Performance Analysis and Allocation Strategy for the WCDMA Second Scrambling Code

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Abstract. The WCDMA downlink is limited by Node-B cell power and the number of channelization codes. With upcoming capacity enhancement techniques, like MIMO and HSDPA, the potential limitation in channelization codes becomes visible more frequently. The WCDMA standard allows for allocation of traffic on a secondary scrambling code, which is non-orthogonal to the primary scrambling code. This paper analyzes the capacity impact of using the secondary scrambling code. In addition this paper introduces an allocation strategy for traffic to the secondary scrambling code. The analysis shows a potential gain in secondary scrambling code usage for this strategy.

1 Introduction

The air-interface is a very expensive resource in cellular systems. In order to utilize this resource to its full extend, WCDMA based systems will be enhanced with techniques like MIMO and HSDPA that improve the capacity of the system. When increasing the capacity of a WCDMA based system, an important limit to consider is the number of channelization codes in the downlink, which create the individual channels. The Orthogonal Variable Spreading Factor (OVSF) technique is used for generating channelization codes. The OVSF technique use of the Hadamard matrix,

$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & -H_n \end{bmatrix} \quad \text{and} \quad H_1 = [1], \tag{1}$$

where each row of H represents a single OVSF code word, and n is the Spreading Factor (SF). Figure 1 shows the way this process works. Both the matrix notation and the figure show that the number of OVSF codes is equal to the SF.

When the capacity increases the risk that the required number of codes exceeds the number of available codes is realistic. The reason for such limitation can be various:

- Capacity enhancement techniques aim at increasing the overall capacity, which typically result in more codes to be allocated.
- Mobile systems are used indoor much. Such environments have little time dispersion, causing little intra-cell interference, and therefore provide very high capacity.
- The code tree can have a scattered allocation. A specific code is only available for allocation when its children are available. (E.g. code $C_4(1)$ is a child of $C_2(1)$.)

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- Some techniques, like SSTD, allocate more codes that they actually use.
- High capacity area Node-Bs will use the HS-DSCH, which occupies semi-statically between 5/16 and 15/16 [7] of a complete code tree. When little HS-DSCH traffic is carried the allocated codes are under-utilised.

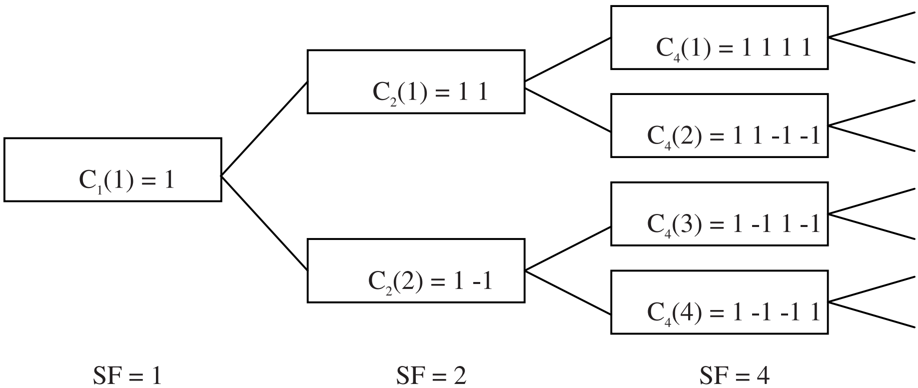

Fig. 1. OVSF channelization code tree [1], [2]

When more channelization codes are required than fit into a single OVSF code tree, WCDMA offers the possibility to allocate a secondary code tree. Surplus traffic is allocated to a secondary scrambling code. This secondary code has its own OVSF code tree. Doing such, the number of channelization codes is doubled. As scrambling codes are non-orthogonal, adding this secondary scrambling code will increase the intra-cell interference. This paper analyzes the capacity impact of adding this secondary scrambling code, and analyzes the performance of a proposed allocation strategy.

2 Performance Analysis

The number of available channelization codes and the available power determine the downlink capacity of the system. To find the downlink capacity of a W-CDMA system requires the combined analysis of both.

2.1 Available Channelization Codes

Common and shared channels occupy a part of the first code tree. The downlink channelization code capacity for dedicated channels is the part that is not allocated to the common and shared channels. For a service with spreading factor SF this capacity in terms of OVSF channelization codes can be calculated as

$$M_{SF} = SF \cdot \left(k - \frac{1}{SF_{common}} - \frac{1}{SF_{shared}} \right), \tag{2}$$

M_{SF}	DL OVSF code capacity for DCHs with spreading factor SF
SF	Spreading factor
SF_{common}	SF for common channels
SF_{shared}	SF for shared channels
k	Number of code trees.

2.2 Available Node-B Transmit Power

The Node-B transmit power is a shared resource. A fixed portion of the power is assigned to common channels. The power assignment of shared channels can be fixed or variable. In the latter case a strategy is to allocate the remainder of the Node-B transmit-power to the shared channel, with a pre-determined minimum and maximum.

2.2.1 General Expressions for Downlink Power

The Node-B dedicated channel transmit power is power-controlled. The UE compares the quality of the received signal with a service dependent target SIR, and requests an increase or decrease of the power to remain at the target as close as possible. Many studies report E_b/N_o instead of SIR. The SIR is the ratio of E_b/N_o and processing gain (PG). The PG is the ratio of the chip rate and bit rate including signalling overhead.

$$\gamma = \frac{E_b / N_o}{PG} = \frac{E_b / N_o}{R_{chip} / R_{DCH}}, \tag{3}$$

γ	SIR
E_b/N_o	Energy per bit over noise density
PG	Processing Gain
R_{chip}	Chip rate
R_{DCH}	DCH bit rate (including signalling overhead).

The received SIR results from the transmit power and the interference. This interference consists of received non-orthogonal power from the own and other Node-Bs.

Signals transmitted with the same scrambling code are in principle orthogonal. The propagation channel between Node-B and UE introduces time dispersion, reducing orthogonality between transmissions using the same scrambling code. This effect is environment dependent, and can vary over a cell. For ease of analysis it is assumed that an average orthogonality factor can be derived in a cell.

The synchronization channel (SCH) is a special case. The SCH is not modulated with any scrambling code, and is therefore by definition non-orthogonal. The SCH power determines the quality of the synchronization, and is therefore of large importance as system parameter. Only extensive analysis can provide a good estimate for its setting. Setting the SCH power to 1% of the maximum power of a Node-B is generally assumed to be a realistic assumption, and is used in this analysis.

The SIR is the ratio between the wanted and the unwanted signals. The wanted signal is the transmitted signal times the path-gain. The unwanted signal is the sum of all non-orthogonal power and thermal noise. The SIR of a received signal at UE i from Node-B j can be expressed as

$$\gamma_{i,j} = \frac{g_{i,j} p_{i,j}}{g_{i,j}(\alpha_{i,j} p_{orth} + p_{non-orth}) + \sum_{j \neq k} g_{i,k} p_k + N}, \tag{4}$$

$\gamma_{i,j}$ SIR of signal at UE *i* of Node-B *j*
$g_{i,j}$ path-gain between UE *i* and Node-B *j*
$p_{i,j}$ power of the signal for UE *i* from Node-B *j*
p_{orth} other power transmitted from the same scrambling code
$p_{non\text{-}orth}$ non-orthogonal transmit power (SCH and other scrambling code(s))
p_k total transmit power of Node-B *k*
$\alpha_{i,j}$ non-orthogonality between UE *i* and Node-B *j*.

When r_t is the received power of a signal that is transmitted orthogonal, and r_n is the received non-orthogonal power of the signal, α is the ratio of r_n over r_t. α depends on the environment and the receiver technology. It does not depend on the signal.

Loaded cells surround the cell under consideration. For a constant transmit power of the surrounding Node-Bs the received power will vary between 1 dB for free space and 5 dB for dense urban, disregarding effects of shadowing. Being small in relation to the variation in received power from the own Node-B, it is of secondary importance to the analysis in this paper. The total interference is modelled as a non-orthogonal cell transmitting at full power p_{max} at distance β times the site-to-site distance. β may vary per environment between 0.38 and 0.55. In this analysis is fixed to 0.4.

Thermal noise is small compared to the inter-cell interference in most cases. It is therefore neglected here. In addition the orthogonality is assumed constant over the cell. Taking the above assumptions the formula for SIR reduces to

$$\gamma_{i,j} = \frac{g_{i,j} p_{i,j}}{g_{i,j}(\alpha p_{orth} + p_{non-orth}) + g_\beta p_{\max}} = \frac{p_{i,j}}{\alpha p_{orth} + p_{non-orth} + p_{\max} \, g_\beta / g_{i,j}}. \tag{5}$$

The SIR $\gamma_{i,j}$ is input to power control, which will keep the effective SIR as close as possible to a target. Instead of having a SIR per connection, the analysis uses the target SIR γ as input and the Node-B transmit power as result. The SIR target is set equal for all DCHs. The power at which the Node-B transmits the signal for UE *i* equals

$$p_{i,j} = \gamma(\alpha \cdot p_{orth} + p_{non-orth} + p_{\max} \, g_\beta / g_{i,j}) \tag{6}$$

The quality of reception at the cell boundary determines the power for common and shared channels. This implies that $g_{i,j}$ equals the gain at the cell edge, being at 0.5 times the site-to-site distance. Common and shared channels transmit at a different bit rate. Assuming that the same E_b/N_o applies to these channels the SIR γ for the DCH can be corrected with the ratio of the bit rates. As a result the combined common and shared channel transmit power is expressed as

$$p_c = R_c \gamma(\alpha \cdot p_{orth} + p_{non-orth} + p_{\max} \cdot k_c) \text{ with } R_c = \frac{R_{common} + R_{shared}}{R_{DCH}} \text{ and } k_c = g_\beta / g_{0.5}, \tag{7}$$

R_{common} combined bit rate on all common channels (including overhead)
R_{shared} combined bit rate on all shared channels (including overhead)
R_{DCH} bit rate on a DCH (including overhead).

The path-gain for the DCH varies over the cell. With a uniform user distribution over the cell area, it is possible to exchange this varying path-gain by an average path-gain, where the average must conserve the sum of transmit powers of all connections. This is valid using the following calculation:

$$p_{\max} \cdot k_{DCH} = p_{\max} \, {}^{g_\beta}\!/_{g_{avg}} = \frac{1}{cellarea} \int_{cell} p_{\max} \, {}^{g_\beta}\!/_{g_{pos}} \, dpos \;\Rightarrow\; k_{DCH} = \frac{1}{cellarea} \int_{cell} {}^{g_\beta}\!/_{g_{pos}} \, dpos \,. \tag{8}$$

So the average transmit-power per DCH equals

$$p_{DCH} = \gamma(\alpha \cdot p_{orth} + p_{non-orth} + p_{\max} \cdot k_{DCH}) \,. \tag{9}$$

The split in orthogonal and non-orthogonal power for the DCH depends on its allocation to primary or secondary scrambling code, and the amount of DCHs on each code. For N_1 DCHs on the primary scrambling code and N_2 DCHs on the secondary scrambling code the sum of powers for all DCHs on primary and secondary scrambling code and the power for the common and shared channel respectively are

$$\begin{aligned} p_1 &= N_1 \cdot \gamma(\alpha \cdot (p_c + p_1) + p_{SCH} + p_2 + p_{\max} \cdot k_{DCH}) \\ p_2 &= N_2 \cdot \gamma(\alpha \cdot p_2 + p_{SCH} + p_c + p_1 + p_{\max} \cdot k_{DCH}) \\ p_c &= R_c \cdot \gamma(\alpha \cdot (p_c + p_1) + p_{SCH} + p_2 + p_{\max} \cdot k_c) \,. \end{aligned} \tag{10}$$

The maximum transmit power of a Node-B p_{max} and the power for common and shared channels p_c are fixed. So dedicated channels can be hosted as long as

$$p_1 + p_2 + p_c + p_{SCH} \le p_{\max} \,. \tag{11}$$

As all values are scaled in p_{max} the analysis simplifies by expressing all powers as a fraction f of p_{max}, resulting in the following set of expressions.

$$\begin{aligned} f_1 &= N_1 \cdot \gamma(\alpha \cdot (f_c + f_1) + f_{SCH} + f_2 + k_{DCH}) \\ f_2 &= N_2 \cdot \gamma(\alpha \cdot f_2 + f_{SCH} + f_c + f_1 + k_{DCH}) \\ f_c &= R_c \cdot \gamma(\alpha \cdot (f_c + f_1) + f_{SCH} + f_2 + k_c) \\ f_1 &+ f_2 + f_c + f_{SCH} \le 1 \,. \end{aligned} \tag{12}$$

2.2.2 Capacity for Only the Primary Scrambling Code

When the power related downlink capacity is less than the number of channelization codes for DCHs M_{SF} (or when disregarding this limit) all DCHs are allocated to the primary scrambling code. In the above formulas N_2 and effectively f_2 equal zero. The capacity than equals the maximum number N_1 that fulfils the set of equations:

$$\begin{aligned} f_1 &= N_1 \cdot \gamma(\alpha \cdot (f_c + f_1) + f_{SCH} + k_{DCH}) \\ f_c &= R_c \cdot \gamma(\alpha \cdot (f_c + f_1) + f_{SCH} + k_c) \\ f_1 &+ f_c + f_{SCH} \le 1 \,, \end{aligned} \tag{13}$$

which can be shown to equal

$$N_1 = \left\lfloor \frac{1 - f_c - f_{SCH}}{\gamma(\alpha \cdot (1 - f_{SCH}) + f_{SCH} + k_{DCH})} \right\rfloor \text{ with } f_c = R_c \cdot \gamma(\alpha \cdot (1 - f_{SCH}) + f_{SCH} + k_c) \,. \quad (14)$$

2.2.3 Capacity for Primary and Secondary Scrambling Code

When the power related capacity limit exceeds the capacity limit for the primary scrambling code, only additional traffic is allocated to the secondary scrambling code. The number of codes on the primary scrambling code N_1 equals the capacity limit M_{SF}. Working out the set of equations 12 leads to a capacity limit N_2 of

$$N_2 = \left\lfloor \frac{1}{\gamma(\frac{1 + k_{DCH}}{f_2} + \alpha - 1)} \right\rfloor \text{ with } f_2 = 1 - f_{SCH} - \frac{M_{SF} \cdot (1 + k_{DCH}) + R_c \cdot (1 + k_c)}{1/\gamma + (1 - \alpha) \cdot (M_{SF} + R_c)} \,. \quad (15)$$

2.3 Example Capacity Limits with Secondary Scrambling Code

Numerical examples in this section provide an interpretation of the formulas. Figure 2 shows the impact of the secondary scrambling code. The figure shows a virtual capacity. This assumes that all DCHs are allocated to the primary code tree, ignoring limit M_{SF}. The true capacity, taking the allocation to the secondary code tree into consideration is significantly less. This shows an impact of the mutual non-orthogonality between scrambling codes.

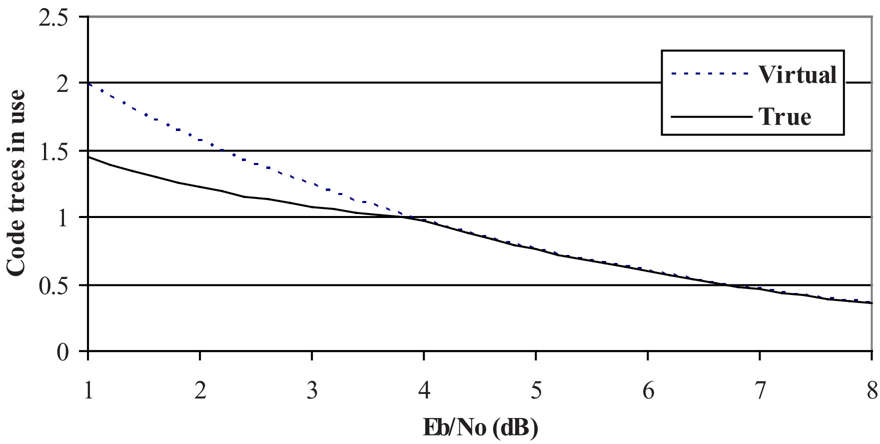

Fig. 2. Capacity impact of secondary scrambling code

This result shows that recovering codes on the primary code tree is very beneficial. There are two main options for recovering codes.

1. Unassigned codes may be unavailable due to scattering of code allocation. A code can only be assigned when all its children codes are unassigned. The SF is service dependent. Different services will be present in the same cell, so a mix of small

and large SF is assigned. Large SF codes, scattered in the code tree, may be unassigned, but not leaving any small SF code assignable. Concatenating free codes by reassigning large SF services to other codes, enables small SF code allocation. Various proposals are provided in literature. [4], [5], [6]

2. The HS-DSCH is of great importance in increasing the performance of W-CDMA. This channel can be assigned semi-statically up to 94% of the code tree. The usage of the HS-DSCH depends on the amount of relevant traffic in the cell. As this traffic can fluctuate heavily, the HS-DSCH may be underutilized during some intervals. At the same time traffic not suitable for HS-DSCH may peak. Freeing codes during a period of low utilization of the HS-DSCH therefore is very important. So far no studies were found in literature.

For a more detailed analysis of the impact of the non-orthogonality between the scrambling codes the true capacity exceeding the primary scrambling code is expressed as a fraction U of the virtual capacity exceeding one code tree:

$$U = \frac{\left\lfloor \dfrac{1}{\gamma((1+k_{DCH})/f_2+\alpha-1)} \right\rfloor}{\left\lfloor \dfrac{1-f_c-f_{SCH}}{\gamma(\alpha\cdot(1-f_{SCH})+f_{SCH}+k_{DCH})} \right\rfloor - M_{SF}} \quad \text{with} \tag{16}$$

$$f_2 = 1-f_{SCH}-\frac{M_{SF}\cdot(1+k_{DCH})+R_c\cdot(1+k_c)}{1/\gamma+(1-\alpha)\cdot(M_{SF}+R_c)} \quad \text{and}$$

$$f_c = R_c\cdot\gamma(\alpha\cdot(1-f_{SCH})+f_{SCH}+k_c)\,.$$

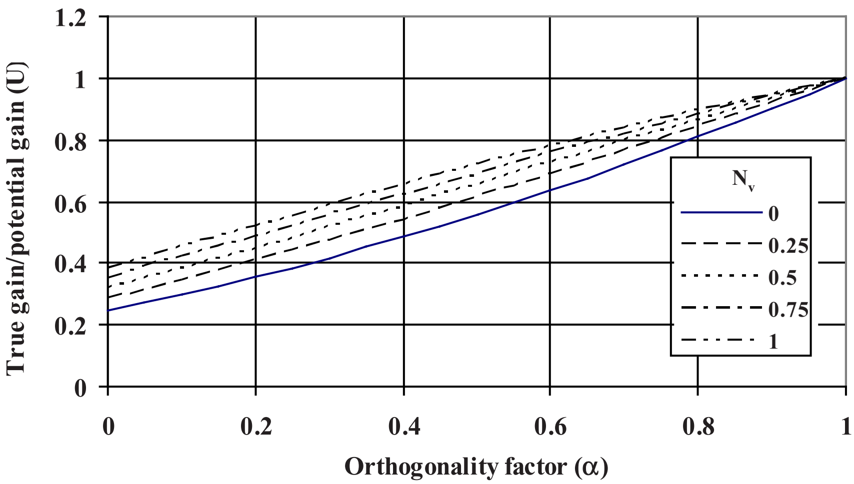

Fig. 3. Usability of the capacity gain on secondary scrambling code

Figure 3 shows the usability of a capacity gain when this exceeds the primary scrambling code. The gain is shown as function of the orthogonality factor and the potential loading of the secondary code tree N_v. N_v is varied between 0 (no traffic on the secondary code tree) and 1 (the secondary code tree could be used to its full extend when the non-orthogonality between code trees would not exist).

The figure clearly shows that the impact on capacity gain is much larger for the orthogonality than for the loading of the second scrambling code. α depends on the environment and indicates the amount of power that is observed as non-orthogonal. Without time dispersion in the received signal α is equal to 0. When α equals 1 all orthogonal power is received non-orthogonal. This corresponds to a hypothetical condition of infinite time dispersion. α depends on receiver technology and environment.

Practical values for α in W-CDMA range roughly from 0.1 in office environments to 0.5 in rural environments. In this range one third to half of the potential gain remains when traffic needs to be allocated to the secondary scrambling code. So reassigning codes from the secondary code tree to the primary code tree pays back. E.g. reassignment of one connection from secondary to primary scrambling code frees sufficient power to allocate one or two additional connections on the primary code tree.

The orthogonality also has a direct impact on the capacity. This effect strongly reduces when a significant amount of traffic is allocated to the secondary scrambling code. Figure 4 shows the capacity versus the orthogonality. As soon as the secondary scrambling code is used, the capacity gain of a smaller α diminishes. Comparing this result with the effect of a reduced SIR shows that the performance gain of reducing SIR and α are quite similar when only the primary scrambling code is in use. When also the secondary scrambling code needs to be used a better performance in SIR provides a much better gain than reducing α.

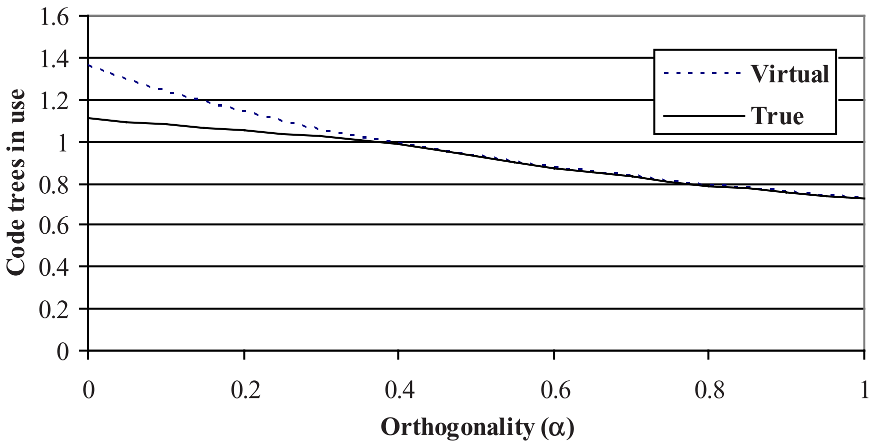

Fig. 4. Capacity impact of orthogonality

2.4 Code Allocation Strategy for a Secondary Scrambling Code

So far the implicit assumption is that traffic on both the primary and secondary code tree is uniformly distributed over the cell area. Traffic on the secondary code tree uses more power than traffic on the primary code tree. Traffic near the cell boundary uses more power than traffic near the cell centre. It may be expected that selecting traffic as near as possible to the cell centre for allocation on the secondary code tree is beneficial. For comparison also the opposite case where as far as possible traffic is selected for allocation on the secondary code.

For analysis of such algorithm the average path-gain is calculated separately for the two scrambling codes, splitting the cell area corresponding to the ratio between traffic using each scrambling code. This gain of such algorithm can be expressed as

$$gain = \frac{N_2(\text{with algorithm}) - N_2(\text{without algorithm})}{N_2(\text{without algorithm})}\,. \tag{17}$$

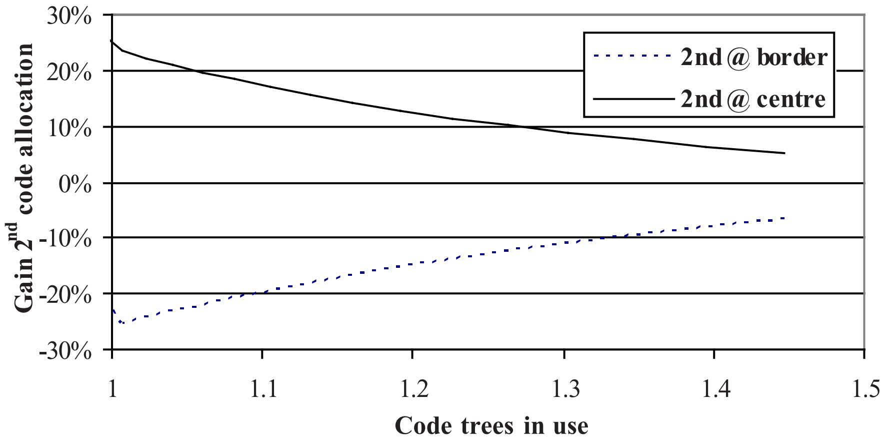

Fig. 5. Capacity gain for code allocation strategies

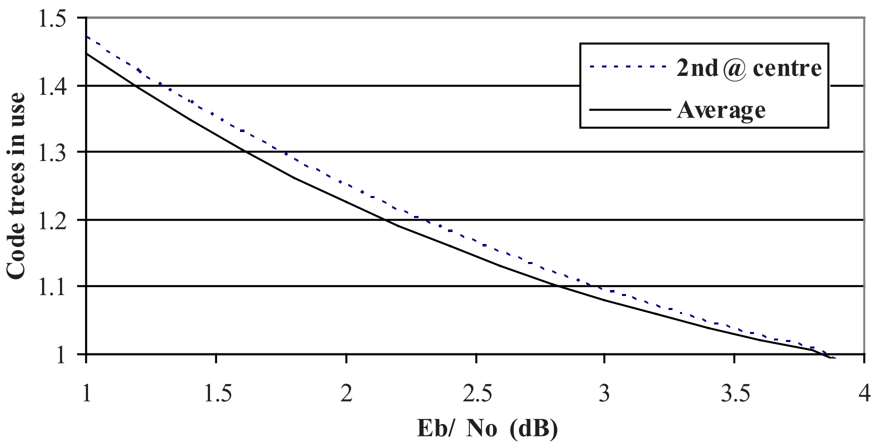

Fig. 6. Effective capacity for code allocation strategies

Figure 5 shows the gain of allocating traffic to the secondary code tree as close as possible to the cell centre or cell border. Clearly allocating near the cell centre is beneficial, while allocating near the cell border costs capacity. The effect however decreases with increasing use of the secondary scrambling code.

Figure 6 compares the resulting capacity for the strategy of allocating connections on the secondary scrambling code as close as possible to the cell centre with the uniform allocation. The capacity gain is apparent, though not dramatic.

3 Conclusions

The DL capacity limit of a Node-B is determined by the available power. The limited number of channelization codes per scrambling code does not directly limit the capacity, but does impact the capacity significantly. The cost for allocating traffic to the secondary scrambling code is two to three times as high as for the primary scrambling code. This cost can be reduced to some extend by preferring traffic far from the Node-B over traffic close to the Node-B for allocation to the primary code tree.

For maximum capacity it is important to manage the codes on the primary code tree very good. Code reallocation can free codes, such that as little traffic needs to be allocated to the secondary code tree. An issue for further study is the management of codes for the HS-DSCH.

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References

1. H. Holma, A. Toskala (Editors), “WCDMA for UMTS - Radio Access for Third Generation Mobile Communications”, John Wiley and Sons, Second Edition, 2002.
2. H.D. Schotten and Hafez Hadinejad-Mahram, “Analysis of a CDMA Downlink with Non-Orthogonal Spreading Sequences for Fading Channels”, Proc. VTC2000-Spring, pages 1782-1786, Tokyo, Japan, May 2000.
3. E. Dahlman, B. Gudmundson, M. Nilsson, and J. Sköld, “UMTS/IMT- 2000 based on Wideband CDMA”, IEEE Communication Magazine, vol. 36, pp. 70 80, Sep. 1998.
4. Y. Tseng, C. Chao and S. Wu, “Code Placement and Replacement Strategies for Wideband CDMA OVSF Code Tree Management”, IEEE Trans. on Mobile Computing, Vol. 1, No. 4, Oct.-Dec. 2002, pp. 293-302.
5. C. Chao, Y. Tseng, and L. Wang, “Reducing Internal and External Fragmentations of OVSF Codes in WCDMA Systems with Multiple Codes”, Proc. WCNC, 2003.
6. A.N. Rouskas, and D.N. Skoutas, “OVSF Codes Assignment and Reassignment at the Forward Link of W-CDMA 3G Systems“, Proc. PIMRC 2002, Vol. 5, pp. 2404-2408, Lisbon, Portugal, September 15-18, 2002.
7. 3GPP, “Spreading and modulation (FDD)”, TS 25.213 v5.4.0, http://www.3gpp.org