is based on a clustered spatial process to generate the MS and the BS are arranged in an irregular layout. In this case we were able to demonstrate that for equal loads the soft handover gain in the inhomogeneous case clearly exceeds the gain in homogeneous networks. Furthermore, we illustrated how soft handover helps to reduce or eliminate outage. Our methods and results can be used in planning tools for UMTS networks like T-Mobile's *Pegasos*.

The proposed method relies on the derivation of statistical values by multiple realizations of a spatial point process. Our aim in the future is to develop a pure analytical model to directly compute the distribution of the interference levels. A first approach that does not yet include soft handover can be found in [17]. Furthermore, the model shall be extended to site diversity. So far only the uplink has been taken into account. In a following study we will also consider the downlink, as well.

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