Information Theoretic Capacity of a Gaussian Cellular Multiple-Access MIMO Fading Channel

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Abstract

Capacity can be increased by exploiting the space dimension inherent to any wireless communication system. Recent information theoretic results show that simultaneous use of multiple receive and multiple transmit antennas can offer dramatic increase in capacity. In this paper each cell-site receiver and each user terminal is assumed to be equipped with multiple antennas. Then,under a per transmit antenna power constraint, a closed form expression for the optimum capacity is found using the well known Wyner's model. The results show that even one antenna per-user is enough to achieve the limit and offer an insight in the behavior of the capacity for a Gaussian cellular Multiple-access Channel (GCMAC) with MIMO in different fading environments.

Index Terms

Information theory, MIMO systems, Capacity, Multipath channels

I. Introduction

In information theoretic literature different approaches have been reported to determine maximum data rate and the means to achieve this under various assumptions and constraints. Shannon was the first that developed a mathematical theory for the channel capacity in [1] providing the framework for studying performance limits in communication. Shannon's work gave birth to the field of information theory. Despite the work in this field, the first important attempt to study the capacity of a cellular system was carried out in the previous decade by Wyner [2]. This model studies the uplink channel and although it considers a very crude approximation to path loss with no path loss variability across the cell, it manages to provide an insight into the cooperation of the base stations and the benefits that can be achieved through that process. Fading was introduced in Wyner's model by Somekh and Shamai in [3]. They again considered a hyper- receiver with delay-less access to all cell-site receivers.

Capacity can also be increased by exploiting the space dimension inherent to any wireless communication system. A possible solution would be to increase the density of the base stations, but this is not desirable due to economical and environmental aspects. Keeping that in mind, it is understandable that antenna arrays are the tools that enable spatial processing. On the other hand the use of arrays at the user terminals had not been considered in the past due to size and cost issues. However recent information theoretic results[4], [5] show that simultaneous use of multiple receive and multiple transmit antennas can offer dramatic increase in capacity. Hence, the deployment of arrays at both base stations and terminals appears as an attractive scenario for the evolution of mobile data access.

The large spectral efficiencies associated with MIMO channels are based on the idea of independent transmissions from each transmit antenna to each receive antenna that a rich scattering environment can provide.The maximum capacity increase requires independent channel gain entries in the full rank channel gain matrix. It also requires that these channels gains are perfectly known (or perfectly estimated) at the receiver end.

For an isolated cell asymptotic results on the sum capacity of MIMO Multiple Access Channels with the number of receive antennas and the number of transmitters increasing to infinity were obtained by Telatar [6] and by Viswanath et al. [7]. The sum capacity with perfect Channel State information available at the receiver (CSIR) was found to grow linearly with $\min(n_r, Kn_t)$. Thus for systems with large number of users, increasing the number of receive antennas at the base station (n_r) while keeping the number of transmit antennas (n_t) constant can lead to linear growth.

A very interesting analysis for the MIMO MAC with perfect CSIR and CDIT was done by Rhee and Cioffi in [8]. They state that for large Kn_t and for a Rayleigh channel model, the limiting capacity is a function of the receive antennas and the power per transmit antenna. In their work they conclude that even one transmit antenna per user terminal can achieve a spectral efficiency close to the limit as long as $K \geq 2n_r$.

In this paper we provide a closed form equation for the maximum per-cell capacity of a MIMO planar cellular system in different environments under the notion of a hyper-receiver. This paper is organized as follows. In section II we present the channel model and the main input versus output equation. In section III the channel matrix is mathematically formulated while in section IV based on the work presented in [9] for large random block circulant matrices the cell capacity under any fading environment is found. In section V the analytical and simulation results are presented. In section VI the information theoretic capacity formula is applied to a more realistic system adjusting accordingly the system parameters. Finally in section VII some conclusions are drawn.

II. CHANNEL MODEL

We consider a Wyner-like [2] hexagonal cellular array model with N^2 cells and K users in each cell. The interference pattern follows the one proposed by Wyner in [2]. Thus a Base station (BS) at a cell receives signals from the transmitters in the six neighboring cells (Figure 1) . Each BS is considered to contain n_r un-correlated receive antennas of the same size. Each transmitter has n_t un-correlated transmit antennas of the same size.

It is more practical to obtain a representation of the cellular system in terms of a rectangular array as the representation in Figure 1 is less tractable. This can be done [2] by scaling and rotating the structure in Figure

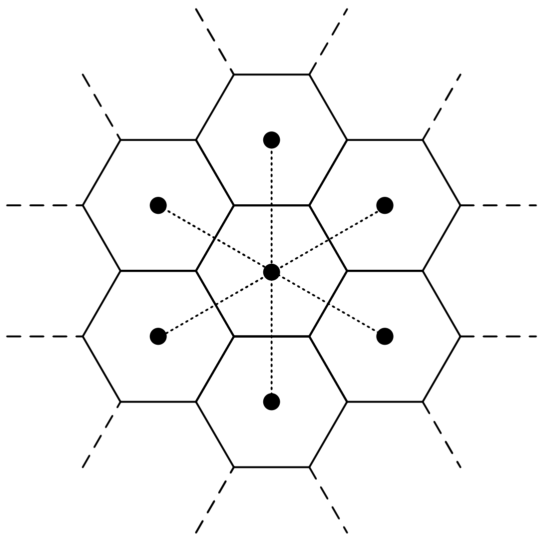

Fig. 1. Hexagonal cellular array model used in this paper. Central cell with its six interfering neighbors. The lines indicate the interference pattern used.

1. The points of the rectangular array are indexed by (m, n) where m and n are the row and column numbers respectively.

The received signal at the BS of cell (m, n) can be written as the sum of the received signals from the same-cell and neighboring-cell transmitters. Each transmitted signal is multiplied by the proper fading and path gain coefficients so as to obtain the received signal. Thus according to the above, the received signal at cell (m, n) can be mathematically expressed by:

$$\begin{aligned}\mathbf{y}_{m,n} = \mathbf{H}_{m,n}\mathbf{x}_{m,n} + \alpha(&\mathbf{H}_{m+1,n}\mathbf{x}_{m+1,n} + \mathbf{H}_{m-1,n}\mathbf{x}_{m-1,n} \\ &+ \mathbf{H}_{m,n+1}\mathbf{x}_{m,n+1} + \mathbf{H}_{m,n-1}\mathbf{x}_{m,n-1} \\ &+ \mathbf{H}_{m+1,n+1}\mathbf{x}_{m+1,n+1} + \mathbf{H}_{m-1,n-1}\mathbf{x}_{m-1,n-1}) + \mathbf{z}_{m,n} \qquad (1)\end{aligned}$$

where:

$\mathbf{H}_{m,n}$ is the channel gain matrix of the K same-cell users, $\mathbf{H}_i, i \in \mathfrak{T} \triangleq \{(m+1,n),(m-1,n),(m,n+1),(m,n-1),(m+1,n+1),(m-1,n-1)\}$ is the channel gain matrix of the neighboring-cell users (of the i^{th} cell).Each of these matrices is a $n_r \times Kn_t$ matrix. The n_i^{th} row of each matrix represents the fading observed between the respective BS antenna and all the users' antennas. It is assumed that the entries of the matrices (fading coefficients) when viewed as random complex processes are i.i.d. Gaussian, strictly stationary and ergodic (independent flat fading channels between the antennas). All the entries are normalized to unit power. Their mean value is defined as:$\mathbb{E}[h^t_{\acute{m},\acute{n},k}] \triangleq \sqrt{\frac{\kappa}{\kappa+1}}\exp(j\phi^t_{\acute{m},\acute{n},k})$ with $\phi^t_{\acute{m},\acute{n},k}$ being the received phase for user's k t antenna in cell $(\acute{m},\acute{n}) \triangleq (m,n) \cup \mathfrak{T}$ and κ is the ratio of the LoS and NLoS components (Rician factor).

$\mathbf{x}_{\acute{m},\acute{n}}$, is the $Kn_t \times 1$ transmit vector of the users in cell $(\acute{m},\acute{n})$. A power constraint, $\mathbb{E}\left[(\mathbf{x}_{\acute{m},\acute{n},k})^2 \leqslant P\right]$, is considered for each user. The power is equally divided among each user's n_t antennas.

$\mathbf{y}_l$ is the $n_r \times 1$ received signal vector at cell $\acute{m}, \acute{n}$.

$\mathbf{z}_l$ is the $n_r \times 1$ received noise vector at cell $\acute{m}, \acute{n}$.The noise vector is considered to have independent circularly symmetric complex Gaussian entries each normalized to unit power.

III. Channel Matrix

The output vector of the system can be written in the form:

$$\bar{\mathbf{y}} = \mathbf{G}\bar{\mathbf{x}} + \bar{\mathbf{z}} \tag{2}$$

where $\bar{\mathbf{y}} = [(\mathbf{y}_{1,1})^T, \cdots, (\mathbf{y}_{N,N})^T]^T$ is the $N^2 n_r \times 1$ received signals vector, $\bar{\mathbf{x}} = [(\mathbf{x}_{1,1})^T, \cdots, (\mathbf{x}_{N,N})^T]^T$ is the concatenation of all the transmitted signals in the system ($N^2 K n_t \times 1$ vector) and $\bar{\mathbf{z}} = [(\mathbf{z}_{1,1})^T, \cdots, (\mathbf{z}_{N,N})^T]^T$ is the $N^2 n_r \times 1$ noise vector

Based on the channel equation (1) and using the raster scan method presented in [3] the overall channel matrix $\mathbf{G}$ is a $N^2 n_r \times N^2 K n_t$ block circulant matrix with $n_r \times K n_t$ blocks and its first row $\mathbf{G}_{[1]}$ given by:

$$\mathbf{G}_{[1]} \triangleq \Big[\mathbf{H}_{m,n} \;\; \alpha\mathbf{H}_{m,n+1} \;\; \overbrace{\mathbf{0}\cdots\mathbf{0}}^{N-2} \;\; \alpha\mathbf{H}_{m+1,n} \;\; \alpha\mathbf{H}_{m+1,n+1} \;\; \overbrace{\mathbf{0}\cdots\mathbf{0}}^{N^2-2N-3} \;\; \alpha\mathbf{H}_{m-1,n-1} \;\; \alpha\mathbf{H}_{m-1,n} \;\; \overbrace{\mathbf{0}\cdots\mathbf{0}}^{N-2} \;\; \alpha\mathbf{H}_{m,n-1} \Big] \tag{3}$$

IV. Cell Capacity

Applying the theorems proved in [3] to the model described above it can be easily shown that for large number of users per cell the maximal achievable per-cell capacity is achieved when all users are allowed to transmit all the time at their maximum power (reported as the WB scheme in [3]). Using Jensen's inequality and considering a large number of users, a tight upper bound on the maximum reliable uplink sum capacity can be found [3], and it is given by:

$$C(\alpha, P, n_r) = \lim_{N\to\infty} \frac{1}{N^2} \log\det \mathbb{E}[\mathbf{\Lambda}] \tag{4}$$

where expectation is taken over all random fading $\mathbf{\Lambda}$ realizations and $\mathbf{\Lambda}$ is the normalized covariance matrix of the output vector, and is given by:

$$\mathbf{\Lambda} = \frac{P}{n_t}\mathbf{G}\mathbf{G}^\dagger + \mathbf{I}_{N^2 n_r \times N^2 n_r} \tag{5}$$

Thus to find the maximum capacity in (4) it is obvious that the expectation of $\mathbf{\Lambda}$ needs to be evaluated. From (3),(5) we have that the $\mathbf{\Lambda}$ matrix is consisted by $N^2 \times N^2$ blocks of the $n_r \times n_r$ product $\mathbf{H}_j \mathbf{H}_{j'}^\dagger$ where the j, j' can take values from the set $\mathfrak{F} \triangleq (m,n) \cup \mathfrak{T}$.

The expectation of the product of a complex fading coefficient with its complex conjugate, is equal to unity as the fading coefficients are assumed normalized to unit power. Furthermore the expectation of the product of a complex fading coefficient with the conjugate of a different one, following the same distribution, is equal to its expected value squared.

Considering the above, it is easy to show that the expectation of the product $\mathbf{H}_j\mathbf{H}_{j'}^\dagger$ is given by:

$$\mathbb{E}[\mathbf{H}_j\mathbf{H}_{j'}^\dagger] = \begin{cases} n_t K\mathfrak{I}, j = j' \\ \\ n_t K\mathfrak{M}, j \neq j' \end{cases} \tag{6}$$

With:

$$\mathfrak{I} \triangleq \begin{bmatrix} 1 & |m_b|^2 & \dots & |m_b|^2 \\ |m_b|^2 & 1 & \dots & |m_b|^2 \\ \ddots & \ddots & \ddots & \ddots \\ |m_b|^2 & |m_b|^2 & \dots & 1 \end{bmatrix} \tag{7}$$

$$\mathfrak{M} \triangleq \begin{bmatrix} |m_b|^2 & |m_b|^2 & \dots & |m_b|^2 \\ |m_b|^2 & |m_b|^2 & \dots & |m_b|^2 \\ \ddots & \ddots & \ddots & \ddots \\ |m_b|^2 & |m_b|^2 & \dots & |m_b|^2 \end{bmatrix} \tag{8}$$

Using (6) and substituting in (5) the $\mathbf{G}$ matrix defined in (3), the expectation of $\mathbf{\Lambda}$ consists of the following $n_r \times n_r$ blocks:

$$\mathbf{R}_Y(r,t) = \mathbb{E}[\mathbf{\Lambda}_N] = \begin{cases} \mathbf{I}_{n_r\times n_r} + \gamma(1+6\alpha^2)\mathfrak{I} & (t,t) \\ \gamma 2\alpha(1+\alpha)\mathfrak{M} & (r,t) \in \mathcal{S}_0 \\ \gamma 2\alpha^2\mathfrak{M} & (r,t) \in \mathcal{S}_1 \\ \gamma\alpha^2\mathfrak{M} & (r,t) \in \mathcal{S}_2 \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where (r,t) is defined as the difference between the cell indices, γ is the cell's total SNR and finally the sets $\mathcal{S}_0, \mathcal{S}_1, \mathcal{S}_2$ are defined as:

$$\begin{aligned} \mathcal{S}_0 &\triangleq \{(-1,-1),(0,-1),(1,0),(1,1),(0,1),(-1,0)\} \\ \mathcal{S}_1 &\triangleq \{(1,2),(2,1),(1,-1),(-1,-2),(-2,-1),(-1,1)\} \\ \mathcal{S}_2 &\triangleq \{(0,2),(2,2),(2,0),(0,-2),(-2,-2),(-2,0)\} \end{aligned} \tag{10}$$

The asymptotic expression for the maximum capacity can be found by applying the two dimensional extension of Szego's theorem [10], [11] to (4). In this case however the matrix is a block circulant matrix and Szego's theorem cannot be directly applied. However using the results in [9] the block circulant matrix in (9) can be transformed to an equivalent matrix, from an eigenvalue point of view, thus allowing us to obtain an asymptotic expression of the maximum capacity for any finite number of users K.

Following a similar methodology as the one presented in [9] for Block Toeplitz matrices we consider the associated matrix:

$$\mathbf{R}'_{\mathbf{Y}} = \begin{bmatrix} \mathbf{T}(\tau^{1,1}) & \mathbf{T}(\tau^{1,2}) & \dots & \mathbf{T}(\tau^{1,n_r}) \\ \mathbf{T}(\tau^{2,1}) & \mathbf{T}(\tau^{2,2}) & \dots & \mathbf{T}(\tau^{2,n_r}) \\ \ddots & \ddots & \ddots & \ddots \\ \mathbf{T}(\tau^{n_r,1}) & \mathbf{T}(\tau^{n_r,2}) & \dots & \mathbf{T}(\tau^{n_r,n_r}) \end{bmatrix} \tag{11}$$

where $\mathbf{T}(\tau^{u,v})$ are the $N^2 \times N^2$ matrices:

$$\mathbf{T}(\tau^{u,v}(r,t)) = \begin{cases} \begin{cases} 1+\gamma(1+6\alpha^2) & (t,t) \\ \gamma 2\alpha(1+\alpha)\left|m_b^2\right| & (r,t)\in\mathcal{S}_0 \\ \gamma 2\alpha^2\left|m_b^2\right| & (r,t)\in\mathcal{S}_1 \\ \gamma\alpha^2 & (r,t)\in\mathcal{S}_2 \\ 0 & otherwise \end{cases} & u=v \\ \\ \begin{cases} \gamma(1+6\alpha^2)\left|m_b^2\right| & (t,t) \\ \gamma 2\alpha(1+\alpha)\left|m_b^2\right| & (r,t)\in\mathcal{S}_0 \\ \gamma 2\alpha^2\left|m_b^2\right| & (r,t)\in\mathcal{S}_1 \\ \gamma\alpha^2 & (r,t)\in\mathcal{S}_2 \\ 0 & otherwise \end{cases} & u\neq v \end{cases} \tag{12}$$

Now taking the two dimensional Fourier transform of each $\mathbf{T}(\tau^{u,v})$ we can find the asymptotically equivalent matrix, from an eigenvalue point of view, of the matrix in (9). This is the circulant $n_r \times n_r$ matrix:

$$\mathbf{R}'_{\mathbf{Y}}(\theta_1,\theta_2) = \begin{bmatrix} \mathcal{A} & \mathcal{B} & \dots & \mathcal{B} \\ \ddots & \ddots & \ddots & \ddots \\ \mathcal{B} & \mathcal{B} & \dots & \mathcal{A} \end{bmatrix} \tag{13}$$

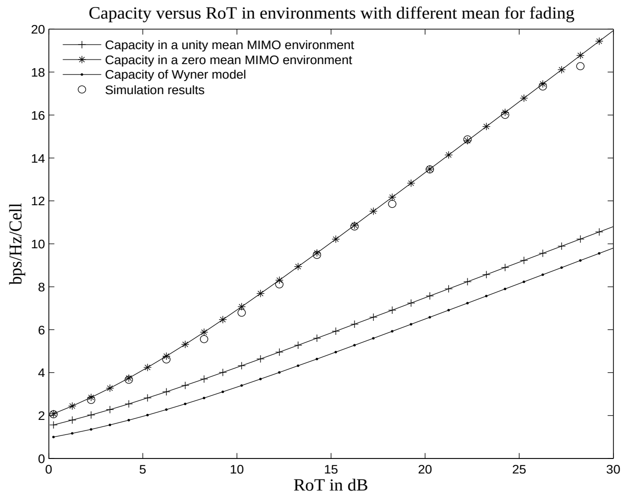

Fig. 2. Capacity versus Rise over Thermal (RoT) in environments with different mean values for the fading for two antennas at each BS and $\alpha = 0.1$. Capacity of Wyner model(AWGN environment, one antenna at each BS) is also plotted for comparison

where:

$$\begin{aligned} \mathcal{A} &= 1 + \gamma \left[\left(1 + 6\alpha^2\right) \left(1 - \left|m_b^2\right|\right) + \right. \\ &\quad \left. + \left|m_b^2\right| \left(1 + 2\alpha F(\theta_1, \theta_2)\right)^2 \right] \\ \mathcal{B} &= \gamma \left|m_b^2\right| \left(1 + 2\alpha F(\theta_1, \theta_2)\right)^2 \end{aligned} \tag{14}$$

and

$$F(\theta_1, \theta_2) = \cos(2\pi\theta_1) + \cos(2\pi\theta_2) + \cos(2\pi(\theta_1 + \theta_2))$$

Now starting from (4) and applying theorem 3 of [9] we can find a closed form for the uplink capacity of a MIMO cellular system.

$$\begin{aligned} C(\alpha, P, n_r) &= \lim_{N\to\infty} \frac{1}{N^2} \log\det \mathbb{E}[\mathbf{\Lambda}] \\ &= \int_0^1 \int_0^1 \sum_{s=1}^{n_r} \log(\lambda_s(\mathbf{R}'_{\mathbf{Y}})) d\theta_1 d\theta_2 \end{aligned} \tag{15}$$

where $\lambda_s(\mathbf{R}'_{\mathbf{Y}})$ are the eigenvalues of the $\mathbf{R}'_{\mathbf{Y}}$ matrix in (13). These eigenvalues can be easily found and thus (15) yields:

$$\begin{aligned} C(\alpha, P, n_r) = \int_0^1 \int_0^1 & \left[\log(\mathcal{A} + (n_r - 1)\mathcal{B}) + \right. \\ & \left. (n_r - 1)\log(\mathcal{A} - \mathcal{B})\right] d\theta_1 d\theta_2 \end{aligned} \tag{16}$$

V. RESULTS

In this section we will present and discuss some interesting results that are yielded by plotting (16) versus various parameters. Figure 2 shows the upper and the lower bounds of the capacity as RoT (the ratio of aggregate received signal power to the additive white Gaussian noise at the receiver) increases. The upper bound capacity gain becomes large, even for two antennas at each BS (when compared to the capacity provided by the simple Wyner model) . The same is not true for the lower bound where the capacity gain is very small in comparison. This can be explained by the fact that for $m_b = 1$ more antennas at the BS don't increase the rank of the channel matrix while the opposite is true when zero-mean is considered. The increased rank of the channel matrix in the latter environment yields increased multi-user diversity effect which explains the large capacity gain. Figure 3 illustrates the transition from the lower bound to the upper bound capacity via the mean axis for up to 20 antennas at each BS. From this figure it's obvious that at the upper bound we experience a linear increase in capacity versus the number of antennas at each BS. At the lower bound, increasing the number of antennas offers a very small gain in capacity.

In real systems there is no way of synchronizing the phases in the uplink. This actually means that the $\phi^t_{\acute{m},\acute{n},k}$ are normally distributed random variables which in turn means that the m_b parameter in most real systems is zero and thus it's safe to claim that in the real systems the capacity is at the upper bound shown in Figures 2, 3.

The circle-points in figure 2 are obtained by simulation. For the simulation, the users were assumed to be co-located at the BSs positions according to the description in section 2. Two antennas were assumed at each BS while each UT was equipped with one antenna. We also generated 100 random fading matrices, $\mathbf{H}$. Each entry of these matrices is a complex, normally distributed random variable with both real and imaginary parts having zero mean and a standard deviation of $1/\sqrt{2}$. The above were used to obtain the channel gain matrix $\mathbf{G}$. Then the maximum capacity was calculated using $\mathbb{E}[\log\det(\mathbf{I} + \frac{P}{n_t}\mathbf{G}\mathbf{G}^\dagger)]$ for a given value of P (normalised SNR). As it is illustrated in figure 2 the simulation results obtained coincide with the theoretical results.

VI. RESULTS FOR PRACTICAL SYSTEMS

In this section we present the theoretical results for the capacity of the MIMO system adjusting various parameters in order to meet the requirements of a practical system. For the results plotted here for practical systems, and according to the analysis done in [12] for the COST-231 macro-cell and the PCS micro-cell models, the following parameters were considered:

- random phase fading environment
- power loss at reference distance: $L_0 = -38$ dB
- distance between adjacent Base Stations: D = 6 Km
- Received power from adjacent cells follows a distance dependent power law loss with path loss parameter 3.5:

$$\alpha = \frac{\sqrt{L_0}}{(1+D)^{3.5/2}}$$

- users per cell: K = 20

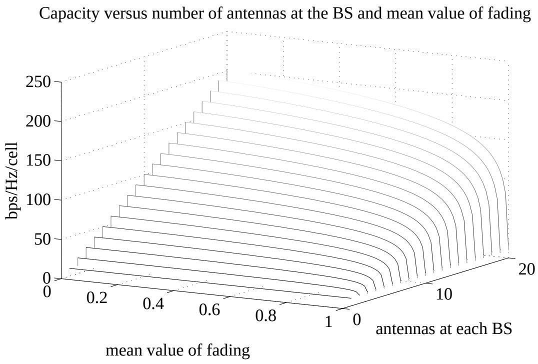

Fig. 3. Capacity versus number of antennas in different environments($\alpha = 0.1$)

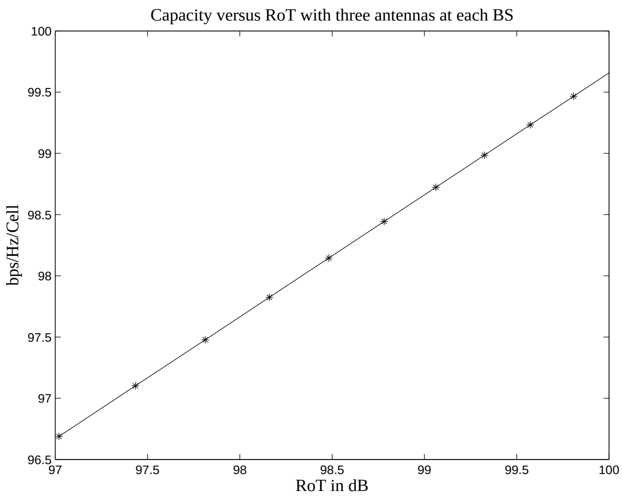

Fig. 4. Per-cell capacity versus Rise-over-Thermal for a planar cellular system. Distance between neighboring Base Stations 6 Km, path loss factor 3.5, 20 users per-cell.

- per user power ranges between 100 and 200 mW
- Carrier frequency 2 GHz and channel bandwidth: B = 5MHz

In Figure 4 we observe linear increase versus dB RoT in the per-cell capacity. It is noted that the variation in RoT is due to the variation to the user power (ranges from 100mW to 200mW).

VII. CONCLUSIONS

In this paper we extend the single antenna Gaussian cellular Multiple access channel (GCMAC) model initially proposed by Wyner and later extended by Somekh and Shamai to account for multi-path fading. The extension is done by adding multiple antennas at the cell-site receivers and the user terminals. Since the resulting channel matrix is a block circulant matrix without circulant blocks the theorems proved by Somekh, Shamai in [3] cannot be directly applied. Hence we use the results presented by Gazzah et.al. in [9] to transform the channel's output covariance matrix to an, from an eigenvalue point of view, equivalent matrix for which the eigenvalues can be easier calculated. Using Szego's theorem we then provide a closed form expression for the capacity of the GCMAC with MIMO. The results show that the capacity of the multiple access channel depends on the number of receive antennas and the power per transmit antenna. Since there are many cellular transmitters, each transmitter only needs one (rather than multiple) antennas in order to achieve the full capacity. This agrees with the results presented by Rhee and Cioffi in [8]. Another interesting insight of the results is the big difference in capacity between the lower and upper bounds. This is due to the decreased rank of the channel matrix when random phase is not present (synchronized phases at the receiver end). The analytical results are also verified by Monte-Carlo simulations. By incorporating in our model some real-system parameters we have also presented the per-cell capacity of a more practical MIMO system.

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