Realization and Optimization of Soft and Softer Handover in UMTS Networks

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Abstract — With the use of user dependent spreading codes in Wideband Code Division Multiple Access (W-CDMA) networks and the application of multi-path aware radio receivers a novel type of handover execution becomes possible. The soft and softer handover describes the situation in which a mobile terminal communicates with the radio access networks via two or even more different links. Instead of breaking an existing connection to an old base station and establishing a new connection to one neighbouring base station, soft handover seamlessly adds another radio link as a parallel connection. In this paper, soft handover parameters, regions, and performance issues are discussed. Results are obtained in an analytical manner as well as by means of dynamic simulation, both considering a realistic dense urban scenario area.

I. Introduction

Unlike the strict separation of physical channels in the time and frequency domain, *Code Division Multiple Access* (CDMA) offers the possibility to operate multiple radio links in parallel. Since the users are separated by unique spreading codes, multiple data flows are transmitted simultaneously via the radio air interface. The detection of a single user's signal is realized by despreading with the same code sequence as used in the transmitter. With the receiver ability to process digital code signals in parallel, CDMA networks also allow to transmit different code signals from multiple locations to the same *User Equipment* (UE) as long as synchronization requirements can be met. Vice versa it is possible to receive the same signal at multiple *Base Station* (BS) positions. Oppositely to transmit or receive diversity where multiple antennas are located rather close to each other, this mechanism is also referred to as macro diversity because of the large local separation of the site's antenna positions.

If a UE is in a favorable situation to operate on similar links to more than one BS, it is called to be in *Soft Handover* (SHO) and with it able to benefit from macro diversity. Depending on radio propagation characteristics, synchronization to the BS, and receiver or transmitter abilities, the radio transmission can gain up to more than 3 dB out of an SHO situation. Therefore, the *Signal to Interference Ratio* (SIR) can significantly be increased. This fact is already known from theoretical analysis quite in the beginning of research on CDMA [1]. Moreover, already existing networks with CDMA technology like cdmaOne (IS-95) in the US and some other American and Asian countries benefit from SHO gains [2].

With the introduction of *Universal Mobile Telecommunication System* (UMTS) as a global standard for 3^{rd} generation networks, a steadily growing interest in the functionality and implementation issues of SHO arises. Key drivers are not only research and development departments but also operators, manufacturers, and network suppliers, who have to build up a preferably optimal performing system. Since SHO is a means to reduce interference and improve radio link quality especially at the cell border where radio coverage is worst, the optimal implementation and parameterization of the algorithm will decide on the customer satisfaction, network capacity and their revenues in the end.

In this paper, an introduction to SHO execution in UMTS is given. Sec. II describes the general characteristics of SHO and the roles of UE and the *UMTS Terrestrial Radio Access Network* (UTRAN) as its counterpart. Analytical evaluation of SHO areas and impact on a realistic network is presented in Sec. III. In the same scenario, the SHO performance is evaluated by means of dynamic simulations. Sec. IV contains the simulation results and afterwards, a conclusion is drawn and some advise is given.

II. Characteristics of Soft Handover

UTRAN topology contains several components that get involved into SHO execution. Fig. 1 illustrates the interworking between the UE on the user side and the BS, *Radio Network Controller* (RNC) and *Mobile Services Switching Center* (MSC) on the UTRAN side.

The mobile assisted UMTS SHO differs significantly from the *Hard Handover* (HHO) known from 2^{nd} generation systems. The main difference is the transmission of identical data over more than one radio link. In *soft* handover, the UE has radio links to *more than one* BS site (situation Ⓐ and Ⓑ in Fig. 1). Whereas Ⓐ is handled by one RNC as an intra-RNC SHO, Ⓑ means an inter-RNC SHO with communication over the Iur interface within UTRAN. The latter case assigns different roles to the

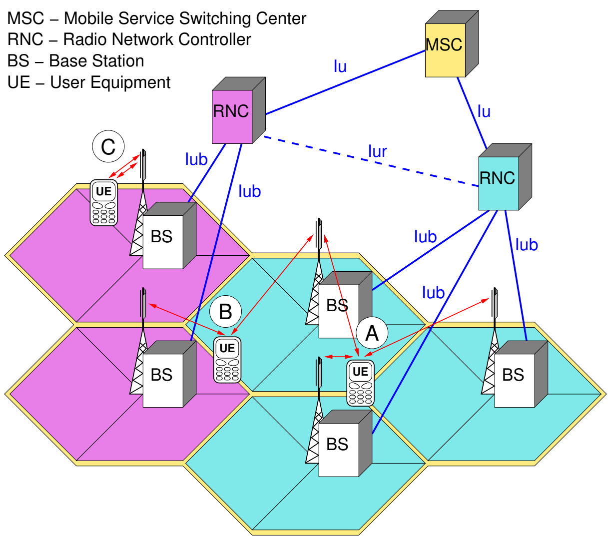

Figure 1: UTRAN topology and elements

RNCs involved. One acts as a *Serving RNC* (SRNC) and provides the reference Iu interface to the core network and data flow combining and splitting. The other will act as *Drift RNC* (DRNC) which manages the additional link and simply forwards data to or from the SRNC. With this mechanism, all SHO execution is transparent to the core network and no MSC takes active part in it.

The so-called *softer* handover (situation Ⓒ) means having radio links to *some* sectors of *one* BS. The UE can be in soft and softer handover at the same time, but may not have more than a restricted total number of links simultaneously. All active links are stored in the active set. The probability for softer handover is said to be 5–15% and 20–40% for soft handover [3]. The advantages that should arise from this technique are achieved in different ways for uplink and downlink.

A. Uplink

In *Uplink* (UL) direction the UE utilizes its unique physical channels, i.e. a certain combination of channelization (or spreading) codes in combination with a unique scrambling sequence. This signal can be received by more than one BS if the BS is aware of the connection parameters, i.e. the codes the UE uses. When entering the SHO, these user specific information and other parameters are signaled to the new BS.

Receiving the signal at the same BS from different sectors can be compared to multi-path reception and thus the signal can be combined by means of Rake processing [2]. Hence, in *softer* handover state the reception uses all the signal components only restricted to the limited number of fingers and time resolution of the Rake processing.

In *soft* handover the signal is received and processed at different BS. The detected bit sequence is then routed to the current SRNC where selection combining of the received data packets from all involved BS is applied.

Because of the multi-path similar reception, the connection should be much more reliable and resistant regarding short and long term fading. Since the signal is received by more than one BS and combined afterwards, the transmission power of the UE can be reduced. Hence, interference decreases. An analytical investigation on this topic can be found in [1].

B. Downlink

In *Downlink* (DL) direction each entry in the active set represents one individual link from a BS to the UE. Data from the UTRAN is duplicated by the SRNC and finally routed to all involved BS. Each BS uses different scrambling codes, so that the UE can distinguish between the signals. Even different channelization codes may be used, because data processing has to be performed on each individual link anyway due to the different scrambling codes used.

The UE combines the physical channels by means of Rake processing, similar to that in multi-path reception, except that the appropriate codes for each Rake finger, respectively for each physical link, have to be generated. The power control commands must be considered separately as they are calculated indepently from each single BS (see below).

On the one hand, the increased number of physical links in DL direction leads to a rise in DL interference. On the other hand, the transmission power of the BS can be lowered because the margins for fast and slow term fading can be lowered due to the macro diversity. This is what is called the macro diversity gain. But if e.g. the *Reporting Range* (RR) (see below) is set too large, the additional interference may be higher than the macro diversity gain and thus there is a loss in capacity.

C. Power Control

In case of SHO multiple radio links are active in DL and thus, the power has to be controlled for each single radio link. Only one TPC command is sent from the UE to the UTRAN (DL TPC command). But it is received by different, spatially separarted BS. The TPC commands are estimated to be either $TPC_{est} = 1$ (increase power) or $TPC_{est} = 0$ (decrease power). Then the current downlink power $P(k-1)$ is adjusted to the new downlink power

$$P(k) = P(k-1) + P_{TPC}(k) + P_{bal}(k)\,, \qquad (1)$$

where

$$P_{TPC}(k) = \begin{cases} +\Delta_{TPC} & \text{if} \quad TPC_{est}(k) = 1 \\ -\Delta_{TPC} & \text{if} \quad TPC_{est}(k) = 0 \end{cases} \qquad (2)$$

and

$$P_{bal}(k) = (1-r)(P_{ref} + P_{P-CPICH} - P(k-1)) \quad (3)$$

with a DL reference power P_{ref}, e.g. the center of the power control range, the power $P_{P-CPICH}$ on the primary *Common Pilot Channel* (CPICH), and the adjustment ratio r set by UTRAN in the range [0. . .1] (a possible value to start with is around 0.9) [4, 5]. With this algorithm the power drifting which occurs in case of a wrong detection of a DL TPC command can be prevented.

Each BS in the active set has a single power control loop with the UE. Hence, the BS control the transmission power of the UE independently from each other, which results in different UL TPC commands for the UE. The UE reacts on these commands by lowering the transmission power as long as at least one BS orders the UE to decrease the power. Unreliable power control commands may be discarded by the UE.

D. Handover Algorithm

In addition to the active set a monitoring set exists in the UE. The monitoring set can hold up to 32 intra frequency cells, including the cells in the active set. These cells are periodically checked against the so called “triggering conditions”. If a triggering condition is fulfilled, the UE creates a report which is sent to the UTRAN. This means, that the evaluation which cell can be added to the active set or dropped from the active set entirely takes place in the UE. This type of handover is called mobile assisted handover. Note, that the report is evaluated by the UTRAN without regarding any measurements. The report contains a measurement identity and the cell concerned. Since the measurement identity is set in the measurement control message, it can be used to figure out which condition triggered the measurement report. An appropriate action is then chosen by the UTRAN. Possible actions are radio link addition, radio link removal and radio link replacement, which is a combined radio link addition and removal. *Call Admission Control* (CAC) in the responsible RNC—as last instance—may deny the addition of a radio link for overload protection or insufficient free resources.

Every action has its own triggering condition. The parameters for the triggering condition are RR R, hysteresis H and a *Time to Trigger* (TtT). These parameters are signaled to the UE at the beginning of a connection and can be updated during the connection, e.g. to adapt to the propagation and traffic environment. The measurements are a cyclic event, executed in the physical layer of the UE. The *Radio Resource Control* (RRC) protocol of the UE receives the measurement values and decides if a cell should be added to or removed from the active set. If the cell should be further considered the UE initiates the appropriate message for the UTRAN.

The entering triggering condition for DL link quality measurements M (e.g. CPICH level or E_c/N_0) is

$$\begin{aligned} 10\log\left(M_{new}\right) \quad &\geq \quad W\cdot 10\log\left(\sum\nolimits_{i=1}^{N_A} M_i\right) \\ &\quad + (1-W)\cdot 10\log\left(M_{best}\right) \\ &\quad - (R - H/2) \end{aligned} \tag{4}$$

A respective leaving triggering condition is then

$$\begin{aligned} 10\log\left(M_{new}\right) \quad &< \quad W\cdot 10\log\left(\sum\nolimits_{i=1}^{N_A} M_i\right) \\ &\quad + (1-W)\cdot 10\log\left(M_{best}\right) \\ &\quad - (R + H/2) \end{aligned} \tag{5}$$

The most important parameter is obviously RR, which basically decides when a new link is to be considered for SHO. The hysteresis is added in order to avoid fast changes in the set management. Unlike in HHO, where a timer starts after the handover took place to avoid ping-pong effects, the TtT starts before the actual SHO is executed.

An example for the mode of operation is depicted in Fig. 2. It shows the reception power of the CPICH from two different BS at the UE. Furthermore, RR and the hysteresis are plotted with respect to the current maximum power.

Two conditions have to be fulfilled in order to select cell 2 as a new cell in the active set:

$a)$ CPICH$_2$ must exceed the upper boundary of the hysteresis in order to start the timer and

$b)$ the level of CPICH$_2$ may not drop below the lower boundary of the hysteresis until the TtT has elapsed.

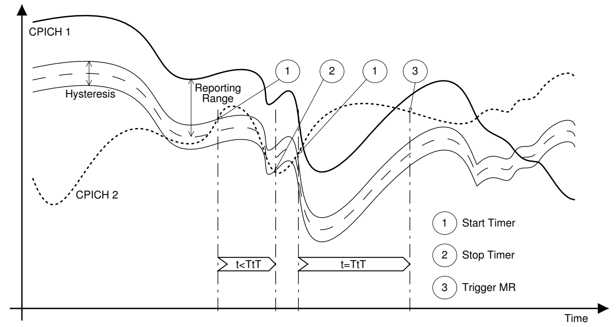

Figure 2: CPICH and resulting handover events

At time instant ① the timer is started because of condition $a)$ being fulfilled. Leaving the hysteresis range at ② causes the timer to be stopped and reset. It gets started again a few moments later. At ③ condition $b)$ is fulfilled and the cell is added to the active set.

III. Analytical Considerations

In a real UMTS scenario the level of the CPICH can be set according to the associated cell size and traffic conditions. High CPICH level may be chosen for large cells and low CPICH level for small cells. The handover algorithm uses the level of the CPICH as input for the decision to add or drop a cell. As the CPICH transmission powers vary, the reception levels vary as well. Therefore, the cell border and the location where a handover is executed are shifted. With a simple scenario the impact of an inhomogeneous CPICH transmission power in the system is evaluated. Since the available power is the limiting factor for the system, the transmission power in SHO and HHO case are compared to one another.

For this scenario, path loss is modeled according to [6] following $L = 128.1+37.6\log d$, where d is the distance in km.

Now, consider two BS with a distance of 1000 m in between. A single mobile travels from BS 1 to BS 2 along the shortest way at 36 kmph. Fig. 3 shows the transmission powers of the BS in the range from 300 m to 700 m. The dashed curve in the upper part represents the summed total power from BS 1 and BS 2 in case of SHO. The solid line is plotted for the power in HHO case. In the lower part of the picture the reception level of the two CPICH at the UE, triggering the handover execution, are shown. SHO will be initiated with RR of 7 dB for adding and 5 dB for dropping each with 2 dB hysteresis [7]. The TtT runs for 4 s [8]. HHO is performed with 6 dB margin. Thus, the time instant when HHO is triggered is the same as when the soft drop timer is started.

Three different constellations have been chosen for the CPICH transmission power. In the leftmost plot CPICH$_2$ is 3 dB above CPICH$_1$. Thus the reception level of the CPICH do not equal at 500 m as they do in the center plot, but they equal at 450 m. In the rightmost plot CPICH$_1$ is 3 dB above CPICH$_2$.

An integration of the transmission power leads to the energy used for this “connection”. In the first case, it can clearly be seen that the SHO uses more energy than the HHO. For this ideal case HHO utilizes 0.44 dB less power. In the other cases, SHO outperforms HHO. An advantage for SHO of 0.48 dB and 1.34 dB can be estimated for these CPICH constellations, respectively. This benefit seems negligible but extrapolated to a network with up to 60% UE in SHO each connection can be operated with slightly less power. This reduces overall interference and with the feedback from CIR based power control another reduction of transmission power might be achieved.

IV. Simulation Results

The event-driven *Generic Object Oriented Simulation Environment* (GOOSE) is used for simulation purposes. As simulation scenario, a real network deployment in a European metropolitan area is recreated considering

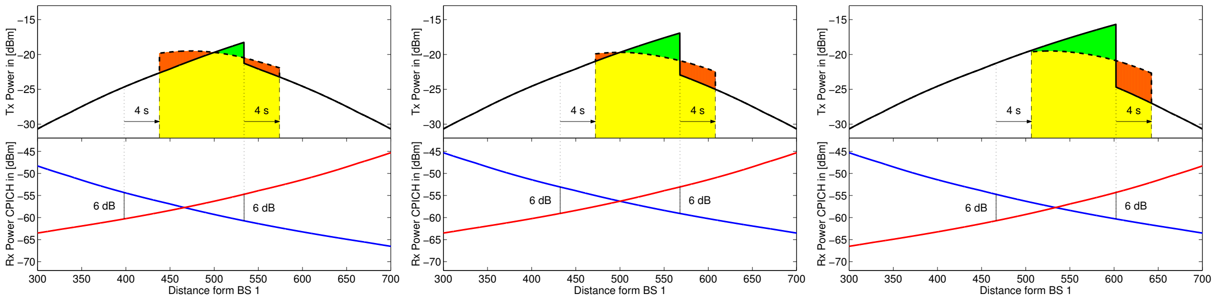

Figure 3: Transmission power in SHO and HHO; $CPICH_2$ 3 dB above $CPICH_1$, equal CPICH powers, and $CPICH_1$ 3 dB above $CPICH_2$

BS positions, propagation characteristics, user's mobility along streets or railways, and the according antenna patterns [9].

Since SHO is rather a topic for circuit switched connections with longer call durations, speech service is used. The C/I_{target} for the C/I based power control is set to -18 dB [10]. The traffic model is a two-state on-off model with a resulting activity of 50% at 12.2 kbps [6]. The traffic is varied between 40 and 80 Erlang per sector.

The expected SHO areas for different RR values are depicted in Fig. 4. Values of 2 dB and 6 dB are considered in the left hand and right hand plot, respectively. As expected, the part of the scenario area potential for SHO increases with RR.

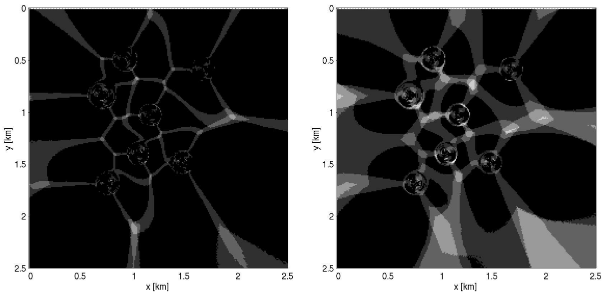

Figure 4: Potential soft handover areas, reporting range 2 dB and 6 dB

SHO requires the utilization of additional radio resources. To estimate the amount of additionally radio resources needed, the mean active set size is evaluated for RR of 2, 4 and 6 dB. Hysteresis is 1 dB and TtT is 3 s.

Independent from the offered traffic, the mean active set size is 1.34, 1.57 and 1.83, respectively. As a result, SHO with 2 dB RR utilizes 34% more resources than an immediate HHO. Hence, lack of resources leads to higher blocking probabilities for increased traffic. Along with the mean active set size the probabilities of the different active set sizes are evaluated. The results are depicted in Tab. 1. The probability to be in soft or softer handover increases with RR. With RR of 2 dB the probability to communicate via more than one radio link is 30%. It increases to 45% for 4 dB and with 6 dB the probability for being in SHO is 61%.

Table 1: Impact of reporting range on probability of active set size

Active Set Size	2 dB	4 dB	6 dB
1	70%	55%	39%
2	25%	33%	38%
3	5%	12%	23%

Fig. 5 illustrates the SHO areas in the network for RR of 4 dB relying on the average active set size. The values vary between one which means no UE in SHO and three which is the maximum active set size. High mean active set sizes far away from the BS, like in the east of the scenario, result from converging reception levels of the different CPICH.

In Fig. 6 and Fig. 7 HHO and SHO are compared with respect to different RR. Tab. 2 lists the corresponding results. The offered traffic is chosen to be 50 Erlang for this comparison. At higher loads the evaluation gets falsified by blocked calls. The blocking arises from insufficient free codes in DL.

Table 2: Reduction of interference for SHO compared to HHO

Direction	2 dB	4 dB	6 dB
UL	2.3 dB	3.7 dB	4.5 dB
DL	-0.3 dB	-0.5 dB	-1.3 dB

In DL interference increases for all RR (negative reduction), whereas in UL the interference decreases for all RR. The higher the RR, the higher is the increase of interference in DL and the higher is the reduction of interference in UL.

Fig. 8 and Fig. 9 show the reduction of interference for UL and DL with respect to the distance between BS and UE if SHO is compared with HHO. Again, for DL the reduction is negative which means higher interference.

In UL two effects can be noticed. SHO is likely to occur at cell borders. Hence, the UE can lower their transmission power there. This is called the diversity gain. It takes effect from around 300 m (Fig. 8). As a con-

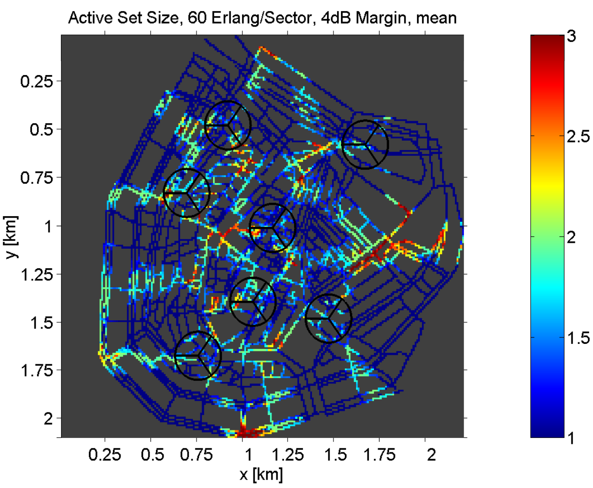

Figure 5: Active set size, 4 dB RR, 60 Erlang

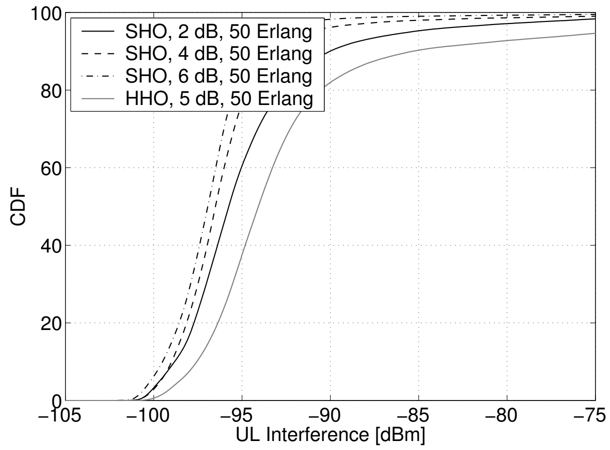

Figure 6: UL interference, 50 Erlang per sector

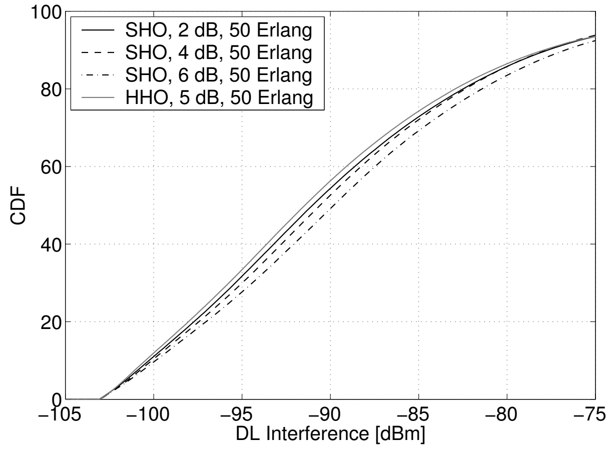

Figure 7: DL interference, 50 Erlang per sector

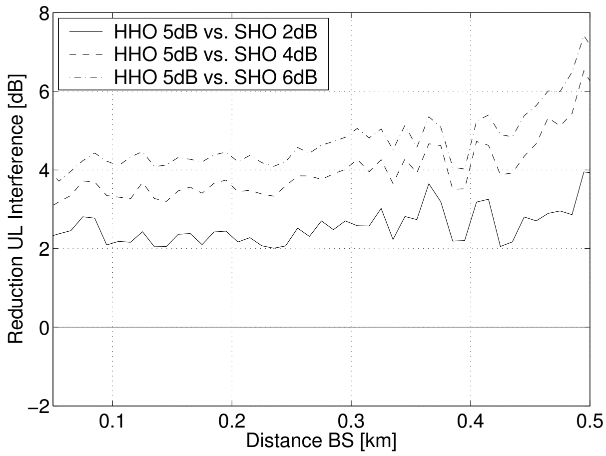

Figure 8: Interference reduction in UL, 50 Erlang per sector

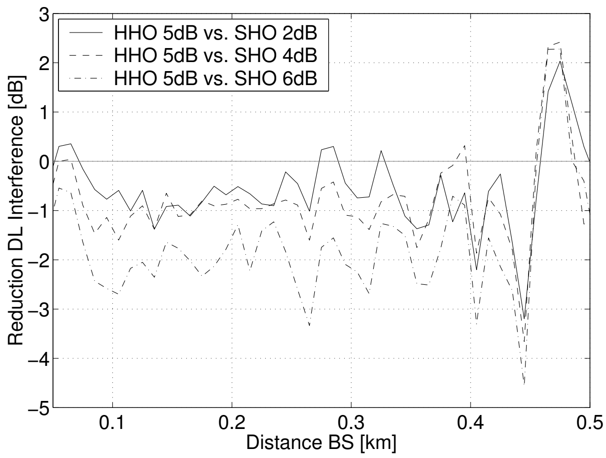

Figure 9: Increased interference in DL, 50 Erlang per sector

sequence thereof, all other UE lower their transmission power and an overall interference reduction is achieved.

V. Conclusion

This paper gives a detailed overview on SHO realization, parameterization and execution in UMTS networks. The important algorithms involved are introduced and described. For a realistic urban environment as currently planned by Vodafone-Netherlands, analysis on SHO probability and a performance evaluation and comparison to HHO execution is given.

The expected SHO gain can only be achieved if parameters are carefully chosen. Mainly UL benefits from SHO. In DL, the network is quickly running out of resources (especially channelization codes) with high RR and high maximum active set sizes. We therefore propose a separate assignment of the SHO algorithm parameters for UL and DL. High RR and high active set sizes should be chosen for UL. In order to counteract the problem of scarce resources in DL, RR and the active set size should be lower than in UL.

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