Increasing Downlink Cellular Throughput with Limited Network MIMO Coordination

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***Abstract*—Single-user, multiuser, and network MIMO performance is evaluated for downlink cellular networks with 12 antennas per site, sectorization, universal frequency reuse, scheduled packet-data, and a dense population of stationary users. Compared to a single-user MIMO baseline system with 3 sectors per site, network MIMO coordination is found to increase throughput by a factor of 1.8 with intra-site coordination among antennas belonging to the same cell site. Intra-site coordination performs almost as well as a highly sectorized system with 12 sectors per site. Increasing the coordination cluster size from 1 to 7 sites increases the throughput gain factor to 2.5.**

***Index Terms*—MIMO, capacity, broadcast channel, multiuser systems, simulations, cellular networks.**

I. Introduction

MULTIPLE antenna techniques, also known as multiple-input multiple-output (MIMO) techniques, can provide significant performance gains over conventional single-antenna techniques [1]. While earlier MIMO research focused on so-called single-user (SU) MIMO techniques, where spatially multiplexed channels are allocated to a single user, a more recent topic is the study of multiuser (MU) MIMO techniques [2], where a transceiver with multiple antennas spatially multiplexes data among multiple users. An important application of MIMO techniques is in cellular networks where intercell interference is an impediment to system performance [3]. By coherently coordinating the transmission and reception among multiple bases, one can achieve improvements in throughput for systems that would otherwise be interference limited. This technique, sometimes known as network MIMO, has been studied for both the downlink [4], [5] and uplink [6].

In this paper, we present a unified comparison of throughput performance for downlink cellular networks employing SU, MU, or network MIMO. We assume a scheduled packet-data operation used in next-generation cellular networks. First we consider SU-MIMO, MU-MIMO and sectorization with no coordination. Secondly, we evaluate the value of network MIMO coordination within a site and across multiple sites.

Studies have addressed the performance of SU-MIMO in the presence of colored interference [7], [8] and in cellular networks [9]–[11]. However they do not consider design tradeoffs with sectorization and MU-MIMO. Performance evaluation of network MIMO often employs an equal-rate (as opposed to scheduled packet) criterion [4], [6] or use simplified cellular models in order to obtain analytic results [5].

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II. System model

We consider a downlink cellular network with B clusters of M antennas each, serving K users with N antennas each. The antennas belonging to a given cluster transmit in a coordinated manner, and clusters operate independently. Under sectorization, each cluster corresponds to the sector of a single cell site. Under coordination, each cluster spans one or more cell sites. Users are dropped uniformly in the network, and each is assigned to the cluster with maximum average SNR based on pathloss and shadowing as described in Section IV. We let $\mathcal{S}_b$ denote the set of users assigned to cluster b, with $b = 0, \ldots, B-1$. We are interested in determining the throughput performance of cluster 0 in the presence of interference from the other $B-1$ clusters. For the kth user assigned to cluster $b = 0$, the received signal is:

$$\mathbf{y}_k = \mathbf{H}_{k,0}\mathbf{x}_0 + \sum_{b=1}^{B-1} \mathbf{H}_{k,b}\mathbf{x}_b + \mathbf{n}_k \quad (1)$$

where $\mathbf{H}_{k,b}$ is the $N \times M$ complex channel matrix between cluster b and user k, $\mathbf{x}_b$ is the M-dimensional transmitted signal from cluster b, and $\mathbf{n}_k \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_N)$ is an additive complex white Gaussian noise vector with identity covariance matrix. Clusters with indices $1, \ldots, B-1$ correspond to the other clusters in the network that cause interference to this user. We assume a block fading model for the channel so that it is static over one symbol interval and assume an average sum power constraint (SPC) P for the M transmit antennas in each cluster, i.e. $\text{trace}(\text{E}[\mathbf{x}_b\mathbf{x}_b^H]) \leq P$, where superscript H denotes the Hermitian transpose.

The transmitted signal $\mathbf{x}_b$ is a summation of the signals for users in $\mathcal{S}_b$, and in general these signals could be non-linearly processed. Under linear precoding the signal transmitted by cluster b is given by $\mathbf{x}_b = \sum_{j\in\mathcal{S}_b} \mathbf{G}_j\mathbf{s}_j$, where d_j, $\mathbf{G}_j \in \mathbb{C}^{M\times d_j}$ and $\mathbf{s}_j = [s_j(1), \ldots, s_j(d_j)]^T$ are the number of transmitted streams, the precoding matrix and the information symbol vector for user j, respectively.

III. Transmission strategies

In order to reflect the operation of a next-generation packet-based cellular network, we assume that the average number of users per sector is much larger than the number of transmit antennas per sector. During the nth transmission interval, a scheduler generates a quality of service (QoS) weight $q_k(n)$ for each user k $(k = 1, \ldots, K)$. Using the multiuser proportional fair scheduling (MPFS) algorithm [12], each user's QoS weight is the reciprocal of its windowed average rate. A resource allocation algorithm, described below, then determines the set of active users $\mathcal{S}(n)$ and user rates to maximize the QoS-weighted sum rate. The MPFS algorithm allows us to maximize the sum rate while maintaining fairness for cell-edge users. In the following, for ease of notation, we drop the cluster index b.

For SU-MIMO, we use the capacity-achieving closed-loop BLAST technique that performs waterfilling over the eigenmodes of a given user's MIMO channel [1]. Since each cluster transmits to only a single user during a given interval, the set $\mathcal{S}(n)$ is simply the index of the single user with the largest weighted rate: $\mathcal{S}(n) = \{\tilde{k}\} = \arg\max_k q_k(n) r_{SU,k}(\mathbf{H}_k(n), P)$, where $r_{SU,k}(\mathbf{H}_k(n), P)$ is the SU MIMO capacity for user k. The actual transmitted rate during interval n is:

$$R_{SU}(n) = r_{SU,\tilde{k}}(\mathbf{H}_{\tilde{k}}(n), P). \quad (2)$$

In case of MU MIMO we consider three different transmission techniques: 1) a scheme based on ZF beamforming that selects the active users and possible multiple streams per user in order to maximize the weighted sum rate (denoted as ZF-m) [13], 2) ZF beamforming where only the dominant eigenmode of each user can be selected for transmission (ZF-1) [13] and 3) the capacity achieving dirty paper coding (DPC) [14]. Both in ZF-m and ZF-1 the streams transmitted by a cluster are non-interfering as a consequence of the ZF constraint. Let us denote the collective set of user MIMO channels in time interval n as $\bar{\mathbf{H}}(n) = \{\mathbf{H}_1(n), \ldots, \mathbf{H}_K(n)\}$. For ZF-1 the rate achievable by user $k \in \mathcal{S}(n)$ as a function of the power w_k assigned to this user is $r_k(w_k, \mathcal{S}(n)) = \log_2(1 + w_k v_k^2(\bar{\mathbf{H}}(n), \mathcal{S}(n)))$ where $1/v_k^2(\bar{\mathbf{H}}(n), \mathcal{S}(n))$ is the effective noise power as a result of the ZF beamforming. This power is a function of the users' MIMO channels in the set $\mathcal{S}(n)$ and its derivation is given in [13]. The optimal achievable rate vector is determined by first finding the optimum power vector $\mathbf{w}$ for a given set $\mathcal{S}$ and then maximizing over all possible sets $\mathcal{S}$, subject to constraints on the power:

$$\left\{\mathbf{r}_{ZF-1}(\mathbf{q}(n), \bar{\mathbf{H}}(n), P), \mathcal{S}(n)\right\} = \arg\max_{\mathbf{r},\mathcal{S}} \max_{\mathcal{S}} \max_{\mathbf{w}} \sum_{k\in\mathcal{S}} q_k(n) r_k(w_k, \mathcal{S}) \quad (3)$$

subject to $w_k \geq 0$ $(k = 1, \ldots, K)$ and $F(\mathbf{w}) \leq P$,

where $F(\mathbf{w})$ is the total transmit power as a function of the individual transmit powers for the users in set $\mathcal{S}$. The optimization with respect to $\mathbf{w}$ is calculated using waterfilling. The outer optimization with respect to $\mathcal{S}$ requires a brute force search over all possible sets. However, we use a simple greedy allocation algorithm based on [15] where users are added successively one at a time up to a maximum of M only if the weighted throughput is increased. This greedy user selection algorithm has been shown to provide near-optimum performance when the number of users K is large. The sum rate throughput is simply the component-wise sum of the rate vector:

$$R_{ZF-1}(\mathbf{q}(n), \bar{\mathbf{H}}(n), P) = \sum_{k\in\mathcal{S}(n)} r_{ZF-1,k}(\mathbf{q}(n), \bar{\mathbf{H}}(n), P). \quad (4)$$

The generalization of this technique for ZF-m is given in [13].

For DPC the resource allocator determines the point on the boundary of the capacity region which maximizes the weighted sum rate:

$$\mathbf{r}_{DPC}(\mathbf{q}(n), \bar{\mathbf{H}}(n), P) = \arg\max_{\mathbf{r}(n)\in\mathcal{C}(\bar{\mathbf{H}}(n),P)} \sum_{k=1}^{K} q_k(n) r_k(n), \quad (5)$$

where $r_k(n)$ is the kth element of vector $\mathbf{r}(n)$, the capacity region $\mathcal{C}$ is defined in [14], and the rate vector $\mathbf{r}_{DPC}(\mathbf{q}(n), \bar{\mathbf{H}}(n), P)$ that maximizes the metric can be computed numerically [16]. The sum rate during this interval is given by the element sum of the rate vector $\mathbf{r}_{DPC}(\mathbf{q}(n), \bar{\mathbf{H}}(n), P)$:

$$R_{DPC}(n) = \sum_{k=1}^{K} r_{DPC,k}(\mathbf{q}(n), \bar{\mathbf{H}}(n), P). \quad (6)$$

IV. Cellular system simulation methodology

The channel coefficient between each transmit and receive antenna pair is a function of distance-based pathloss, shadow fading, and Rayleigh fading. We let the (n, m)th element $(n = 1, \ldots, N, m = 1, \ldots, M)$ of the kth user's MIMO channel matrix $\mathbf{H}_{k,b}$ from cluster b be given by:

$$\mathbf{H}_{k,b}^{(n,m)} = \beta_{k,b}^{n,m} \sqrt{A(\theta_{k,b(m)}) \left[\mu_{k,b}/\mu_0\right]^{\gamma} \rho_{k,b}\Gamma} \quad (7)$$

where $\beta_{k,b}^{n,m}$ is independent Rayleigh fading, $\beta_{k,b}^{n,m} \sim \mathcal{CN}(0, 1)$, $A(\theta_{k,b(m)})$ is the antenna element response as a function of the direction from the mth antenna of the bth cluster to the kth user, $\mu_{k,b}$ is the distance between the bth cluster and the kth user, μ_0 is a fixed reference distance, $\gamma = 3.5$ is the pathloss coefficient, and $\rho_{k,b}$ is the lognormal shadowing between the bth cluster and kth user with standard deviation $\sigma_\rho = 8$ dB. Since shadowing is caused by large scatterers we assume that antennas of the same cell are close enough to be characterized by the the same shadowing effect. We assume universal frequency reuse, so that all clusters transmit on the same frequency. The variable Γ is the reference SNR defined as the SNR measured at the reference distance μ_0, assuming a single antenna at the cell center transmits at full power and accounting only for the distance-based pathloss. If we let μ_0 be the distance from the cell center to the cell boundary, a reference SNR $\Gamma = 20$dB captures the various power and noise parameters associated with a typical outdoor cellular network operating in the interference-limited regime [6].

For all simulations, there are 12 antennas per cell site. The antennas are grouped and oriented so there are $S = 3, 6$ or 12 sectors per cell, with the orientations shown in Fig. 2. The antennas are spaced sufficiently far apart so they are spatially uncorrelated. We model the antenna element response as an inverted parabola that is parameterized by the 3 dB beamwidth θ_{3dB} and the sidelobe power A_s measured in dB: $\left(A(\theta_{k,b(m)})\right)_{\text{dB}} = -\min\{12(\theta_{k,b(m)}/\Theta_{3dB})^2, A_s\}$ where $\theta \in [-\pi, \pi]$ is the direction of user k with respect to the broadside direction of the mth antenna of cluster b. For the case of coordination, the broadside direction could be different for the M antennas as we discuss later. As the sectorization order increases, the beamwidth decreases, and the physical width of each sector's antenna changes inversely proportionally to the beamwidth [17]. For $S = 3, 6, 12$, the corresponding parameters are $\Theta_{3dB} = (70/180)\pi, (35/180)\pi, (17.5/180)\pi$ and $A_s = 20, 23, 26$ dB, respectively.

A total of 60 users are uniformly dropped in each cell site, and users are assigned to the cluster with the highest average SNR accounting for distance-based pathloss and shadowing. For each drop of users, the channel is modelled as $\mathbf{H}_{k,b} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ and we assume a time-division duplexed (TDD) system with stationary users so that channel state information (CSI) at the transmitter is ideal. Perfect CSI is also assumed at the receiver. Each simulation is run over thousands of transmission intervals and to provide fairness in the network, after each interval, the user QoS weights are updated according to the MPFS algorithm with fairness factor $\tau = 10$ time slots.

We model the link performance using the Shannon limit with a 3dB (factor of 1/2) power penalty per stream for all techniques except for DPC so it provides a true upper bound. With this approach we are implicitly assuming that there is a rich set of modulation and coding rates but at the same time we provide a practical way to account for link inefficiency. The 3dB offset provides a good approximation for the performance of an AWGN link using typical 3G coding, modulation and block sizes at 1% packet error rate [18].

The cell layout and the number of cells in the network depends on the type of simulation. First we consider $S = 3, 6, 12$ sectors per cell site without coordination (no-C) in a $B = 19$-cell network, as in Fig. 1A.

For the second set of numerical results, we study the impact of coordination. We let C denote the number of cell sites in the coordination cluster and consider no-C, $C = 1, 3$, and 7. We assume that the antenna elements are sectorized according to the parameters for $S = 3$ and the corresponding sector orientation in Fig. 2. For $C = 1$, the 12 co-located antennas for each cell site form a coordination cluster. The number of independent clusters is $B = 19$ as shown in Fig. 1A. For $C = 3$ and 7, each cluster uses $M = 36$ and 84 antennas, respectively, and the layouts are given by Fig. 1B and C, respectively. The number of clusters in the network is $B = 7$ for both $C = 3$ and 7. [1]

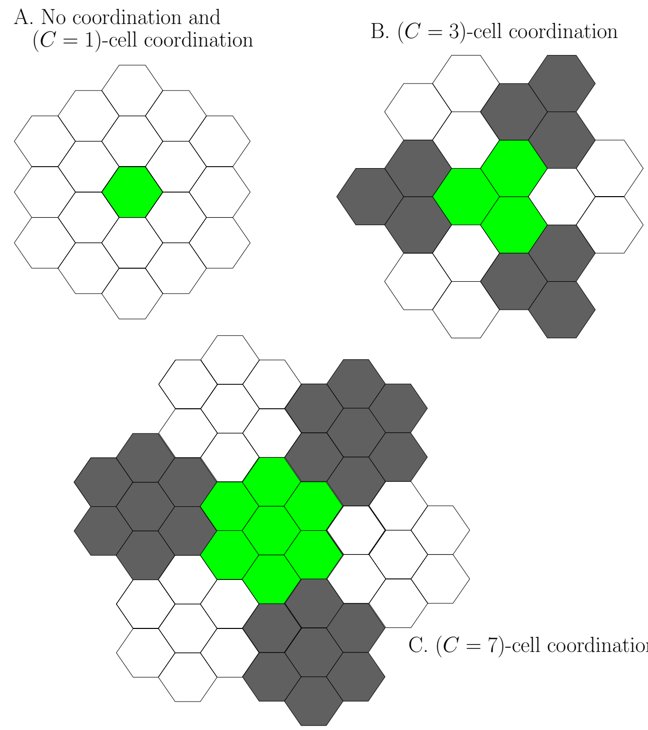

Fig. 1. Cell layout showing clusters of coordinated cell site antennas. Under sectorization with no coordination, $S = 3, 6, 12$ independent sectors per cell are used. Under coordination, antenna elements are sectorized according to parameters and orientation for $S = 3$.

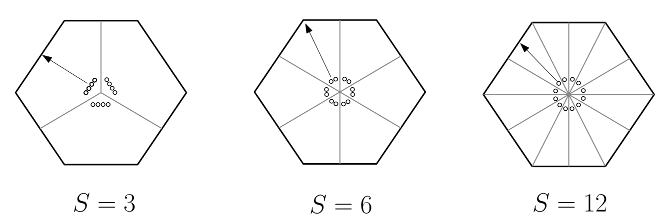

Fig. 2. Sectorization with $S = 3, 6, 12$ sectors per cell ($M = 4, 2, 1$ antennas per sector, respectively) where the arrow indicates the boresight direction of a representative sector's antennas. If a user lies in the direction of the arrow, then $(A(\theta_{k,b}))_{dB} = 0$.

Colored inter-cluster interference is accounted for using a two-phase methodology. In the first phase, the resource allocation and transmit covariance calculations are performed assuming the inter-cluster interference is spatially white and estimating the achievable SINR assuming all clusters transmit at full power and accounting for path loss and shadowing. In the second phase, the actual achievable rates are computed assuming that the transmit covariances are colored according to sample covariances generated from the first phase. The assumption of spatially white noise in the first phase is the worst-case noise and results in a somewhat pessimistic rate. This methodology circumvents the problem of resource

[1] We note that in case of coordination between spatially separated antennas ($C = 3, 7$) it would be necessary to consider an average per-site power constraint instead of the SPC introduced in Section II. Off-line analysis of the power allocation per site indicates that under SPC, the distribution of power is nearly the same for all sites. This observation indicates the marginal performance difference under a per-site constraint would be minimal.

allocation when the statistics of the colored spatial noise are not known. In order to achieve the rates predicted in the presence of colored noise, we assume that fast incremental redundancy or some other higher level medium access protocol is employed to progressively adapt the rates.

Cell-site wraparound is used to prevent network edge effects by ensuring each cell is surrounded by a sufficient number of interfering cells. For the case of no-C and $C = 1$-cell coordination, wraparound is used so each cell is surrounded by two rings of cells. Each cell is at the center of its own network, as shown in Fig. 1A. Similarly, for the case of $C = 3$ and $C = 7$-cell coordination, cluster wraparound is used so that each cluster is surrounded by one ring of clustered cells. Even though the network topology changes with C, the comparisons are valid because at least two rings of interfering cells are always considered; considering more cells as source of interference would have a negligible effect on the user SINR statistics.

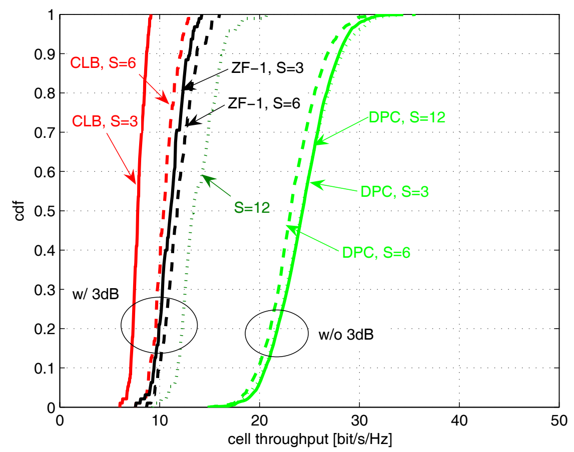

Fig. 3. CDF of spectral efficiency per cell (bps/Hz) for fixed number of antennas per cell. $S = 3, 6, 12$ sectors per cell, 12 antennas per cell, $N = 1$ antenna per user, no coordination. The CLB and ZF performance includes a 3dB power penalty per stream.

V. Numerical results

We present two sets of simulation results showing the cumulative distribution function (CDF) of spectral efficiency per cell calculated according to the sum rate expressions given in Section III. Performance is measured per cell to facilitate comparison across all results.

A. *Impact of Sectorization*

In the first set of results, we compare the per cell throughput with 12 antennas per site, arranged in $S = 3, 6, 12$ sectors with $M = 4, 2, 1$ antennas per sector, respectively. We first consider the SU-MIMO performance using CLB for $N = 1$ in Fig. 3. With only a single antenna, no spatial multiplexing is possible. In going from $S = 3$ to 6, the diversity and combining order drops from $M = 4$ to 2. However, this drop which occurs *per sector* is offset by the doubling in the number of sectors per cell. Overall, the median cell spectral efficiency increases by about 35%. A similar gain is observed for $N = 2$ in Fig. 4 where multiple receive antennas allow for spatial multiplexing.

Comparing CLB and ZF-1, CLB transmits to a single user using N streams whereas ZF-1 transmits a single stream to as many as M users. For the case of $S = 6, M = 2, N = 2$, even though CLB and ZF-1 have the same multiplexing order, the ZF-1 performance is superior because of the multiuser diversity advantage. For the other cases with $S = 3$ or 6, ZF-1 has a clear multiplexing advantage. For MU MIMO when $N = 2$ (see Fig. 4) we have the option of allocating multiple streams to a single user using ZF-m. We observe that the performance gain over the more restrictive ZF-1 is minimal, meaning that multiuser diversity can compensate for the reduced potential multiplexing gain per user. Moreover, ZF-1 is more robust in the presence of colored intercell interference and less complex to implement, requiring less control signalling and feedback overhead.

For both CLB and ZF, performance improves in going from three to six sectors. For CLB, the improvement is the result of higher order multiplexing. However for ZF, the maximum number of spatial channels per cell is fixed to 12, indicating that the spatial channels formed by sectorization are more effective than those formed by ZF beamforming. For both CLB and ZF, the performance is further improved in going from $S = 6$ to 12 sectors. In this case, since there is only $M = 1$ antenna per sector, no spatial multiplexing can be achieved, and the CLB and ZF techniques are equivalent. The superior performance of $S = 12$ comes at the expense of larger antenna elements, as mentioned in Section IV. In general, we observe that without coordination, higher-order sectorization improves throughput for a fixed number of antennas per cell site.

Regarding DPC, in the case of single antenna users, the opposite trend regarding sectorization is observed. In other words, the CDF slightly shifts to the left as the number of sectors goes from $S = 3$ to 6. The reason is that the spatial channels formed with DPC are more effective than those formed by sectorization. On the other hand, for $N = 2$ under DPC, the performance improves as S increases. The reason is that the transmit covariances during the first phase of the simulation methodology are created assuming spatially white interference while performance is measured in the presence of colored interference. Therefore with higher order sectorization, inter-cell interference appears more spatially white and there is less performance loss when the spectral efficiency is actually computed.

B. *Impact of network coordination*

We compare the per-cell throughput when coordinating antennas among $C = 1, 3, 7$ sites with $M = 12, 36, 84$ antennas, respectively. In going from no coordination up to $C = 7$-cell coordination for ZF-1, the median spectral efficiency increases by about 70% for single antenna users (see Fig. 5) and 60% for multiple antenna users (see Fig. 6). Coordinating antennas within the same site provides the largest gains by eliminating intra-site interference. Diminishing returns occur as the coordination cluster size increases, indicating that interference mitigation is not effective once the interference power is equal or below that of the background additive noise.

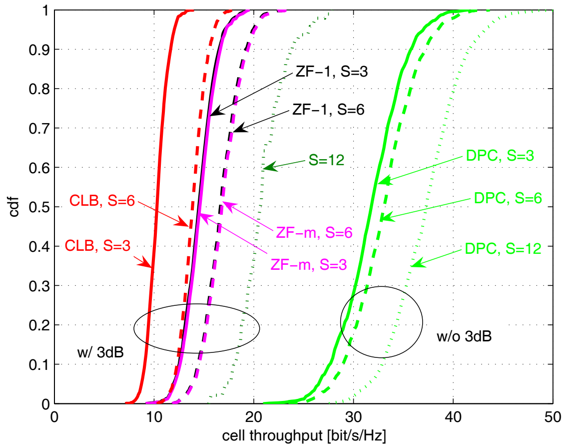

Fig. 4. CDF of spectral efficiency per cell (bps/Hz) for fixed number of antennas per cell. $S = 3, 6, 12$ sectors per cell, 12 antennas per cell, $N = 2$ antennas per user, no coordination. The CLB and ZF performance includes a 3dB power penalty per stream.

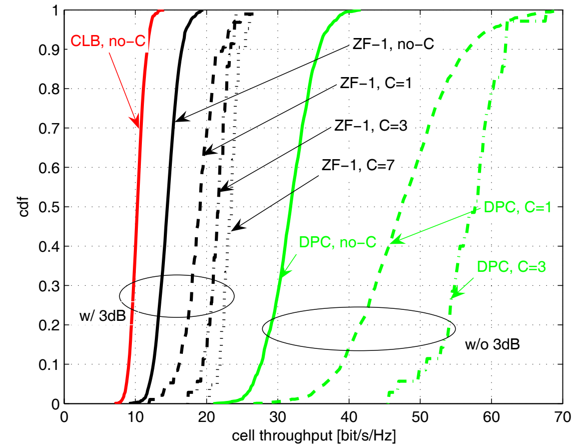

Fig. 6. CDF of spectral efficiency per cell (bps/Hz), 12 antennas per cell, $S = 3$ antenna configuration, no-C, $C = 1, 3, 7$-cell coordination, $N = 2$ antennas per user. The CLB and ZF performance includes a 3dB power penalty per stream.

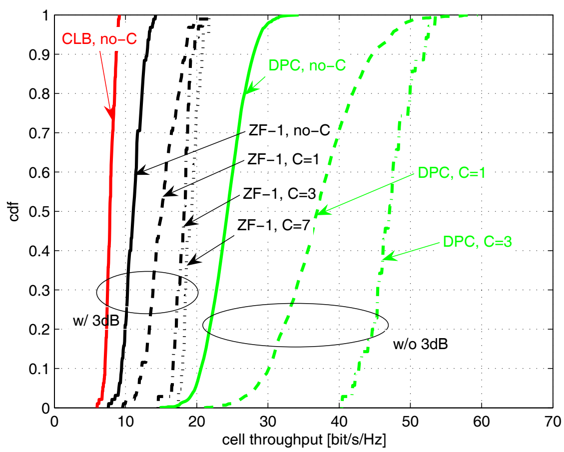

Fig. 5. CDF of spectral efficiency per cell (bps/Hz), 12 antennas per cell, $S = 3$ antenna configuration, no-C, $C = 1, 3, 7$-cell coordination, $N = 1$ antenna per user. The CLB and ZF performance includes a 3dB power penalty per stream.

Therefore network coordination gains are higher for higher transmit powers (in other words, higher cell edge SNR). A similar observation was made for uplink network coordination in [6]. Note that the ZF-1 performance with $C = 1$-cell coordination is comparable to the $S = 12$-sector case. ZF-1 with $C = 1$ presents a favorable performance-complexity tradeoff since it can be implemented with a much smaller antenna array and minimally complex coordination among co-located antennas. The gains of coordination for DPC are much higher where, with $C = 3$-cell coordination, the CDF median is almost double the case of no coordination. If we consider CLB with $S = 3$ sectors and $M = 4$ antennas per sector as a baseline, then ZF-1 with $C = 7$-cell coordination gives an approximate 2.5-fold improvement in median spectral efficiency for both $N = 1$ and 2.

VI. Conclusions

We evaluated the throughput performance of MIMO techniques under a unified simulation environment that models a multicell system with 12 antennas per cell site, serving a dense population of stationary users with scheduled packet data.

For a given sectorization order, MU-MIMO outperforms SU-MIMO because of more efficient spatial multiplexing. For a fixed number of antennas per cell, throughput increases as the number of sectors per cells increases, at the cost of larger antennas. Coordinating transmissions via network MIMO across one or more cells improves throughput by mitigating interference but requires additional backhaul resources and higher computational complexity.

Compared to a SU-MIMO baseline with $S = 3$ sectors per cell, network MIMO, using the same antenna architecture but with only modest coordination among co-located antennas, effectively eliminates the notion of sectors and increases the median throughput by a factor of 1.8. Its performance nearly matches the case of maximum sectorization order but requires a much smaller antenna array. By coordinating a cluster of seven cells, the throughput gain increases to 2.5.

These results assume a narrowband model and ideal channel state information at both the transmitter and receivers. Future studies should consider wideband channels with time-frequency scheduling and the impact of imperfect channel state information.

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