Framework to Compare the Uplink Capacity of the Cellular Systems with Variable Inter Site Distance

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***Abstract*—In this paper we derive the information theoretic capacity of the uplink of a cellular system with variable inter site distance and a generalised fading environment. The capacity is shown to be a direct function of the ratio of total received signal power (from within and outside of a cell) to the AWGN noise power, at any BS. This ratio is defined as the Rise over Thermal (RoT). It is shown that the variation in system parameters like the path loss exponent, number of users, transmit power constraint and the inter site distance, changes the region of operation on a capacity-versus-RoT curve. Results are interpreted for practical channel models and it is shown that RoT provides a useful framework to compare various practical systems.**

I. Introduction

With increasing demand of spectrally efficient communication systems the search for capacity limits of uplink cellular systems gained momentum. First concrete finding in this regard was reported in Wyner's seminal work [1], supporting earlier observations of [2]. This was extended for fading channels in [3]. These papers assume that all Base Station (BS) receivers cooperate in the uplink channel to jointly process the signals at a centralised receiver – termed as a hyper receiver. These models provide the foundation for several extensions but all the findings retain two original assumptions of Wyner's model i.e. the collocation of the users in each cell and fixed Inter Site Distance (ISD) with the interference from adjacent cells only. Furthermore, the model presented in [3] assumed that the signals received at each base station from various users, over the specular path, are synchronised. This assumption is only reasonable for the collocated model. An extended model and analysis is required if users are assumed to be spatially distributed. A recent work [4] provides insights to a system where the ISD is variable but the collocation of users is still maintained and only a linear cellular system is studied for mathematical tractability. The concept of hyper receiver is adopted in other recent practical investigations (e.g. [5], [6]).

In this paper, a planar cellular system with variable ISD is assumed along with a generalised fading model. We show that the information theoretic capacity of the system is a function of a metric, defined here as the Rise over Thermal, at each receiving antenna of the system.

In the practical engineering design of cellular systems, the main figure of merit that determines the capacity (maximum reliable transmission rate with vanishingly small error rate) of a User Terminal (UT), is the Signal to Interference and Noise Ratio (SINR) at the BS receiver, given as

$$\text{SINR} = \frac{P_R}{I + \sigma^2} \tag{1}$$

where P_R is the received power at the BS of interest, σ^2 is the thermal AWGN at the receiving BS and I is the inter-cell and intra-cell interference received from other UTs of the system.

However, we will show here that for the information-theoretic analysis of a cellular systems that uses a hyper receiver approach, the main figure of merit that determines the per-cell capacity (at any BS) is:

$$\text{RoT} = \frac{\sum_i \alpha_i P_T}{\sigma^2}, \tag{2}$$

assuming that all UTs in the system transmit at their maximum allowable power constraint, P_T. The factor α_i denotes the relative attenuation experienced by the transmitted signal of each UT until it reaches the receiver. The numerator term $\sum_i \alpha_i P_T$ is the total received signal power (desired signal power for the base station in consideration and also the power of the signals intended for the other base stations in the system). Splitting the numerator into desired, P_R, and (conventionally termed) undesired signal, I, we can express RoT as:

$$\text{RoT} = \frac{P_R + I}{\sigma^2}, \tag{3}$$

This shows that the information theoretic approach of using a hyper receiver has the potential of converting the conventionally harmful interference into a factor that increases the figure of merit by moving the interference term from the denominator to the numerator – compare (1) and (3).

It shall be noted that the problem of finding the (per-cell) capacity of a cellular system can be greatly simplified by focusing on the single BS receiver and its RoT. Due to the symmetry of the problem (ignoring the edge effects) all BS receivers are identical and system capacity is simply the per-cell capacity times the number of cells. The mathematical formulation in the following sections of the paper, backs the heuristic idea introduced here.

The rest of the paper is organised as follows. In Section II the extended model is described. In Section III, the model is used to derive the per-cell capacity of the system. In Section IV the approach used to model the path loss in the system with a specific user distribution is explained. In section V we discuss the results and the paper is concluded in the last section.

II. System Model

Assume a 2D hexagonal cellular array and a network of cells where the BSs are uniformly distributed in a hexagonal grid. All the antennas are considered to be omnidirectional. A BS, located at the center of each cell, receives signals from all the users in the system, attenuated according to the power-law path loss and the multipath fading. We assume that all the BSs cooperate to jointly decode the received signals ("hyper-receiver" scheme). The users are spatially distributed over the cells. Similar to Hanly's circular array model (for a linear system) [2], a wrap-around toric model is adopted for the planar system. In such a model, every cell has the same number of surrounding cells in order to avoid the edge effects. Nevertheless, for large number of cells the edge effects do not significantly affect the results [1].

A. Channel

Consider a network of N cells and K users in each cell. According to our model, the received signal at the BS antenna of cell n is the sum of the transmitted signals from the users within the same cell and also from the rest of the cells in the system, each appropriately scaled by the path gain and fading coefficients. Hence, the received signal in a cell n is given by:

$$y_n = \sum_{k=1}^{K} \left[\varsigma_{n,k}^n g_{n,k}^n x_{n,k}\right] + \sum_{\substack{m=1\\ m\neq n}}^{N} \sum_{k=1}^{K} \left[\varsigma_{m,k}^n g_{m,k}^n x_{m,k}\right] + z_n \quad (4)$$

where y_n and z_n represent the received signal and the AWGN noise at the receiver of cell n. The variable $x_{m,k}$ represents the circularly symmetric complex Gaussian inputs for a transmitter k in cell m and $\varsigma_{m,k}^n,\ g_{m,k}^n$ represent the path gain coefficients and the fading coefficients between a transmitter k in cell m and the receiver at the BS of cell n. All the complex fading coefficients are normalized to unit power and when viewed as complex random processes are circularly symmetric i.i.d. Gaussian, stationary and ergodic. It is assumed that each user has average power constraint P_u, i.e. $\mathbb{E}\left[x_{m,k}x_{m,k}^*\right] \leq P_u$.

B. Path Loss

A widely used model that maps the path gain (defined as the ratio of the received over the transmitted power) and the distance in a power-law path loss environment is expressed as:

$$\varsigma_{m,k}^n = \sqrt{L_0}\left(\frac{D_0}{\hat{D}}\right)^{\eta/2} \quad (5)$$

where L_0 is defined as the power received at a reference distance D_0 when transmitted power is unity and η is the power-law path loss exponent. The distance of the user terminal from the antenna is $\hat{D}$. If we define the distance from the reference point to the user terminal as $D^{'}$, it is clear that $\hat{D} = D^{'} + D_0$. Making this substitution in (5) and considering a reference distance of 1 meter, the power-law path gain from the user k to the receiver of cell n is expressed as:

$$\varsigma_{m,k}^n = \frac{\sqrt{L_0}}{\left(1 + D_{m,k}^n\right)^{\eta/2}} \quad (6)$$

with $D_{m,k}^n \approx \frac{D^{'}}{D_0}$ defined as the distance between a user k in a cell m from the reference point in cell n.

C. Fading

Considering the uniformly distributed random received phase $\Phi_{m,k}^n$ on the specular path between a transmitter k in cell m and the BS of cell n, a generalised model for the fading coefficients can be given by [7], [8], [9]:

$$g_{m,k}^n = \sqrt{\frac{\kappa}{\kappa+1}}\ \mathrm{e}^{j\Phi_{m,k}^n} + \sqrt{\frac{1}{\kappa+1}}\mathcal{CN}(0,1) \quad (7)$$

where $\mathbb{E}[gg*] = 1$, κ is the ratio of the power in the specular path and the non-specular multipaths and $\mathcal{CN}(0,1)$ represents a complex Gaussian random variable with independent real and imaginary components each normally distributed with mean zero and variance $1/2$.

III. Capacity Analysis

To facilitate capacity analysis, the output vector of all the received signals in the system can be expressed in matrix form. Consider the representation of the cellular system as a rectangular array, as described by Wyner in [1], and the raster scanning method that was used by Somekh and Shamai in [3] to define the order of the system output vector elements. Thus, the system output can be expressed as:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z} \quad (8)$$

where $\mathbf{y} = [y_1, y_2, ...y_N]^T$ is the $N \times 1$ received signal column vector, $\mathbf{x} = \left[\mathbf{x}_1{}^T, \mathbf{x}_2{}^T, ...\mathbf{x}_N{}^T\right]^T$ is the $NK \times 1$ column vector of the transmitted signals of all the users, with $\mathbf{x}_n = [x_{n,1}, ..., x_{n,K}]^T$, denoting the concatenation of the transmitted signals from the K users in cell n, $\mathbf{z}$ is the $N \times 1$ column vector of noise and $\mathbf{H}$ is the overall $N \times NK$ system gain matrix given by:

$$\mathbf{H} = \mathbf{\Sigma} \odot \mathbf{G} \quad (9)$$

where $\mathbf{\Sigma}$ is a deterministic $N \times NK$ matrix that contains all the path gain coefficients and $\mathbf{G}$ is the $N \times NK$ matrix of all the fading coefficients of the channels. In $\mathbf{H}$ matrix, each row corresponds to a specific receiver and each column to a specific transmitter.

The maximum per-cell rate is achieved when all UTs are allowed to transmit all the time at their maximum transmit power constraint (wide band scheme presented in [3]), and in this case the capacity is given by [10]:

$$C = \lim_{N\to\infty} \mathbb{E}\left[\frac{1}{N}\log\det\left(\frac{\mathbf{\Lambda_y}}{\sigma^2}\right)\right] \quad (10)$$

where the expectation is taken over all the fading realizations and $\mathbf{\Lambda_y}$ is the covariance matrix of the system output vector:

$$\mathbf{\Lambda_y} = P_u\mathbf{H}\mathbf{H}^\dagger + \sigma^2\mathbf{I}_{N\times N} \quad (11)$$

Taking into consideration equation (9) and the fact that the path gain and fading coefficients are uncorrelated with each other we have

$$\mathbf{H}\mathbf{H}^\dagger = (\mathbf{\Sigma}\odot\mathbf{G})\cdot\left(\mathbf{\Sigma}^T\odot\mathbf{G}^\dagger\right) = \left(\mathbf{\Sigma}\mathbf{\Sigma}^T\right)\odot\left(\mathbf{G}\mathbf{G}^\dagger\right) \quad (12)$$

$$\mathbb{E}\left[g_{m,k}^{n}\left(g_{\acute{m},\acute{k}}^{\acute{n}}\right)^{*}\right]=\mathbb{E}\left[\left(A_{m,k}^{n}\mathrm{e}^{j\Phi_{m,k}^{n}}+\left(\alpha_{m,k}^{n}+j\beta_{m,k}^{n}\right)\right)\cdot\left(A_{\acute{m},\acute{k}}^{\acute{n}}\mathrm{e}^{-j\Phi_{\acute{m},\acute{k}}^{\acute{n}}}+\left(\alpha_{\acute{m},\acute{k}}^{\acute{n}}-j\beta_{\acute{m},\acute{k}}^{\acute{n}}\right)\right)\right]=$$
$$\mathbb{E}\left[A_{m,k}^{n}A_{\acute{m},\acute{k}}^{\acute{n}}\mathrm{e}^{j\left(\Phi_{m,k}^{n}-\Phi_{\acute{m},\acute{k}}^{\acute{n}}\right)}+A_{m,k}^{n}B_{\acute{m},\acute{k}}^{\acute{n}}\mathrm{e}^{j\left(\Phi_{m,k}^{n}-\Theta_{\acute{m},\acute{k}}^{\acute{n}}\right)}+B_{m,k}^{n}A_{\acute{m},\acute{k}}^{\acute{n}}\mathrm{e}^{j\left(\Theta_{m,k}^{n}-\Phi_{\acute{m},\acute{k}}^{\acute{n}}\right)}+B_{m,k}^{n}B_{\acute{m},\acute{k}}^{\acute{n}}\mathrm{e}^{j\left(\Theta_{m,k}^{n}-\Theta_{\acute{m},\acute{k}}^{\acute{n}}\right)}\right] \quad (13)$$

Considering a specific wrap-around toric model and that users follow the same spatial distribution in every cell, $\mathbf{\Sigma}$ can be considered as a block-circulant matrix, in terms of its row-vector elements, each of length K. Moreover as the elements of $\mathbf{\Sigma}$ are real, $\mathbf{\Sigma}\mathbf{\Sigma}^{T}$ can be shown to be a real circulant matrix.

Unlike $\mathbf{\Sigma}$, $\mathbf{G}$ matrix does not have symmetry because of the randomness of the phase. Furthermore, each element of $\mathbf{G}\mathbf{G}^{\dagger}$ is the KN sum of random variables multiplied with the conjugate transpose of other random variables which follow the same distribution. When $K\rightarrow\infty$ for every fixed N, the horizontal dimension of $\mathbf{G}\mathbf{G}^{\dagger}$ grows much faster than the vertical dimension. In this case the law of large numbers applies to each element of $\mathbf{G}\mathbf{G}^{\dagger}$

$$\left(\mathbf{G}\mathbf{G}^{\dagger}\right)_{ij}\cong KN\mathbb{E}\left[g_{m,k}^{n}\left(g_{\acute{m},\acute{k}}^{\acute{n}}\right)^{*}\right],\forall i,j\in\{1,...,N\} \quad (14)$$

and $\mathbf{G}\mathbf{G}^{\dagger}$ converges to the deterministic matrix $\mathbb{E}\left[\mathbf{G}\mathbf{G}^{\dagger}\right]$.

There are two different types of product elements:

Product of a fading coefficient with the complex conjugate of the same fading coefficient. Since all the complex fading coefficients are assumed to be normalized to unit power:

$$\mathbb{E}\left[g_{m,k}^{n}\left(g_{m,k}^{n}\right)^{*}\right]=\mathbb{E}\left[\left|g_{m,k}^{n}\right|^{2}\right]=1 \quad (15)$$

This product takes place at the diagonal entries of $\mathbf{G}\mathbf{G}^{\dagger}$.

Product of a fading coefficient with the complex conjugate of a different fading coefficient. The off-diagonal entries of $\mathbf{G}\mathbf{G}^{\dagger}$ are the KN sum of the product elements given in (13) where $A_{m,k}^{n}$,$B_{m,k}^{n}$ are real values and $B_{m,k}^{n}\mathrm{e}^{j\Theta_{m,k}^{n}}=\left(\alpha_{m,k}^{n}+j\beta_{m,k}^{n}\right)$. Note that Φ and Θ are uniformly distributed random variables over $(0,2\pi)$. In that case, (13) converges to:

$$\mathbb{E}\left[g_{m,k}^{n}\left(g_{\acute{m},\acute{k}}^{\acute{n}}\right)^{*}\right]=0 \quad (16)$$

which implies that $\mathbf{\Lambda_{y}}$ converges to a diagonal matrix. Considering that the number of cells grows very large, $\mathbf{\Lambda_{y}}$ becomes a large random matrix. We use Jensen's inequality that provides an upper bound for the capacity of the system:

$$\lim_{N\rightarrow\infty}\frac{1}{N}\log\left(\det\mathbb{E}\left[\mathbf{\Lambda_{y}}\right]\right)\geqslant\lim_{N\rightarrow\infty}\mathbb{E}\left[\frac{1}{N}\log\det\mathbf{\Lambda_{y}}\right] \quad (17)$$

According to the above, if we assume that the number of UTs per cell is growing large, the law of large numbers ensures that the upper bound presented in (17) is tight [3]. Hence,

$$C=\lim_{N\rightarrow\infty}\left(\frac{1}{N}\log\left(\det\mathbb{E}\left[\mathbf{\Lambda_{y}}\right]\right)\right)\text{ for }K\rightarrow\infty \quad (18)$$

IV. Path Loss Approximation Approach

In the following we formulate a path-loss approximation so as to investigate in more detail the factors that compose matrix $\mathbf{\Sigma}\mathbf{\Sigma}^{T}$ and hence to evaluate their impact on the capacity.

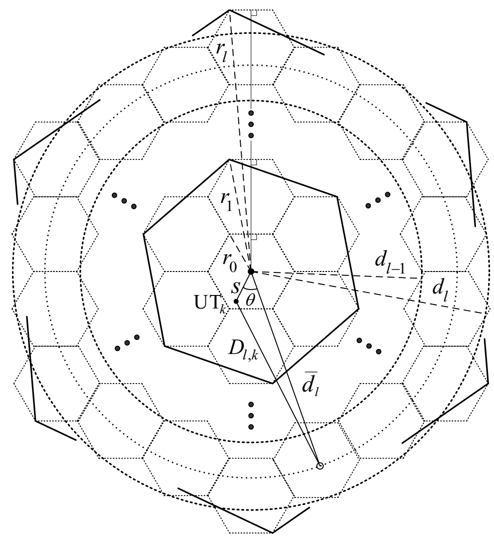

Fig. 1. Multiple tiers of interference and the geometry of the cellular system

A. Cell and System Geometry

Consider a regular hexagonal cell with side length of r_0 and minimal radius of $r=r_0\cos\left(\frac{\pi}{6}\right)$. We assume multiple tiers of interference around each cell (Figure 1). The irregular boundary of each tier can be represented by an equivalent regular hexagon with the length of its side given by:

$$r_l=\sqrt{\left[(2l+1)\,r\right]^{2}+\left(\frac{r_0}{2}\right)^{2}} \quad (19)$$

where l stands for the l^{th} tier of interference. The hexagonal boundary of any tier can be approximated by an equivalent circular boundary with its radius given by:

$$d_l=\frac{6}{\pi}\int_{0}^{\frac{\pi}{6}}\frac{r_l}{\cos\theta}\cos\left(\frac{\pi}{6}\right)d\theta \quad (20)$$

For evaluating the capacity under any user distribution with large K, it is useful to group the users in each interference tier and represent their squared path gain coefficients with an appropriate mean value, $\overline{\varsigma_{l}^{2}}$. This mean value is calculated by focusing on a single cell and averaging the path loss of all users in this cell, with reference to the receiver position. This average can be expressed as a function of the distance between the center of the cell in focus and the receiver. As the distance of various cells in a given interference tier slightly vary from one cell to the other, we can further estimate this distance using the approximate distance $\bar{d}_l$, from the inner and outer circular boundary of the l^{th} tier of interference:

$$\bar{d}_l\approx\frac{d_l+d_{l-1}}{2},\textit{with }\bar{d}_0=0 \quad (21)$$

B. User Distribution and Mean Squared Path Loss

The mean squared path loss for the user terminals in a cell will depend on the proximity of the cell to the receiver of interest and also on the user distribution over the cell. We define the distance $D_{l,k}$ of a user in a cell in the l^{th} tier of interference from the receiver of interest. It can be proved that:

$$D_{l,k}(\theta, s) = \sqrt{\left(s\sin\theta + \bar{d}_l\right)^2 + (s\cos\theta)^2} \tag{22}$$

where s and θ respectively define the radial and angular location of a UT, with respect to the receiver of a BS. Three different cases of user distribution are examined here.

Uniform Distribution: The UTs are uniformly distributed over the planar system. The mean squared path gain for each of the K users in a cell which belongs in the l^{th} tier of interference from the receiver of interest is given by:

$$\overline{\varsigma_{l-uni}^2} = \frac{1}{\pi {d_0}^2}\int_0^{d_0}\int_{-\pi}^{\pi}\frac{1}{\left(1 + D_{l,k}(\theta, s)\right)^{\eta}} s d\theta ds \tag{23}$$

Truncated Cell-Centre Uniform Distribution: Here, the UTs are uniformly distributed around the centre of their cell and

$$\overline{\varsigma_{l-centre}^2} = \frac{1}{\pi\rho^2}\int_0^{\rho}\int_{-\pi}^{\pi}\frac{1}{\left(1 + D_{l,k}(\theta, s)\right)^{\eta}} s d\theta ds \tag{24}$$

where ρ (with $0 < \rho \leq d_0$) is the truncation radius around each BS in which the K users are distributed.

Truncated Cell-Edge Uniform Distribution: In this case, the users are uniformly distributed on an annular segment close to the edge of their cell. We have,

$$\overline{\varsigma_{l-edge}^2} = \frac{1}{\pi(d_0^2 - \acute{\rho}^2)}\int_{\acute{\rho}}^{d_0}\int_{-\pi}^{\pi}\frac{1}{\left(1 + D_{l,k}(\theta, s)\right)^{\eta}} s d\theta ds \tag{25}$$

where $\acute{\rho}$ ($0 \leq \acute{\rho} < d_0$) is the radial distance from the center of the cell to the boundary where the annular section starts.

Assuming a specific user distribution, a maximum of L tiers of interference for every cell and considering that there are always $6 \cdot l$ cells in the l^{th} tier of interference, from (18) we have that the achievable per-cell capacity is

$$C = \log\left[1 + \frac{KP_u}{\sigma^2}\left(\overline{\varsigma_0^2} + \sum_{l=1}^{L} 6 \cdot l \cdot \overline{\varsigma_l^2}\right)\right] \tag{26}$$

where $\overline{\varsigma_0^2}$ denotes the mean squared path gain for the users inside the cell of interest.

V. Results

An important issue is to establish the relation of the various system modelling parameters with real-world scenarios so as to interpret the information theoretic results for these systems. To model the propagation in real-world systems more accurately we need to obtain a one-to-one correspondence between the simplified path loss model and the existing empirical models. As an example, we have selected two well-known empirical models for micro-cellular (Wideband PCS Microcell Model [11]) and macro-cellular (PCS extension to Hata model by COST-231 [11]) systems. Based on the limitations of the two models we use the following parameters to approximate the path loss. We use $f_c = 1.9$GHz, $h_{re} = 1.5m$ and $L_0 = -38$dBW where f_c is the carrier frequency, h_{re} is the effective height of the receive antennas and L_0 is equal to the path loss in decibels at reference distance $D_0 = 1$m. We use the minimum allowed transmit antenna height for the macrocellular (30m) and the maximum allowed for the microcellular (13.3m) system models. We assume a line-of-sight dual slope environment for microcellular and a small/medium sized city environment for the macrocellular system. It is widely accepted that the microcellular model suggests a smaller value of $\eta = 2$ while the macrocellular model suggests a larger value of $\eta = 3.5$. We find the empirical value for the constant L_0 (-38 dBW) that achieves a close-fit between the simplified path loss model and the empirical models over a large range of distances.

In Figures 2 and 3, all the results have been verified by running Monte Carlo simulations to generate random fading coefficients for various system snapshots. The simulation capacity is obtained by finding the average over a large number of fading and user distribution snapshots using:

$$C_{\mathrm{sim}} = \frac{1}{N}\mathbb{E}\left[\log_2\det\left(\mathbf{I} + \frac{P_u}{\sigma^2}\mathbf{H}\mathbf{H}^{\dagger}\right)\right] \tag{27}$$

where the AWGN noise spectral density is considered to be -169 dBm/Hz and $\mathbf{I}$ is the identity matrix of appropriate size. Both figures present the importance of RoT as a parameter directly connected with capacity. The independent parameters of a practical system that affect the per-cell capacity are the user distribution over the cell, the cell size, the path loss exponent, the user transmit power constraint and the number of users per cell. Every change on these parameters changes accordingly the RoT and thus the area of the capacity that the system operates according to a general equation:

$$C = \log_2(1 + \mathrm{RoT}) \tag{28}$$

Fig. 2 illustrates how the system capacity-range changes depending on the Inter Site Distance (ISD $= 2r$). It can be observed that as ISD decreases the system operates with higher capacity. Moreover, it is shown that low path loss exponent, larger number of users per cell and higher transmitted per user P_u increase the per-cell capacity of the system.

Fig. 3 compares the capacity obtained by the three different types of user distribution. A more detailed view of the effect of P_u on capacity is also provided. Cell-centre user distribution provides the highest capacity and this can be explained from the fact that the users will always be close to at least one BS no matter how large the size of the cells is. Furthermore, uniform user distribution provides a higher capacity than the cell-edge, but both are close to each other. For the above results, we considered $L = 5$. Nevertheless, it was observed that for these provided practical system parameters the number of tiers of interference had a minimal effect on the capacity.

VI. Conclusion

Rise over Thermal has been presented as a unified parameter that defines the capacity of the uplink of a cellular system

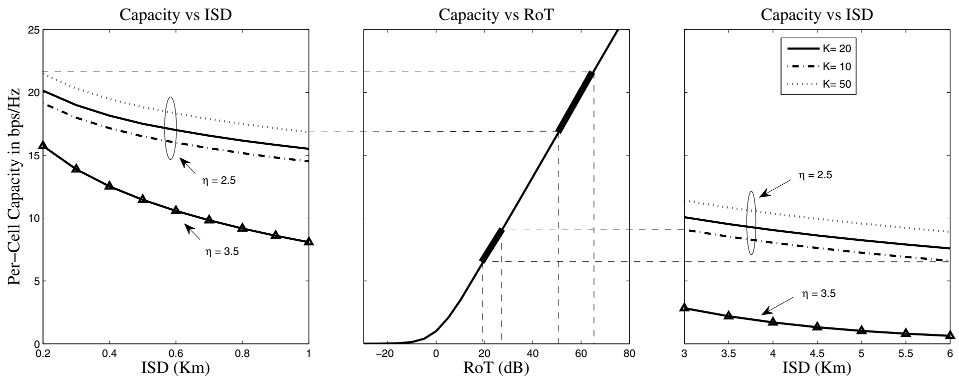

Fig. 2. Capacity versus RoT and ISD for various number of users ($K = 10, 20, 50$), path loss exponents ($\eta = 2.5, 3.5$). User transmit power $P_u = 100$mW.

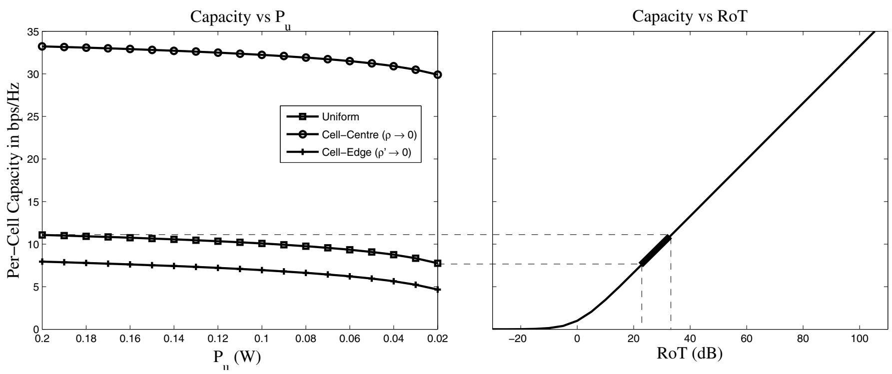

Fig. 3. Per-Cell Capacity versus RoT and user transmit power constraint P_u for various types of user distributions (Uniform, CC with $\rho \rightarrow 0$ and CE with $\acute{\rho} \rightarrow 0$), path loss exponent $\eta = 2.5$, $K = 20$ users per cell and Inter Site Distance of 3km.

that uses full cooperation at the multiple BS receivers of the system. Capacity increases with RoT at each BS. RoT depends on four important parameters: the size of the cells, the transmit power constraint, the large scale path loss exponent and the number of transmitters in each cell. Maximum RoT and hence high capacity region can be achieved for a given number of users per cell if smaller cells are used with largest possible power constraint for each user, in an environment of smallest possible path loss exponent. Introducing larger number of users in each cell will result in higher per-cell sum rate capacity when a joint decoding system is considered. Finally, with the not realistic concept of the hyper receiver used in this paper, the consideration of network clustering poses a very interesting question to be further analysed in our future approach.

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