Diversity Effects on the Soft Handover Gain in UMTS networks

Klaus Heck, Dirk Staehle, and Kenji Leibnitz
University of Würzburg, Am Hubland, 97074 Würzburg, Germany
E-mail: {heck,staehle,leibnitz}@informatik.uni-wuerzburg.de

***Abstract*—In cellular Wideband Code Division Multiple Access (WCDMA) networks, interference on the uplink is the limiting factor for the number of users that can be served in a single cell. Thus, interference reduction mechanisms are of significant importance. Soft handover, which is primarily a mechanism for seamless handovers (make before break), also reduces the interference within the cells by exploiting multiple simultaneous connections to lower the transmit power of the mobile stations (see [1], [2]). In this article we present an analytical model for soft handover where multiple connections between a mobile station and the base stations within reach are taken into account. An approximation of the frame error rate based on the received signal strength in the uplink is provided for 12.2 kbps service. In addition the approach taken to calculate the soft handover gain is described and results are presented.**

***Index Terms*— UMTS, soft handover gain, site/selection diversity**

I. Introduction

In future Universal Mobile Telecommunication System (UMTS) networks Wideband Code Division Multiple Access (WCDMA) will be used as the air interface [3]. By utilizing the same frequency band for all transmissions the total amount of interference becomes the main restricting factor in UMTS environments. Therefore, one of the most important objectives in the planning of 3rd generation mobile networks is the reduction of the mobiles' transmission powers.

Power control mechanisms are used to achieve this goal. Inner Loop power control is used to keep the received signal strength at a given Signal-to-Interference ratio (target SIR value). Power control commands are sent from each base station (BS) to all the mobile stations (MS) within reach, while each MS reduces its transmission power until no "power down" command is received. This simple mechanism will guarantee that the BS with the least requirement on signal strength determines the MS's transmission power, which is not necessarily the nearest.

On the other hand, Outer Loop power control is used to keep the quality of a link at the target Frame Error Rate (FER). Data packets received at a BS are forwarded to the Radio Network Controller (RNC) which measures the actual FER of the connection and compares it to the target FER. In order to keep the quality at a specific level, the RNC updates the target SIR value of a MS in the base stations. Increasing this value results in a lower FER, whereas decreasing it leads to a higher FER. Outer Loop power control, therefore, helps to keep the interference caused by a single MS at the lowest possible level.

In addition, the WCDMA air interface allows for further improvement in interference reduction. Due to the fact that a MS shares the frequency band with all others, its signal can be received by a number of BSs in close proximity. Thus, data packets of a MS are received at different sites (*site diversity*) and the multiple packets can be combined in the RNC to recover the original data with fewer bit errors. The mechanism of choice in UMTS is *selection diversity*, where the packet with the least errors is chosen while duplicates are dropped. The combination of site and selection diversity is often referred to as macrodiversity.

The main goal of this article is to show the gain in terms of interference reduction by site/selection diversity. In [4] a model was presented that showed the gain when utilizing Inner Loop power control compared to the scenario where each MS is only connected to the closest BS. This gain, however, is only one part of the Soft Handover Gain. In this article, we extend the model to incorporate multiple uplink connections from one MS to a number of BSs. Assuming perfect Inner Loop power control, the additional gain in interference reduction achieved by site/selection diversity and Outer Loop power control can be calculated.

In Section II the basic model will be introduced and the extensions we made will be explained. In order to perform Outer Loop power control, the FER values of uplink packets need to be estimated. The approach used in our extended model will be described in Section III. Results will be shown in Section IV. Conclusions and an outlook are given in Section V.

II. Model Description

In the following we will explain the models used for the calculation of the soft handover gain caused by site/selection diversity. The basic model is taken as the reference to evaluate the improvement in interference reduction when multiple connections are incorporated in our extended model.

A. Basic Model

The basic model was taken from [4], which uses a set of formulas to iteratively calculate specific characteristics of a given UMTS scenario. The interference level at a single BS l can be computed by

$$\hat{I}_l = \frac{1}{W} \sum_k \hat{S}_k \hat{d}_{k,l} \nu_k, \tag{1}$$

where $\hat{S}_k$ and ν_k denote the transmission power and activity factor of MS k, respectively, $\hat{d}_{k,l}$ stands for the path loss of MS

k to BS l, and W marks the system bandwidth in Hertz. Here, for any variable X expressed in decibels (dB), $\hat{X}$ denotes $10^{\frac{X}{10}}$. The power control equations (see e.g. [5])

$$\hat{\epsilon}_k^* = \frac{\frac{\hat{S}_k \hat{d}_{k,l}}{R_k}}{\hat{N}_0 + \hat{I}_l - \frac{\hat{S}_k \hat{d}_{k,l} \nu_i}{W}} \quad (2)$$

define a way to calculate the effective E_b/N_0 $\hat{\epsilon}_k^*$ for each MS k. Here R_k denotes the bit rate of MS k and $\hat{N}_0$ specifies the background noise power spectral density. Solving Eq. (2) for $\hat{S}_k$ yields

$$\hat{S}_k = \frac{W}{\hat{d}_{k,l}} (\hat{N}_0 + \hat{I}_l) \frac{\beta_k}{W + \beta_k \nu_k} \quad (3)$$

with $\beta_k = \hat{\epsilon}_k^* R_k$, an abbreviation for the product of bit rate and target E_b/N_0 of MS k.

Given a hexagonal cell layout with 39 base stations, the authors of [4] randomly create a number of MSs using a spatial homogeneous Poisson process where the given user density λ specifies the mean number of users per square kilometer. Then, Eq. (3) is used to calculate the initial transmission power $\hat{S}_k$ for each MS k. The parameter l states the assignment of a MS k to its controlling BS l. Initially, l is set to the BS that is closest for each MS. Solving Eq. (2) with the transmission powers $\hat{S}_k$ that were just derived allows for the calculation of the actual E_b/N_0 values of MS k at all BS. The case, that for a given MS k the maximum E_b/N_0 value is found for a BS other than the controlling one, indicates that the current assignment of MS k to BS l is not optimal due to the interference distribution in the UMTS environment. Changing the assignments and iteratively recalculating the transmission powers and E_b/N_0 values for all MSs yields the gain by Inner Loop power control in terms of interference reduction.

Each step of this iterative algorithm leads to a reduction in the overall interference level. Thus, the algorithm will ultimately converge to the minimum in transmission powers.

The gain, then, can be calculated by

$$\hat{I}_{gain} = \sum_l (\hat{I}_l^{final} - \hat{I}_l^{initial}), \quad (4)$$

where $\hat{I}_l^{initial}$ defines the interference at BS l after the first iteration and $\hat{I}_l^{final}$ specifies the interference after the last iteration. In fact, this measure is used as the criterion to decide if the convergence already reached a sufficient level of accuracy.

In this model, user movement is not taken into account, but each analyzed scenario can be seen as a snap-shot of a UMTS network. Mobile stations are not restricted in transmit power in order to separate the effects of site/selection diversity and to exclude other factors that might influence the interference.

B. Extended Model

In order to take Outer Loop power control and site/selection diversity into consideration, this basic model needs to be extended. While in the basic model only single connections are used, the extended model must account for all connections.

In UMTS each BS sends a 30 dBm pilot signal. Each MS checks for received pilot signals and measures their strengths. All the BSs received with a minimum pilot signal strength of no less than the reporting range (6 dBm) below the strongest received pilot signal are suitable to establish simultaneous connections and are, therefore, combined to the Active Set (AS) of the MS. Since the Active Sets are independent of the interference in the UMTS environment, assignments are no longer necessary.

As for the basic model, the algorithm starts by using Eq. (3) and a predefined target E_b/N_0 value depending on the bit rate of a MS. These calculated transmission powers can, again, be used in Eq. (2) to derive the actual E_b/N_0 values for all BSs in the Active Set of a MS.

All BSs in the Active Set of a MS receive the data packets (site diversity) and forward them to the RNC, which chooses the packet with the least errors (selection diversity using selection combining) as depicted in Figure 1. Depending on the E_b/N_0 value of each single connection, the bit error probability on the air interface differs. The estimation of the bit error probability and the approximation of the frame error probability are described in Section III.

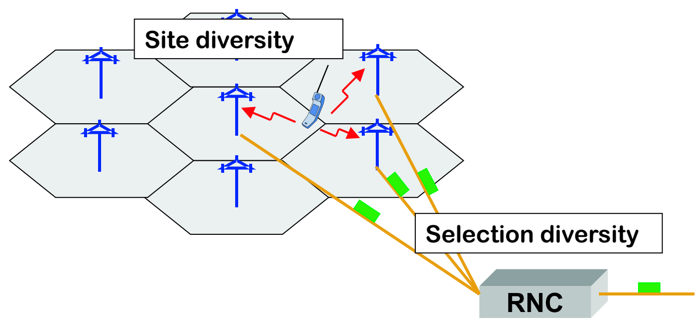

Fig. 1. Site and selection diversity

Assuming independent FER for the different connections of a single MS, the overall FER of MS k can be derived by

$$FER_k = \prod_{k \in AS_k} (FER^{(k,l)}). \quad (5)$$

The difference of this approach to the basic model is that there the FER of a MS k is implicitly calculated by

$$FER_k = \min_{k \in AS_k} (FER^{(k,l)}). \quad (6)$$

Here, AS_k denotes the Active Set of MS k and $FER^{(k,l)}$ is the frame error rate of MS k at BS l.

Now, the RNC compares the value FER_k to the target FER for each MS and adapts the target E_b/N_0 value for the MS in order to adapt the actual FER. Increasing the target E_b/N_0 results in a lower FER_k while decreasing the target E_b/N_0 yields a higher FER_k. The standard states that the step size for the adaptation is ± 1 dB (see [3]). However, a different adaptation of the target E_b/N_0 is used in this article, since we are interested in the theoretical maximum of the gain introduced by site/selection diversity. Therefore, the step size is not constant, but is chosen proportionally to the difference between the actual and the target FER such that iterative convergence is reached.

After these adjustments, the next iteration can be started by recalculating Eq. (3). The extension of the basic model still leads to a reduction of the overall interference in the UMTS environment and, thus, will finally converge to some minimum. Comparing the results of the basic and the extended model indicates the gain by site/selection diversity and Outer Loop power control.

The assumption made about the independent FER values on the different connections of a single MS is not valid in practice. Therefore, this approach is a best-case consideration and yields the maximum gain reachable with site/selection diversity.

III. BER AND FER APPROXIMATION

In this article only voice traffic is considered where the data rate is 12.2 kbps and the initial target E_b/N_0 is 5.5 dB.

The proposed modulation schemes for UMTS are BPSK and QPSK. For both the bit error probability can be estimated by

$$p_b = Q(\sqrt{2\hat{\epsilon}_{k,l}}), \qquad (7)$$

where the error function Q is given by

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{\frac{x^2}{2}} dx \qquad (8)$$

and the term $\hat{\epsilon}_{k,l}$ denotes the actual bit energy E_b/N_0 of MS k at BS l.

The channel coding scheme defines two interleaving mechanisms, that allow to neglect burst errors (see [6], [7]). Instead bit errors can be assumed to be independent which allows for an easy analysis. This bit error probability is, however, referring to the bits on the physical channel and not to bits within the packets that the FER is related to. In order to find an approximation of the FER based on the bit error probability on the air interface a simulation was implemented.

From the standardized channel coding and multiplexing mechanisms it can be derived, that for 12.2 kbps data (AMR speech) the following parameters are important for the approximation of the FER from a given BER. The data is split up in 3 separate transport blocks as described in [8]. The first transport block has a length of 81 information bits and is the only one provided with a cyclic redundancy check of 12 bits. Therefore, a bit error can only be detected for this block while bit errors in the other two transport blocks cannot be discovered.

In the FER simulation, a random data packet with length 93 bits was created and encoded using a convolutional code with a coding rate of 1/3. After encoding the packet, the above calculated BER is used to independently disrupt the bits. A soft-decision Viterbi decoder was used to decode the packet afterwards. By comparing the original data packet to the "transmitted" data packet, remaining bit errors could be found. By repeating this simulation for a given BER, the FER can be derived. This simulation was performed for a number of BER values and the results are shown as black dots in Figure 2.

In order to approximate the FER for intermediate, not simulated values of BER the function

$$f(x) = \frac{tanh(32x-5)}{2} + \frac{tanh(5)}{2} \qquad (9)$$

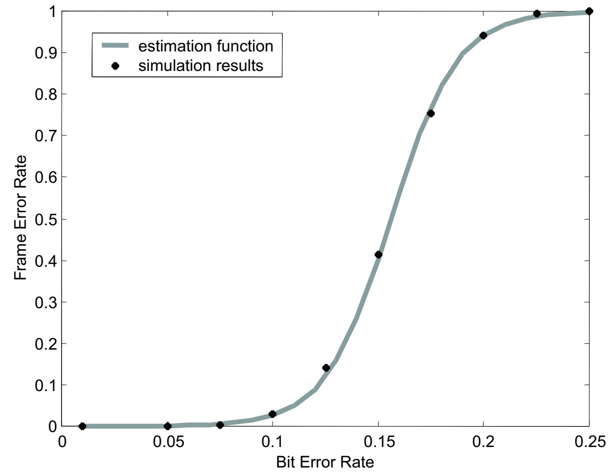

Fig. 2. FER approximation function

was chosen as indicated by the grey curve in Figure 2. The figure allows the conclusion that the approximation is appropriate since the dots and the curve almost always coincide.

IV. RESULTS

The analyzes were performed on the scenario depicted in Figure 3. An area consisting of 39 cells with hexagonal cell layout was considered. Within this area 12.2 kbps voice users were randomly created based on a parameter λ defining the average number of users per square kilometer and using a spatial homogeneous Poisson process. The distance between neighboring base stations was set to 2 km.

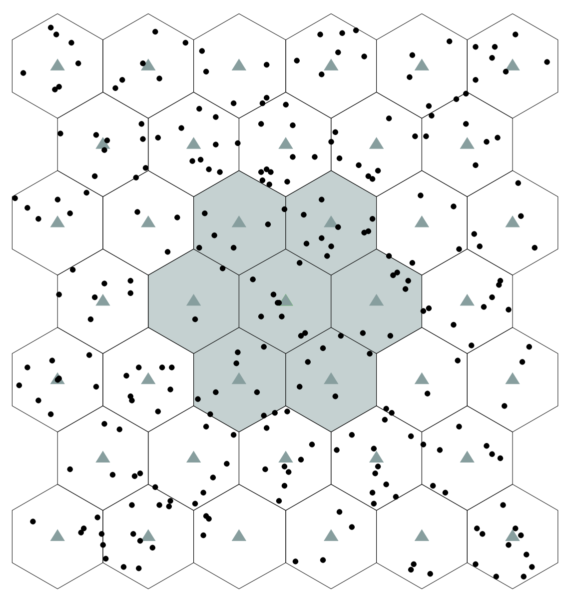

Fig. 3. Scenario under study

In order to evaluate the impact of the user density on the soft handover gain, calculations were performed for values of λ ranging from 1 to 16, which corresponds to a range of 3 to 55 voice users per cell or 135 to more than 2000 voice users in the whole scenario.

For each analyzed scenario, the gain resulting from site/selection diversity was calculated by different measures, such as the reduction of interference within a cell, and the reduction of the transmit power of a single mobile. Since multiple connections for each MS are taken into consideration, the results can be further distinguished by the size of the ASs which in our simulations range from 1 to 3.

In WCDMA systems, the interference produced in one cell (in-cell interference) influences the interference perceived by neighboring cells (other-cell interference). To account for this, only those cells in the analyzed scenario which experience other-cell interference (highlighted in grey) are taken into account for the calculation of the results.

For each value of λ several scenarios were considered and the calculated results were used to derive the mean values and the 90% confidence intervals which help to evaluate the results.

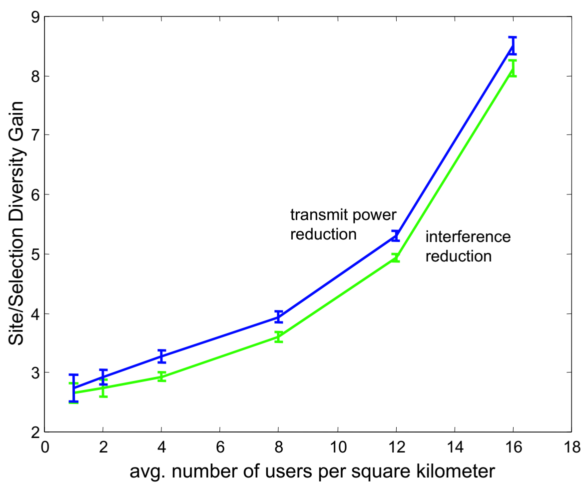

Fig. 4. Site/selection diversity gain measures

Figure 4 shows the mean site/selection diversity gain by means of interference and transmit power reduction. In terms of interference reduction the site/selection diversity gain increases with higher user densities and ranges from 2.5 dB for $\lambda = 1$ up to 8 dB for 16 users per square kilometer in the inner seven cells.

The mean transmit power required by the users within those inner cells shows a similar behavior as it decreases with higher user densities and the transmit power reduction generally can be found to be approximately 0.5 dB higher than the interference reduction.

The position of a MS within the given area determines the Active Set (AS) as described in Section II. The size of the AS ranges from 1 to 3 in our simulations which will have great impact on the individual site/selection diversity gain a single MS experiences. Therefore, Figure 5 separately displays the mean reduction of transmit power for the groups of MSs with AS sizes 1, 2, and 3. The different curves show a similar behavior. However, the number of simultaneous connections determines an additive factor and thus the gain for MSs with AS

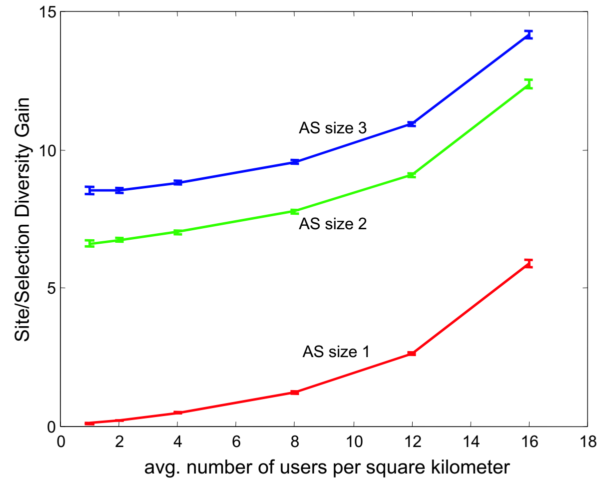

Fig. 5. Transmit power reduction depending on AS size

size 2 is about 6.5 dB above the gain for MSs with only single connections. A MS with AS size 3 even yields a benefit of about 8.5 dB compared to single connections.

Considering the fact that the reduction of transmit power might well exceed 5 dB for just single connections underlines the great importance of site/selection diversity gain. The maximum gain, as indicated in Figure 5 can be found for MSs with AS size 3 with a mean of around 14 dB.

However, the results are based on the assumption that the FERs on the multiple connections are identical and independently distributed (iid) which does not hold in practice. Therefore, Eq. (5) is definitely an optimistic approach and the gain perceived in practice will be slightly below the results found in our analysis.

V. Conclusion and Outlook

We derived a method to calculate the soft handover gain achieved by site and selection diversity within WCDMA systems. In order to approximate the FER for the multiple connections of a single MS an estimation method was presented for 12.2 kbps voice users using convolutional codes.

The results show that site/selection diversity offers a great potential in the context of soft handover and helps to clearly increase the capacity of UMTS networks. An overall interference reduction ranging from 2.5 to 8 dB within a single cell could be found. However, the gain in terms of transmit power reduction for single mobiles was shown to greatly depend on the number of BSs a MS is simultaneously connected to. We proved that the gain in terms of transmit power reduction for mobiles with single connections might well exceed 5 dB and can reach a level of around 14 dB for mobiles with 3 simultaneous connections.

The proposed method relies on an approximation method to derive the FER from a given BER. To do so, the channel coding schemes have to be analyzed. In this paper, an estimation function was derived for convolutional codes, which are utilized for 12.2 kbps voice traffic. This estimation function allows to enhance the analysis methods found in the literature. Starting from a given received signal strength E_b/N_0 the BER can be derived by some well-known error function. Given the BER, we can now calculate the true FER perceived by the system and model the real behavior of the power control mechanisms which are based on a comparison of the target FER to the actual FER.

This paper definitely underlines the great impact of site/selection diversity on the planning of 3rd generation mobile networks. Further studies need to be performed to research the impact of site/selection diversity gain on other data rates, such as 64, 128, 144, and 384 kbps packet data. In order to analyze these types of traffic an estimation function for Turbo codes has to be derived.

As shown in [9], soft handover gain even increases if an uneven user distribution is chosen. Further studies will evaluate such cases on the site/selection diversity, as well.

REFERENCES

[1] A. Sendonaris and V. Veeravalli, "The capacity-coverage tradeoff in CDMA systems with soft handoff," in *Proc. Asilomar Conf. Sig. Sys. Comput.*, (Pacific Grove, CA), November 1997.

[2] P. S. Kumar, S. Nanda, and K. M. Rege, "Characterization of capacity gain due to macro-diversity in CDMA systems," in *Proc. of the 15th International Teletraffic Congress*, (Washington, DC), pp. 1149–1158, June 1997.

[3] H. Holma and A. Toskala, *WCDMA for UMTS*. John Wiley & Sons, Ltd., June 2000.

[4] D. Staehle, K. Leibnitz, K. Heck, B. Schröder, A. Weller, and P. Tran-Gia, "Analytical Characterization of the Soft Handover Gain in UMTS," in *Proc. of VTC'01 Fall*, (Atlantic City, NJ), Oct. 2001.

[5] V. V. Veeravalli and A. Sendonaris, "The coverage-capacity tradeoff in cellular CDMA systems," *IEEE Transactions on Vehicular Technology*, vol. 48, pp. 1443–1450, september 1999.

[6] V. K. Bhargava and I. J. Fair, *The Communications Handbook*, ch. Forward Error Correction Coding, pp. 166–180. CRC Press, Inc., 1997.

[7] S. C. Yang, *CDMA RF System Engineering*. Norwood, MA: Artech House, 1998.

[8] 3GPP, "Channel coding and multiplexing examples," Report TR25.944, 3GPP, TSG RAN WG4, June 2001.

[9] D. Staehle, K. Leibnitz, K. Heck, B. Schröder, A. Weller, and P. Tran-Gia, "Approximating the Othercell Interference Distribution in Inhomogeneous UMTS Networks," in *Proc. of VTC'02 Spring*, (Birmingham, AL), 2002.