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PERFORMANCE ANALYSIS OF WIDEBAND CDMA MIMO SYSTEM

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Abstract – *In this paper we analyze capacity of advanced WCDMA MIMO system in case of imperfections in the operation of the system components. In addition to the standard WCDMA technology both, base stations and mobile units use antenna beam forming and self steering to track the incoming (and transmitted) signal direction. It is assumed that the tracking is perfect and only the beamforming is analyzed. In order to exploit the available propagation diversity, signals arriving from different directions (azimuth ψ, elevation φ) and delay τ, are combined in 3D (ψ,φ,τ) RAKE receiver. Further elaboration of these results, including extensive numerical analysis based on the offered analytical framework, would provide enough background for understanding of possible evolution of advanced W-CDMA and MC CDMA towards the fourth generation of mobile cellular communication networks.*

1. INTRODUCTION

Physical layer of the third generation of mobile communication system (3G) is based on wideband CDMA. The CDMA capacity analysis is covered in a number of papers [1].

The effects of adaptive base station antenna arrays on CDMA capacity have been studied e.g. in [3], [4] . The results show that significant capacity gains can be achieved with quite simple techniques.

By using *M*-element antenna arrays at the base station the spatial filtering effect can be further improved. The multiple beam adaptive array would not reduce the network trunking efficiency unlike sectorization and cell splitting [5]. These adaptive or smart antenna techniques can be divided into switched-beam, phased array and pure adaptive antenna systems. Advanced adaptive systems are also called spatial division multiple access (SDMA) systems. Advanced SDMA systems maximize the gain towards the desired mobile user and minimize the gain towards interfering signals in real time.

Some practical examples of the impact of the use of advanced antenna techniques on the existing cellular standards are described in [6] and [7].

In our paper we go even beyond the existing proposals and assume that both base station and the mobile unit are using beam forming and self-steering to continuously track transmitter-receiver direction (two side beam pointer tracking 2SBPT).

Due to user mobility and tracking imperfections there will be always the tracking error that will result in lower received signal level causing the performance degradation.

In this paper we provide a general framework for performance analysis of a network using this technology . It is anticipated that this technology will be used in 4G systems.

2. SYSTEM MODEL

Although the general theory of MIMO system modeling is applicable for the system description, performance analysis will require more details and slightly different approach will be used. This model will explicitly present signal parameters sensitive to implementation imperfections.

The complex envelope of the signal transmitted by user $k \in \{1,2,...,K\}$ in the *n*th symbol interval $t \in [nT,(n+1)T]$ is

$$s_k = A_k T_k(\psi,\varphi) e^{j\phi_{k0}} S_k^{(n)}(t-\tau_k), \tag{1}$$

where A_k is the transmitted signal amplitude of user *k*, $T_k(\psi,\varphi)$ is the transmitting antenna gain pattern as a function of azimuth ψ and elevation angle φ, τ_k is the signal delay, ϕ_{k0} is the transmitted signal carrier phase, and $S_k^{(n)}(t)$ can be represented as

$$\begin{aligned} S_k^{(n)}(t) &= S_k^{(n)} = S_k = S_{ik} + jS_{qk} = d_{ik}c_{ik} + jd_{qk}c_{qk} \\ d_{ik} &= b_{ik}^{(n)}\alpha(t-nT) \\ c_{ik} &= \sum_{p=0}^{N_c-1} c_{ikp}^{(n)}\beta(t-pT_c) \\ d_{qk} &= b_{qk}^{(n)}\alpha(t-nT-\varepsilon_b T) \\ c_{qk} &= \sum_{p=0}^{N_c-1} c_{qkp}^{(n)}\beta(t-pT_c-\varepsilon_c T_c) \end{aligned} \tag{2}$$

In (2), b_{ik} and b_{qk} are two information bits in the *I*- and *Q*-channel, respectively, $\alpha(t)$ is the bit pulse shape, and ε_b is the bit offset in the *Q*-channel. Parameters $c_{ikp}^{(n)}$ and $c_{qkp}^{(n)}$ are the *p*th chips of the *k*th user PN codes in the *I*- and *Q*-channel respectively, $\beta(t)$ is the chip shape, ε_c is the chip offset, T_c is the chip interval, and N_c is the PN code length. In practical applications, ε_b and ε_c will have values either zero or 1/2. Equations (1) and (2) are general, and different combinations of the signal parameters cover most of the signal formats of practical interest.

The channel impulse responses consist of discrete multipath components. If antenna lobes are narrow we can use a discrete approximation of this functions in spatial domain too and implement 3D RAKE receiver as follows:

$$\begin{aligned} h_k^{(n)}(\psi,\varphi,t) &= \sum_{l=1}^{L} h_{kl}^{(n)}\delta(\psi-\psi_{kl},\varphi-\varphi_{kl},t-\tau_{kl}^{(n)}) \\ &= \sum_{l=1}^{L} H_{kl}^{(n)} e^{j\phi_{kl}}\delta(\psi-\psi_{kl},\varphi-\varphi_{kl},t-\tau_{kl}^{(n)}) \end{aligned} \tag{3a}$$

$$h_{kl}^{(n)} = H_{kl}^{(n)} e^{j\phi_{kl}} \tag{3b}$$

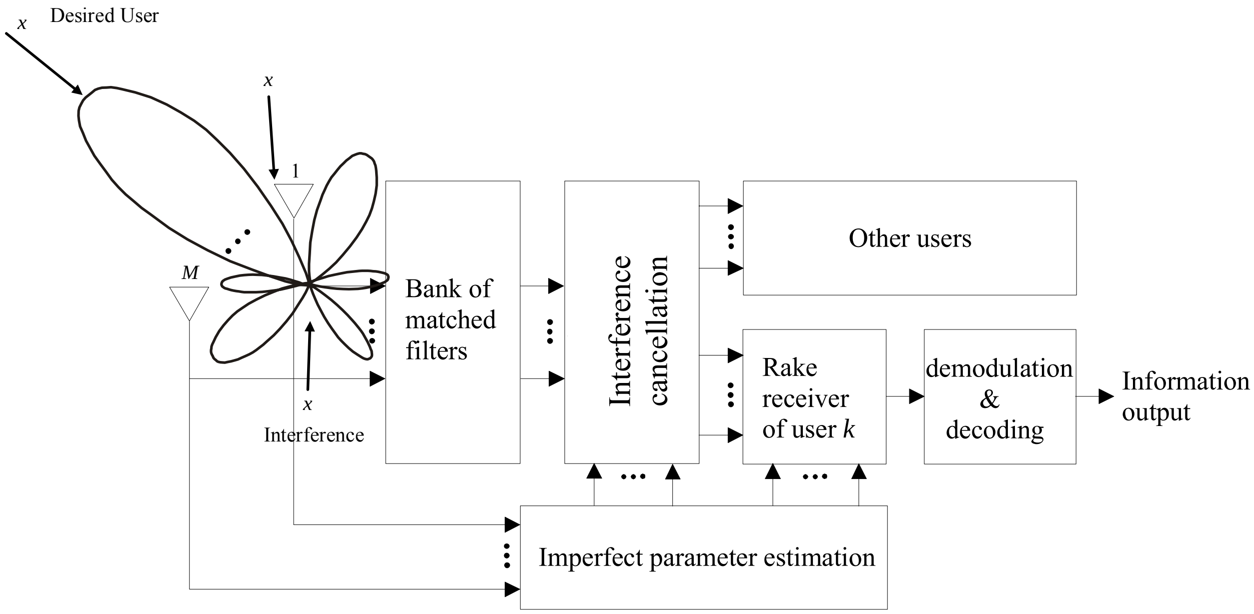


Fig.1 *Receiver block diagram*

where L is the overall number of spatial-delay multipath components of the channel. Each path is characterized by a specific angle of arrival (ψ,φ) and delay τ. Parameter $h_{kl}^{(n)}$ is the complex coefficient (gain) of the lth path of user k at symbol interval with index n, $\tau_{kl}^{(n)} \in [0,T_m)$ is delay of the lth path component of user k in symbol interval n and $\delta(t)$ is Dirac delta function. We assume that T_m is delay spread of the channel. In what follows indices n will be dropped when ever this does not produce any ambiguity. It is also assumed that $T_m < T$.

The base station receiver block diagram is shown in Fig.1. The overall received signal at the base station site during N_b symbol intervals can be represented as

$$\begin{aligned} r(t) &= \mathrm{Re}\left\{ e^{j\omega_0 t} \sum_{n=0}^{N_b-1} \sum_{k=1}^{K} s_k^{(n)}(t) * h_k^{(n)}(t) \right\} \\ &\quad + \mathrm{Re}\left\{ z(t) e^{j\omega_0 t} \right\} \\ &= \mathrm{Re}\left\{ e^{j\omega_0 t} \sum_{n=0}^{N_b-1} \sum_{k} \sum_{l} a_{kl} S_k^{(n)}(t - nT - \tau_k - \tau_{kl}) \right\} \\ &\quad + \mathrm{Re}\left\{ z(t) e^{j\omega_0 t} \right\} \end{aligned} \tag{4}$$

where $a_{kl} = A_k T_k(\psi,\varphi) H_{kl}^{(n)} e^{j\Phi_{kl}} = A'_{kl} e^{j\Phi_{kl}}$, $\Phi_{kl} = \phi_0 + \phi_{k0} - \phi_{kl}$, ϕ_0 is the frequency down-conversion phase error and $z(t)$ is a complex zero mean additive white Gaussian noise process with two-sided power spectral density σ^2 and ω_0 is the carrier frequency. In general, in the sequel we will refer to A'_{kl} as received signal amplitude. This amplitude will be further modified by the receiver antenna gain pattern. The complex matched filter of user k with receiver antenna pattern $R_k(\psi,\varphi)$ will create two correlation functions for each path

$$\begin{aligned} y_{ikl}^{(n)} &= \int_{nT+\tau_k+\tau_{kl}}^{(n+1)T+\tau_k+\tau_{kl}} r(t) R_k(\psi,\varphi) c_{ik}(t - nT - \tau_k + \tau_{kl}) \cdot \\ &\quad \cdot \cos(\omega_0 t + \tilde{\Phi}_{kl}) dt \\ &= \sum_{k'} \sum_{l'} A_{k'l'} \big[d_{ik'} \rho_{ik'l',ikl} \cos \varepsilon_{k'l',kl} \\ &\quad + d_{qk'} \rho_{qk'l',ikl} \sin \varepsilon_{k'l',kl} \big] \\ &= \sum_{k'} \sum_{l'} y_{ikl}(k'l') \end{aligned} \tag{5}$$

where $A_{k'l'} = A'_{k'l'} R_k(\psi,\varphi)$, parameter $\tilde{\Phi}_{kl}$ is the estimate of Φ_{kl} and

$$\begin{aligned} y_{ikl}(k'l') &= y_{iikl}(k'l') + y_{iqkl}(k'l') \\ &= A_{k'l'} \big[d_{ik'} \rho_{ik'l',ikl} \cos \varepsilon_{k'l',kl} + d_{qk'} \rho_{qk'l',ikl} \sin \varepsilon_{k'l',kl} \big], \end{aligned} \tag{6}$$

where $\rho_{x,y}$ are crosscorrelation functions between the corresponding code components x and y. The quadrature correlation function is similar to the in-phase one, and may be found in [2].

Each of these components is defined with three indices. Parameter $\varepsilon_{a,b} = \Phi_a - \tilde{\Phi}_b$ where a and b are defined with two indices each.

In order to receive the incoming signal without any losses, the receiving antenna should be directing (pointing) the maximum of its radiation diagram towards the angle of arrival of the incoming signal. In this paper we will assume that the tracking is perfect.

3. PERFORMANCE ANALYSIS

The starting point in the evaluation of CDMA system capacity is the parameter $Y_m = E_{bm}/N_0$, the received signal energy per symbol per overall noise density in a given reference receiver with index m. For the purpose of this analysis we can represent this parameter in general case as

$$Y_m = \frac{E_{bm}}{N_0} = \frac{ST}{I_{oc} + I_{oic} + I_{oin} + \eta_{th}} \tag{7}$$

where I_{oc}, I_{oic} and I_{oin} are power densities of intracell, intercell and overlay type internetwork interference, respectively and η_{th} is thermal noise power density. S is the overall received power of the useful signal and $T = 1/R_b$ is the information bit interval. Contributions of I_{oic} and I_{oin} to N_0 are parameterized by introducing $\eta_0 = I_{oic} + I_{oin} + \eta_{th}$, and the contribution of teh intracell interference is analyzed in [2].

It was shown in [2] that the received signal energy per symbol per overall noise density, for mth user, may be represented as

$$Y_b = \frac{r^{(L_0)} G}{f(\boldsymbol{\alpha}) K + L_0 \eta_0 W / S} \tag{8}$$

where $r^{(L_0)}$ is the rake receiver efficiency, and is defined as

$$r^{(L_0)} = \left(\sum_{r=1}^{L_0} \cos \varepsilon_\theta \sqrt{\alpha_r} \right)^2 \tag{9}$$

$$f(\boldsymbol{\alpha}) = \frac{L_0}{K} \sum_{k=1}^{K} \sum_{l=1}^{L} \overline{\alpha}_{kl} (1 - C_{kl}) + \frac{L_0}{K} \sum_{l=2}^{L} \overline{\alpha}_l (1 - C_{ml}) \tag{10}$$

L_0 is the number of Rake fingers, $G = W / R_b$ is the system processing gain and W is the system bandwidth (chip rate). C_{kl} is the efficiency of the canceller, and for DPSK it may be approximated as $C_{kl} = 2Y_b - 1$.

Averaged power coefficients in the multipath intensity profile are

$$\overline{\alpha_l} = \overline{\alpha_0} e^{-\lambda l} \quad l, \lambda \geq 0 \tag{11}$$

where λ is the decay parameter of the profile.

Now, if we accept some quality of transmission, BER = 10^{-e}, that can be achieved with the given SNR = Y_0, then the system capacity is [2]

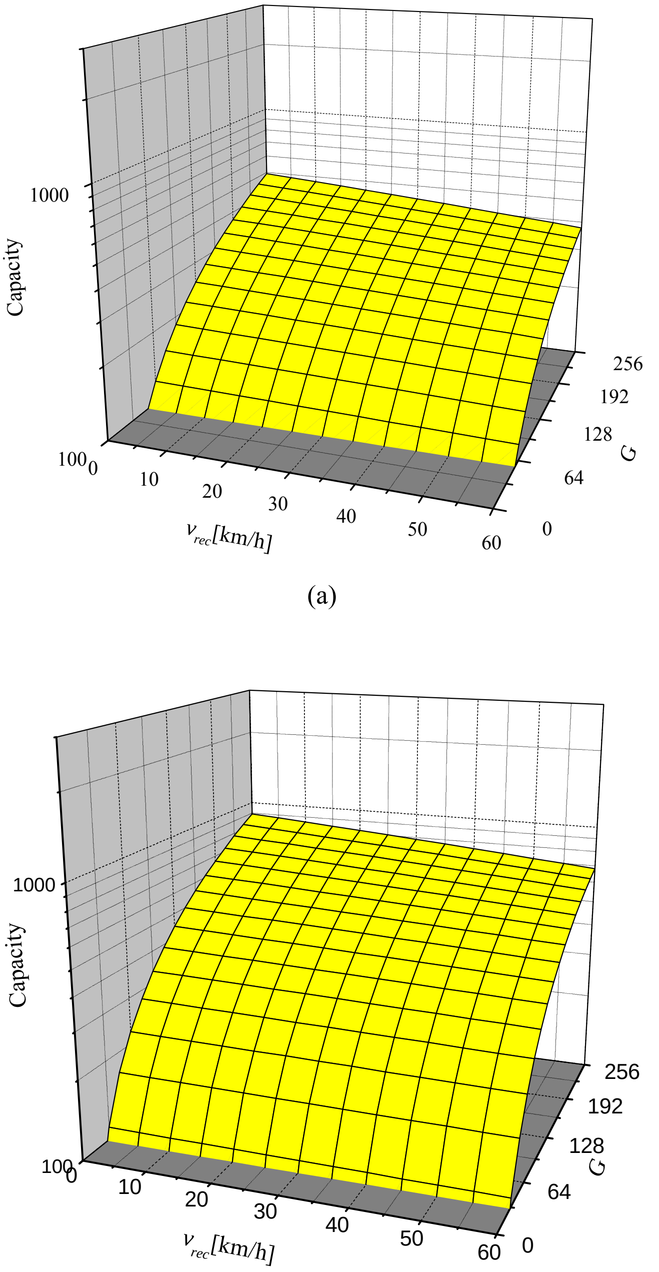
$$K = \frac{r^{(L_0)} G}{Y_0 f(\boldsymbol{\alpha})} - L_0 \eta' W / S f(\boldsymbol{\alpha}) \, . \tag{12}$$

4. NUMERICAL EXAMPLES

The results are obtained for a channel with double exponential (space and delay) profile with decay factors λ_s and λ_t. The base station amplitude antenna pattern is given as

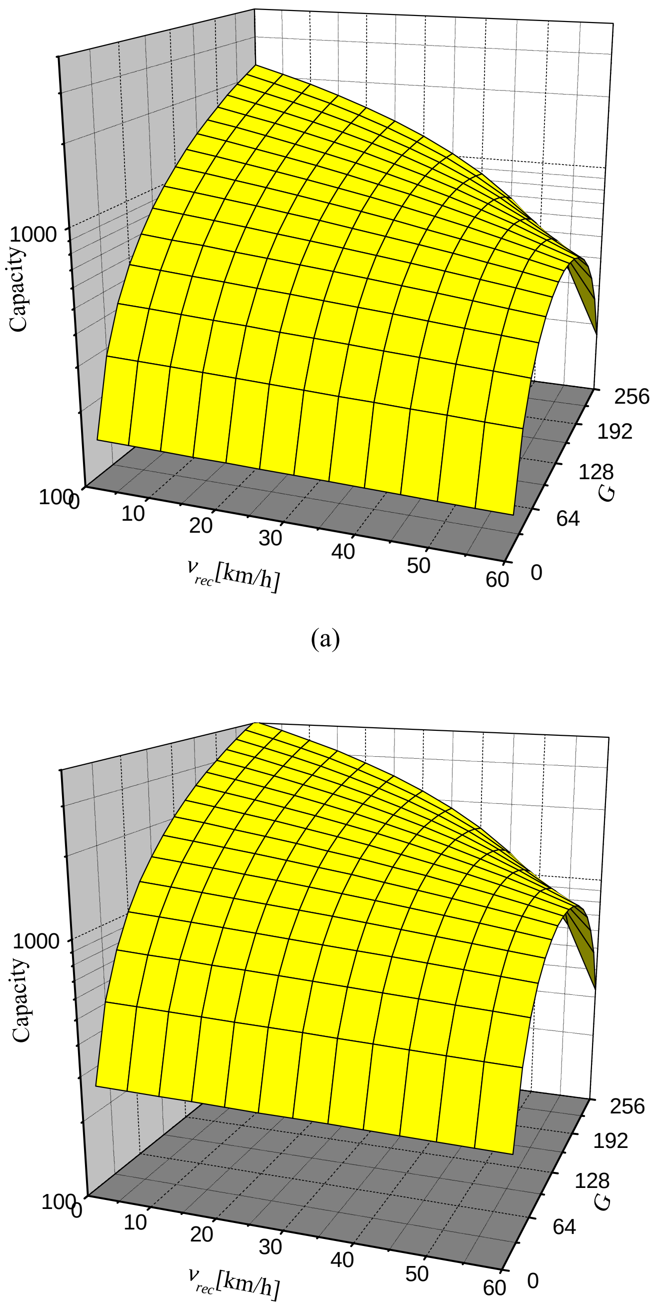
$$A(\varphi, \psi) = \frac{1}{N} \sum_{n=1}^{N} \exp \left\{ -\pi \left[\rho_c \sin \psi \cos \left(\varphi - 2\pi \frac{n}{N} \right) \right]^2 \right\}$$

with $N = 4$, and $\rho_c = 1$. In the case of 3db-approximation of the real antenna the beam forming is approximated with rectangular shape of antenna pattern in the range $\varphi_{3\text{dB}} = 30°$, $\lambda_s = \lambda_t = 0$ (i.e. flat profile) if not specified otherwise, $Y_0 = 2$, $L = 4$. The users are uniformly distributed in the semi-sphere (φ, ψ) with $\varphi \in (0, 360°)$, $\psi \in (0, 90°)$. At mobile station an omni directional antenna pattern $A(\varphi, \psi) = 1$ is assumed.



(b)

Fig. 2. *System cacapity as a function of receiver velocity and processing gain for 4×1 Rake*
(a) Real antenna, (b) 3dB approximation of real antenna



(a)

(b)

Fig. 3. *System capacity as a function of receiver velocity and processing gain for 4×4 Rake*
(a) Real antenna, (b) 3dB approximation of real antenna

Figs. 2 and 3 show the capacity of the system, defined as the number of users with data rate $R = chiprate / G$, where *chiprate* = 4.096 Mchip/s, as a function of receiver velocity and processing gain for different Rake configurations. In general higher *G* means more users in the network and more MAI resulting in more impact of imperfections. A 4×4 rake performs better for lower *G*, but for higher *G* (more users) it deteriorates faster. The degradation is more severe for higher receiver velocities. It can be seen that the parameters have the simillar influence on system capacity, regardless of base station antenna pattern definition (real pattern or approximation). The only difference is that the use of 3dB-approximation gives slightly better performances.

5. CONCLUSIONS

In this paper we have presented a capacity analysis of an advanced CDMA network. This approach provides a relatively simple way to specify the required quality of a number of system components. This includes multiple access interference canceller and rake receiver, taking into account all their imperfections. In general, under ideal conditions, the system capacity is increased if the number of fingers is increased, but the system with 4×4 Rake is more sensitive to the imperfections in the Rake operations than the one with 4×1 Rake. Analyzed parameters influence the system capacity in the simillar way in case of both real antenna pattern and its 3dB-approximation. Because of that, it is possible to use only much simplier 3dB-approximation in order to have insight in the system performance.

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