Performance of MMSE Multiuser Detection in Cellular DS-CDMA Systems Using Distributed Antennas

Lie-Liang Yang
School of ECS, University of Southampton, SO17 1BJ, UK
Tel: +44-23-8059 3364; Fax: +44-23-8059 4508
E-mail: lly@ecs.soton.ac.uk; http://www-mobile.ecs.soton.ac.uk

***Abstract*— In this contribution we propose and investigate a high-capacity cellular direct-sequence code-division multiple-access (DS-CDMA) wireless communications system, where numerous antennas are distributed in the area covered by the system. The bit error rate (BER) performance of the distributed antenna cellular DS-CDMA system is investigated, when minimum mean-square error (MMSE) multiuser detection is employed, and when transmission pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading are considered. Our study suggests that the distributed antenna cellular DS-CDMA system constitutes a high power-efficiency wireless system. For utilizing the same set of system parameters, it is capable of providing an extremely higher capacity, than the cellular DS-CDMA system designed based on the conventional cellular concepts. Furthermore, the proposed distributed antenna cellular system can be operated without having to use power-control.**

I. Introduction

Among radio technologies, multiple-input-multiple-output (MIMO) systems using multiple transmit and/or receive antennas have attracted wide research interests in recent years [1], [2]. In this contribution we propose and investigate a cellular DS-CDMA system using distributed antennas, where many antennas are distributed in the area covered by the system. Here we consider the DS-CDMA technique, since it has been a typical multiple-access scheme in both the second- and the third-generation wireless communications systems [3]. Without any doubt, DS-CDMA technique will constitute an important candidate in the future generations of wireless communications systems. In our proposed distributed antenna cellular DS-CDMA system, the distributed antennas are connected with a number of signal processing centers, which are referred to as base-stations (BSs), using optical fibers. The reason for emphasis on optical fiber instead of wireless for implementing communications between distributed antennas and BSs is mainly for the sake of saving the highly limited wireless resources. Note that, we still use the concept of BS, however, in the proposed distributed antenna cellular DS-CDMA system the BS is now rather a signal processing center than a conventional BS. The antennas at the BSs of the proposed distributed antenna system are assumed have no priority in comparison with the other distributed antennas. A BS or a signal processing center is mainly responsible for the signal processing of the users within the area covered by the distributed antennas connected with this BS.

In this contribution we first describe the distributed antenna cellular DS-CDMA system. Then, the MMSE multiuser detection for the distributed antenna cellular DS-CDMA system is investigated. The BER performance of the cellular DS-CDMA system using distributed antennas is evaluated, when communicating over composite lognormal shadowing slow fading and Nakagami-m fast fading channels associated with transmission pass-loss. Our study shows that, in the distributed antenna cellular DS-CDMA system the detection is location-aware. The distributed antenna cellular DS-CDMA system constitutes a high power-efficiency wireless system. When using the same set of system parameters and the same number of antennas, our proposed distributed antenna cellular DS-CDMA system is capable of supporting an extremely higher number of users, than a conventional concept-based cellular DS-CDMA system, which employs centralized BS antennas.

II. Cellular DS-CDMA System with Distributed Antennas

A. System Description

The structure of the proposed cellular DS-CDMA system using distributed antennas can be well-described with the aid of Fig. 1. It is well-known that, in conventional cellular systems [4], [5] each cell is centered around a BS, which may employ a set of antennas. By contrast, in the proposed distributed antenna aided cellular concept, as shown in Fig. 1, each cell has numerous sets of antennas, which are distributed within the area covered by a cell and are connected to the BS using optical fiber, as we mentioned previously. In the distributed antenna cellular systems of Fig. 1, the antennas near the borders may be connected with two or three BSs, so that soft-handoff can be achieved. For example, as shown in Fig. 1, each of the antennas within the dash-dotted box or the dashed circle may be connected with BS_1 of Cell 1, BS_2 of Cell 2 or BS_3 of Cell 3.

In the considered distributed antenna system, for the convenience of analysis, we assume that the cells are shaped as hexagons with the common radius of R. We assume that any a pair of adjacent antennas are separated by a distance of r. Hence, each antenna is surrounded by numerous distributed antennas located at the corners of the layered hexagons. Specifically, for the antenna marked as A_3 in Fig. 1, the first layer has six antennas, the second layer has 12 antennas including the antenna located at BS_1, and so on. Note that, the structure of Fig. 1 is sufficiently general for approximately modeling the distributed antenna systems having an arbitrary antenna density. This can be done by appropriately changing the radius value of R in Fig. 1.

In distributed antenna systems as shown in Fig. 1, we assume that the distributed antennas only implement the functions of conveying a signal from radio frequency (RF) to baseband or from baseband to RF, in order to make the computation burden at a distributed antenna as low as possible. The above assumption might be due to the size constraint of the distributed antennas and the constraint arising from some supported signal processing. For example, when advanced multiuser detection (MUD) is employed, information associated with each mobile terminal (MT) and each antenna should be shared by any individual processor. In this case, using distributed processing in the context of each distributed antenna would require an extremely powerful network for conveying the information timely and efficiently, which might not be practical in the near future. Hence, in our distributed antenna system all signals received from the MTs by the distributed antennas are conveyed to the BSs, where the processing is carried out. Simultaneously, all the distributed antennas are also used for transmitting signals from the BSs to the MTs, in order to improve the down-link transmission quality.

0-7803-9392-9/06/$20.00 (c) 2006 IEEE

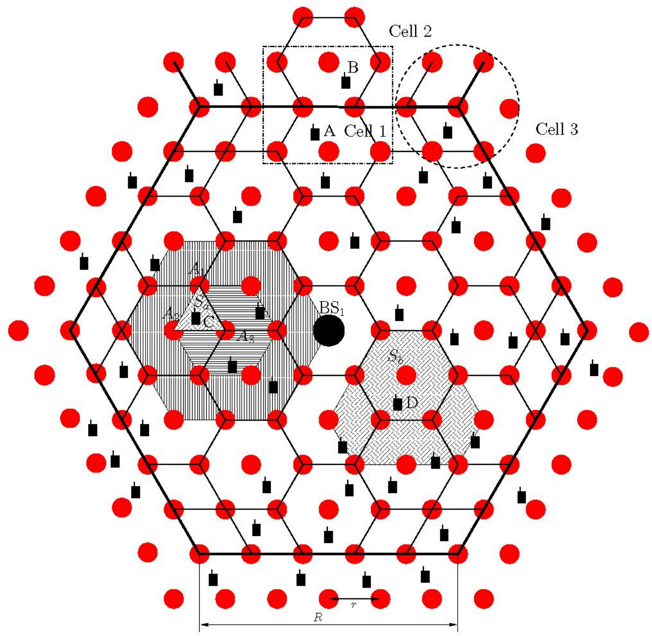

Fig. 1. A conceptual cellular DS-CDMA system structure with distributed antennas, where the distributed antennas are connected with one, two or three base-stations (BSs) located at the centers of the cells using optical fiber.

In this contribution, specifically, we consider and investigate the distributed antenna systems using DS-CDMA signaling. Hence, when considering conventional binary phase shift keying (BPSK) baseband modulation, the transmitted DS spread spectrum signal, say by the kth MT, can be expressed as

$$s_k(t) = \sqrt{2P}b_k(t)c_k(t)\cos\left(2\pi f_c t + \phi_k\right) \tag{1}$$

where P is the user's transmitted power, f_c is the carrier frequency, while ϕ_k denotes the initial phase angle associated with the carrier modulation. The data stream's waveform $b_k(t) = \sum_{n=-\infty}^{\infty} b_k[n]P_{T_b}(t - nT_b)$ consists of a sequence of mutually independent rectangular pulses of duration T_b and of amplitude of +1 or -1, where T_b is the bit duration. Finally, in (1) $c_k(t) = \sum_{j=-\infty}^{\infty} c_{kj}\psi_{T_c}(t - jT_c)$ denotes the signature sequence waveform of the kth user, where c_{kj} assumes values of +1 or -1 with equal probability, while $\psi_{T_c}(t)$ is the chip waveform, which is defined over the interval $[0, T_c)$ and has the property of $\int_0^{T_c} \psi_{T_c}^2(t)dt = T_c$.

Note that, in this contribution we assume that each MT employs only a single antenna, which is sufficient for fulfill our objectives by focusing on the issues of the distributed antenna systems. However, our investigation can be extended to the distributed antenna systems that use multiple MT antennas aided by some advanced transmit and receive schemes [6], [7]. Furthermore, we assume that the distributed antenna cellular DS-CDMA uses no power-control. This is because, as shown in Fig. 1, no matter where a MT is, it communicates with a number of antennas located within its line-of-sight (LoS) area. The signals sampled from the antennas within the LoS area of the considered MT usually fall within the cluster of strongest signal. Consequently, the considered MT conflicts no or light near-far problem.

B. Propagation Channel Modeling

In distributed antenna cellular systems, for any a given MT, there are a number of antennas within the LoS area of the MT. The LoS area of a MT is referred to as its virtual cell. The antennas within the virtual cell of a MT are used to communicate between this MT and its BS. Hence, the propagation channel between a MT and any of the antennas within its virtual cell can be well modeled by a composite shadowing-fading model [8], where (slow) shadowing can be described by a lognormal distribution [8], while (fast) fading by a Rician or Nakagami-m distribution [9]. Specifically, in this contribution frequency non-selective Nakagami fading [9] is used to model the fast fading.

Let MT_0 be the reference terminal and assume that the signal transmitted by the reference terminal MT_0 is being detected. The reference terminal MT_0 randomly moves within the triangle area with three antennas at its corners. For example, MT C in Fig. 1 randomly moves within the triangle area S_a. We assume that there are U antennas within the virtual cell of MT_0. Signals collected from these U antennas are processed, in order to detect the information transmitted by MT_0. Consequently, when assuming that K user signals in addition to that from MT_0 are received by the uth antenna, the received complex low-pass equivalent signal can then be expressed as

$$\begin{aligned} r_u(t) = \sqrt{2P}h_{0u}b_0(t)c_0(t) + \sum_{k=1}^{K} \sqrt{2P}h_{ku} \\ \times b_k(t-\tau_k)c_k(t-\tau_k) + n_u(t) \end{aligned} \tag{2}$$

where $n_u(t)$ is the complex-valued additive white Gaussian noise (AWGN) received by the uth receive antenna, which has zero-mean and a single-sided spectrum density of N_0 per dimension, τ_k represents the channel delay associated with asynchronous transmission and propagation, which is assumed to be uniformly distributed within $[0, T_b)$. Furthermore, in (2) h_{ku} represents the channel gain connecting MT_k and the uth antenna. The channel gain h_{ku} takes into account both shadowing and fading, which can be expressed as

$$h_{ku} = \beta_{ku}\alpha_{ku}e^{j\theta_{ku}}, \tag{3}$$

where, without loss of any generality, the initial phase seen in (1) and the phase due to channel have been absorbed into θ_{ku}, and θ_{ku} is assumed to be uniformly distributed in $[0, 2\pi)$. In (3) β_{ku} represents the lognormal shadowing factor, accounting for large scale geographical variation, while α_{ku} represents the fast fading envelope. We assume that the transmission pass-loss is absorbed in the shadowing factor β_{ku}, so that the mean-square value of α_{ku} is unit, i.e., $\Omega = E\left[\alpha_{ku}^2\right] = 1$. Furthermore, we assume that β_{ku} and α_{ku} are mutually independent and both of them are also independent of θ_{ku}.

Since the fast fading α_{ku} is modeled by Nakagami-m distribution, hence, α_{ku}^2 is Gamma distributed with the probability density function (PDF) expressed as [9]

$$p_{\alpha_{ku}^2}(y) = \frac{m^m}{\Gamma(m)}y^{m-1}\exp\left(-my\right),\ y \geq 0 \tag{4}$$

where $\Gamma(\cdot)$ is the Gamma function, and, again, m is a parameter accounting for the fading severity. In (3) β_{ku} represents the shadowing, which can be modeled as lognormal distribution [9]. It can be shown that β_{ku}^2 also obeys lognormal distribution having the PDF given by [9]

$$p_{\beta_{ku}^2}(r) = \frac{\xi}{\sqrt{2\pi}\sigma_\beta r}\exp\left[-\frac{(10\log_{10} r - \mu_{ku})^2}{2\sigma_\beta^2}\right],\ r > 0 \tag{5}$$

where $\xi = 10/\ln 10 = 4.3429$, and μ_{ku} (dB) and σ_β (dB) are the mean and standard deviation of $10\log_{10} r$, respectively. Finally, since we assumed that both the fast Nakagami-m fading and the shadowing slow fading are independent random processes, hence the PDF of $|h_{ku}|^2$ is simply the product of (4) and (5).

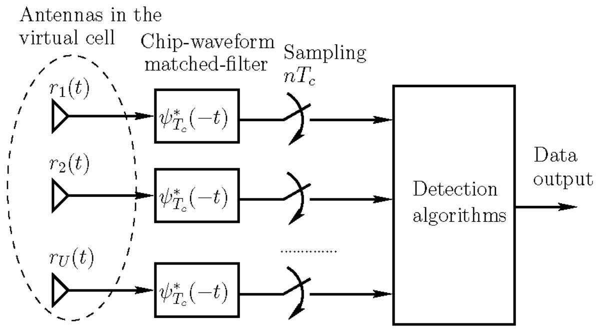

Fig. 2. Receiver block diagram for the reference MT in the distributed antenna cellular DS-CDMA system.

C. Representation of The Received Signal

The receiver structure for detection of the reference signal from MT_0 is shown in Fig.2. As shown in Fig.2 the received signals from the U antennas in the virtual cell of MT_0 are first passed through a bank of filters matched to the chip-waveform pulse of $\psi_{T_c}(t)$. Then, the outputs of the matched-filters are sampled at a rate of $1/T_c$. Hence, in correspondence with each data bit, a total of N samples can be obtained from each antenna, where N represents the number of chips per bit or the spreading factor. Let us consider the detection of the first data bit transmitted by MT_0. Then, the λth sample of the uth antenna can be expressed as

$$y_{\lambda u} = \left(\sqrt{2P/NT_b}\right)^{-1} \int_{\lambda T_c}^{(\lambda+1)T_c} r_u(t)\psi^*_{T_c}(t-\lambda T_c)dt \tag{6}$$

where $\lambda = 0, 1, \ldots, N-1$; $u = 1, 2, \ldots, U$, $\sqrt{2P/NT_b}$ is a normalization factor, and * represents the complex conjugate.

Let

$$\begin{aligned} \boldsymbol{y}_u &= \left[y_{0u}, y_{1u}, \ldots, y_{(N-1)u}\right]^T, & (7)\\ \boldsymbol{n}_u &= \left[n_{0u}, n_{1u}, \ldots, n_{(N-1)u}\right]^T & (8) \end{aligned}$$

be the N-length observation vector and noise vector corresponding to the uth antenna. According to (6), we can know that the element $n_{\lambda u}$ in $\boldsymbol{n}$ is a complex Gaussian random variable with zero-mean and a variance of $\sigma^2 = N_0/2E_b$ per dimension, where $E_b = PT_b$ represents the energy per bit. Let us assume that $\tau_{ku} = l_{ku}T_c + v_{ku}$, where $l_{ku} \geq 0$ and $0 < v_{ku} < T_c$. Then, upon substituting the received signal in the form of (2) into (6) and expressing in vector and matrix forms, it can be shown that $\boldsymbol{y}_u$ can be expressed as

$$\boldsymbol{y}_u = h_{0u}\boldsymbol{c}_0 b_0[0] + \sum_{k=1}^{K} h_{ku}\boldsymbol{C}_{ku}\boldsymbol{R}_\psi(v_{ku})\boldsymbol{b}_k + \boldsymbol{n}_u \tag{9}$$

where $\boldsymbol{b}_k = [b_k[-1], b_k[0]]^T$ contains the two data bits transmitted by the kth MT within $[0, T_b)$, while the other arguments in (9) are given by

$$\boldsymbol{c}_0 = \frac{1}{\sqrt{N}}\left[c_{00}, c_{01}, \ldots, c_{0(N-1)}\right]^T$$

$$\boldsymbol{C}_{ku} = \frac{1}{\sqrt{N}}\begin{bmatrix} c_{k(N-l_{ku}-1)} & c_{k(N-l_{ku})} & 0 & 0\\ c_{k(N-l_{ku})} & c_{k(N-l_{ku}+1)} & 0 & 0\\ \vdots & \vdots & \vdots & \vdots\\ c_{k(N-2)} & c_{k(N-1)} & 0 & 0\\ c_{k(N-1)} & 0 & 0 & c_{k0}\\ 0 & 0 & c_{k0} & c_{k1}\\ \vdots & \vdots & \vdots & \vdots\\ 0 & 0 & c_{k(l_{ku}-2)} & c_{k(l_{ku}-1)}\\ 0 & 0 & c_{k(l_{ku}-1)} & c_{kl_{ku}} \end{bmatrix}$$

$$\boldsymbol{R}_\psi(v_{ku}) = \begin{bmatrix} R_\psi(v_{ku}) & 0\\ \hat{R}_\psi(v_{ku}) & 0\\ 0 & R_\psi(v_{ku})\\ 0 & \hat{R}_\psi(v_{ku}) \end{bmatrix}$$

where $R_\psi(v_{ku})$ and $\hat{R}_\psi(v_{ku})$ are the chip auto-correlation functions, which are defined as $\hat{R}_\psi(s) = \frac{1}{T_c}\int_s^{T_c}\psi_{T_c}(t)\psi_{T_c}(t-s)dt$ and $R_\psi(s) = \hat{R}_\psi(T_c - s)$ for $0 \leq s < T_c$, respectively.

Furthermore, let

$$\boldsymbol{y} = \left[\boldsymbol{y}_1^T, \boldsymbol{y}_2^T, \ldots, \boldsymbol{y}_U^T\right]^T \tag{10}$$

which collects all the samples from the U antennas related to the detection of the first bit of MT_0. Then, $\boldsymbol{y}$ can be expressed as

$$\boldsymbol{y} = (\boldsymbol{I}_U \otimes \boldsymbol{c}_0)\boldsymbol{h}_0 b_0[0] + \sum_{k=1}^{K}\boldsymbol{C}_k\boldsymbol{R}_{\psi k}\boldsymbol{H}_k\boldsymbol{b}_k + \boldsymbol{n} \tag{11}$$

where

$$\boldsymbol{n} = \left[\boldsymbol{n}_1^T, \boldsymbol{n}_2^T, \ldots, \boldsymbol{n}_U^T\right]^T \tag{12}$$

is an UN-length Gaussian noise vector,which has zero mean and a co-variance matrix of $2\sigma^2\boldsymbol{I}_{UN}$, $\otimes$ represents the *Kronecker product* [10] operation, and the other arguments in (11) are given as follows:

$$\begin{aligned} \boldsymbol{h}_0 &= [h_{01}, h_{02}, \ldots, h_{0U}]^T & (13)\\ \boldsymbol{C}_k &= \text{diag}\left\{\boldsymbol{C}_{k1}, \boldsymbol{C}_{k2}, \ldots, \boldsymbol{C}_{kU}\right\} & (14)\\ \boldsymbol{R}_{\psi k} &= \text{diag}\left\{\boldsymbol{R}_\psi(v_{k1}), \boldsymbol{R}_\psi(v_{k2}), \ldots, \boldsymbol{R}_\psi(v_{kU})\right\} & (15)\\ \boldsymbol{H}_k &= \left[\boldsymbol{H}_{k1}^T \quad \boldsymbol{H}_{k2}^T \quad \ldots \quad \boldsymbol{H}_{kU}^T\right]^T & (16) \end{aligned}$$

where $\boldsymbol{H}_{ku} = h_{ku}\boldsymbol{I}_2$. Let us now discuss the MMSE detection in the distributed antenna cellular DS-CDMA systems.

III. Location-Aware MMSE Multiuser Detection

In this section we investigate the location-aware detection in the distributed antenna cellular DS-CDMA systems, where a user signal, say MT_0, is detected by the MMSE principles based on the observation data sampled from the antennas within the considered user's virtual cell. The detection is on the basis of symbol-by-symbol.

For a linear MMSE assisted MUD, the received observation vector $\boldsymbol{y}$ given in (11), which is obtained from the LoS area of MT_0, is linearly processed to form the decision variable, Z_0, i.e., we have

$$Z_0 = \Re\left\{\boldsymbol{w}^H\boldsymbol{y}\right\} \tag{17}$$

where $\Re\{x\}$ represents the real part of x, while $\boldsymbol{w}$ is the weight vector, the optimum weight vector of which in MMSE sense can be expressed as

$$\boldsymbol{w}_0 = \boldsymbol{R}_y^{-1}\boldsymbol{r}_{yb_0} \tag{18}$$

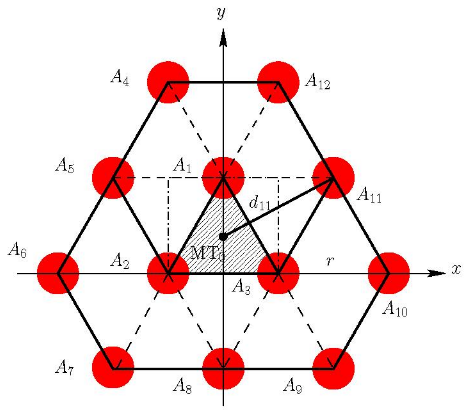

Fig. 3. Antennas whose signals may be collected for detection of MT$_0$, when MT$_0$ is within the filled area.

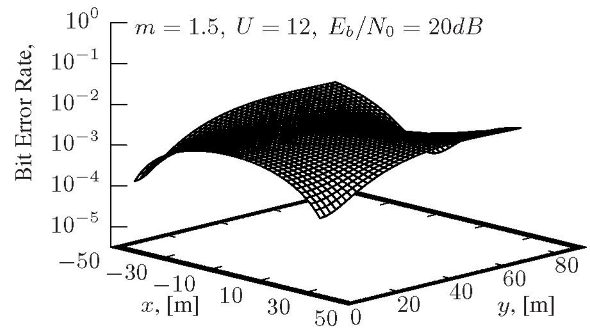

Fig. 4. **Single-user bound**: BER versus coordinates (x, y) performance of the distributed antenna cellular DS-CDMA system supporting single user using the specific parameters of $m = 1.5$, $U = 12$, $E_b/N_0 = 20dB$, when the user signal experiences pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading.

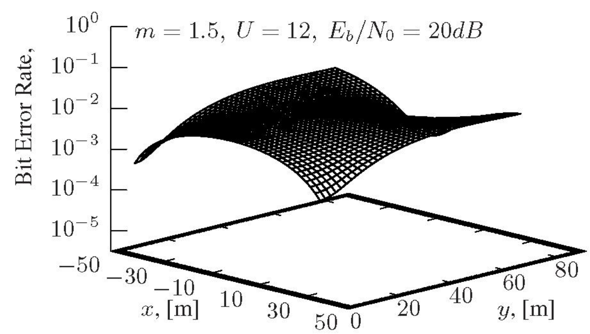

Fig. 5. **MMSE**: BER versus coordinates (x, y) performance of the distributed antenna cellular DS-CDMA system supporting K=10000 users using the specific parameters of $m = 1.5$, $U = 12$, $E_b/N_0 = 20dB$, when user signals experience pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading.

where $\boldsymbol{R}_y$ is the autocorrelation matrix of the received vector $\boldsymbol{y}$, while $\boldsymbol{r}_{yb_0}$ is the cross-correlation vector between the received vector $\boldsymbol{y}$ and the desired symbol $b_0[0]$. They can be, respectively, expressed as

$$\boldsymbol{R}_y = E\left[\boldsymbol{y}\boldsymbol{y}^H\right], \quad \boldsymbol{r}_{yb_0} = E\left[\boldsymbol{y}b_0[0]\right] \tag{19}$$

Assume that all the data bits transmitted by different MTs are independent. Then, we have

$$\begin{aligned} \boldsymbol{R}_y &= \left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)\boldsymbol{h}_0\boldsymbol{h}_0^H\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0^T\right) \quad (20)\\ &\quad + \underbrace{\sum_{k=1}^{K} E\left[\boldsymbol{C}_k\boldsymbol{R}_{\psi k}\boldsymbol{H}_k\boldsymbol{H}_k^H\boldsymbol{R}_{\psi k}^T\boldsymbol{C}_k^T\right] + 2\sigma^2\boldsymbol{I}_{UN}}_{\boldsymbol{\Sigma}_0} \\ \boldsymbol{r}_{yb_0} &= \left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)\boldsymbol{h}_0 \quad (21) \end{aligned}$$

where $\boldsymbol{\Sigma}_0$ represents the covariance matrix of the interfering signals plus background noise. Finally, upon substituting (20) and (21) into (18), we obtain

$$\boldsymbol{w}_0 = \left[\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)\boldsymbol{h}_0\boldsymbol{h}_0^H\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0^T\right) + \boldsymbol{\Sigma}_0\right]^{-1}\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)\boldsymbol{h}_0 \tag{22}$$

With the aid of the *matrix inverse lemma* [10], (22) can be simplified as

$$\boldsymbol{w}_0 = \frac{\boldsymbol{\Sigma}_0^{-1}\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)\boldsymbol{h}_0}{1 + \boldsymbol{h}_0^H\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0^T\right)\boldsymbol{\Sigma}_0^{-1}\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)\boldsymbol{h}_0} \tag{23}$$

Furthermore, the resultant MMSE is given by

$$\begin{aligned} \text{MMSE} &= 1 - \boldsymbol{r}_{yb_0}^H\boldsymbol{w}_0 \\ &= \left[1 + \boldsymbol{h}_0^H\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0^T\right)\boldsymbol{\Sigma}_0^{-1}\left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)\boldsymbol{h}_0\right]^{-1} \quad (24) \end{aligned}$$

Let us now show a range of BER performance results, in order to characterize the distributed antenna cellular DS-CDMA systems.

IV. Examples of Performance Results

In this section we provide a range of results for illustrating the achievable performance of the exemplified distributed antenna cellular DS-CDMA system using a set of specific parameters. Due to the symmetric structure of the distributed antenna system shown in Fig.1, it is sufficient for us to evaluate the BER performance of MT$_0$, when it moves within the triangular area shown in Fig.3[1], which shows the antennas within the virtual cell of MT$_0$. Note that the SNR per bit of E_b/N_0 used in the figures of this section represents the average SNR per bit at the MT transmitter location. Conventionally, when transmission pass-loss is not considered or ideal power-control is assumed, the average SNR at the receiver is usually used. Due to the transmission path-loss, it can be readily show that the SNR measured at the transmitter side is significantly higher than that measured at the receiver side for a given value of transmitted power.

[1]We note that, for the sake of convenience for drawing the figures, in Figs. 4 and 5 the BER within the dash-dotted square was evaluated. However, only the BER corresponding to the triangular area is meaningful.

In Figs. 4 and 5 we evaluated the BER performance of MT$_0$, when it moved within the triangular area as marked in Fig.3. Specifically, in the context of Fig. 4 using $U = 12$ receive antennas, we assumed that the distributed antenna cellular DS-CDMA system supported only

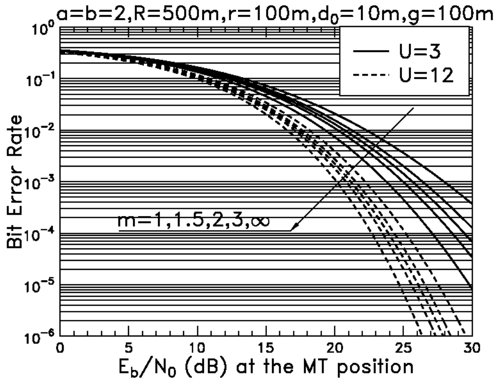

Fig. 6. **Single-user bound**: BER versus SNR per bit, E_b/N_0, performance of the distributed antenna cellular DS-CDMA system supporting single user, when the user signal experiences pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading.

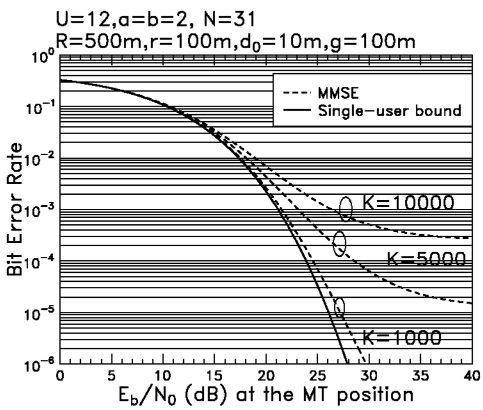

Fig. 7. **MMSE**: BER versus SNR per bit, E_b/N_0, performance for the distributed antenna cellular DS-CDMA system using MMSE detectors, when user signals experience pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading ($m = 2$).

one user. Hence, the corresponding BER performance represents the single-user BER bound. By contrast, Fig.5 corresponds to the distributed antenna cellular DS-CDMA system supporting $K = 10000$ users per cell. From the results of Figs. 4 and 5, we can observe that the BER performance does not vary significantly, when a MT moves within the system, provided that it is not too close to an antenna. However, when a MT is close to an antenna, the received power by this antenna will dominate the achievable BER performance of the MT and the resultant BER is lower than that achieved, when the MT is away from all the antennas at certain distances. By comparing the results of Fig. 4 and Fig.5, it can be shown that the multiuser interference also slightly degrades the achievable BER performance.

The results in Figs. 6 and 7 were evaluated, when MT_0 is at the center of the shadowed triangle seen in Fig.3. In Fig.6 the single-user BER bound versus SNR per bit of E_b/N_0 performance was evaluated in the context of the distributed antenna cellular DS-CDMA system for $m = 1, 1.5, 2, 3$ and ∞, and for $U = 3$ and $U = 12$. Explicitly, the BER performance improves, when the fast fading becomes less severe, i.e., when the value of the fading parameter m increases. The detection using the signals collected from $U = 12$ antennas outperforms that from $U = 3$ antennas, and the gain for $m = 1$ is about 5dB, while for $m \rightarrow \infty$ is about 3dB, at the BER of 10^{-3}. By contrast, in Fig. 7 the achievable BER performance of MMSE detector is depicted. The benchmark single-user BER bound is also shown in Fig. 7. As shown in Fig. 7, when the number of users supported by a cell is $K = 1000$, we observe no error-floor for the MMSE detector. However, when the number of users per cell is $K = 5000$ or $K = 10000$, explicit error-floors are observed. This might be because, although the interfering signals are weak, but the number of interfering signals received by each antenna is high, which may be far beyond the interference suppression capability of the MMSE detector.

Furthermore, as shown in Fig. 7, for the target BER of 10^{-2}, the MMSE assisted distributed antenna cellular DS-CDMA system using a spreading factor of $N = 31$ is capable of supporting upto $K = 10000$ users per cell with the SNR per bit of 19dB at the transmitter site. Supporting $K = 10000$ users per cell is far beyond the capability of a conventional cellular DS-CDMA concept, when it uses the spreading factor of $N = 31$ and employs 91 antennas located at the BS. This is because, in this case, the total number of degrees-of-freedom available at a BS in the conventional cellular DS-CDMA system is about $31 \times 91 = 2821$. Any linear detector using this number of degrees-of-freedom is impossible to distinguish $K = 10000$ signals, which have a similar power-level due to using power control.

In conclusions, in this contribution we have proposed and investigated a distributed antenna cellular DS-CDMA wireless system, where a big number of antennas are distributed in the area of a cell and are connected with the signal processing center referred to as BS. From our analysis and results, we may argue that the distributed antenna cellular DS-CDMA system consists of one of the high power-efficiency wireless systems. When using the same set of system parameters, the distributed antenna cellular DS-CDMA system is capable of supporting an extremely higher number of users, than the conventional cellular DS-CDMA systems using centralized BS antennas.

ACKNOWLEDGMENT

The author would like to acknowledge with thanks the financial assistance from EPSRC of UK.

REFERENCES

[1] I. E. Telatar, "Capacity of multiantenna Gaussian channels," *European Trans. on Telecomm.*, vol. 10, pp. 585–595, Nov./Dec. 1999.
[2] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, "An overview of MIMO communications - A key to Gigabit wireless," *Proc. of the IEEE*, vol. 92, pp. 198 – 218, Feb. 2004.
[3] L. Hanzo, L.-L. Yang, E.-L. Kuan, and K. Yen, *Single- and Multi-carrier DS-CDMA*. John Wiley and IEEE Press, 2003.
[4] A. J. Viterbi, *CDMA: Principles of Spread Spectrum Communications*. New York: Addison-Wesley Publishing Company, 1995.
[5] W. C. Y. Lee, *Mobile Communications Engineering*. New York: McGraw-Hill, 2nd ed., 1998.
[6] D. Gesbert, M. Shafi, and et. al, "From theory to practice: An overview of MIMO space-time coded wireless systems," *IEEE J. on Select. Areas in Commun.*, vol. 21, pp. 281–302, April 2003.
[7] B. Hochwald, T. L. Marzetta, and C. B. Papadias, "A transmitter diversity scheme for wideband CDMA systems based on space-time spreading," *IEEE J. on Select. Areas in Commun.*, vol. 19, pp. 48–60, Jan. 2001.
[8] T. S. Rappaport, *Wireless Communications Principles and Practice*. New York: Prentice Hall, Inc, 2 ed., 2002.
[9] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*. New York: John Wiley & Sons, 2000.
[10] H. L. V. Trees, *Optimum Array Processing*. Wiley Interscience, 2002.