Aligning Guard Zones of Massive MIMO in Cognitive Femtocell Networks

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***Abstract*—Femtocells may coexist with macrocells in the same band and significantly improve the spatial reuse (SR) of spectrum. To avoid high interference to the scheduled macrocell users (MUs), femtocell base stations (BSs) sense and access the channel opportunistically. When massive MIMO is deployed at macrocell BS, we find that this cognitive behavior forms too many guard zones scattered over macrocell's coverage area and seriously degrades spatial reuse efficiency. In this work, we consider not only the inter-user channel orthogonality, but also geographic locations for massive MIMO user scheduling in cognitive two-tier networks. We propose to choose MUs not far from each other as receivers of the macrocell's downlink spatial multiplexing streams, such that guard zones can be aligned spatially and more SR opportunities can be provided to femtocells. Simulations show that our scheme can significantly improve femto-tier throughput while only slightly sacrificing macro-tier throughput.**

***Index Terms*—Femtocell, scheduling, massive MIMO.**

I. Introduction

FEMTOCELLS enable significant cellular capacity increase by aggressive spatial reuse (SR) of spectrum. When randomly deployed femtocell base stations (FBSs) coexist with macrocells, they may produce high interference to macrocell users (MUs) in shared spectrum scenario. If the interference generated by FBS exceeds a tolerable level, cognitive sensing requires FBSs to abandon the SR opportunity. Thus, a guard zone around a scheduled MU is formed [1], [2] (Fig.1a).

Massive multiple-input and multiple-output (MIMO) [3] is another emerging technology to meet the future mobile data demands by mounting a large antenna array at a macrocell base station (MBS) and providing preeminent precoding/beamforming capabilities [3], [4]. A MBS relies on spatial multiplexing to transmit to multiple MUs simultaneously. Existing scheduling schemes [5] are unaware of femto-tier. For massive MIMO, a large number of randomly located MUs will force nearby FBSs to backoff and form too many guard zones [1], which deprives femtocells' SR opportunities.

In this paper, we propose a geographic metric aware multiuser MIMO scheduling scheme that allows high femtocell SR efficiency without compromising macro-tier's performance. Our scheme picks MUs adjacent to each other such that their guard zones are aligned spatially (Fig.1b). In this way, FBSs over a large area can still be active and reuse the spectrum. The impact of macro-tier's massive spatial multiplexing (SM) to its underlying femto-tier is minimized.

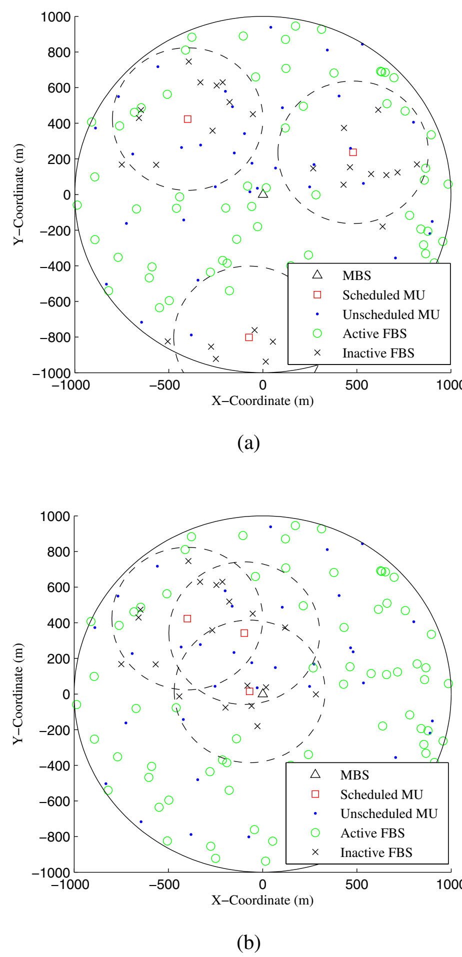

Fig. 1. (a) Guard zones scattering over the plane in conventional schemes. (b) Guard zones aligned in our proposed scheme.

II. System Model

We consider the downlink of a two-tier network consisting of a macrocell and many indoor femtocells. The MBS has a circular coverage region $\mathcal{R}$ of radius R. It serves outdoor MUs that distribute according to a homogeneous Spatial Poisson Point Process (SPPP) with intensity λ_M. The MU set is denoted as $\mathcal{M}$ and has mean cardinality of $N_M = \mathbb{E}\left[|\mathcal{M}|\right] = \lambda_M \pi R^2$. The MBS has N_t transmit antennas while FBS and each user have single antenna. The MBS can transmit to a

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set of scheduled MUs, $\mathcal{A} \subseteq \mathcal{M}$, simultaneously. The number of the multi-user MIMO streams is $N_s = |\mathcal{A}|$. For Massive MIMO system, $N_t \gg N_s$.

Each FBS serves an indoor femtocell user (FU) in closed access mode [6]. Femtocells' location distribution follows SPPP of density λ_F. Denote the femtocell set as $\mathcal{F}$. Femtocells utilize macro-tier spectrum opportunistically. The scheduled MUs transmit beacons to let their surrounding FBSs be aware of the interference to these MUs. Similar to [2], a femtocell shall not transmit if its interference power to any of the active MUs exceeds a threshold δ.

A. Channel Model and Uplink Training

We consider pathloss factor α, wall penetration power loss of indoor-to-outdoor propagation ψ and small scale fading for channel model. The small scale fading coefficients are $\mathbf{h}_m \in \mathbb{C}^{N_t}$ for MBS-to-MU $m \in \mathcal{M}$ channel, $\mathbf{h}_f \in \mathbb{C}^{N_t}$ for MBS-to-FU $f \in \mathcal{F}$ channel, $g_{f,f'}$ for FBS f'-to-FU f channel and $g_{m,f'}$ for FBS f'-to-MU m channel. Here, FU can be referred by the femtocell index without ambiguity because there is only one FU per femtocell. We assign index 0 for macrocell. The distance between $user$ and the $cell$'s BS can be denoted by $r_{user,cell}$, where $user \in \mathcal{M} \bigcup \mathcal{F}$ and $cell \in \{0\} \bigcup \mathcal{F}$.

Assume Orthogonal Frequency Division Multiplexing (OFDM) is used, and the transmission power is equally assigned to flat fading OFDM subcarriers. We use index to retrieve MUs in set $\mathcal{M}$ as $\mathcal{M}(\cdot)$. The spatial correlated channel for macrocell, $\mathbf{h} = \begin{bmatrix} \mathbf{h}^{\mathrm{T}}_{\mathcal{M}(1)} & \mathbf{h}^{\mathrm{T}}_{\mathcal{M}(2)} & \cdots & \mathbf{h}^{\mathrm{T}}_{\mathcal{M}(|\mathcal{M}|)} \end{bmatrix}^{\mathrm{T}} \in \mathbb{C}^{N_t|\mathcal{M}|}$, can be represented by $\mathbf{h} = \mathbf{U}\mathbf{\Lambda}^{\frac{1}{2}}\mathbf{w}$, where $\mathbf{w} \in \mathbb{C}^{N_t|\mathcal{M}|}$ and $\mathbf{w} \sim \mathcal{CN}(0, \mathbf{I}_{Nt})$, $\mathbf{I}_{N_t}$ is $N_t \times N_t$ identity matrix. $\mathbf{U}$ and $\mathbf{\Lambda}$ are from eigenvalue decomposition of channel's autocorrelation matrix $\mathbf{R} = \mathbb{E}\left[\mathbf{h}\mathbf{h}^{\mathrm{H}}\right] = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^{\mathrm{H}}$. Since the massive-MIMO channels of users being too close to each other will be highly correlated [7], to carefully evaluate the impact of scheduling adjacent MUs, we model the propagation in macrocell according to geometry-based stochastic model (GBSM) [8]. Since MBS has tower-mounted antennas with no significant local scattering, we consider GBSM with parameter $I = 2$. The elements in $\mathbf{R}$ can be obtained from Eq.(10) in [8]. We assume independent Rayleigh fading for $\mathbf{h}_f$, $g_{f',f}$ and $g_{m,f}$ whose coefficients follow i.i.d. $\mathcal{CN}(0, 1)$.

We assume MBS acquires channel state via uplink training according to the channel reciprocity in time division duplexing (TDD) mode. K orthogonal pilot sequences of length κ are reused among MUs when $|\mathcal{M}| > K$. Denote the MU set using the kth pilot sequence as $\mathcal{U}_k$, $1 \leq k \leq K$. For MU $m \in \mathcal{U}_k$, after correlating the received pilot signal with its pilot sequence, the observation is the channel response contaminated by the other MUs using the same pilot sequence,

$$\mathbf{y}^{UL}_k = r^{-\alpha/2}_{m,0} \sqrt{\kappa \cdot p_m}\mathbf{h}_m + \sum_{u \in \mathcal{U}_k, u \neq m} r^{-\alpha/2}_{u,0} \sqrt{\kappa \cdot p_u}\mathbf{h}_u + \mathbf{n}_0 \tag{1}$$

where $\mathbf{n}_0$ is Gaussian noise at MBS with $\mathcal{CN}\left(\mathbf{0}, \sigma^2_n \mathbf{I}_{Nt}\right)$. To avoid over-degraded channel estimation for the cell-edge MU caused by the near-far effect, the MU m's pilot is assigned transmit power $p_m \propto r^{\alpha}_{m,0}$. We assume that the MUs' spatial correlation matrices are known by MBS since they can be tracked with low overhead [9]. The MMSE estimation of MU m's channel is $\hat{\mathbf{h}}_m = \mathbf{R}_{mm}{\mathbf{Q}_k}^{-1}\mathbf{y}^{UL}_k$, where $\mathbf{R}_{mm} = \mathbb{E}\left[\mathbf{h}_m\mathbf{h}^{\mathrm{H}}_m\right]$ and $\mathbf{Q}_k = \sum_{n \in \mathcal{U}_k} r^{-\alpha}_{n,0}\kappa \cdot p_n \mathbf{R}_{nn} + \sigma^2_n \mathbf{I}_{Nt}$. We consider that the pilot sequence are assigned to MUs according to their channel correlation matrices [9].[1]

B. Throughput in Macro-tier and Femto-tier

FBS transmits with a constant power p_f. The set of active femtocells that satisfy the interference level requirement is $\mathcal{F}_{\text{act}} = \left\{ f \in \mathcal{F} : \psi r^{-\alpha}_{m,f} |g_{m,f}|^2 p_f < \delta, \forall m \in \mathcal{A} \right\}$. The received signal at the scheduled MU $m \in \mathcal{A}$ is

$$y_m = r^{-\alpha/2}_{m,0}\, \mathbf{h}^{\mathrm{H}}_m \mathbf{V}\mathbf{s} + \sum_{f \in \mathcal{F}_{\text{act}}} \psi^{1/2}\, r^{-\alpha/2}_{m,f}\, g_{m,f} s_f + n_m \tag{2}$$

where $\mathbf{s}$ is the $N_s \times 1$ signal vector constituted by the signals desired by each user in $\mathcal{A}$, $\mathbb{E}\left[\mathbf{s}\mathbf{s}^{\mathrm{H}}\right] = \frac{1}{N_t}\mathbf{I}_{N_t}$. $\mathbf{V}$ is the $N_t \times N_s$ precoding matrix with vectors $\{\mathbf{v}_m : m \in \mathcal{A}\}$, as its columns. $\mathbf{v}_m$ is the scheduled MU m precoding vector. The last term is the additive white Gaussian noise which follows $\mathcal{CN}\left(0, \sigma^2_n\right)$.

The aggregate interference at MU m from femto-tier is $I_{m,F} = \sum_{f \in \mathcal{F}_{\text{act}}} \psi r^{-\alpha}_{m,f} |g_{m,f}|^2 p_f$. Then, the Signal to Interference and Noise Ratio (SINR) of scheduled MU m is

$$\gamma_m = \frac{r^{-\alpha}_{m,0} \left|\mathbf{h}^{\mathrm{H}}_m \mathbf{v}_m\right|^2 p_0 / N_s}{\sum_{\substack{u \in \mathcal{A},\\ u \neq m}} r^{-\alpha}_{m,0} |\mathbf{h}^{\mathrm{H}}_m \mathbf{v}_u|^2 p_0/N_s + I_{m,F} + \sigma^2_n} \tag{3}$$

For indoor-to-other femtocell's indoor propagation, we assume double-wall penetration loss, ψ^2. FBS in femtocell f transmits signal s_f for its user, $\mathbb{E}\left[|s_f|^2\right] = p_f$. The received signal at a user of active femtocell $f \in \mathcal{F}_{\text{act}}$ is

$$\begin{aligned} y_f = {} & r^{-\alpha/2}_{f,f}\, g_{f,f} s_f + r^{-\alpha/2}_{f,0}\, \psi^{1/2}\, \mathbf{h}^{\mathrm{H}}_f \mathbf{V}\mathbf{s} \\ & + \sum_{j \in \mathcal{F}_{\text{act}}, j \neq f} \psi r^{-\alpha/2}_{f,j}\, g_{f,j} s_j + n_f \end{aligned} \tag{4}$$

The FU suffers the intra-tier aggregate interference $I_{f,\mathcal{F}} = \sum_{j \in \mathcal{F}_{\text{act}}, j \neq f} \psi^2 r^{-\alpha}_{f,j} |g_{f,j}|^2 p_j$. It has SINR of

$$\gamma_f = \frac{r^{-\alpha}_{f,f} |g_{f,f}|^2 p_f}{\sum_{m \in \mathcal{A}} \psi r^{-\alpha}_{f,0} \left|\mathbf{h}^{\mathrm{H}}_f \mathbf{v}_m\right|^2 p_0/N_s + I_{f,\mathcal{F}} + \sigma^2_n}. \tag{5}$$

We assume $\mathbf{s}$ and s_f to be i.i.d. Gaussian and receivers treat interference as noise. Assume that each user can measure the effective channel of its data stream perfectly. We can obtain each's tier per-cell throughput averaged over all ergodic fading channel states, $T_m = \mathbb{E}\left[\sum_{m \in \mathcal{A}} \log_2(1 + \gamma_m)\right]$ and $T_f = \mathbb{E}\left[\log_2(1 + \gamma_f) \cdot \mathbf{1}(f \in \mathcal{F}_{\text{act}})\right]$, $\mathbf{1}(\cdot)$ is indicator function.

[1]Initially, randomly pick a MU to $\mathcal{U}_1$. Then, we choose the first users for each of the rest pilot user groups $2 \leq k \leq K$ sequentially: when $\mathcal{U}_1$, $\mathcal{U}_2$, $\cdots$, $\mathcal{U}_{k-1}$ have been created, the MU unfitted to any of these user groups (with highest MSE) will be assign to a new user group, $\mathcal{U}_k = \{n\}$, where $n = \arg \max_{m \in \mathcal{M} \setminus \bigcup_{j<k} \mathcal{U}_j}\, \min_{k' \leq k-1} tr\left(\mathbf{R}_{mm}{\mathbf{Q}_{k'}}^{-1}\mathbf{R}_{mm}\right)$. After that, we add the rest MUs sequentially. For $\forall m \in \mathcal{M} \setminus \bigcup_{1 \leq k \leq K} \mathcal{U}_k$, we add it to the group $k' = \arg \min_{1 \leq k \leq K} tr\left(\mathbf{R}_{mm}{\mathbf{Q}_k}^{-1}\mathbf{R}_{mm}\right)$ is updated after each user adding.

III. Massive-MIMO User Scheduling with Guard Zone Alignment

Opportunistic user scheduling can exploit multi-user diversity (MUD) and achieve high sum rate in macrocell. The small-scale fading of channel $\hat{\mathbf{h}}_m$ is exploited by the scheduler. The pathloss is ignored to prevent the scheduling opportunities all occupied by cell-center MUs. We adopt an iterative greedy user selection framework. In the ith iteration, the MU served by the ith stream is determined, denoted as $\mathcal{A}(i)$. And the set of all currently determined scheduled MU is denoted by $\mathcal{A}^{(i)} = \{\mathcal{A}(1), \mathcal{A}(2), \cdots, \mathcal{A}(i)\}$. To suppress the ith stream's interference leakage to all other scheduled MUs, we consider the procedures with Signal to Leakage and Noise Ratio (SLNR) criterion:

1) Determine the Candidate MU set $\mathcal{M}_C^{(i)}$:

$$\mathcal{M}_C^{(i)} = \mathcal{M} \backslash \mathcal{A}^{(i-1)}. \tag{6}$$

2) Calculate SLNR: The SLNR of MU $m \in \mathcal{M}_C^{(i)}$ is

$$\eta_m^{(i)}(\mathbf{v}) = \Big(\sum_{u \in \mathcal{A}^{(i-1)}} \left(\hat{\mathbf{h}}_u^{\mathrm{H}} \mathbf{v}\right)^{\mathrm{H}} \hat{\mathbf{h}}_u^{\mathrm{H}} \mathbf{v} + \sigma_n^2 \Big)^{-1} \left(\mathbf{v}^H \hat{\mathbf{h}}_m \hat{\mathbf{h}}_m^{\mathrm{H}} \mathbf{v}\right) \tag{7}$$

Its precoding vector is assumed to be $\mathbf{v} = \hat{\mathbf{h}}_m / \left\|\hat{\mathbf{h}}_m\right\|$.

3) Select MU: $\mathcal{A}(i) = \arg\max_{m \in \mathcal{M}_c^{(i)}} \eta_m^{(i)} \left(\hat{\mathbf{h}}_m / \left\|\hat{\mathbf{h}}_m\right\|\right)$. [2]

Repeat above steps until all N_s MUs are determined, $\mathcal{A} = \{\mathcal{A}(1), \mathcal{A}(2), \cdots, \mathcal{A}(N_s)\}$. So, finally, the max-SLNR precoding vector for ith scheduled MU shall be $\mathbf{v}_{\mathcal{A}(i)} = \tilde{\mathbf{v}}_{\mathcal{A}(i)} / \left\|\tilde{\mathbf{v}}_{\mathcal{A}(i)}\right\|$, $\tilde{\mathbf{v}}_{\mathcal{A}(i)} = \big(\sum_{u \in \mathcal{A}} \hat{\mathbf{h}}_u \hat{\mathbf{h}}_u^{\mathrm{H}} + \mathbf{I}_{Nt} \sigma_n^2\big)^{-1} \hat{\mathbf{h}}_{\mathcal{A}(i)}$.

The $\mathcal{M}_C^{(i)}$ determined by (6) is beneficial to macrocell capacity. However, it ignores the impact to femto-tier. Next, we analyze the impact and propose techniques for generating better $\mathcal{M}_C^{(i)}$ to reduce this impact.

A. Guard Zone Alignment (GZA) via Ideal Geo-Information

In the above process, the initial density of FBSs that can be active at location X is $\lambda_{F|\mathcal{M}_c^{(0)}}(X) = \lambda_F$. The interference regulation in (1) thins the SPPP of femtocell and forms Poisson hole process [1]. When MU m at location X_m is scheduled, the thinning factor at location X can be represented by

$$\beta_{X_m}(X) = \mathrm{F}_{|g|^2}\left(\frac{\delta}{|X - X_m|^{-\alpha_{m,f}} p_f}\right), \tag{8}$$

where $\mathrm{F}_{|g|^2}(\cdot)$ is the Cumulative Distribution Function of small scale channel fading power gain $|g|^2$. When MU m is scheduled in the ith iteration, the active FBS density becomes

$$\lambda_{\mathcal{F}|\mathcal{A}^{(i-1)} \bigcup \{m\}}(X) = \lambda_{\mathcal{F}|\mathcal{A}^{(i-1)}}(X) \, \beta_{X_m}(X). \tag{9}$$

Eq. (8) indicates that this thinning process is inhomogeneous. Since $\beta_{X_m}(Y) < \beta_{X_m}(Z)$ for $\forall Y, Z \in \mathcal{R} : |Y - X_m| < |Z - X_m|$, the thinning is expected to be more intensive at a place closer to X_m. So, statistically, the femtocells' backoff behavior forms a guard zone centered at each scheduled MU. In fact, the potential active FBS density decays gradually when approaching X_m and the guard zone has no explicit boundary. The expected active femtocell number is

$$\mathbb{E}\left[\left|\mathcal{F}_{\text{act}}^{(i)}(X_m)\right|\right] = \int_{X \in \mathcal{R}} \lambda_F \prod_{n \in \mathcal{A}^{(i-1)} \bigcup \{m\}} \beta_{X_n}(X) dX \tag{10}$$

Thus, to minimize the impact to femto-tier, the newly scheduled MU shall be $\arg\max_{m \in \mathcal{M}_c^{(i)}} \mathbb{E}\left[\left|\mathcal{F}_{\text{act}}^{(i)}(X_m)\right|\right]$.

Obviously, user selection by only using geographic factor will deprive macrocell of MUD gain and be solely beneficial for femtocells. Thus, a tradeoff between the expected active femtocell number and MUD shall be made. So the MUs with K-largest $\mathbb{E}\left[\left|\mathcal{F}_{\text{act}}^{(i)}(X_m)\right|\right]$ can be counted as the candidates. However, it has to retrieve all MUs and has high complexity.

To avoid the burden, intuitively, we consider choosing users from neighboring region of existing scheduled users. The region is an circular area with radius $D^{(i)}$ and centered at $\bar{X}_i$, which is the geometric center of MUs in $\mathcal{A}^{(i-1)}$. Thus, the candidate MU set in the ith round ($i \geq 2$) is

$$\mathcal{M}_c^{(i)} = \left\{m \in \mathcal{M} : \left|X_m - \bar{X}_i\right| \leq D, m \neq \mathcal{A}^{(i-1)}\right\} \tag{11}$$

The candidate MU number $\left|\mathcal{M}_c^{(i)}\right|$ follows Poisson distribution with mean, $\lambda_M \pi \big(D^{(i)}\big)^2 - i + 1$ (if $D^{(j)} \geq D^{(j-1)}, \forall j \leq i$). Since the scheduled MUs are excluded from candidate set, the probability of $\mathcal{M}_c^{(i)} = \varnothing$ will be high for large i. If this happens, the scheduler relaxes the constraint on MUs' proximity in this round and allows all unscheduled MUs to be candidates. GZA will lose effect in this round. To reduce its probability, we consider expanding $D^{(i)}$ in each iteration, $D^{(i)} = \sqrt{D^2 + \frac{i-1}{\lambda_M \pi}}$, so that a constant expected MUD gain can be achieved. A larger D enables higher MUD gain, but degrades the effect on GZA and reduces $\mathbb{E}\left[\left|\mathcal{F}_{\text{act}}^{(i)}(X_m)\right|\right]$.

B. Guard Zone Alignment via Interfering FBS Information

The acquiring of $\mathcal{M}_c^{(i)}$ in the above procedure relies on MUs' location information. For practical consideration, we improve the scheme by exploiting MUs' interfering FBS information which is available in cellular networks. Each MU reports the set of FBSs which are the N_{IF} strongest interferers to MBS. For MU m, the set is $\mathcal{F}_m$, $|\mathcal{F}_m| = N_{IF}$. The interference level can be obtained by scanning the preamble signal of FBSs. The long-term scanning result can cancel out small-scale channel fading and tends to be $\psi r_{m,f}^{-\alpha}$.

Initially, there is no geographic constraint on MU scheduling, so $\mathcal{M}_c^{(1)} = \mathcal{M}$. For the ith iteration ($i \geq 2$), the neighboring FBS set of the scheduled MUs $\mathcal{A}^{(i-1)}$ is $\mathcal{L}\left(\mathcal{A}^{(i-1)}\right) = \bigcup_{j=1}^{i-1} \mathcal{F}_{\mathcal{A}(j)}$. If a MU has at least N_{com} common neighboring FBSs with scheduled MUs, we can infer that it is very adjacent to these MUs. So, the candidate MU set can be determined by

$$\mathcal{M}_c^{(i)} = \left\{m \in \mathcal{M} \backslash \mathcal{A}^{(i-1)} : \left|\mathcal{F}_m \bigcap \mathcal{L}\left(\mathcal{A}^{(i-1)}\right)\right| \geq N_{com}\right\} \tag{12}$$

[2]Note that the users too close to a scheduled MU may have channels highly correlated with the scheduled MU's channel. Step 3) precludes these users if their channel orthogonality with scheduled MUs' channel is bad.

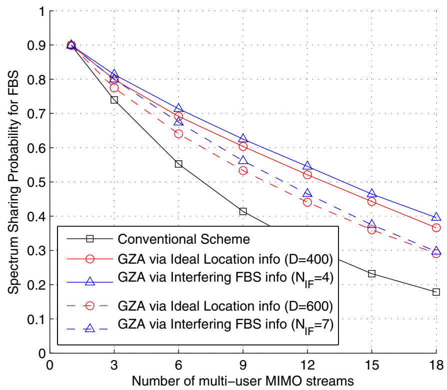

Fig. 2. The impact of MU-MIMO stream number to femtocell spectrum sharing probability which is defined as $\bar{\beta} = E\left[|\mathcal{F}_{\text{act}}|\right]/E\left[|\mathcal{F}|\right]$ ($N_{com} = 1$)

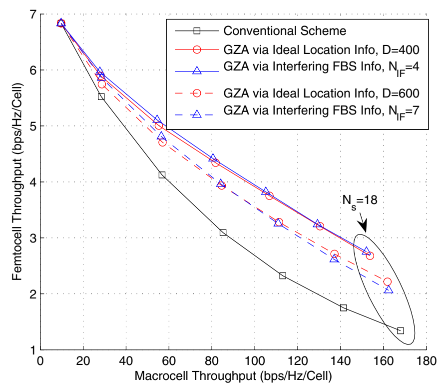

Fig. 3. The tradeoff between macro- and femto-tier throughput ($N_{com} = 1$). The tradeoff is implemented by changing N_s from 1 to 3, 6, 9, 12, 15, 18 (from top-left to down-right).

Since $\mathcal{L}\left(\mathcal{A}^{(i-1)}\right)$ grows with i, the probability of $\mathcal{M}_c^{(i)} = \varnothing$ is low. If $\mathcal{M}_c^{(i)} = \varnothing$, the scheduler relaxes the constraint on MUs' proximity in this round by decreasing N_{com} by 1 till $\mathcal{M}_c^{(i)} \neq \varnothing$. For $N_{com} = 0$, (12) will be equivalent to (6).

Larger N_{IF} and smaller N_{com} allow a higher macrocell MUD gain but suppress the effect of GZA. Here, we choose parameters empirically. The optimal choice is for further study.

We reduce the user selection's computational complexity for massive-MIMO. In ith iteration of conventional user selection, there are $N_M - i + 1$ MUs' SLNR evaluation with large matrices operations. Our schemes reduce candidate number, so there are usually only $|\mathcal{M}_c^{(i)}|$ SLNR evaluations. Further, rather than using max-SLNR MMSE precoding, we consider MRT precoding when evaluating SLNR in (7). So, the leakage-and-noise's spatial covariance matrix inversion can be avoided.

IV. Simulation Results

We evaluate the system performance with parameters: $p_0 =$ 40dBm, p_f = 23dBm ($\forall f \in \mathcal{F}$), $\sigma_n^2 = -97$dBm, $\alpha = 4$, $R = 1000$m, $r_{f,f} = 30$m, $\mathbb{E}\left[|\mathcal{F}|\right] = 100$, $\mathbb{E}\left[|\mathcal{M}|\right] = 40$, $K = 8$, $\psi = 5$dB, $\delta = -84$dBm. MBS is equipped with uniform circular array with $N_t = 128$ equally spaced isotropic antenna elements. The distance between adjacent elements is half-wavelength. Uplink channel estimation SNR after pilot sequence correlating process is $r_{m,0}^{-\alpha}\kappa p_m/\sigma_n^2 = 15dB$.

In Fig.2, we compare FBSs' spectrum sharing opportunities under the conventional scheduling scheme and our scheme. It shows that by using (11) or (12) rather than (6) in Step 1) of the user scheduling algorithm, the scheduled MUs can be gathered in a local region and the consequent guard zones are aligned, which means more SR opportunities for femtocells.

Fig.3 shows that a better tradeoff between macro-tier and femto-tier throughput can be achieved by our scheme. When $N_s = 18$, comparing to the conventional scheme, our practical one with setting $N_{IF} = 4$ and $N_{com} = 1$ allows femtocells to have 2.24 times spectrum sharing opportunities and 2.05 times throughput, while achieves 93% throughput in macro-tier. The loss in macro-tier throughput is very small. It can be interpreted that the loss of macrocell's MUD gain is small when the schedule-able MU set grows on per-iteration basis. Note that we choose $D = 400m$ which is much larger than the distance that candidate MUs have high inter-user channel correlations. Hence, there are plenty of candidate MUs that have uncorrelated channels with the scheduled MUs.

V. Conclusions

In this work, we proposed a novel scheme for user scheduling in the two-tier networks with massive-MIMO and cognitive femtocell technology.

Our scheme spatially aligns MUs' guard zones and provides more spectrum reuse opportunities for FBS than existing schemes. Simulation shows that it can achieve significant throughput gain at femto-tier without sacrificing macrocell performance.

References

[1] C. Lee and M. Haenggi, "Interference and outage in Poisson cognitive networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1392–1401, 2012.

[2] V. N. Tien, F. Baccelli, *et al.*, "Stochastic modeling of carrier sensing based cognitive radio networks," in *Proc. 2010 Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, pp. 472–480.

[3] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: opportunities and challenges with very large arrays," *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, 2013.

[4] K. Hosseini, J. Hoydis, S. ten Brink, and M. Debbah, "Massive MIMO and small cells: how to densify heterogeneous networks," in *Proc. 2013 IEEE Int. Conf. Commun.*

[5] P. Cheng, M. Tao, and W. Zhang, "A new SLNR-based linear precoding for downlink multi-user multi-stream MIMO systems," *IEEE Commun. Lett.*, vol. 14, no. 11, pp. 1008–1010, 2010.

[6] S. Park, W. Seo, Y. Kim, S. Lim, and D. Hong, "Beam subset selection strategy for interference reduction in two-tier femtocell networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3440–3449, 2010.

[7] J. Hoydis, C. Hoek, T. Wild, and S. ten Brink, "Channel measurements for large antenna arrays," in *Proc. 2012 IEEE Int. Symposium on Wireless Commun. Systems*, pp. 811–815.

[8] X. Cheng, C.-X. Wang, H. Wang, X. Gao, X.-H. You, D. Yuan, B. Ai, Q. Huo, L.-Y. Song, and B.-L. Jiao, "Cooperative MIMO channel modeling and multi-link spatial correlation properties," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 388–396, 2012.

[9] A. Adhikary, J. Nam, J.-Y. Ahn, and G. Caire, "Joint spatial division and multiplexing—the large-scale array regime," *IEEE Trans. Inf. Theory*, vol. 59, no. 10, pp. 6441–6463, 2013.