

Effects of Soft Handover on the UMTS Downlink Performance

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Abstract— The 3gpp standard proposes two methods to perform soft handover on the downlink. In the first one all base stations (BS) or Node-B belonging to the Active Set (AS) transmit simultaneously to the mobile station (MS). All these signals are added at the MS using maximal ratio combining. The downlink power control adjusts the BS transmit powers such that the E_b/N_0 achieved by maximal ratio combining reaches the desired target E_b/N_0 . According to the 3gpp standard all BS in the AS transmit with an equal power to the MS. The other possibility to perform soft handover is called site selection diversity. In this case a single BS of the AS is selected and only this BS transmits to the MS while all other BSs in the AS switch their power off. The advantage of this strategy is that the other BSs in the AS produce no interference while the benefits of soft handover are maintained by fast site selection. If the radio link quality drops abruptly due to fading effects the MS can switch rapidly to another BS. In this paper we analytically compare the two methods with respect to the system capacity. Furthermore, we investigate soft handover mechanisms that allocate not necessarily equal proportions of the total power to the BSs in the AS. These mechanisms provide a compromise between equal power allocation and SSdT.

I. INTRODUCTION

The expected introduction of third generation mobile systems which is the *Universal Mobile Telecommunication System* (UMTS) in Europe demands a sophisticated network planning. Most work, e.g. [1], [2], investigating the capacity of mobile communication systems operating with CDMA or W-CDMA (*Wideband-CDMA*) focus on the uplink, since it was generally accepted that the capacity of cdma-one systems is uplink limited. These systems carry mostly symmetric voice traffic while packet data traffic occurs only sparsely. In 3G systems the set of offered applications evolves from pure voice telephony to a large variety of services including internet traffic as well as audio and video streaming. These applications produce strongly asymmetric traffic with as much as ten times more data volume on the downlink than on the uplink, see e.g. [3]. While the uplink is still important, in particular for the coverage planning of UMTS networks, see e.g. [4], [5], more and more research is dedicated to the downlink. Important issues regarding the performance of the downlink in W-CDMA systems are rate and power allocation strategies which are investigated e.g. in [6], [7] or scheduling algorithms as in [8]. Furthermore, the capacity of the UMTS downlink is researched e.g. in [9], [10]. In [11] the performance of W-CDMA systems with soft handover is analyzed, however, under the assumption that the base station (BS) power is allocated equally among all its mobile stations (MS). In [12] the system performance in terms of outage probabilities both on the uplink and on the downlink are investigated analytically and by simulations. The results show that on the uplink soft handover always leads to a better per-

formance whereas on the downlink the effects of soft handover are more ambiguous.

On the uplink, soft handover helps to reduce the MS's transmit power and thus leads to an increase of the system capacity, which is also shown in e.g. [13], [14], [15]. Furthermore, soft handover makes the system more robust against fading influences and the only disadvantage is additional traffic between the BS and the Radio Network Controller (RNC). Soft handover leads to more robustness against fading on the downlink, as well. However, the total power dedicated to one MS from multiple BSs exceeds the power required if only a single BS transmits.

Therefore, the 3gpp standard [16] proposes a basic and an optional method to perform soft handover on the downlink. In the basic method all BSs belonging to the Active Set (AS) transmit simultaneously to the MS. These signals are combined by the Rake receiver using maximal ratio combining. The other possibility to perform soft handover is called *site selection diversity transmit* (SSdT) power control. In this case one BS of the AS is selected and only this BS transmits to the MS while all other BS switch their power off. The advantage of this strategy is that the BSs in the AS produce no interference to each other. The robustness against fading influences is partly maintained by fast site selection which means that in case of a dropping radio link quality the MS can switch rapidly to another BS.

In this paper we investigate the effects of soft handover on the system capacity for both methods. If basic soft handover is applied all BSs in the AS transmit with equal power while with SSdT only the "best" BS transmits. We propose a method to allocate the transmit power to the BSs in the AS proportionally to their signal strength which corresponds to an intermediate way to perform soft handover. The remainder of the paper is organized as follows. In Section II we explain the soft handover mechanism on the downlink in more detail. The models to determine the resulting system performance are given in Section III and in Section IV the required BS transmit powers are compared for the proposed methods. Furthermore, the influence of traffic intensity, service mixture, reporting range, and orthogonality factor are shown. Finally, we conclude in Section V.

II. SOFT HANDOVER ON THE DOWNLINK

In CDMA systems, a MS in soft handover mode is connected to several BSs which constitute the AS. The AS is de-

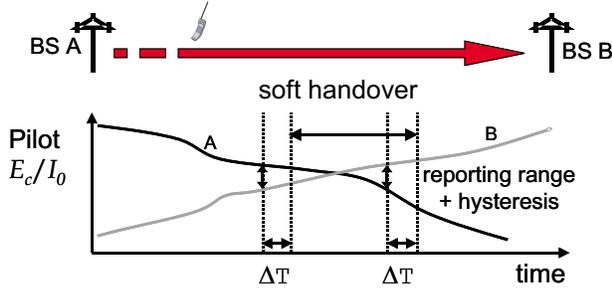


Fig. 1. Soft handover mechanism

fined by the pilot signal which is transmitted by every BS with 30dBm [17]. The MS detects the BS with the strongest received pilot signal. This BS together with those BSs having a signal strength within the *reporting range* form the AS. Fig. 1 illustrates how the AS of a MS moving from BS A to BS B changes. First, the strength of the pilot signal from A is much larger than that of the pilot signal from B. Then the MS moves towards B and the gap between the pilots becomes smaller until it falls below the reporting range plus the hysteresis for a time ΔT and BS B joins the AS. The hysteresis and the waiting time ΔT avoid repeated adds and drops of a BS. After a certain time the pilot of B exceeds the pilot of A for more than the reporting range plus the hysteresis and A is dropped from the AS.

A. Power Control in Soft Handover Mode

On the uplink a MS in soft handover mode receives power control commands from all BSs in its AS and increases its power only if all BSs demand a higher power. Otherwise, the MS decreases its power. All BSs determine the power control command individually by comparing the E_b/N_0 received from the MS with their target- E_b/N_0 values. That values are equal for all BSs and the RNC determines them in the outer loop power control. Thus, the MS is always controlled by the best BS and the minimum transmit power is required.

On the downlink, the 3gpp standard [16] defines a basic mechanism for the power control in soft handover mode and SSDDT as an optional way to perform power control. With the basic method all BSs in the AS transmit to the MS and the Rake receiver of the MS adds the signals using maximal ratio combining. Using this technology the E_b/N_0 values of all fingers are added and result in one total E_b/N_0 which is compared to the target E_b/N_0 of the MS. If the total received E_b/N_0 exceeds the target E_b/N_0 the MS sends a power down command to all BSs in the AS. Otherwise, the BSs receive a command to increase their power. Thus, in the ideal case all BSs are transmitting with equal power. However, power drifting may occur which means that power control commands may be erroneous such that the BSs in the AS execute different power updates. Therefore, the 3gpp standard defines a method to compensate for power drifting such that we can assume in our model that

all BSs transmit with equal power.

With SSDDT a MS selects the BS with the largest pilot signal strength from the AS and only this BS actually transmits data to the MS. The other BSs turn their power for the dedicated packet data channel (DPDCH) off. However, the connections between the MS and the other BSs in the AS remain active as the BSs transmit signaling information in the dedicated packet data control channel (DPCCH). Thus, with SSDDT the benefits from macro-diversity still exist since the MS can switch between the BSs in the AS on a frame by frame basis and so the effects of fading are partially compensated.

III. DOWNLINK SOFT HANDOVER MODEL

In our model we consider a UMTS network consisting of L BSs and K stationary MSs which transmit continuously. The signal attenuation $d_{x,k}$ in dB from BS x to MS k is constant such that fading effects are not considered. Furthermore, each MS k operates with a service t which is defined by its bit rate R_t in bps and its target E_b/N_0 -value $\hat{\epsilon}_t^*$. Note that linear values are marked with a hat while the corresponding values in decibels are written without a hat. The Active Set $AS(k)$ of MS k is determined by

$$AS(k) = \{x | \max_y \{d_{y,k}\} - d_{x,k} < r\}, \quad (1)$$

where x and y denote BSs and r is the reporting range. Since the model assumes stationary users the hysteresis is neglected. Additionally, we assume perfect power control. The E_b/N_0 -value $\hat{\epsilon}_{x,k}$ obtained if BS x transmits with power $\hat{S}_{x,k}$ to MS k is given as

$$\hat{\epsilon}_{k,x} = \hat{S}_{x,k} \hat{d}_{x,k} / (R_k (\hat{N}_0 + \hat{I}_{x,k})). \quad (2)$$

The variable \hat{N}_0 denotes the thermal noise spectral density and N_0 is set to -174dBm/Hz. The interference density $\hat{I}_{x,k}$ for the signal of BS x at MS k is

$$\hat{I}_{x,k} = \left(\sum_{y \neq x} \hat{T}_y \hat{d}_{y,k} + \alpha (\hat{T}_x - \hat{S}_{x,k}) \hat{d}_{x,k} \right) / W. \quad (3)$$

The variable \hat{T}_x refers to the total power of BS x and is the sum of the transmit powers $S_{x,k}$ to the single MS with x in their AS. The power required for control channels is neglected to expose the influences of the different soft handover variants. In Eqn. (3) the interference caused by BS x is reduced by the orthogonality factor α since, although the codes used at one BS are orthogonal, a part of the base station signal is seen as interference [17] due to the delay spread of the multipath propagation.

Employing maximal ratio combining the total E_b/N_0 -value $\hat{\epsilon}_k$ of MS k corresponds to the sum of the E_b/N_0 -values of all BSs in the AS, i.e. $\hat{\epsilon}_k = \sum_{x | x \in AS(k)} \hat{\epsilon}_{x,k}$. Assuming perfect power control the total E_b/N_0 corresponds to the target- E_b/N_0 $\hat{\epsilon}_k^*$ in the case of a converged system. Hence, the transmit powers $\hat{S}_{x,k}$ have to fulfill the following equation for all

BSs x and MSs k :

$$\hat{\epsilon}_k^* = \sum_{x \in AS(k)} \hat{S}_{x,k} \hat{d}_{x,k} / (R_k (\hat{N}_0 + \hat{I}_{x,k})). \quad (4)$$

These powers are computed iteratively by a repeated calculation of the required powers $\hat{S}_{x,k}$ and the corresponding BS transmit powers T_x and interference densities $I_{x,k}$. However, the way to solve Eqn. (4) differs for the considered soft handover mechanisms.

A. Basic Soft Handover Mechanism

If the basic soft handover mechanism is applied, all BSs in the AS transmit with an equal power, i.e. $\hat{S}_{x,k} = \hat{S}_k, \forall x \in AS(k)$. Furthermore, we have to introduce a new variable $\hat{I}'_{x,k}$ which is the interference for the signal from x to k except the interference caused by the other signals devoted to k .

$$\hat{I}'_{x,k} = \sum_{y \neq x} \frac{(\hat{T}_y - \delta_{y,k} \hat{S}_k) \hat{d}_{y,k}}{W} + \frac{\alpha (\hat{T}_x - \hat{S}_k) \hat{d}_{x,k}}{W}, \quad (5)$$

with $\delta_{x,k} = 1$ if $x \in AS(k)$ and $\delta_{x,k} = 0$, otherwise. Hence, Eqn. (4) becomes

$$\hat{\epsilon}_k^* = \sum_{x \in AS(k)} \frac{\hat{S}_k \hat{d}_{x,k} / R_k}{\hat{N}_0 + \hat{I}'_{x,k} + \sum_{y \neq x} \delta_{y,k} \hat{S}_k \hat{d}_{y,k} / W}. \quad (6)$$

After some transformations the equation yields a polynomial of \hat{S}_k from a degree corresponding to the AS size. The minimum positive value of the roots of this polynomial delivers the desired transmit power \hat{S}_k . By a repeated application of Eqn. (6) and Eqn. (5) we receive transmit powers \hat{S}_k such that the target E_b/N_0 is matched for all MSs.

B. Site Selection Diversity

With SSDT each MS k selects the BS y_k with least signal attenuation for transmission and without fading effects the assignment remains unchanged. Thus, Eqn. (4) becomes

$$\hat{\epsilon}_k^* = \hat{S}_{y_k,k} \hat{d}_{y_k,k} / (R_k (\hat{N}_0 + \hat{I}_{y_k,k})), \quad (7)$$

with $\hat{d}_{y_k,k} = \max_{x \in AS(k)} \hat{d}_{x,k}$. Solving the equation for $\hat{S}_{y_k,k}$ yields

$$\hat{S}_{y_k,k} = \hat{\epsilon}_k^* R_k (\hat{N}_0 + \hat{I}_{y_k,k}) / \hat{d}_{y_k,k} \quad (8)$$

and the repeated computation of Eqn. (8) and Eqn. (3) results in the desired transmit powers $\hat{S}_{y_k,k}$ after convergence.

C. Alternative Soft Handover Mechanisms

The two proposals of the 3gpp standard for the power control in soft handover mode are two extreme cases. In the basic method all BSs in the AS transmit with equal power regardless of their signal attenuation to the MS and with SSDT only the best BS transmits regardless of how much it actually outperforms the next best BS. We propose the following intermediate

ways to allocate power or target- E_b/N_0 values to the BSs in the AS of a MS k :

1. Each BS x transmits with a proportion q_x of the total power \hat{S}_k^{tot} devoted to MS k
2. Each BS x has to maintain a proportion q_x of the total target- E_b/N_0 $\hat{\epsilon}_k^*$ of MS k .

In the following we describe in general how the transmit powers of a system in convergence are determined. In Sec. IV we show results for several possibilities to allocate the power and the target- E_b/N_0 proportions to the BSs, respectively.

C.1 Proportional Allocation of Transmit Power

The computation of the required total power \hat{S}_k^{tot} dedicated to MS k is similar to the computation of the basic method. Assume that $q_{x,k} \hat{S}_k^{tot}$ is the share of power for MS k allocated to BS x . Then Eqn. (6) becomes

$$\hat{\epsilon}_k^* = \sum_{x \in AS(k)} \frac{q_{x,k} \hat{S}_k^{tot} \hat{d}_{x,k} / R_k}{\hat{N}_0 + \hat{I}'_{x,k} + \sum_{y \neq x} q_{y,k} \hat{S}_k^{tot} \hat{d}_{y,k} / W}. \quad (9)$$

Note that $q_{x,k} = 0$ if $x \notin AS(k)$ and $\sum_x q_{x,k} = 1$. Again, after some transformations we obtain a polynomial of \hat{S}_k^{tot} and the smallest positive root delivers the total power. After repeated computations of the total powers \hat{S}_k^{tot} and the resulting interferences $\hat{I}'_{x,k}$ the system converges.

C.2 Proportional Allocation of Target- E_b/N_0 Values

The other possibility to distribute the power among the BSs in the AS is to assign each BS a certain target- E_b/N_0 and to control them individually. Then, we receive the following power control equations for all MSs k and BSs x contained in the AS of k :

$$q_{x,k} \hat{\epsilon}_k^* = \hat{S}_{x,k} \hat{d}_{x,k} / (R_k (\hat{N}_0 + \hat{I}_{x,k})), \quad (10)$$

As in the case of SSDT the equation can be easily solved for $\hat{S}_{x,k}$ and a repeated computation of transmit powers and interference densities leads to a converged system.

IV. NUMERICAL RESULTS

In this section we compare the different soft handover mechanisms with respect to the required BS transmit power. The considered UMTS network consists of 39 BS which are arranged in a hexagonal layout. A snapshot of MSs is generated according to a homogeneous spatial Poisson process and a series of such snapshots yields mean values with 90% confidence intervals or CDFs. Each MS takes one of the following services with probability p_t for service t :

Service	p_t	R_t	ϵ_t^*
Voice	0.5	12.2 kbps	5.5 dB
Medium Speed Data	0.3	64 kbps	4 dB
High Speed Data	0.2	144 kbps	3.5 dB

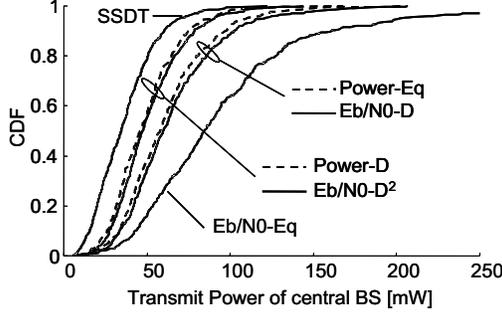


Fig. 2. CDF of BS transmit power

The soft handover mechanisms in comparison comprise SSDT, the basic method (Power-Eq) with equal transmit powers for all BSs in the AS, and the following additional methods:

Power-D: Power allocation with

$$q_{x,k} = \hat{d}_{x,k} / (\sum_{x \in AS(k)} \hat{d}_{x,k})$$

Eb/N0-D: target- E_b/N_0 allocation with

$$q_{x,k} = \hat{d}_{x,k} / (\sum_{x \in AS(k)} \hat{d}_{x,k})$$

Eb/N0-D²: target- E_b/N_0 allocation with

$$q_{x,k} = \hat{d}_{x,k}^2 / (\sum_{x \in AS(k)} \hat{d}_{x,k}^2)$$

Eb/N0-Eq: equal target- E_b/N_0 for all BSs in the AS

In the first scenario the traffic intensity is 14 MS per BS, the orthogonality factor is 0.4, the reporting range is 6dB, the BS distance in the hexagonal layout is 2km and the signal attenuation is calculated by $d_{x,k} = -128.1 - 37.6 \log_{10}(dist_{x,k})$ according to the pathloss model in [18] where $dist_{x,k}$ is the distance from BS x to MS k in km. If not stated otherwise this parameter set is also valid for the other results presented here.

Fig. 2 shows the CDF of the transmit power of the central BS in the converged system. Note, that we take statistics only for the central BS to avoid border effects with too little othercell interference. We can see that SSDT requires conspicuously less power than the basic method. In particular, the 90%-quantile of SSDT is about 60mW whereas the 90%-quantile of Power-Eq is nearly double with about 97mW. EbN0-Eq yields the by far worst results. Eb/N0-D showed results similar to the method with equal powers. Of course, this makes sense since with an equal power \hat{S}_k and assuming an equal interference \hat{I}_k for all BS in the AS of MS k , we obtain the following target- E_b/N_0 proportion for BS x

$$q_{x,k} = \frac{\hat{e}_{x,k}}{\hat{e}_k} = \frac{\frac{\hat{S}_k \hat{d}_{x,k}}{(R_k(N_0 + \hat{I}_k))}}{\sum_{x \in AS(k)} \frac{S_k \hat{d}_{x,k}}{(R_k(N_0 + \hat{I}_k))}} = \frac{\hat{d}_{x,k}}{\sum_{x \in AS(k)} \hat{d}_{x,k}} \quad (11)$$

and that are the proportions used for Eb/N0-D. The difference between the two methods results from the different interferences $\hat{I}_{x,k}$. Analogously, the results for Power-D and Eb/N0-D² are similar, as well. The required transmit powers for these methods are between SSDT and the basic method Power-Eq.

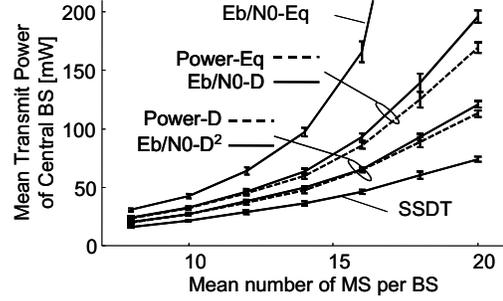


Fig. 3. Influence of the traffic density

This makes sense, as well, since the equal power distribution is shifted somewhat in direction of SSDT. More power and higher target- E_b/N_0 values are allocated to the BSs with stronger signals, i.e. larger \hat{d} . In the following, the influence of various system parameters on the mean of the transmit power required by the BS of the central cell is investigated. Fig. 3 shows the required transmit power versus the traffic intensity which is given as the mean number of users generated per BS. Both the transmit power and the difference between SSDT and Power-Eq increase exponentially with the number of users. While for a load of 14 MS per BS Power-Eq needs 1.6 times more power than SSDT, the factor grows up to 2.2 with 20 MS per BS. The curves for Power-D and Eb/N0-D² are located in between and the gap to SSDT is growing slower than for Power-Eq. A similar effect can be seen in Fig. 4 where we consider orthogonality factors from 0 to 0.6. The observation results from the fact that less orthogonality means more load in the system.

One of the most important parameters in the investigation of soft handover is the reporting range as it determines the size of the ASs. Fig. 5 compares the different soft handover mechanism for reporting ranges from 0dB to 8dB. Obviously, a reporting range of 0 leads to an AS size of 1 such that no soft handover occurs and the transmit powers are independent of the adopted soft handover variant. Further, with SSDT the reporting range has no influence on the transmit power. All other methods require more power for larger reporting ranges. However, the curves of Power-D and Eb/N0-D² flatten with higher reporting ranges whereas Power-Eq and Eb/N0-D still increase. The additional power with regard to SSDT grows exponentially.

The previous scenarios considered a homogeneous traffic distribution with equal load for all 39 BS. In the following example, the MS are generated with different traffic densities at the BS. The load of the BSs is an i.i.d. r.v. that follows a Normal distribution with mean μ and std. dev. σ that is truncated at 0 and 2μ . Fig. 6 shows the 95%-quantile of the required transmit power for $\mu = 15$ and the values of σ on the x-axis. We can see that with increasing σ , i.e. with greater differences in the load of the BSs, the 95%-quantiles increase. More important, however, the required power with Power-Eq grows much

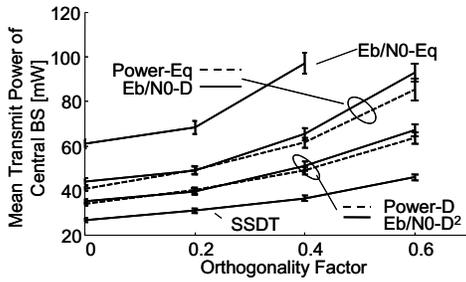


Fig. 4. Influence of orthogonality factor

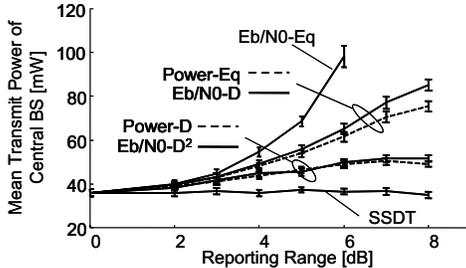


Fig. 5. Influence of reporting range

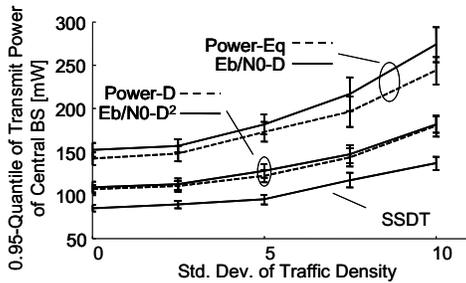


Fig. 6. Influence of differing traffic densities

faster than with Power-D and that again grows faster than with SSDT. Thus, we can conclude that in contrast to the uplink, see e.g. [14], the highly loaded BSs are not relieved by less loaded BSs through soft handover. On the contrary, with Power-Eq different cell loads lead to even higher transmit powers.

V. CONCLUSION

In this paper we proposed a method to compute transmit powers in a UMTS network assuming perfect power control. This method is valid for both soft handover mechanisms proposed in the 3gpp standard, the basic method with equal transmit powers of all BSs in the AS of a MS and SSDT whereby only one transmitting BS is selected. Furthermore, other methods for power control in soft handover mode are presented which subdivide the power or the target- E_b/N_0 value among the BS in the AS, respectively. The different soft handover variants are compared with respect to the required transmit

powers and the influence of various system parameters is investigated. The results for SSDT prove to be the best in the sense that the system needs the least power. Furthermore, the power additionally required for the basic power control mechanism in soft handover mode increases exponentially both with system load and with a less uniform traffic distributions. The methods with non equal power and E_b/N_0 -allocations constitute an intermediate way between the proposals in the standard. This paper studies the effect of soft handover on the downlink transmit power, only. The other important aspect of soft handover, however, the influence on the robustness against fading effects has to be investigated in another paper and finally the pros and cons have to be weighed up.

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