Intercell-Interference in the Gaussian MISO Broadcast Channel

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***Abstract*—Intercell interference (ICI) is the substantial difference between a cellular and a non-cellular communication system. Effective modeling of the cellular downlink as a Gaussian broadcast channel requires that the ICI powers at the user positions are known to the basestation (BS), as it otherwise, cannot attempt to approach (or even know) its capacity region. However, ICI depends on the transmit processing of the BSs in the neighboring cells, which furthermore is subject to change quickly due to temporal scheduling. The BS therefore only has limited knowledge about the true ICI powers. In this paper, the implications of this lack of knowledge about ICI power on the achievable sum-rate of a Gaussian MISO (multi-input, single-output) broadcast channel is examined. Four different approaches on dealing with unpredictable ICI are discussed and their performance compared to the single-cell (or non-cellular) Gaussian broadcast channel.**

I. Introduction

The downlink of a non-cellular communication system, like for instance WLAN, can be modeled by a Gaussian broadcast channel [1]. This model is appealing because of several reasons. It covers multiple transmit and receive antennas. The region of achievable rates (the capacity region) is known exactly [2], [3]. Furthermore, the application of "dirty-paper" coding [4] can indeed achieve the whole capacity region [5]. Finally, the duality between the broadcast and the multiple access channel [6], [7], paves the way to an efficient solution of finding the optimum transmit signal processing for the broadcast channel [8], [9]. An interesting open question is, however, to what extent can the Gaussian broadcast channel be used as a model for the downlink of a *cellular* communication system, like for instance 3GPP-LTE or future 4G.

The key difference between a cellular and a non-cellular communication system is the intercell interference (ICI). In order to support high peak data rates, it is highly desirable to use the whole available spectrum bandwidth in all cells (frequency reuse one). This leads to the fact that for most users in such a cellular environment the ICI dominates over thermal noise. Since the ICI power also depends on the position in the cell, each user experiences, in general, a different ICI power level at a given time. These ICI power levels have to be known by the basestation before it can attempt to approach or even know the capacity region.

However, the ICI power levels depend on the transmit processing of the other basestations in the neighboring cells. In case that all basestations work independently of each other, the ICI power becomes unpredictable. This leads to a mismatch between the *assumed* ICI power used to compute the transmit processing, and the *true* ICI power which may be different from the assumed one, since the neighboring basestations may have changed their transmit processing and, hence, they now interfere differently. Furthermore, the ICI power level can change quickly, typically in the range of milliseconds (e.g. half millisecond for 3GPP-LTE [10]), although the actual propagation channel may change very slowly due to low user mobility. The reason is that usually there are (much) more users to serve in a cell, than the basestation is able or willing to serve at the same time. In this way, the users need to wait to get service. In order to maintain fairness among users and keep the latency time low, the basestations need to perform a fast scheduling. As a result, the transmit processing (e.g. formed beams and their assigned transmit power) can change on a millisecond time-scale. When ICI power dominates over thermal noise (frequency reuse one), it follows that the channel quality varies quickly. This quick variation can lead to a permanent mismatch between assumed and true ICI power levels [11]. There are different ways to deal with this mismatch problem.

1) **Genie assistance:** the mismatch could be avoided completely if all basestations would know the true ICI power levels that will be generated by their neighbors. This could be achieved by basestations with centralized control at the expense of a huge signaling overhead.
2) **Conservative gambling:** One can also accept the ICI power mismatch and use somewhat conservative link adaptation. One problem with this approach is that one cannot take advantage if the ICI power is lower than expected. Another problem is that occasionally the link adaptation fails completely, such that no user can decode its data.
3) **Isolation:** Another way of avoiding or at least lowering the amount of mismatch is to isolate the cells by increasing the frequency reuse factor. Of course, this comes at the big expense of reduced usable bandwidth.
4) **Stabilization:** Mismatch can also be avoided or largely reduced by refraining to apply user-specific transmit signal processing. As long as the propagation channels do not change too much (low mobility), the ICI power at a user position remains essentially constant. Of course, this approach loses most benefits of spatial signal processing and coding.

In this paper, we investigate the influence of these four approaches on the sum-capacity in a cellular Gaussian broadcast channel. We restrict the discussion to the case where only the basestation is equipped with multiple antennas, the so-called MISO (multi-input single-output) case.

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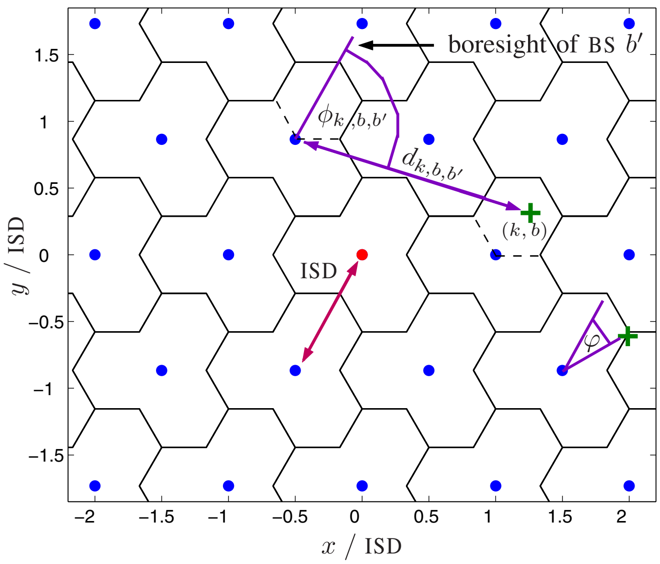

Figure 1. Cellular network topology. The circles indicate three co-located basestations, each serving a hexagonal cell. The plus-shaped markers represent user positions. Note that the basestations are located at the edge of the cell they are serving.

II. Cellular System Model

A. Network Topology

Let us consider a cellular network topology, which employs sectorization, such that three BS are co-located at one position. Each BS serves the users of its own, hexagonal-shaped *cell*, while the three cells together form a *site*. A particular BS is identified by the tuple

$$b = (i, j) \in \{1, 2, \dots, S\} \times \{1, 2, 3\} \stackrel{\text{def}}{=} \mathcal{B}, \qquad (1)$$

where $i \in \{1, 2, \dots, S\}$ specifies its site, while $j \in \{1, 2, 3\}$ tells which cell it is serving. We define the function $\text{cell}(b)$ to return the number j of the cell that BS b is serving. A user is specified by the tuple (k, b), meaning user number $k \in \{1, 2, \dots, K_b\} \stackrel{\text{def}}{=} \mathcal{K}_b$ served by BS $b \in \mathcal{B}$. The distance $d_{k,b,b'}$ between the user (k, b) and the BS $b' \in \mathcal{B}$, and the angle $\phi_{k,b,b'}$ with respect to the boresight direction of the antenna array of BS $b' \in \mathcal{B}$, will be used later for ICI calculation and are defined in Figure 1. The cell size is determined by the inter-site distance (ISD).

B. BS Antenna Beam Pattern

Since the BSs are not located in the center of the cell they are serving, the distance to the cell edge largely depends on the azimuthal angle φ (see lower right part of Figure 1). In order to ensure that nevertheless (roughly) the same power can be received on the whole cell edge, the elements of the BS antenna array need to have a correctly shaped beam pattern $A(\varphi)$. In the following we use [12]:

$$10 \log_{10} A(\varphi) = -\min\left(12\left(\frac{\varphi}{70^\circ}\right)^2, 25\right). \qquad (2)$$

The limited backward attenuation (here $25\,\text{dB}$) has large impact on ICI produced by those BSs which actually look away from the user of interest.

C. User Positions

The user positions are drawn by random from a distribution which is uniform in the area of the cell. However, in order to be able to use standard far-field approximations of the path-loss we restrict the minimum distance of a user to its own BS to $d_{\min} = 100\lambda$, where λ is the carrier wavelength.

D. Channel Model

The propagation channel between user (k, b) and the N elements of the antenna array of BS b' is modeled as frequency flat Rayleigh fading by:

$$\mathbb{C}^{1\times N} \ni \boldsymbol{h}_{k,b,b'}^{\mathrm{T}} = \sqrt{\rho(d_{k,b,b'})} \cdot \boldsymbol{g}_{k,b,b'}^{\mathrm{T}} \boldsymbol{Q}(\phi_{k,b,b'}). \qquad (3)$$

Herein,

$$\rho(d_{k,b,b'}) = \widehat{A} \cdot \left(\frac{\lambda/1\mathrm{m}}{4\pi}\right)^2 \cdot \left(\frac{d_{k,b,b'}}{1\mathrm{m}}\right)^{-\gamma} \cdot 10^{\chi_{k,b,b'}/10}, \qquad (4)$$

is the combined average distance-dependent path-gain and log-normal shadowing, which is modeled by the zero-mean, Gaussian random variable $\chi_{k,b,b'}$, where a variance of 36 is typical [13]. The term $\widehat{A}$ denotes the maximum antenna gain (in boresight direction) of each antenna element of the transmit antenna array.[1] The constant $\gamma \geq 2$ is the so-called path-loss exponent [13]. The vector $\boldsymbol{g}_{k,b,b'} \in \mathbb{C}^{N\times 1}$ contains i.i.d. zero-mean, unity variance, complex, circularly symmetric, Gaussian random variables, while $\boldsymbol{Q}(\phi_{k,b,b'}) \in \mathbb{C}^{N\times N}$ is any matrix square root of the transmit fading covariance matrix

$$\boldsymbol{R}_{\mathrm{Tx}}(\phi_{k,b,b'}) = \mathrm{E}\left[\boldsymbol{h}_{k,b,b'}^{*} \boldsymbol{h}_{k,b,b'}^{\mathrm{T}} \mid \chi_{k,b,b'}\right] \big/ \rho(d_{k,b,b'}), \qquad (5)$$

which is calculated as:

$$\boldsymbol{R}_{\mathrm{Tx}}(\phi_{k,b,b'}) = \alpha \int_{-\pi}^{\pi} p(\varphi - \phi_{k,b,b'}) \cdot \boldsymbol{a}^{*}(\varphi)\boldsymbol{a}^{\mathrm{T}}(\varphi)\mathrm{d}\varphi, \qquad (6)$$

where $p(\varphi)$ is a function that models the angle-spread by returning the relative amount of received power which originates from a transmit azimuthal angle φ. We use [12]:

$$p(\varphi) = \sum_i b_i \cdot \exp\left(-\frac{(\varphi - \theta_i)^2}{2\zeta^2}\right), \qquad (7)$$

where the θ_i denote the centers of discrete directions of departure with Gaussian angle-spread of variance ζ^2 and corresponding (relative) powers b_i. The particular values for these constants depend on the scenario. In this paper, we use the D1-rural scenario from [12],[2] which leads to an RMS angle-spread of about 9°. The vectors $\boldsymbol{a}(\varphi)$ in (6) are the steering

[1] We assume that the user receive antenna has unity antenna gain which corresponds to an omni-directional antenna pattern.

[2] We use the following specification: (θ_i) = (-35.1, -23.8, -12.5, -8.5, -6.8, -2.8, -0.7, -0.3, 1.1, 2.1, 3.0, 3.5, 6.7, 6.8, 6.9, 10.1, 14.5, 15.5, 20, 21.4)°, (b_i) = (0.036, 0.016, 0.058, 1.0, 0.017, 0.055, 0.01, 0.02, 0.25, 0.16, 0.63, 0.17, 0.026, 0.21, 0.096, 0.030, 0.038, 0.054, 0.062, 0.14), $\zeta = 1.5°$. This is a slight modification of the specification from [12], in that we have shifted the (θ_i) by 8.5° in order to make $\max_{\phi} \operatorname{tr} \boldsymbol{R}_{\mathrm{Tx}}(\phi)$ occur at $\phi = 0$.

vectors of the BS antenna array. In this paper, we assume a uniform linear array with half-wavelength spaced elements:

$$\mathbf{e}_i^{\mathrm{T}} \boldsymbol{a}(\varphi) = \sqrt{A(\varphi)} \cdot \exp\Big((i-1)\mathrm{j}\pi \sin\varphi\Big), \tag{8}$$

where $A(\varphi)$ is the antenna beam pattern defined in (2), $\mathbf{e}_i$ is the i-th unit vector $\big(i \in \{1, 2, \ldots, N\}\big)$, and $\mathrm{j}^2 = -1$. The constant α in (6) is chosen such that $\max\big(\mathrm{tr}\, \boldsymbol{R}_{\mathrm{Tx}}(\phi)\big) = N$, w.r.t. to ϕ. Consequently, $\rho(d_{k,b,b'})$ is the maximum average path-gain between a transmit array element of BS b' and user (k, b), where averaging is performed over Rayleigh fading.

E. Signal and Interference

The received signal of user (k, b) can be written as:

$$r_{k,b} = \boldsymbol{h}_{k,b,b}^{\mathrm{T}} \boldsymbol{t}_{k,b} \cdot s_{k,b} + \sum_{k' \in \mathcal{K}_b \setminus \{k\}} \boldsymbol{h}_{k,b,b}^{\mathrm{T}} \boldsymbol{t}_{k',b} \cdot s_{k',b} + \nu_{k,b}, \tag{9}$$

where $\boldsymbol{t}_{k,b} \in \mathbb{C}^{N \times 1}$, and $s_{k,b} \in \mathbb{C}$, are the transmit beamforming vector and the transmitted zero-mean signal for user (k, b), respectively. Defining $\mathrm{E}[|s_{k,b}|^2] = 1$, the transmit power assigned to user (k, b) is given by $P_{k,b} = ||\boldsymbol{t}_{k,b}||_2^2$, while the total transmit power of BS b equals $P_b = \sum_k P_{k,b} = P_{\mathrm{T}}$, and is defined to be constant for all times and basestations. Finally, the term $\nu_{k,b}$ denotes intercell interference plus thermal noise, which power becomes for a reuse one system:

$$\mathrm{IPN}_{k,b} := \mathrm{E}\left[|\nu_{k,b}|^2\right] = \sigma_{k,b}^2 + \sum_{b' \in \mathcal{B} \setminus \{b\}} \sum_{k' \in \mathcal{K}_{b'}} \left|\boldsymbol{h}_{k,b,b'}^{\mathrm{T}} \boldsymbol{t}_{k',b'}\right|^2, \tag{10}$$

where $\sigma_{k,b}^2$ is the power of the thermal noise, and $\mathcal{B}$ is defined in (1). For a reuse three system we replace in (10) $\mathcal{B}$ by

$$\mathcal{B}_b = \big\{1, 2, \ldots, S\big\} \times \big\{\mathrm{cell}(b)\big\}. \tag{11}$$

III. Channel Coding and Beamforming

Let the data stream for user (k, b) be encoded *after* the data streams for all users $(k' > k, b)$ are encoded. From the principle of dirty-paper coding [4], a code for user (k, b) can be found, such that this user receives interference only from the signals transmitted for the users $(k' \le k-1, b)$. The effective signal to interference plus noise ratio $\Gamma_{k,b}$ then becomes:

$$\Gamma_{k,b} = \frac{P_{k,b} |\boldsymbol{h}_{k,b,b}^{\mathrm{T}} \boldsymbol{u}_{k,b}|^2}{\mathrm{IPN}_{k,b} + \sum\limits_{k'=1}^{k-1} P_{k',b} |\boldsymbol{h}_{k,b,b}^{\mathrm{T}} \boldsymbol{u}_{k',b}|^2}, \tag{12}$$

where

$$\boldsymbol{u}_{k,b} = \boldsymbol{t}_{k,b} \cdot ||\boldsymbol{t}_{k,b}||_2^{-1}. \tag{13}$$

Assuming that the ICI plus thermal noise is (almost) Gaussian, the achievable rate for user (k, b) is given by [14]:

$$R_{k,b} = B \cdot \log_2\left(1 + \Gamma_{k,b}\right) \quad \text{bit/s}, \tag{14}$$

where B is the Nyquist bandwidth. Let the goal of the BS be to maximize the sum-rate for its cell. The beamforming vectors and transmit powers must be chosen such that

$$\sum_{k=1}^{K_b} R_{k,b} = \max! \quad \text{s.t.} \quad \sum_{k=1}^{K_b} P_{k,b} = P_{\mathrm{T}}, \quad \forall b \in \mathcal{B}, \tag{15}$$

where K_b is the number of considered users for BS b. This problem is best solved by means of the duality between the broadcast and the multiple access channel [6], [7]. By defining $\tilde{\boldsymbol{h}}_{k,b,b} = \boldsymbol{h}_{k,b,b} / \sqrt{\mathrm{IPN}_{k,b}}$, we can rewrite (12) as

$$\Gamma_{k,b} = \frac{P_{k,b} |\tilde{\boldsymbol{h}}_{k,b,b}^{\mathrm{T}} \boldsymbol{u}_{k,b}|^2}{1 + \sum\limits_{k'=1}^{k-1} P_{k',b} |\tilde{\boldsymbol{h}}_{k,b,b}^{\mathrm{T}} \boldsymbol{u}_{k',b}|^2}. \tag{16}$$

In the dual multiple access channel (MAC), the $\boldsymbol{u}_{k,b}$ now become receive beamforming vectors. Assume that successive interference cancellation is performed such that the signal of user (k, b) is decoded *after* the signals for the users $(k' < k, b)$ have been successfully decoded and their effect subtracted from the received signal. In this way, only the users $(k' \ge k+1, b)$ produce interference for user (k, b). The effective signal to noise and interference ratio $\Gamma_{k,b}^{\mathrm{MAC}}$ for the dual MAC becomes:

$$\Gamma_{k,b}^{\mathrm{MAC}} = \frac{P_{k,b}^{\mathrm{MAC}} \cdot |\tilde{\boldsymbol{h}}_{k,b,b}^{\mathrm{T}} \boldsymbol{u}_{k,b}|^2}{1 + \sum\limits_{k'=k+1}^{K_b} P_{k',b}^{\mathrm{MAC}} \cdot |\tilde{\boldsymbol{h}}_{k',b,b}^{\mathrm{T}} \boldsymbol{u}_{k,b}|^2}, \tag{17}$$

where $P_{k,b}^{\mathrm{MAC}}$ are the transmit powers of the users, which have to sum up to P_{T} for every basestation. If all the $P_{k,b}^{\mathrm{MAC}}$ are given for $k \in \{1, 2, \ldots K_b\}$, the sum of achievable rates of the MAC is maximized if the beamforming vectors are chosen as Wiener filters [15]:

$$\boldsymbol{u}_{k,b} = \boldsymbol{w}_{k,b} \cdot ||\boldsymbol{w}_{k,b}||_2^{-1}, \tag{18}$$

where

$$\boldsymbol{w}_{k,b} = \left(\boldsymbol{I}_{K_b} + \sum_{k'=k}^{K_b} P_{k',b}^{\mathrm{MAC}} \tilde{\boldsymbol{h}}_{k',b,b}^{*} \tilde{\boldsymbol{h}}_{k',b,b}^{\mathrm{T}}\right)^{-1} \tilde{\boldsymbol{h}}_{k,b,b}^{*}, \tag{19}$$

where $\mathbf{I}_{K_b}$ is the $K_b \times K_b$ identity matrix. By substituting (19) into (18) and the latter into (17), the maximization of the sum of achievable rates is reduced to finding the optimum powers

$$\forall b \in \mathcal{B}: \left(P_{k,b,\mathrm{opt}}^{\mathrm{MAC}}\right)_{k=1}^{K_b} = \underset{\left(P_{k,b}^{\mathrm{MAC}}\right)_{k=1}^{K_b}}{\arg\max} \sum_{k=1}^{K_b} \log_2\left(1 + \Gamma_{k,b}^{\mathrm{MAC}}\right),$$

$$\text{s.t.} \ \ \forall k: P_{k,b}^{\mathrm{MAC}} \ge 0, \ \sum\nolimits_{k=1}^{K_b} P_{k,b}^{\mathrm{MAC}} = P_{\mathrm{T}}, \tag{20}$$

which can be solved numerically. The vectors

$$\boldsymbol{u}_{k,b}^{\mathrm{opt}} = \frac{\boldsymbol{w}_{k,b}^{\mathrm{opt}}}{||\boldsymbol{w}_{k,b}^{\mathrm{opt}}||_2}, \ \ \text{with} \ \ \boldsymbol{w}_{k,b}^{\mathrm{opt}} = \boldsymbol{w}_{k,b} \Big|_{\left(P_{k,b}^{\mathrm{MAC}}\right)_{k=1}^{K_b} = \left(P_{k,b,\mathrm{opt}}^{\mathrm{MAC}}\right)_{k=1}^{K_b}} \tag{21}$$

are then used for the original broadcast channel, such that

$$\boldsymbol{t}_{k,b} = \boldsymbol{u}_{k,b}^{\mathrm{opt}} \cdot \sqrt{P_{k,b}}. \tag{22}$$

The transmit powers $P_{k,b}$ for the broadcast channel can be computed recursively, by equating (12) and (17):

$$P_{k,b} = P_{k,b,\mathrm{opt}}^{\mathrm{MAC}} \cdot \frac{\mathrm{IPN}_{k,b} + \sum\limits_{k'=1}^{k-1} P_{k',b} \cdot |\boldsymbol{h}_{k,b,b}^{\mathrm{T}} \boldsymbol{u}_{k',b}^{\mathrm{opt}}|^2}{\mathrm{IPN}_{k,b} + \sum\limits_{k'=k+1}^{K_b} P_{k',b,\mathrm{opt}}^{\mathrm{MAC}} \cdot |\boldsymbol{h}_{k',b,b}^{\mathrm{T}} \boldsymbol{u}_{k,b}^{\mathrm{opt}}|^2}. \tag{23}$$

IV. Scheduling and Cell Sum-Rate

We assume that there are more users in the cell than its BS can serve at the same time when employing the maximum sum-rate algorithm from Section III. Therefore, each BS $b \in \mathcal{B}$ performs temporal scheduling such that a number of K_b users is selected to form the user-set $\mathcal{K}_b = \{1, 2, \ldots, K_b\}$, for the maximum sum-rate algorithm. In order to maintain fairness among the users and keep the delay low, this user-set is changed for each radio frame. We model this scheduling by drawing the user positions, and their corresponding channel vectors for each user-set independently by random:

① $\forall b \in \mathcal{B}$: generate K_b random user positions,
② $\forall (b, b', k) \in \mathcal{B}^2 \times \mathcal{K}_b$: compute $\phi_{k,b,b'}$ and $d_{k,b,b'}$, and
③ Generate random $\boldsymbol{h}_{k,b,b'}$ from (3).

The cell sum-rate is characterized by its cumulative distribution function (cdf), which we compute by Monte Carlo simulation. We distinguish the following four cases to obtain one random realization of the sum-rate for one cell, say the one served by BS b_0. For each drop all user positions are drawn by random (see above).

❶ **Genie assistance**: All BSs know the true ICI powers, which we compute iteratively:

① $\mathrm{IPN}_{k,b} \leftarrow \sigma^2_{k,b}, \forall (k,b) \in \mathcal{K}_b \times \mathcal{B}$
② Compute $\boldsymbol{t}_{k,b}, \forall (k,b) \in \mathcal{K}_b \times \mathcal{B}$ from (22)
③ Compute true $\mathrm{IPN}_{k,b}, \forall (k,b) \in \mathcal{K}_b \times \mathcal{B}$ from (10)
④ Continue at step ② until $\mathrm{IPN}_{k,b}$ have converged
⑤ Return $\sum_{k=1}^{K_{b_0}} R_{k,b_0}$ for cell of interest from (14)

❷ **Conservative gambling**: The BSs only know the IPN from the previous radio frame and hope that the next IPN will not differ much. To lower the risk of a wrong choice of the "dirty-paper" code-rates, a "backoff" β is introduced. Initially – for the first drop, only – we set $\boldsymbol{t}_{k,b} = \boldsymbol{0}, \forall (k,b) \in \mathcal{K}_b \times \mathcal{B}$.

① Compute assumed $\mathrm{IPN}_{k,b}, \forall (k,b) \in \mathcal{K}_b \times \mathcal{B}$ from (10)
② Compute $\boldsymbol{t}_{k,b}, \forall (k,b) \in \mathcal{K}_b \times \mathcal{B}$ from (22)
③ Compute assumed capacities $R_{k,b_0}, \forall k \in \mathcal{K}_{b_0}$ from (14)
④ Set code-rates to $R^{\mathrm{set}}_{k,b_0} = (1-\beta) \cdot R_{k,b_0}, \forall k \in \mathcal{K}_{b_0}$
⑤ Compute true $\mathrm{IPN}_{k,b_0}, \forall k \in \mathcal{K}_{b_0}$ from (10)
⑥ Compute true capacities $R^{\mathrm{true}}_{k,b_0}, \forall k \in \mathcal{K}_{b_0}$ from (14)
⑦ Compute user rates: $R^{\mathrm{user}}_{k,b_0} = \begin{cases} R^{\mathrm{set}}_{k,b_0}, & R^{\mathrm{true}}_{k,b_0} \geq R^{\mathrm{set}}_{k,b_0} \\ 0, & \text{else} \end{cases}$
⑧ Return $\sum_{k=1}^{K_{b_0}} R^{\mathrm{user}}_{k,b_0}$ for cell of interest

The key difference between ① and ⑤ is that in the latter we use the new beamforming vectors $\boldsymbol{t}_{k,b}$, and therefore obtain different IPN. Since the rates in ③ are based on out-dated $\boldsymbol{t}_{k,b}$s, the code-rates are set conservatively in ④, allowing a backoff $\beta \in (0;1)_{\mathbb{R}}$. Finally, the users can (at most) achieve these conservative rates iff the true achievable rates are larger or at least equal. Otherwise, the users cannot decode correctly, and their rate is zero (step ⑦). The backoff provides a new degree of freedom in system optimization. In this paper, we set the backoff such that the average sum-rate is maximized.

❸ **Isolation**: The problem of not knowing the correct ICI is greatly released by isolating the cells in the frequency bands. For a reuse three system we follow:

① $\mathcal{B} \leftarrow \mathcal{B}_b$, see eq. (11)
② $B \leftarrow B/3$, (bandwidth reduction)
③ Follow algorithm for "conservative gambling"

Step ① tells that only the cells with the same frequency band interfere. With proper frequency assignment, each cell is isolated from its closest neighbors, which reduces ICI power. Step ② accounts for the price there is to pay for this isolation.

❹ **Stabilization**: All BS only aim at transmit diversity. In this way the IPN remain essentially constant, hence predictable, as long as the propagation channels do not change too much.

① $\mathrm{IPN}_{k,b_0} = \sigma^2_{k,b_0} + \sum_{b' \in \mathcal{B} \setminus b_0} ||\boldsymbol{h}_{k,b_0,b'}||^2_2 \cdot P_{\mathrm{T}} / N$
② Return $\max\limits_{k \in \mathcal{K}_{b_0}} B \cdot \log_2 \left(1 + \frac{P_{\mathrm{T}}}{N} ||\boldsymbol{h}_{k,b_0,b_0}||^2_2 / \mathrm{IPN}_{k,b_0}\right)$

Since there is no beamforming, the IPN essentially only depends on the channel vectors (step ①). Assuming the channels do not change from one radio frame to the other, the IPN also remains unchanged. Maximum sum-rate is now obtained by selecting the user with the highest achievable rate, and by assigning to it all the transmit power (step ②).

V. Performance Evaluation

We consider a network consisting of $S = 19$ sites (57 cells) with $\mathrm{ISD} = 2\mathrm{km}$, where the cell of interest is surrounded by two "rings" of sites. The size of the user-set is fixed to $K_b = 6$ for all BSs, each of which is equipped with a $N = 4$ antenna uniform linear array (half-wavelength spacing), transmitting a total power $P_{\mathrm{T}} = 10\mathrm{W}$ at carrier-wavelength $\lambda = 0.15\mathrm{m}$, and providing a maximum antenna gain of $10 \log_{10} \widehat{A} = 17\mathrm{dB}$. The path-loss exponent equals $\gamma = 3.8$, while the variance of the log-normal shadowing is $\mathrm{var}[\chi] = 36$. The Nyquist bandwidth is set to $B = 4\mathrm{MHz}$ and equals the noise-bandwidth (root Nyquist pulse shape). With receivers at $300\mathrm{K}$ temperature, and amplifier noise figure of 7dB, the thermal noise power equals $\sigma^2_{k,b} = 8.3 \times 10^{-14}\,\mathrm{W}, \forall (k,b) \in \mathcal{K}_b \times \mathcal{B}$.

The performance of the cellular network is evaluated by Monte Carlo simulation in terms of the cumulative distribution function (cdf) of the cell sum-rate. The four introduced approaches of dealing with ICI in the Gaussian broadcast channel – Genie-assistance, conservative gambling, isolation (here reuse three), and stabilization (here transmit diversity) – are compared quantitatively. The backoff, if necessary, is chosen such that maximum average sum-rate is achieved. For the conservative gambling approach, it turns out (from a numerical analysis) that $\beta = 0.12$ is optimum in this respect. For the isolation approach, the intercell interference is much less severe because of the frequency reuse of three, however it is still present. Since the thermal noise makes a bigger part of the IPN, the latter becomes more predictable. Hence, the optimum backoff is lower and turns out to be

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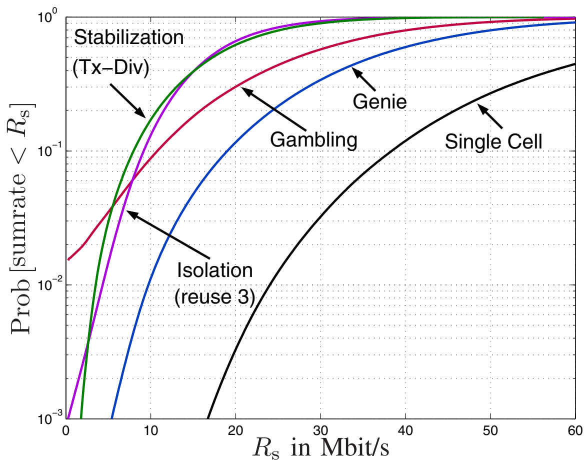

Figure 2. Sum-rate CDF for different strategies of ICI-handling.

$\beta = 0.06$ for the isolation approach. Let us first look at the *average* cell sum-rate. Both the absolute sum-rate (in Mbit/sec) and the relative performance w.r.t. a *single-cell* system (no ICI) are shown below:

AVERAGE CELL SUM-RATE

Single Cell	Genie	Gambling	Isolation	Stabilization
66.0 (100%)	37.8 (57%)	28.5 (43%)	17.8 (27%)	18.3 (28%)

If the ICI-power is known beforehand (genie approach), more than half of the sum-rate (57%) of the single-cell Gaussian MISO broadcast channel can be retained. Conservative gambling still achieves a remarkably high average performance (75% of the genie), while both the reuse-three, and the transmit diversity approach clearly fall behind on average. However, average performance does not tell the whole story.

The cdf of the sum-rate (outage sum-rate) shows us a more complete picture. As we can observe from Figure 2, the genie-approach performs well w.r.t. the single-cell system for virtually all outage probabilities. This is *not* true for conservative gambling which suffers dramatically at outage probabilities lower than about 10%. Outage probabilities lower than 1.5% cannot be achieved at all, since even the conservative link adaptation (backoff $\beta = 0.12$) fails completely for all users (zero sum-rate) with this probability. Isolating the cell (reuse three) makes this problem less severe, however, note that almost the same performance could be achieved by the much simpler transmit diversity system. The gain in sum-rate which comes from optimum beamforming and "dirty-paper" coding is essentially eaten up by the reduction of the bandwidth by a factor of three, which was introduced to isolate the cell. This shows that cell isolation is *not* an attractive remedy for ICI mismatch. When we look at an outage probability of 5%, we find from Figure 2:

5%-OUTAGE CELL SUM-RATE

Single Cell	Genie	Gambling	Isolation	Stabilization
32.8 (100%)	15.3 (47%)	6.72 (20%)	7.48 (23%)	5.88 (18%)

With the help of the genie the performance is still good. However, the other approaches lose considerably, with the best non-genie approach only achieving 49% of the genie's performance. Even though the simple transmit diversity system (stabilization approach) now performs worst, the gap in performance to the isolation approach is not too big. Together with the fact that the BS does not need to know the channel vectors, makes transmit diversity an attractive candidate for cellular broadcast channels. On the other hand, if a practical way can be found to perform close to the genie, considerable gains in cell sum-rate could be achieved, like an increase of the 5%-outage sum-rate by 160% compared to transmit diversity.

VI. CONCLUSION

Intercell interference (ICI) is the substantial difference between a cellular and a non-cellular communication system. If the ICI power is known apriori (genie approach), about half of the sum-capacity of a non-cellular system is retained in cellular environments. However, not knowing the true ICI power (conservative gambling) causes severe performance degradation in terms of outage sum-rate. Applying a reuse factor of three in order to isolate the cell from close neighbors, is not attractive, since almost the same outage sum-rate can be achieved with a much simpler transmit diversity system. The performance gap to the genie approach is however large enough, that finding ways to obtain performance close to the genie approach, but without (or at least very low amount of) central BS control, is an attractive challenge for future research.

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