ANALYSIS OF CDMA DOWNLINK CAPACITY ENHANCEMENTS

Seppo Hämäläinen[1], Harri Holma[1], Antti Toskala[1] and Mika Laukkanen[2]

[1]Nokia Research Center, P.O.Box 407, FIN-00045 Nokia Group, Finland
[2]Nokia Mobile Phones, P.O.Box 50, 90571 Oulu, Finland
email: harri.holma@research.nokia.com, antti.toskala@research.nokia.com,
seppo.hamalainen@research.nokia.com

ABSTRACT

CDMA downlink capacity obtained by system simulator is considered in this paper. Capacity improvements with macro diversity, with reception antenna diversity and with interference reduction techniques are analyzed. A cellular system simulator is utilized in assessing the achievable capacity gains with these techniques. Interference reduction can be achieved with e.g. interference canceling or with appropriate spreading code design. Algorithms for canceling interference are not described in this paper nor are considered antenna hardware requirements but the possible capacity gains are evaluated. Urban macro and micro cell environments are studied. The intra-cell interference cancellation is found important for the macro-cell environment, where as for micro-cell environment macro or antenna diversity means are seen essential.

1. INTRODUCTION

The third generation mobile radio systems are being standardized. In ETSI the standards towards Universal Mobile Telecommunications System (UMTS) and in ITU the standards towards IMT-2000 are being considered. One of the key targets in UMTS is high cellular capacity. The services that are expected to be important in UMTS networks are data services like WWW-browsing. These services set high requirements on the capacity, especially in downlink. Unfortunately, the CDMA downlink capacity has turned out to be lower than uplink capacity [1]. Thus the capacity can be easily downlink limited with wideband CDMA systems as the uplink uses coherent reception together with base station antenna diversity. In this paper downlink capacity enhancement methods in a CDMA cellular network is considered. Cellular system simulator is build to evaluate downlink capacity with different capacity enhancement features. Downlink capacity improvements that can be achieved with mobile receiver antenna techniques and with interference reduction techniques are analyzed and compared with the help of the developed simulator.

2. CDMA SYSTEM PARAMETERS

The simulated system is a DS-CDMA system whose key features include flexible transport scheme, large 5.1 MHz bandwidth, coherent demodulation and fast mobile controlled handover with inter frequency handover capability. The wideband CDMA system concept with uplink multi-user detection, MUD-CDMA has been presented in [2]. The uplink capacity of the presented system is shown in [3, 4]. This paper concentrates on the downlink capacity features of the proposed system. The main parameters of the downlink are presented in Table 1.

Table 1. Key parameters of the downlink physical layer

Feature	Solution
Receiver type	RAKE
Data rates	0-640 kbits/s, locally up to 2 Mbit/s
Chip rate	5.1 Mchip/s
Channel spacing	6 MHz
Handover	Mobile controlled
Multirate concept	Parallel code channels
Multirate flexibility	Rate change possible from frame to frame
Spreading codes	255 chip Gold-like and modified Walsh-sequences
Fast power control	0.5 or 1 kHz with adaptive step size from 0.25 to 1 dB
Power control dynamics	15 - 20 dB

3. SIMULATION ENVIRONMENT AND MODELING

The system performance for CDMA downlink is analyzed by a simulation tool, containing two different environments, macro and micro-cellular ones. Block diagram for the simulator is shown in Fig. 2. The performance measure for system simulations is outage percentage. Maximum of 5 % of obtained SIR values are allowed to be lower than threshold SIR. The maximum number for each environment that can fulfill the quality criteria is given as an output from the simulator.

Interference calculations and channel model

The main parameters for the simulated macro and micro-cell environment are shown in Table 2. In the simulator the mobile stations are placed randomly on the system area. Each base station transmits user specific signals and a common pilot signal. Powers of all the transmitted signals are summed together at the base station transmitter.

Signal from a base station to a mobile station propagates via several Rayleigh fading paths. The different multipath components have different average power levels according to the selected environment channel profile. Gain for the strongest path is 0 dB, and the other paths are attenuated according to the environment. Paths are scaled so that the sum of their average value will be 1. Additionally the received signal is attenuated due to distance dependent path loss and shadowing. Here, we suppose that the received signals are combined coherently with maximal ratio combining. Maximal ratio combining is modeled by taking sum of SNR values of paths [5]. In the CDMA network simulations, the interference is assumed Gaussian since interference is composed from transmission to several independent users when simulating medium bit rate services. The attained SNR will be:

$$SNR = \frac{\sum_{i=0}^{N} g_i \cdot L_{p,l} \cdot P_{tx}}{\sum_{i=0}^{N} \hat{g}_i} \cdot I_{total}^{-1} \qquad (1)$$

N is the number of perceived paths in the channel model with the selected bandwidth. $L_{p,l}$ is pathloss between the mobile stations and the base station l, P_{tx} is the transmission power for the selected user and I_{total} is total interference experienced by that user. g_i is instantaneous path gain and $\hat{g}_i$ average gain for path i.

Instantaneous signal to interference ratio is calculated by dividing the received signal by the interference, and multiplying by the processing gain. Interference that propagates via the same paths than the desired signal is multiplied by an *orthogonality factor* α. Orthogonality factor of 1 corresponds to perfectly orthogonal intra-cell users while with the value of 0 the intra-cell interference has the same effect as inter-cell interference. Signal-to-interference ratio will be:

$$SIR = \frac{\dfrac{\sum_{i=0}^{N} g_i \cdot L_{p,l} \cdot P_{tx}}{\sum_{i=0}^{N} \hat{g}_i} \cdot G_p}{(1-\alpha) \cdot I_{\text{intra}} + I_{\text{inter}} + N_0} \qquad (2)$$

No is thermal noise, G_p is processing gain, I_{intra} is intra-cell interference and I_{inter} inter-cell interference. Since the system is interference limited, thermal noise N_0 is assumed small and neglected. I_{intra} and I_{inter} are equal to:

$$I = \sum_{l=0}^{M} \left[L_{p,l} \cdot \frac{\sum_{i=0}^{N} g_{i,l}}{\sum_{i=0}^{N} \hat{g}_i} \left(\sum_{k=0}^{R} P_{tx,k} + P_{pilot,l} \right) \right] \qquad (3)$$

In the equation R is number of own cell or other cell interferers. Each path of desired user experience the same interference in average. M is number of base station causing inter or intra-cell interference and $P_{pilot,l}$ is pilot power of base station l. The pilot transmission power is 6 dB higher than the maximum power of single code channel. One 144 kbps user exploits 24 code channels and has maximum power of 1 W, thus the relative pilot power level will be 0.17 W.

The orthogonality factor α is calculated from (4). Eb/No is the performance figure for one user case without own cell interference and Eb/Io is the corresponding figure for the case in which own cell interference is high and noise is negligible. The produced α will be

$$\alpha = \frac{E_b}{I_0} \cdot \left(\frac{E_b}{N_0} \right)^{-1} \qquad (4)$$

When the signals are completely orthogonal α gets value 0, and when the signals are not orthogonal α gets value 1.

Macro diversity can be modelled in two ways at the system level. First approach is to simulate macro diversity in the link level so that separate Eb/No levels are obtained for users in soft handover state. With separate values for soft handover state, the mobile can be assumed to be able to receive all the paths directed to it in the system level. Another way is to transmit signal from several base stations to mobile stations so that the mobile station cannot receive all the paths directed to it. Paths not captured to the RAKE processing are contributing to the interference. Now the same Eb/No threshold is used for all the mobile stations. The latter method has been used in simulations due to straight forward modelling, although it is not quite as accurate as the preceding method.

Active set, i.e., set of active base stations is selected randomly from candidate set base stations. Candidate set base stations are those base stations that fit into the handover margin. This non-ideal handover selects maximum of three base stations to active set.

Propagation calculations

The pathloss between a mobile station and a macro cell base station is modeled as

$$L = 29 + 36\log_{10}(R) + 31\log_{10}(f) \qquad (5)$$

In (5) f is carrier frequency in kHz's and R distance between transmitter and receiver in km's. Resulting pathloss L is given in dB's.

Pathloss between a mobile station and a micro cell base station is calculated with a multi-slope model. The micro-cell base stations are located in every second street intersection. The slopes are non-line-of-sight slope, line-of-sight slope for small distance and line-of-sight slope for long distances. If the connection between transmitter and receiver is line-of-sight attenuation is calculated as

$$L_{LoS} = \begin{cases} 82 + 20\log(\frac{x}{300}), if & x \le 300 meters \\ 82 + 40\log(\frac{x}{300}), if & x > 300 meters \end{cases} \qquad (6)$$

At distance of 300 meters a breakpoint marks the separation between two line-of-sight segments. Turning round a corner causes an additional loss, L_{corner}, seen in (7). Attenuation between a transmitter and a receiver that have non-line-of-sight connection constitutes a line-of-sight segment, a non-line-of-sight segment, and an additional corner attenuation, as seen in (7).

$$L_{nLoS} = L_{LoS}(x_{corner}) + 17 + 0.05x_{corner} + (25 + 0.2x_{corner})\log(\frac{x}{x_{corner}}) \qquad (7)$$

Line-of-sight attenuation is calculated between a corner and receiver, and non-line-of-sight connection between a corner and transmitter.

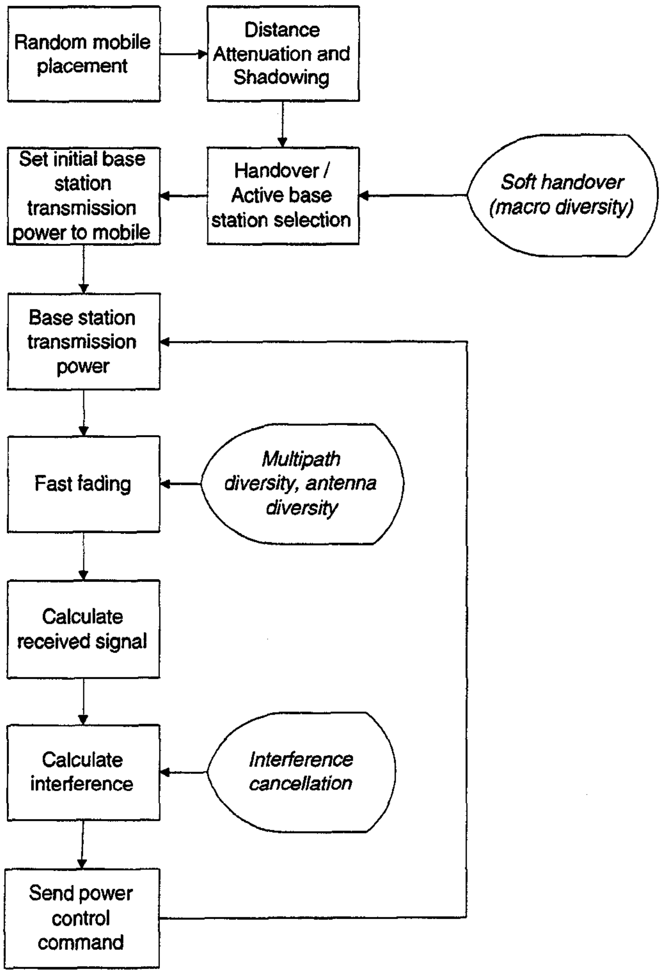

Figure 1. Block diagram of the simulation tool.

Table 2. Simulation environment

	Micro	Macro
Shadowing	mean 0dB, std dev 4dB	mean 0dB, std dev 10dB
Base station amount	128	19
Base station layout	Manhattan	hexagonal
Base station spacing	200 m	800 m
Building width	100 m	-
Street width	30 m	-
Mobile speed	5 km/h	5 km/h

Table 3. Simulation parameters

Outage requirement	< 5 %
Active set size in soft handover	3
Handover margin in non-ideal handover	3 dB
Carrier spacing	6 MHz
User bit rate	144 kbit/s
Voice activity	100 %
RAKE fingers	9
PC dynamics	20 dB
PC step size	1 dB
Pilot strength	0.17 W

4. CDMA DOWNLINK CAPACITY

Link level Eb/No and Eb/Io values used are shown in Table 4. The orthogonality factor is derived according to (4) from the link level results. The obtained orthogonality is in the order 0.8 in macro cell channel and in the order of 0.3 in micro cell channel due lower number of multipath.

Table 4. Eb/No and Eb/Io and calculated orthogonality factor for 128 kbps service.

	Downlink Eb/No	Downlink Eb/Io	Orthogonality factor
Macro	4.0 dB	3.0 dB	0.79
Micro	6.1 dB	0.9 dB	0.3

In Table 5., capacity results for uplink and downlink are shown. Downlink capacity is approximately 2 - 2.5 times (3 - 4 dB) lower than the corresponding uplink capacity in both environments [4]. In the downlink the needed Eb/No is 4.0 dB in macro-cell environment and 6.1 dB in the micro-cell environment. In CODIT micro cell delay spread is rather short, thus downlink receiver cannot obtain diversity although the code channels remain more orthogonal. In the uplink antenna diversity offers the required diversity. The link level gain in the micro cell environment from the antenna diversity is similar to the gain in AWGN environment (in the order of 3 dB) but in macro cell environment the actual gain is very small especially if the total number of Rake fingers is kept the same regardless of adding a second antenna branch to the mobile.

In the studies done for uplink in [3] the major reason for higher capacity in addition to base station antenna diversity is the use of multi-user detection (MUD) in uplink providing almost two-fold capacity if compared to a conventional receiver. In downlink the corresponding factor for MUD gain is orthogonality factor, with the difference that signals from the different base stations are not orthogonal in the case of downlink soft handover. Orthogonality factor gives, however, only a modest capacity gain in macro-cell channel.

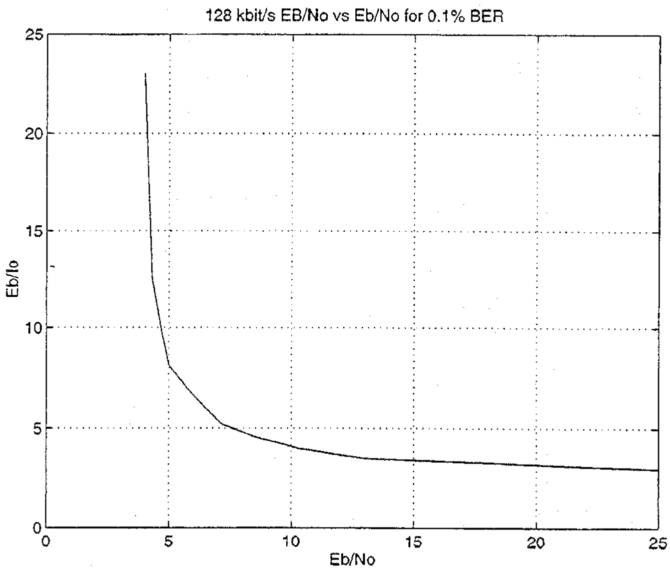

Figure 2. Downlink link level example performance for CODIT macro cell channel with 128 kbit/s data service.

Table 5. Cellular capacity in kbit/s/cell/MHz. Service 144 kbit/s with uplink antenna diversity and downlink single antenna.

[kbit/s/cell/MHz]	Uplink[3,4]	Downlink
Macro	334	169
Micro	349	222

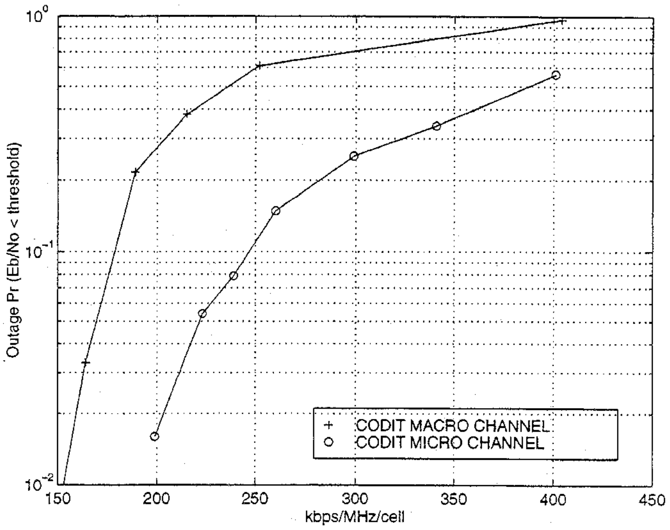

Figure 3. System level performance for CODIT macro cell and micro cell channels with 144 kbps user data.

5. SOFT HANDOVER AND MACRO DIVERSITY

Macro-cell capacity degreases only by 10 % if soft handover and macro diversity is not utilized. Capacity loss is not remarkable even if soft handover gain and macrodiversity gain is lost. CODIT macro-cell channel gives sufficient multipath diversity even if the mobile station was in a hard handover state. On the other hand the limited number of RAKE fingers cannot fully exploit attained diversity from soft handover in the macro-cellular environment. On the contrary, a large part of the energy generated by soft handover base stations is lost and contributing to the interference.

The situation is different for micro cell, since CODIT micro cell channel provides only little multipath diversity. Thus, macro diversity is essential for high capacity in micro cell environment. Similar with antenna diversity the micro cell environment has more benefit. Especially if the total number of Rake fingers is limited, then adding the diversity brach has only a limited gain in micro cellular environment with the channel model used.

Table 6. Downlink capacity with hard and soft handover

[kbit/s/cell/MHz]	Hard handover	Soft handover
Macro	155	169
Micro	139	222

6. INTERFERENCE CANCELLATION IN MOBILE / ORTHOGONAL CODES IN DOWNLINK

Intra-cell interference cancellation

Intra-cell interference can be canceled by having such spreading codes that make user signals orthogonal or by interference canceling techniques. In case of interference cancellation all the intra-cell interference can not be included canceling process. Here we suppose that IC can cancel 20 % of macro-cell intra-cell interference and 70 % of micro cell intra-cell interference.

Since major part of interference is intra-cell interference cancellation, orthogonalization of signals gives high capacity gain. If orthogonalization was ideal, as high gain as 7.5 dB could be achieved if compared to case where interference was random. An example implementation for downlink interference cancellation can be found in [6]. The results in Table 8 are given as lower and upper bounds, with the value 1.0 corresponding to random codes and large number of multipaths and value 0.0 for single path case with orthogonal codes or with ideal interference cancellation. Also capacities with actual simulated orthogonality factors are presented.

Table 7. Downlink capacity with reduced own cell (intra-cell) interference in [kbit/s/cell/MHz].

	Capacity for different orthogonality factors		
Orthogonality factor	Worst case 0.0	Macro 0.2 Micro 0.7 (=values from link level simulations)	Ideal 1.0
Macro	141	169	502
Micro	78	222	436

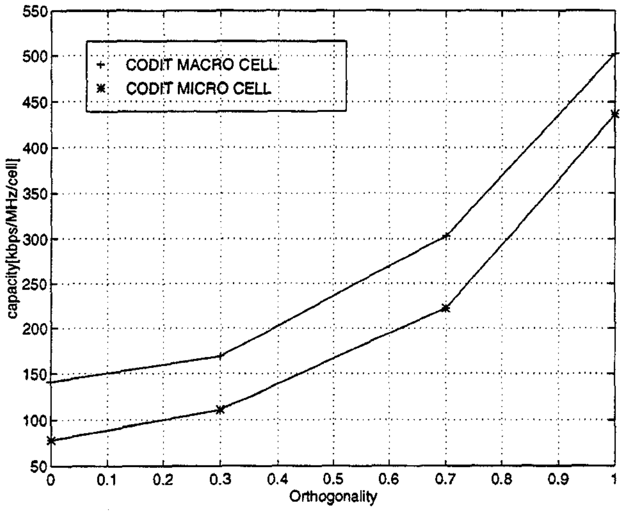

Figure 4. Downlink capacity as a function of orthogonality of intra-cell interference

Adjacent cell interference cancellation

There are several ways to implement interference cancellation in the system level. The approach studied here is to search certain number of strongest interfereres and cancel them. Here we assume that intra-cell interference is not canceled by interference cancellation process. Intra-cell interference is reduced by orthogonal codes.

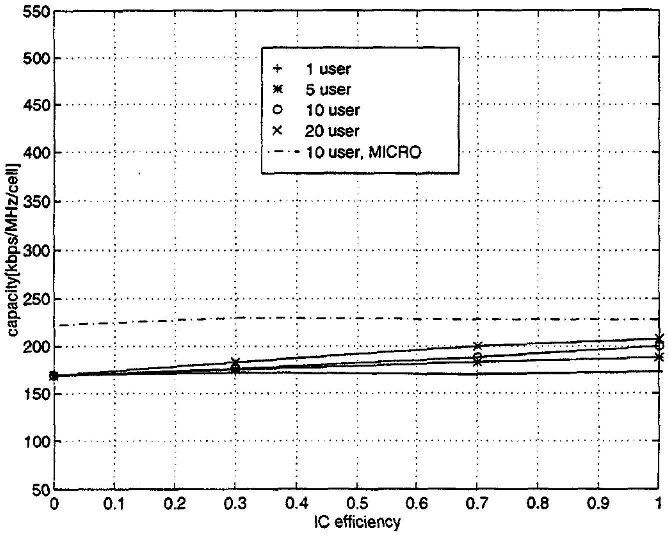

Figure 5. Downlink capacity as a function of orthogonality of inter-cell interference in macro-cell environment.

Table 8. Downlink capacity with reduced adjacent cell (inter-cell) interference. N is number of canceled users.

[kbit/s/cell/MHz]	IC efficiency			
	0.0	0.3	0.7	1.0
Macro, (N=10)	169	176	188	200
Micro, (N=10)	222	230	228	228

Mobile station IC that cancel inter-cell interference does not offer remarkable gain since major part (ca. 70 - 80 %) of interference that a mobile station experience is intra-cell interference. The capacity gain also depends on the bit rate. If lower bit rates are used, then there are more interferers and the capacity gain is lower. But if higher bit rates are used, then a higher percentage of interferers can be included in the interference cancellation process.

7. CONCLUSIONS

From the studies done it can be concluded, that in macro cell environment it is important to cancel intra-cell interference due multipath propagation, which destroys part of the channel orthogonality. Canceling inter-cell interference provides only marginal gain from the capacity view point, although for a single mobile unit the inter-cell interference cancellation can bring large quality improvement as the resistance towards unideal handover conditions increases.

The macro diversity (i.e.) soft handover is important from the capacity view point in micro-cell environment where the number of separable paths is small, as in the macro-cell environment several separable multipaths al ready exists and thus the gain from macrodiversity is small. The same applies for the mobile station antenna diversity, as the low delay spread micro channel offers only limited diversity for RAKE reception.

From the complexity point of view the use of antenna diversity adds additional RF parts to the mobile while interference cancellation keeps the RF as it is and adds complexity to the baseband processing. Which is then more economical in terms of cost vs. gain is then depending on the relative cost between additional RF parts and baseband processing power.

REFERENCES

[1] Westman, T. Holma, H. "CDMA System for UMTS High Bit Rate Services", Proceedings of VTC'97, vol. 2, pp. 825-829, Phoenix, USA, May 1997.
[2] Ojanperä, T., *et.al.*, "Design of A 3rd Generation Multirate CDMA System with Multiuser Detection, MUD-CDMA", Proceedings of ISSSTA'96 conference, vol. 1, pp. 334-338, Mainz, Germany, September 1996.
[3] Hämäläinen, S., Holma, H., Toskala, A., "Capacity Evaluation of a Cellular CDMA Uplink with Multiuser Detection", Proceedings of ISSSTA'96 conference, Vol 1 pp 339 - 343, Mainz, Germany, September 1996.
[4] Toskala, A., Hämäläinen, S., Holma, H., "Link and System Level Performance of Multiuser Detection CDMA Uplink", to appear in Wireless Personal Communications", Kluwer Academic Publisher.
[5] Proakis, John, G., "Digital Communications", pp.778 - 785, McGraw-Hill, 1995.
[6] Wichman R., Hottinen, A "Multiuser Detection for Downlink CDMA Communications in Multipath Fading Channels" VTC'97, pp. 572-576, Phoenix, USA, May 1997.