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Analytical Characterization of the Soft Handover Gain in UMTS

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Abstract—**In this paper we present an analytical model for computing the interference distribution in a third generation UMTS network. Our main focus lies on quantifying the interference reduction due to the combination of the power control signals from multiple base stations when the mobile stations are in soft handover. Our model also includes upper bounds of the mobile's transmission power, i.e. outage is considered. These effects influence the coverage areas and, therefore, play an important role in the planning of 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 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. While capacity in GSM is a fixed quantity, it is influenced in WCDMA by the interference from 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.

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 [1], [2].

The influence of soft handover on coverage and capacity was also investigated in [3]. 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 [4] 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 [5] 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 [6] 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, as well.

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. This leads to a characterization of outage probability which can be used for network planning.

The paper is organized as follows. Section II 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 III we will present numerical results from the analysis. The paper is concluded in Section IV with an outlook on future work.

II. Model Description

A. 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 ℓ is denoted by $\hat{I}_\ell$, $\hat{S}_k$ and ν_k define the transmission power and the activity of MS k, and the path loss from MS k to BS ℓ is given by $\hat{d}_{k,\ell}$. The interference level is computed as

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

The variables $\hat{\alpha}$ written with a hat are always linear values and the corresponding values α are decibel values 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. [7],

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

with the target E_b/N_0 $\hat{\epsilon}_k^*$, the bit rate R_k, and the activity ν_k specifying the service of user k. Note that in this case ℓ 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.

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

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

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

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.

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

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 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

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

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

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

The matrix E is the $L \times L$ identity matrix. Similar to the A_{out} case defined in [7] 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 [8]. 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.

B. Soft Handover

In CDMA systems, MS in soft handover can be connected not only to one 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 [9]. 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 ℓ 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 ℓ of an MS

k has to be changed if for another BS j

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

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 effects only the matrix Q, i.e.

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

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 another time. This iteration finally converges since any change in Q leads to a reduction of the interference level at each BS.

C. 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

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

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

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

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.

III. Numerical Results

A. System Description

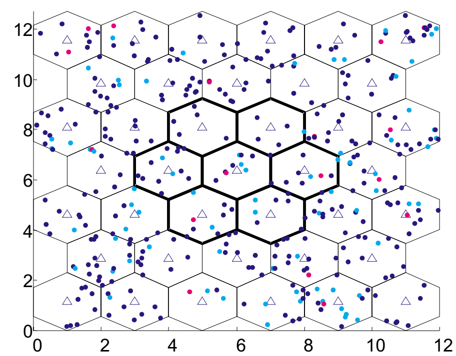

Fig. 1. Hexagonal cell layout

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 [10]. Such a process is characterized with an intensity λ, 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 λ to $E[N]$, the following equation is used:

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

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 [11]

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

with $dist_{k,\ell}$ being the distance between MS k and BS ℓ 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. I 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

bit rate [kbps]	8	12.2	64	144
target E_b/N_0 [dB]	6.5	5.5	4.0	3.5
traffic mix 1	75%		20%	5%
traffic mix 2		50%	30%	20%
traffic mix 3			50%	50%

TABLE I
MODEL PARAMETERS OF SERVICES

other parameters used in the model are 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.

B. 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, 4, and 5 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.

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

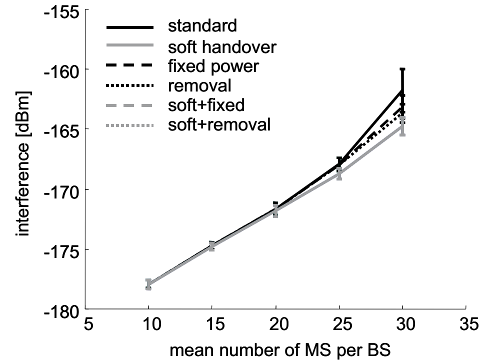

Fig. 2. Mean interference depending on the user density

this definition since they make a comparison of interference levels impossible due to the different effective number of MS in the system. 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.

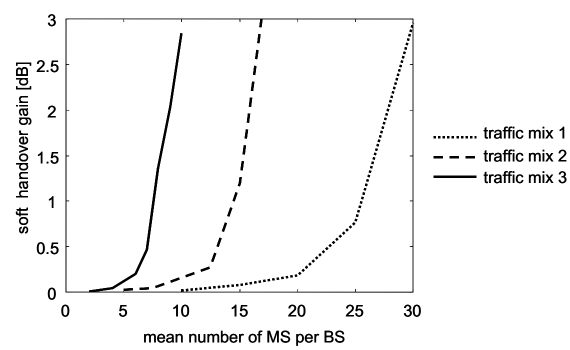

Fig. 3. Soft handover gain

Another item of interest is how the BS density influences the results. Therefore, the BS distance is varied for a fixed traffic density of 30 MS per BS. The mean interferences with confidence intervals are depicted in Fig. 4. 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.

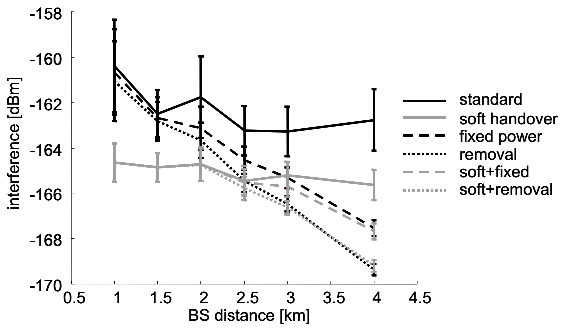

Fig. 4. Mean interference depending on the BS distance

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. 5 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.

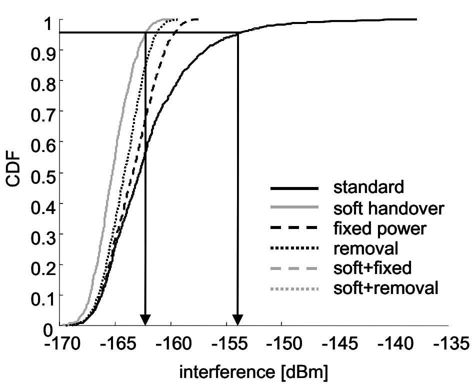

Fig. 5. CDF of the interference for different methods

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

$$S_k^R = W\left(\hat{N}_0 + \hat{I}_{BS(k)}\right)\beta_k\left(W + \beta_k\nu_k\right)^{-1} \quad (14)$$

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.

IV. Conclusion

In this paper we extended the basic model presented in [8] by considering power limitations and soft handover. 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. Furthermore, we illustrated how soft handover helps to reduce or eliminate outage. Our methods can be implemented 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 the spatial point process. Our aim in the future is to develop a completely analytical model to directly compute the distribution of the interference levels. Furthermore, the model shall be extended to site diversity, as well. So far only the uplink has been taken into account. In a following study we will also consider the downlink.

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