Coverage Spectral Efficiency of Cellular Systems with Cooperative Base Stations

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***Abstract*— Coverage spectral efficiency (CSE) characterizes the tradeoff between efficient channel reuse and the achievable rates per cell, under the assumption of detection by a single base station and intra-cell FDMA. It is well known that intra-cell FDMA is not in general optimal. In this paper we study an alternative intra-cell wide-band scheme as well as the base station cooperation in detection, which has demonstrated potential capacity gain. The effect on CSE of different schemes are then compared and the optimal reuse distance is determined for each scheme.**

I. Introduction

The radio spectrum is one of the most precious resources in wireless systems. Many communication designs target increasing spectral efficiency. The basic premise behind cellular systems is to exploit the power falloff with distance of signal propagation to reuse the same channel in spatially separated cells, which increases system spectral efficiency and also reduces co-channel interference. A small reuse distance enables channels to be reused more frequently but increases co-channel interference and reduces the capacity of each cell, while a large reuse distance has the opposite effect.

In [1] the concept of area spectral efficiency (ASE) was introduced to characterize this tradeoff between efficient channel reuse and the achievable rates per cell. Considering a two-dimensional hexagon cellular array, the ASE is defined as the achievable sum rates (of all users in a cell) per unit bandwidth per unit area. For example, if each cell is allocated a bandwidth of B, there are K users in each cell with achievable rate C_k, $1 \leq k \leq K$, and the reuse distance is D, then the ASE is given by

$$A_e = \frac{\sum_{k=1}^{K} C_k}{\pi B (D/2)^2}. \quad (1)$$

Most 2G systems assume users within the same cell orthogonally access the channel through either TDMA or FDMA, which is also the case considered in [1]. Orthogonal schemes have the advantage of simplified receiver design, but are not necessarily optimal from an information theoretical perspective. An alternative is to let all users within the same cell share the channel simultaneously, which is called the intra-cell wideband (WB) scheme in [2]. Under the assumption of single base station (BS) detection, the superiority of the achievable rate for the intra-cell WB scheme versus that of orthogonal schemes can go either way, depending on system parameters.

Base station cooperation has been recently considered as a new approach to increase the cellular system capacity [3]. Under the assumption of full cooperation, multiple BS's can be viewed as a single BS with multiple geographically dispersed antennas. Full cooperation leads to a fundamental performance limit in cellular systems, but the tradeoff is increased encoding/decoding complexity. A more practical scheme is to introduce adjacent BS cooperation [2].

In this paper we consider the uplink of a one-dimensional linear cellular array which best models the highway cellular system and is similar to the model initially proposed by Wyner in [4]. Since the coverage of a cell now has the unit of length instead of area, we modify the metric and define the coverage spectral efficiency (CSE) as

$$\text{CSE} = \frac{\sum_{k=1}^{K} C_k}{BD}. \quad (2)$$

The unit of CSE is [bps/Hz/m]. We investigate the effect on CSE of various intra-cell schemes such as FDMA and WB. We also consider different assumptions of base station cooperation such as single BS detection and joint adjacent BS detection.

The rest of the paper is organized as follows. We introduce the system model in Section II. The intra-cell FD and WB schemes are analyzed in Section III for single BS detection and in Section IV for joint BS detection. Conclusions are given in Section V.

II. System Model

We consider the uplink of a one-dimensional linear cellular array. In a traditional deployment, base stations are located in the center of a cell. The coverage of a base station extends in both directions along the linear array. The decoding of any mobile user is undertaken by the nearest base station with co-channel interference simply treated as noise, as shown in Figure 1. We also study the case of adjacent BS cooperation, i.e. the decoding of any mobile user is undertaken by the *two* nearest base stations instead of *the closest*. All mobile users which share the same *two* nearest base stations will be grouped into the same cell. Under this assumption, the cell boundaries

This work was supported by grants from Hitachi, LG Electronics, and the Korea Electronics Technology Institute.

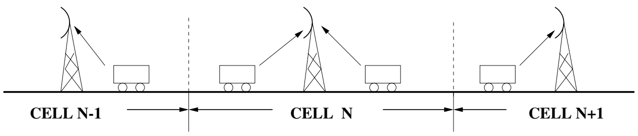

Fig. 1. Linear cellular array, single BS detection

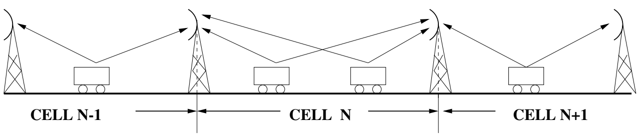

Fig. 2. Linear cellular array, joint BS detection

shift from the middle of two adjacent base stations to the location of the base stations, as shown in Figure 2.

We first consider the case without fading and only incorporate path loss into our analysis using the *two-slope* path-loss model [5]. The average received signal power $\bar{S}$ is given by

$$\bar{S} = \frac{A}{r^a(1+r/d_c)^b} S_t \tag{3}$$

where A is a constant, r [m] is the distance between the mobile and the BS, a is the basic path-loss exponent ($a \approx 2$), b is the additional path-loss exponent (ranges from 2 to 6), S_t [W] is the total transmitted power, and d_c is the critical distance. In this model the power falloff with distance is assumed to behave differently in the near field ($r \ll d_c$) than in the far field ($r \gg d_c$). For a 900 MHz system with carrier wavelength λ_c, BS antenna height $h_B = 10$m, and mobile antenna height $h_m = 2$m, the critical distance is $d_c = 4h_B h_m/\lambda_c \approx 240.3$m.

Two adjacent base stations are separated by $2R$, which is also the cell length. Mobile users are independently uniformly distributed within the cell, but the closest distance they can be from the BS is denoted as R_0. As a result, in the single BS detection case, if a BS is located at the origin, then the mobiles in this cell are independently uniformly distributed over $[-R, -R_0] \cup [R_0, R]$. All mobile users (both within the cell and out-of-cell interferers) transmit at the same power level S_t. We are interested in the interference-limited regime where the thermal noise can be ignored ($\sigma^2 = 0$). In this case the exact value of A and S_t does not enter into the analysis. Therefore we assume $A = 1$, $S_t = 1$ and focus on the attenuation factor

$$g(r) = r^{-a}(1+r/d_c)^{-b}. \tag{4}$$

III. Single base station detection

A. Intra-cell FDMA

Under intra-cell FDMA, users within the same cell access the channel orthogonally and do not interfere with each other. Assuming each cell has K users and a bandwidth allocation of B, under FDMA each user has a bandwidth of B/K. The same channel is reused at a distance $D = D_u \cdot (2R)$, where the integer D_u is the normalized reuse distance. We only consider the interference from two nearest co-channel cells due to power falloff with distance.

For the k^{th} user in the current cell and its two interferers, denote x_k, x_{I1}, x_{I2} as the random positions with regard to their respective base stations. We assume x_k, x_{I1}, x_{I2} are i.i.d. uniformly distributed over $[-R, -R_0] \cup [R_0, R]$. The received signal-to-interference ratio (SIR) is

$$\gamma_k(x_k, x_{I1}, x_{I2}) = \frac{g(|x_k|)}{g(|x_{I1} - D|) + g(|x_{I2} + D|)}, \tag{5}$$

where $g(r)$ is the attenuation factor defined in (4). Assuming users transmit Gaussian codebooks, the k^{th} user can achieve a rate

$$C_k = \mathbb{E}\left\{\frac{B}{K}\log(1+\gamma_k)\right\} \tag{6}$$

and the coverage spectral efficiency

$$\text{CSE}^{\text{S}}_{\text{FD}} = \frac{\sum_k C_k}{BD} = \frac{1}{D}\int \log(1+\gamma_k) p(x_k, x_{I1}, x_{I2}) dx_k dx_{I1} dx_{I2} \tag{7}$$

where the superscript S stands for single BS detection and subscript FD stands for intra-cell FDMA. In (7) we also use the fact that all users have the same rate under the assumption of i.i.d. random locations, i.e. C_k does not depend on k. The CSE of this scheme is further analyzed in Section III-C.

B. Intra-cell Wideband

For a single isolated cell, it is well-known that to maximize uplink sum-rate all users should transmit simultaneously (intra-cell WB) and the BS should implement multiuser detection [6]. However intra-cell WB is not necessarily optimal when co-channel interference from other cells is taken into consideration. Under the assumption of single BS detection, the achievable rate of the intra-cell WB scheme can be larger or smaller than that of orthogonal schemes, depending on system parameters [2].

Next we consider the CSE of the intra-cell WB scheme. Under the assumption of equal transmit power the overall received SIR is

$$\gamma_{\text{WB}} = \frac{\sum_{k=1}^{K} g(|x_k|)}{\sum_{i=1}^{K} g(|x_{Ii} - D|) + \sum_{i=K+1}^{2K} g(|x_{Ii} + D|)}, \tag{8}$$

where the numerator is the total power of desired users within the cell and the denominator is the total interference power. The achievable sum rate is

$$\sum_k C_k = \mathbb{E}\left\{B\log(1+\gamma_{\text{WB}})\right\}, \tag{9}$$

and the coverage spectral efficiency is

$$\text{CSE}^{\text{S}}_{\text{WB}} = \frac{1}{D}\int \log(1+\gamma_{\text{WB}}) p(\boldsymbol{x}, \boldsymbol{x}_I) d\boldsymbol{x} d\boldsymbol{x}_I, \tag{10}$$

where $\boldsymbol{x} = \{x_1, \cdots, x_K\}$ and $\boldsymbol{x}_I = \{x_{I1}, \cdots, x_{I,2K}\}$ are the relative positions of mobile users with respect to their own base stations. The intra-cell FDMA and WB schemes are compared in Section III-C.

C. Performance Analysis

First we want to identify what parameters will affect the CSE. As we mentioned before, if all users transmit at the same power S_t, then the exact value of S_t does not matter as long as the system is in the interference-limited regime. Moreover, since we consider the spectral efficiency instead of rates, the bandwidth B does not enter into our analysis either. As a result we study the effect on CSE of the path loss components a and b, the cell length $2R$, normalized reuse distance D_u, and the number of users per cell K.

Here we can make some immediate observations: the additional path loss component b mainly affects the far field users (interferers), so we expect the CSE to increase with b, which is verified in [1] for a different model and also holds here.

The CSE in (7) assumes a random location of interferers. We can easily see that it is bounded above by the best case CSE when all interferers are on the far boundary of their respective cells, and bounded below by the worst case CSE when all interferers are on the near boundary. In Figure 3 we plot the best, average and worst case CSE for both the FD scheme $(K = 1)$ and the WB scheme $(K = 2)$. We see that the upper and lower bounds become tight as D_u increases, since the distance between interferers and the decoding base station is $|D \pm x_I|$ and the random effect of x_I diminishes when imposed on a large reuse distance $D = 2RD_u$. We also see that the worst case CSE favors a reuse distance $D_u = 2$ but both the best and the average CSE are maximized when $D_u = 1$, i.e. the channel is reused in every cell.

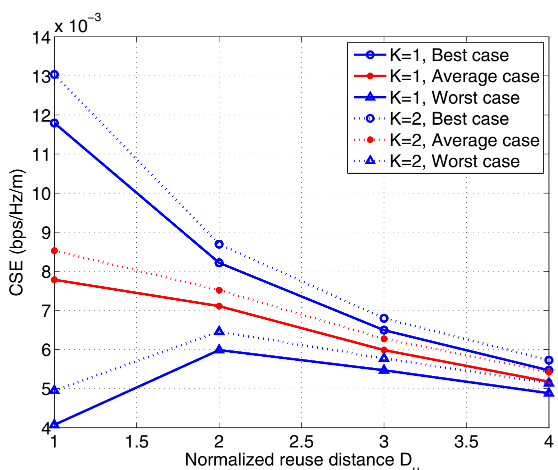

Fig. 3. Single BS detection, $R = 200$m, $R_0 = 20$m, $a = b = 2$

We then compare the intra-cell FDMA and WB schemes and plot the average case CSE for a different number (K) of users per cell in Figure 4. Under the assumption of single BS detection, we see that the WB scheme always performs better than the FD scheme and the advantage is more prominent for more users per cell. The CSE is always maximized by reusing the channel in every cell $(D_u = 1)$ regardless of K.

We want to emphasize that in general the relationship between the CSE of WB and FDMA schemes can go either way [2]. A rule of thumb is that FDMA performs better in a strong interference environment by reducing the number of interferers, while WB is advantageous for low interference, since it results in an averaging effect on the random fluctuation of the desired mobile user's received power. The observed superiority of the WB scheme here suggests that the interference has been significantly attenuated by the path loss effect. In other words, we expect the advantage of WB over FDMA to be more prominent with larger path loss exponents. To gain more insight into this, we analyze the following example and show that the WB scheme performs better than FD even for very small path loss exponents. We assume $b = 0$ and focus on the effect of the path loss exponent a. In [7] we derive that for $0 \leq a < 1$, $D_u = 1$ and $R_0 = 0$, the CSE of the WB scheme with a large number of users per cell is

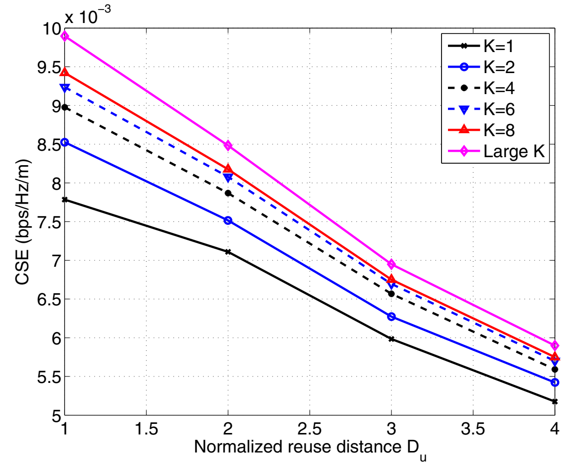

Fig. 4. Single BS detection, $R = 200$m, $R_0 = 20$m, $a = b = 2$

$$\lim_{K \to \infty} \mathrm{CSE}_{\mathrm{WB}}^{\mathrm{S}} = \frac{1}{D} \log \left\{ 1 + \frac{1}{3^{1-a} - 1} \right\} \quad (11)$$

and the CSE of the FDMA scheme is

$$\mathrm{CSE}_{\mathrm{FD}}^{\mathrm{S}} \approx \frac{1}{D} \left[\frac{G(3) - G(1)}{4} - \frac{9H(3) - H(1)}{4} + 2H(\infty) \right] \quad (12)$$

where

$$G(z) = az \left[{}_2F_1 \left(\frac{1}{a}, 1; 1 + \frac{1}{a}; -\frac{z^a}{2} \right) - 1 \right] + z \log \left(1 + \frac{z^a}{2} \right)$$
$$H(z) = \frac{a}{z} \left[{}_2F_1 \left(-\frac{1}{a}, 1; 1 - \frac{1}{a}; -\frac{z^a}{2} \right) - 1 \right] - \frac{1}{z} \log \left(1 + \frac{z^a}{2} \right) \quad (13)$$

and ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is the hypergeometric function [8, Sec 9.10]. In Figure 5 we plot both the analytical formula (11) (12) and the Monte Carlo simulation of the ratio $\mathrm{CSE}_{\mathrm{WB}}^{\mathrm{S}} / \mathrm{CSE}_{\mathrm{FD}}^{\mathrm{S}}$. Both curves increase with a, which confirms that the WB scheme is more advantageous for small interference in the system. The two curves coincide well for small a but are slightly offset when a approaches 1. This is because in the Monte-Carlo simulation we choose $K = 1000$ to approximate infinite K and it may not be "large" enough for $a \approx 1$.

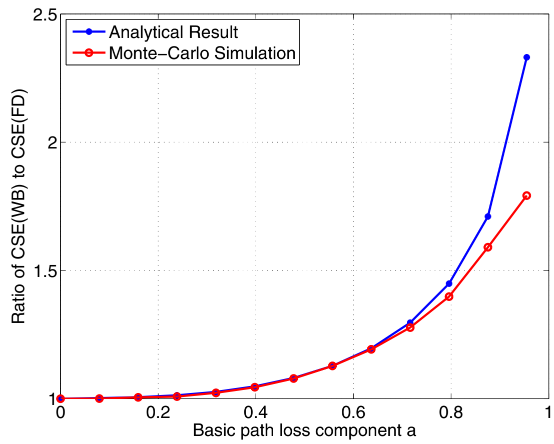

Fig. 5. CSE Ratio of WB to FDMA, $b = 0, D_u = 1, R_0 = 0, R = 200$m

As mentioned before, the cell length $2R$ also affects CSE. It was observed in [1] that the CSE favors small R in a two-dimensional cellular array. Simulations, omitted here due to space constraints, show the same result in our model for both WB and FD schemes, i.e. in view of CSE, when decreasing R the gain from reduced coverage exceeds the loss from increased interference.

IV. Adjacent Base Stations Joint Detection

A. Intra-cell FDMA

Similar to the setup in Section III-A, each user is allocated a bandwidth of B/K and has two co-channel interferers. The difference is that the desired signal and interference are now received at two base stations and then jointly processed. This is equivalent to a vector multiple access channel (MAC) with 3 users and 2 receive antennas.

We denote $\{x_k, x_{I1}, x_{I2}\}$ as the relative mobile position to the respective *cell centers*. The relative positions $\{x_k, x_{I1}, x_{I2}\}$ are i.i.d. uniformly distributed over $[-R + R_0, R - R_0]$. This is slightly different from the case of single BS detection where the relative position is with respect to the base stations.

The channel gain for the k^{th} desired user is

$$\boldsymbol{h}_k = \begin{bmatrix} g(|x_k + R|)^{1/2} \\ g(|x_k - R|)^{1/2} \end{bmatrix} \tag{14}$$

and the interference channel gain is

$$\begin{aligned} \boldsymbol{h}_{I1} &= \begin{bmatrix} g(|x_{I1} - D + R|)^{1/2} \\ g(|x_{I1} - D - R|)^{1/2} \end{bmatrix}, \\ \boldsymbol{h}_{I2} &= \begin{bmatrix} g(|x_{I1} + D + R|)^{1/2} \\ g(|x_{I1} + D - R|)^{1/2} \end{bmatrix}. \end{aligned} \tag{15}$$

Note that the attenuation factor $g(r)$ corresponds to power gains and here we convert it to channel gains by taking the square root. The covariance matrices of the desired signal and the interference are

$$\boldsymbol{R}_k = \boldsymbol{h}_k \boldsymbol{h}_k^T, \quad \boldsymbol{R}_I = \sum_{i=1}^{2} \boldsymbol{h}_{Ii} \boldsymbol{h}_{Ii}^T. \tag{16}$$

The achievable rate for user k is

$$C_k = \mathbb{E}\left\{ \frac{B}{K} \log \frac{\det(\boldsymbol{R}_k + \boldsymbol{R}_I)}{\det(\boldsymbol{R}_I)} \right\} \tag{17}$$

and the coverage spectral efficiency is

$$\text{CSE}_{\text{FD}}^{\text{J}} = \frac{1}{D} \int \log \frac{\det(\boldsymbol{R}_k + \boldsymbol{R}_I)}{\det(\boldsymbol{R}_I)} p(x_k, x_{I1}, x_{I2}) dx_k dx_{I1} dx_{I2}. \tag{18}$$

B. Intra-cell Wideband

We can also let K users within each cell transmit simultaneously. The channel gains for the K desired users are defined in a way similar to (14). We assume interferers $\{1, \cdots, K\}$ are from the co-channel cell on the left and $\{K+1, \cdots, 2K\}$ are from the right, i.e the interference channel gain

$$\boldsymbol{h}_{Ii} = \begin{bmatrix} g(|x_{Ii} - D + R|)^{1/2} \\ g(|x_{Ii} - D - R|)^{1/2} \end{bmatrix}, \quad 1 \leq i \leq K \tag{19}$$

and

$$\boldsymbol{h}_{Ii} = \begin{bmatrix} g(|x_{Ii} + D + R|)^{1/2} \\ g(|x_{Ii} + D - R|)^{1/2} \end{bmatrix}, \quad K+1 \leq i \leq 2K. \tag{20}$$

The covariance matrices for desired signals and interferences are

$$\boldsymbol{R} = \sum_{k=1}^{K} \boldsymbol{h}_k \boldsymbol{h}_k^T, \quad \boldsymbol{R}_I = \sum_{i=1}^{2K} \boldsymbol{h}_{Ii} \boldsymbol{h}_{Ii}^T. \tag{21}$$

The achievable sum rate is

$$\sum_{k=1}^{K} C_k = \mathbb{E}\left\{ B \log \frac{\det(\boldsymbol{R} + \boldsymbol{R}_I)}{\det(\boldsymbol{R}_I)} \right\}, \tag{22}$$

and the coverage spectral efficiency is

$$\text{CSE}_{\text{WB}}^{\text{J}} = \frac{1}{D} \int \log \frac{\det(\boldsymbol{R} + \boldsymbol{R}_I)}{\det(\boldsymbol{R}_I)} p(\boldsymbol{x}, \boldsymbol{x}_I) d\boldsymbol{x} d\boldsymbol{x}_I, \tag{23}$$

where $\boldsymbol{x} = \{x_1, \cdots, x_K\}$, $\boldsymbol{x}_I = \{x_{I1}, \cdots, x_{I,2K}\}$, and x_k, x_{Ii} are i.i.d. uniformly distributed over $[-R+R_0, R-R_0]$. In the limit of large K, using the strong law of large numbers, we can verify that for $a = b = 2$,

$$\frac{\boldsymbol{R}}{K} \to \overline{\boldsymbol{R}} = \begin{bmatrix} \mu_0 & \nu_0 \\ \nu_0 & \mu_0 \end{bmatrix}, \frac{\boldsymbol{R}_I}{K} \to \overline{\boldsymbol{R}_I} = \begin{bmatrix} \mu_1 + \mu_2 & \nu_1 + \nu_2 \\ \nu_1 + \nu_2 & \mu_2 + \mu_1 \end{bmatrix} \tag{24}$$

and

$$\text{CSE}_{\text{WB}}^{\text{J}} \to \frac{1}{D} \log \frac{\det(\overline{\boldsymbol{R}} + \overline{\boldsymbol{R}_I})}{\det(\overline{\boldsymbol{R}_I})} \tag{25}$$

where for $j = 0, 1, 2$

$$\mu_j = \frac{1}{r_j^2 - A^2} + \frac{1}{(r_j + d_c)^2 - A^2} - \frac{1}{A d_c} \log \frac{R_M (R_0 + d_c)}{R_0 (R_M + d_c)} \tag{26}$$

with $r_0 = R$, $r_{1,2} = D \mp R$, $A = R - R_0$, $R_M = R + A$ and

$$\nu_0 = \frac{d_c}{2A(2R+d_c)} \left\{ \frac{1}{R} \log \frac{R_M}{R_0} - \frac{1}{R+d_c} \log \frac{R_M + d_c}{R_0 + d_c} \right\}$$

$$\nu_1 = \nu_2 = \frac{d_c}{4AR} \left\{ \frac{1}{2R+d_c} \log \frac{(D-R_0)(D+R_0+d_c)}{(D-R_M)(D+R_M+d_c)} + \frac{1}{2R-d_c} \log \frac{(D+R_M)(D-R_M+d_c)}{(D+R_0)(D-R_0+d_c)} \right\}.$$

The analytical solution together with the Monte Carlo simulation is plotted in Figure 6.

C. Performance Analysis

Comparing with the case of single BS detection, the first difference observed is that the best/worst case interferers are not necessarily on the far/near boundary of their respective cells. For example, consider the case when $a = b = 2$, $R = 200$m, $R_0 = 20$m, $D_u = 1$, an intra-cell FD scheme and the desired user is randomly located between $[0, R - R_0]$. Simulations show that in the best case, the interferer from the right cell is located on the far boundary with $x_{I2} = R - R_0 = 180$ m as expected, however when the desired mobile is within a certain range $[L_1, L_2]$, the best case interferer from the left cell is surprisingly located on the near boundary instead of the far boundary. This observation is further investigated in [7] and the aforementioned range $[L_1, L_2]$ is directly calculated. Intuitively, in the single BS detection case the interference is fully characterized by the power which in turn corresponds to the distance between the interferer and the BS. When adjacent BS's cooperate as a multiple antenna system, the interference depends not only on the power, but the differentiability between the spatial signatures (vector channel gains) of the desired mobile and the interferers.

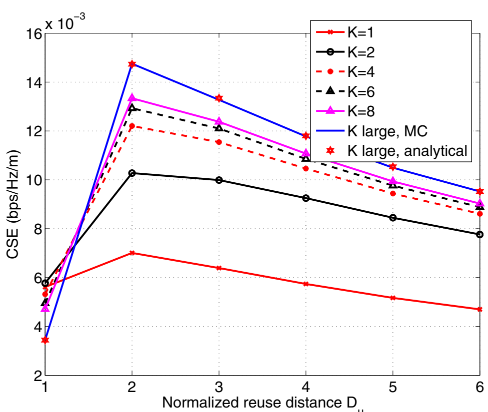

Fig. 6. Joint BS detection, $R = 200$m, $R_0 = 20$m, $a = b = 2$

Unlike the previous single BS detection case, there is no simple upper or lower bound for CSE. We primarily rely on Monte Carlo simulations to gain insight into the performance of joint BS detection as shown in Figure 6. First we compare the FD and WB schemes. When the channel is reused in every cell ($D_u = 1$), we notice that the CSE increases when the number of users per cell K goes from 1 to 2. The CSE then decreases if K further increases. This is different from the observation in Section III-C. Actually, for $D_u = 1$ the interference comes directly from adjacent cells. It is possible that the interference is even closer to one of the decoding base stations than the desired mobile is. For example, if $x_k > 0$ and $x_{I1} > 0$ then the left interferer is closer to the left BS than the desired user. In general the small interference assumption in Section III-C no longer holds. On the other hand, when the reuse distance $D_u \geq 2$ and the interference is significantly attenuated, the WB scheme always performs better than FD does and is more advantageous for larger K as before.

In contrast to the single BS detection case where the CSE is maximized at $D_u = 1$, in the joint detection case reusing channels in every cell causes strong interference and exhibits worse performance than larger reuse distances. In Figure 6 the optimal reuse distance is shown to be $D_u = 2$ regardless of K. Comparing Figure 4 and 6 we see that when $D_u = 1$ the joint BS detection is even worse than the single BS detection while for $D_u \geq 2$ the situation is reversed.

V. Conclusion

Coverage spectral efficiency characterizes the tradeoff between efficient channel reuse and the achievable rates per cell. We show that with single BS detection, the intra-cell WB scheme can achieve higher CSE than the FD scheme since interference is significantly attenuated by path loss. We expect the advantage of WB over FD to be more prominent with larger path loss exponents and this is verified by both analytical results and simulations. The CSE can be further improved by cooperative decoding of adjacent base stations. In this case we notice that the best/worst interferers are not necessarily on the far/near boundary of co-channel cells. Unlike the case of single BS detection, where the channel is reused in every cell to optimize CSE, with joint BS detection the channel should be reused in every other cell. The WB scheme also performs better than the FD scheme at this reuse distance.

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