Aligning Spectrum-Holes of Massive MIMO in Cognitive Femtocell Networks

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***Abstract*—In this work, we consider supplementing geometric dimension metric for multi-user MIMO scheduling in cognitive two-tier networks. In shared spectrum use between the macrocell and its underlay femtocells, to suppress the cross-tier interference on the scheduled macrocell users(MUs), the femtocell BSs produce high interference to MUs shall not reuse the spectrum. It forms spectrum holes scatter over macrocells coverage and degraded the efficiency of spectrum reuse. We propose that the users adjacent to each other are picked as the receivers of the macrocells downlink multiplexing streams, so that spectrum holes are aligned spatially. Simulation shows that it can significantly improve the throughput of femto-tier.**

***Index Terms*—spatial reuse, scheduling, power control, coordination mechanism, aggregate interference, femtocell.**

I. Introduction

The femtocell and massive MIMO (a.k.a. large-scale MIMO system [1]) technology has been emerged to address the explosive demands for mobile data by providing higher spatial reuse(SR) and spatial multiplexing respectively. In this work, we consider an efficient way to combine these promising technologies.

When randomly deployed femtocell BSs(FBSs) coexist with macrocells, they may produce strong interference to macrocell users (MUs) in shared spectrum scenario. The cognitive sensing mechanism enables FBS to abandon a SR opportunity if the interference exceeds a maximal tolerable level[2], [3]. This process produces a spectrum hole around the scheduled MU and protects MU from cross-tier interference, as show in Fig.1a.

Due to the limited physical size and cost, the number of antennas at each user is small. To improve macrocell throughput, multi-user MIMO allows transmission to multiple MUs simultaneously. Then, the throughput of macrocells depends on how many antennas the macrocell BS (MBS) has and how many users can be scheduled simultaneously. The massive MIMO technology allows very large antenna array mounted at MBS and provides extreme high spatial degree of freedom(DoF) [4], [1]. With the awareness of users channel state and the cooperation among macrocells, the signal at MU can be boosted while the inter-stream interference can be mitigated [5]. In this case, the interference from FBSs becomes dominate at MU. Thus, it further implies the significance of femtocell cognitive sensing.

The inter-tier interference can be canceled by exploiting DoF unused by signal [4]. However, it requires both MBS and FBSs have abundant of antennas. The conventional macrocells multi-user MIMO scheduling schemes aim at its local tier throughput without the concern of its underlay femto-tiers SR. These schemes exploit the channel state information and schedule MUs scatter over the coverage area of macrocell[6]. The stochastically located MUs force their nearby FBSs to backoff and cause spatial uncorrelated spectrum holes which form Poisson hole process [2]. And these scheduling schemes may cause each MU to occupy a spectrum hole. When large amount of MUs are selected simultaneously to accommodate with massive MIMO, the SR opportunity for femtocells is squeezed fiercely.

We proposed geographic location aware multiuser MIMO scheduling scheme which allows high spatial reuse efficiency without the compromise of macro-tiers performance. It picks the MUs adjacent to each other so that the spectrum holes are aligned spatially as shown in Fig.1b. Thus, the FBSs over a large area can still be active and reuse the spectrum. The impact of macro-tiers massive spatial multiplexing to its underlay femto-tier is minimized.

The rest of this paper is organized as follows. In Section II, we introduce the system model. Then, we review a conventional multi-user MIMO scheduling scheme and adopt it as baseline in our framework. By analyzing the impact of scheduled MUs geometric location to femto-tier in Spatial Poisson Point Process (SPPP) model, we propose an multi-user MIMO scheduling scheme with spectrum hole alignment via ideal geometric information. Further, from practical considerations, we improve it by exploiting the interfering FBS information so that it doesnt have to rely on the exact geometric information. Section IV gives the simulation results and section V concludes the paper.

II. System Model

We consider the downlink scenario of a two-tier network which consists of a single macrocell and its underlay femtocells. The MBS has a circular coverage region $\mathcal{R}$ of radius R. It serves MUs which distributes according to homogeneous SPPP with intensity of λ_M. The set of MUs is denoted as $\mathcal{M}$ and has mean cardinality of $N_M = E\left[|\mathcal{M}|\right] = \lambda_M \pi R^2$. The MBS is equipped with N_t transmit antennas while FBS and each user has single antenna. Thus, the multi-user MIMO schemes allows simultaneous transmission to a set of scheduled MUs, $\mathcal{M}_a \subseteq \mathcal{M}$. The number of the spatial multiplexing streams is $N_s = |\mathcal{M}_a|$. We assume that $N_s \leq N_t$ so that there could be no inter-stream interference.

Each FBS serves a FU in closed access mode. The femtocells' location distribution follows SPPP of density λ_F. Denote

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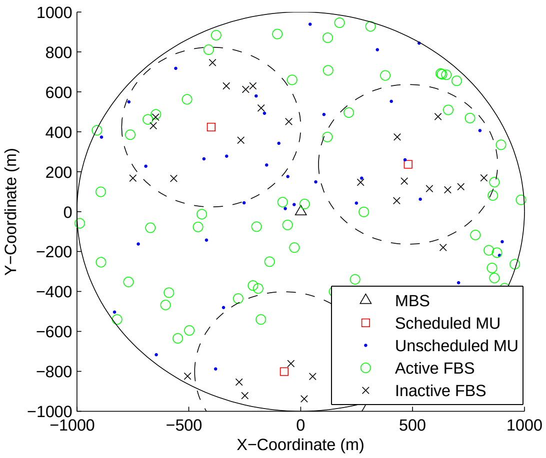
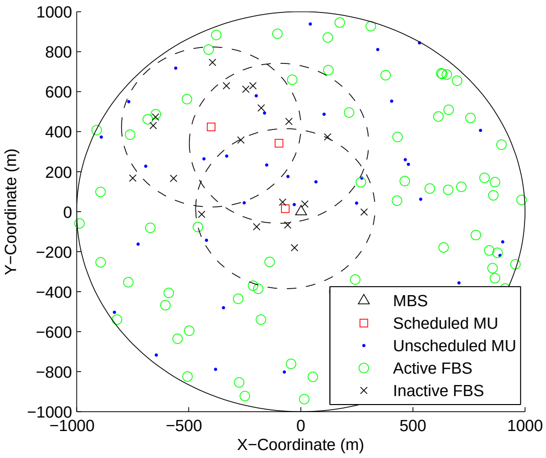


(a)



(b)

Fig. 1. The region with dash-line boundary shows where FBS is inactive with high probability. Spectrum-holes scatter over the plane in conventional scheme in (a). Spectrum holes aligned in our proposed scheme (b). Partial of FBSs which shall be inactive are shared among multiple scheduled MUs.

the femtocell set as $\mathcal{F}$. Femtocells utilize macro-tier spectrum opportunistically. The scheduled MUs can transmit a beacon to let their surrounding FBSs be aware of the interference to them. Similar to the protection of multicast primary users in cognitive network[3], the femtocell shall not transmit if its interference power to any of the active MUs exceeds a threshold δ.

Assign index 0 for macrocell. Denote the distance between MU m and BS in cell $x \in \{0\} \bigcup \mathcal{F}$ as $r_{m,0,x}$. We consider following factors for channel model, the small scale fading factor of the FBS f-to-MU ms interfering channel $g_{m,f}$, the pathloss factor α, and the wall penetration power loss for indoor-to-outdoor propagation ψ. FBS has the constant transmit power p_f. Then, the set of active femtocells which satisfy the interference constraint is

$$\mathcal{F}_a = \left\{ f \in \mathcal{F} \middle| \psi r_{m,0,f}^{-\alpha} |g_{m,f}|^2 p_f < \delta, \ \forall m \in \mathcal{M}_a \right\}$$

The received signal at the scheduled MU $m \in \mathcal{M}_a$ is

$$y_m = r_{m,0,0}^{-\alpha/2} \, \mathbf{h}_m \mathbf{V} \mathbf{s} + \sum_{f \in \mathcal{F}_a} \psi^{1/2} \, r_{m,0,f}^{-\alpha/2} \, g_{m,f} s_f + n \qquad (1)$$

where $\mathbf{s}$ is the $N_s \times 1$ signal vector constituted by the signals desired by each user in $\mathcal{M}_a$. $E\left[\mathbf{s}\mathbf{s}^H\right] = \frac{1}{N_t}\mathbf{I}_{N_t}$, where $\mathbf{I}_{N_t}$ is $N_t \times N_t$ identity matrix. $\mathbf{V}$ is the $N_t \times N_s$ precoding matrix with the scheduled MUs' precoding vectors $\mathbf{v}_m, m \in \mathcal{M}_a$, as its columns. $\mathbf{h}_m \in \mathbb{C}^{1\times N_t}$ is the MBS-to-MU ms signal channel fading coefficient vector. We assume Rayleigh fading for all channels. Then, the channel fading coefficients are with elements of $CN(0,1)$. $n \tilde{} CN\left(0, \sigma_n^2\right)$ is the Gaussian noise.

The aggregate interference at MU m from femto-tier is $I_{m,F} = \sum_{f \in \mathcal{F}_a} \psi r_{m,0,f}^{-\alpha} |g_{m,f}|^2 p_f$. Then, the Signal to Interference and Noise Ratio (SINR) of scheduled MU m is

$$\gamma_m = \frac{r_{m,0,0}^{-\alpha} |\mathbf{h}_m \mathbf{v}_m|^2 p_0 / N_s}{\sum_{\substack{n \in \mathcal{M}_a, \\ n \neq m}} r_{m,0,0}^{-\alpha} |\mathbf{h}_m \mathbf{v}_n|^2 p_0 / N_s \ + I_{m,F} + \sigma_n^2}$$

For indoor-to-other femtocells indoor propagation, we assume double-wall penetration loss. The distance between FU in femtocell f and BS in cell $x \in \{0\} \bigcup \mathcal{F}$ is denoted as $r_{f,x}$. And small scale channel fading coefficient between FU in femtocell $f \in \mathcal{F}$ and FBS in femtocell k is denoted as $g_{f,k}$. FBS in femtocell f transmits signal s_f for its user, $E\left[|s_f|^2\right] = p_f$. The received signal at the user of an active femtocell $f \in \mathcal{F}_a$ is

$$\begin{aligned} y_f = {} & r_{f,f}^{-\alpha/2} \, g_{f,f} s_f + r_{f,0}^{-\alpha/2} \, \psi^{1/2} \, \mathbf{h}_f \mathbf{V} \mathbf{s} \\ & + \sum_{k \in \mathcal{F}_a, k \neq f} \psi r_{f,k}^{-\alpha/2} \, g_{f,k} s_k + n \end{aligned}$$

The FU suffers the intra-tier aggregate interference $I_{f,\mathcal{F}} = \sum_{k \in F_a, k \neq f} \psi^2 r_{f,k}^{-\alpha} |g_{f,k}|^2 p_k$. It has SINR of

$$\gamma_f = \frac{r_{f,f}^{-\alpha} |g_{f,f}|^2 p_f}{\sum_{m \in \mathcal{M}_a} \psi r_{f,0}^{-\alpha} |\mathbf{h}_f \mathbf{v}_m|^2 p_0 / N_s \ + I_{f,\mathcal{F}} + \sigma_n^2}.$$

III. Multi-user MIMO Scheduling with Spectrum-hole Alignment

To achieve high macrocell capacity, opportunistic user scheduling can leverage multi-user diversity (MUD) gain. We consider resource-level fairness among MUs that they have equal opportunities to be scheduled in long term. Only the small-scale fading of channel $\mathbf{h}_m$ is exploited by the scheduler. The pathloss is normalized. Or else, the cell-center MUs can get far more scheduling opportunities than their cell-edge counterparts.

For the optimal user selection, every user combinations shall be tested and the one with highest capacity shall be chosen. It has complexity of $\frac{\text{factorial}(N_M)}{\text{factorial}(N_s) \cdot \text{factorial}(N_M - N_s)}$. For massive MIMO with large user and stream number, the computational complexity is too high. Thus, we adopt an iterative greedy user selection framework.

Denote the scheduled user in ith iteration as $\mathcal{M}_a(i)$. To suppress the interference leakage produced by the ith stream to all other scheduled MUs, we consider the procedures with Signal to Leakage and Noise Ratio (SLNR) criterion:

1) SLNR calculation: Since the remaining MUs to be scheduled is not yet known, the leakage channel in ith iteration can be temporally represented by $\mathbf{H}_L^{(i)} = \left[\mathbf{h}_{\mathcal{M}_a(1)}{}^T \quad \mathbf{h}_{\mathcal{M}_a(2)}{}^T \quad \cdots \quad \mathbf{h}_{\mathcal{M}_a(i-1)}{}^T\right]^T$. When choosing the first MU, there is no leakage information and $\mathbf{H}_L^{(1)}$ is empty. For any user m with a precoding vector $\mathbf{v}$, it has SLNR $\eta_m^{(i)}(\mathbf{v}) = \left(\left(\mathbf{H}_L^{(i)}\mathbf{v}\right)^H \mathbf{H}_L^{(i)}\mathbf{v} + \mathbf{I}_{Nt}\sigma_n^2\right)^{-1}\left(\mathbf{v}^H \mathbf{h}_m{}^H \mathbf{h}_m \mathbf{v}\right)$. Denote the maximal eigenvalue of matrix $\mathbf{T}$ as $\varphi(\mathbf{T})$ and the corresponding eigenvector as $\nabla\mathbf{T}$. To maximize SLNR, $\mathbf{v}$ shall be $\nabla\mathbf{T}_m^{(i)}$, where $\mathbf{T}_m^{(i)} = \left(\left(\mathbf{H}_L^{(i)}\right)^H \mathbf{H}_L^{(i)} + \mathbf{I}_{Nt}\sigma_n^2\right)^{-1}\left(\mathbf{h}_m{}^H \mathbf{h}_m\right)$. And, the resulting SLNR is $\eta_m^{(i)} = \varphi\left(\mathbf{T}_m^{(i)}\right)$.

2) Candidate MU set: Denote the candidate MU set as $\mathcal{M}_C^{(i)}$, which shall be the subset of all unscheduled MUs, $\mathcal{M}_C^{(i)} \subseteq \{m \,|m \in \mathcal{M}, m \neq \mathcal{M}_a(k), k = 1, 2, \cdots, i-1\}$.

3) MU selection: We can evaluate the SLNR of all candidate MUs and choose the MU with maximal SLNR, $\mathcal{M}_a(i) = \arg\max_{m\in\mathcal{M}_c^{(i)}} \eta_m^{(i)}$.

Repeat above steps until all N_s MUs are selected, $\mathcal{M}_a = \{\mathcal{M}_a(1), \mathcal{M}_a(2), \cdots, \mathcal{M}_a(N_s)\}$.

When the scheduled MU set $\mathcal{M}_a$ is determined, the final leakage channel for each scheduled user can be known as, $\mathbf{H}_{L,\mathcal{M}_a(i)}^{(N_s)} = \left[\mathbf{h}_{\mathcal{M}_a(1)}{}^T \quad \cdots \quad \mathbf{h}_{\mathcal{M}_a(i-1)}{}^T \quad \mathbf{h}_{\mathcal{M}_a(i+1)}{}^T \quad \cdots \quad \mathbf{h}_{\mathcal{M}_a(N_s)}{}^T\right]^T$. So the eventual precoding vector for ith scheduled MU is $\nabla\mathbf{T}_{\mathcal{M}_a(i)}$ where $\mathbf{T}_{\mathcal{M}_a(i)} = \left(\left(\mathbf{H}_{L,\mathcal{M}_a(i)}^{(N_s)}\right)^H \mathbf{H}_{L,\mathcal{M}_a(i)}^{(N_s)} + \mathbf{I}_{Nt}\sigma_n^2\right)^{-1}\left(\mathbf{h}_{\mathcal{M}_a(i)}{}^H \mathbf{h}_{\mathcal{M}_a(i)}\right)$. In each iteration, the conventional multi-user scheduling algorithm picks user from all unscheduled ones,

$$\mathcal{M}_C^{(i)} = \mathcal{M}\backslash\{\mathcal{M}_a(k), k = 1, 2, \cdots, i-1\}. \qquad (2)$$

It maximizes the MUD gain for macrocell. However, it ignores the impact to the underlay femto-tier.

A. Spectrum-hole alignment via Ideal geometric information

In above process, the initial density of FBSs which can be active at location X is $\lambda_{F\left|\mathcal{M}_c^{(0)}\right.}(X) = \lambda_F$. Due to the interference regulation in (1), the SPPP of femtocell is thinned each time. The thinning factor at location X when MU m at location X_m is scheduled can be represented by

$$\beta_{X_m}(X) = F_{|g|^2}\left(\frac{\delta}{|X - X_m|^{-\alpha_{m,f}} p_f}\right) \qquad (3)$$

where $F_{|g|^2}(\cdot)$ is the Cumulative Distribution Function of small scale channel fading power gain $|g|^2$. Then, the resulting potential active FBS density is

$$\lambda_{F\left|\mathcal{M}_a^{(i-1)}\bigcup\{m\}\right.}(X) = \lambda_{F\left|\mathcal{M}_a^{(i-1)}\right.}(X)\,\beta_{X_m}(X).$$

From (3), we can see that this thinning process is inhomogeneous. Since $\beta_{X_m}(X_i) < \beta_{X_m}(X_j)$ for $|X_i - X_m| < |X_j - X_m|$, the punch is expected to be more intensive close to the location X_m. It implies that by statistics, the femtocells backoff behavior forms a spectrum hole centered at each scheduled MU. Note that due to channel fading, the potential active FBS density decays gradually when approaching X_m and the spectrum hole has no cutting edge. The expected active femtocell number is

$$\begin{aligned} &E\left[\left|\mathcal{F}_a^{(i)}(X_m)\right|\right] \\ &= E\left[\mathbf{1}\left(|X_f - X_i|^{-\alpha}|h_{m,0,f}|^2 p_f \geq \delta \left| f \in \mathcal{F}_a^{(i-1)}\right.\right)\right] \\ &= \int_{X\in\mathcal{R}} \lambda_F \prod_{X\in\mathcal{M}_a^{(i-1)}\bigcup\{m\}} \beta_{X_m}(X)dX \end{aligned}$$

Thus, to minimize the impact to underlay femto-tier, the newly scheduled MU shall be $\arg\max_{m\in\mathcal{M}_c^{(i)}} E\left[\left|\mathcal{F}_a^{(i)}(X_m)\right|\right]$. Since the surrounding of new MU has low β_{X_m} while the vicinity of existing scheduled MUs has low $\lambda_{F\left|\mathcal{M}_a^{(i-1)}\right.}$, the new user picked by MBS could be the one closest to the existing ones, intuitively.

Obviously, the user selection by only geographic factor will deprive the MUD gain for the macrocell and be solely beneficial for femtocells. Thus, the tradeoff between the expected active femtocell number and MUD shall be made. We consider choosing from the users in the neighboring region of existing scheduled users. The region is an circular area with radius $D^{(i)}$ and centered at $\bar{X}_i$ where is the geometric center of all previously scheduled MU $\mathcal{M}_a^{(i-1)}$. Thus, the candidate MU set in ith round ($i \geq 2$) is

$$\mathcal{M}_c^{(i)} = \left\{m \in \mathcal{M}\left|\left|X_m - \bar{X}_i\right| \leq D, m \notin \mathcal{M}_c^{(i-1)}\right.\right\} \qquad (4)$$

The number of MU in candidate set $\left|\mathcal{M}_c^{(i)}\right|$ follows Poisson distribution with expected value, $\lambda_M\pi\left(D^{(i)}\right)^2 - i + 1$. Since the scheduled MUs shall be excluded from the candidate set, the radius $D^{(i)}$ shall keep expending during the iterations. Or else, it may occur with high probability that after few iterations, $\mathcal{M}_c^{(i)} = \varnothing$. If it happens, the scheduler has to relax the constraint on MUs proximity in this round and allows all unscheduled MUs be the candidates. Here, we consider keeping a constant MUD gain by letting $D^{(i)} = \sqrt{D^2 + \frac{i-1}{\lambda_M\pi}}$. A larger D enables higher MUD gain, but degrades the effect on spectrum hole alignment and reduces $E\left[\left|\mathcal{F}_a^{(i)}(X_m)\right|\right]$.

B. Spectrum-hole alignment via interfering FBS information

The determination of the candidate MU set $\mathcal{M}_c^{(i)}$ in above procedures relies on the geo-location of MUs. For practical consideration, we improve its implementation by exploiting the MUs' interfering FBS information which is native in cellular networks.

Each MU can scan the preamble signal of FBSs which produce strong interference to it. We assume that the detected FBSs are ranked by the large-scale channel gain $\psi r_{m,0,f}^{-\alpha}$ rather than the instantaneous channel gain $|g_{m,f}|^2$. Despite that knowing $|g_{m,f}|^2$ helps getting better interference management performance, this information on specific resource block is hard to obtain. When detecting the preamble across multiple subchannels and average the signal over multiple frames to get higher measurement accuracy, the egodicity of channel fading causes the result more tends to be $\psi r_{m,0,f}^{-\alpha}$. Thus, we consider the worst-case which has only information of $\psi r_{m,0,f}^{-\alpha}$.

Initially, there is no geometric constraint on MU scheduling, so $\mathcal{M}_c^{(1)} = \mathcal{M}$. Denote the set of FBSs which are with N_{IF} strongest interference to MU m as $\mathcal{F}_m$, $|\mathcal{F}_m| = N_{IF}$. In $i$the iteration, the neighboring FBSs set of the scheduled MUs is $\mathcal{F}_{\mathcal{M}_a}^{(i)} = \bigcup_{k=1}^{i-1} \mathcal{F}_{\mathcal{M}_a(k)}$. If a MU has at least N_{common} common neighboring FBSs with existing scheduled MUs, we can infer that it is very adjacent to these MUs. So, the candidate MU set can be determined by

$$\mathcal{M}_c^{(i)} = \left\{ m \left| m \in \mathcal{M}, \left| \mathcal{F}_m \bigcap \mathcal{F}_{\mathcal{M}_a}^{(i)} \right| \geq N_{common} \right. \right\} \quad (5)$$

By using (4) or (5) rather than (2) in Step 2), we can gather the scheduling MUs in a local region and align the consequent spectrum holes. Thus, it provides much more spectrum sharing opportunities for femtocells.

IV. Numerical Results and Conclusions

We evaluate the system with following parameters: $p_0 =$ 40dBm, $p_f =$ 23dBm for $\forall f \in \mathcal{F}$, $\sigma_n^2 = -97$dBm, $\alpha = 4$, $R = 1000$m, $r_{f,f} = 30$m, $E[|\mathcal{F}|] = 100$, $E[|\mathcal{M}|] = 40$, $\psi = 5$dB, $\delta = -84$dBm, $N_t = 20$. The locally interfering FBS number is reduced more significantly in Spectrum hole alignment schemes than in conventional one. It could only partially compensate the macrocells MUD gain loss. To make sensible comparison, we set a lower sensing threshold so that the interference at MU is further reduced to compensate the MUD loss and allow the macrocell throughput is unchanged.

FBS's spectrum sharing opportunity in the conventional schemes and our proposed ones are compared in Fig.2. FBSs spectrum sharing probability defined as $\bar{\beta} = E\left[\left|\mathcal{F}_a^{(i)}(X_m)\right|\right] / E[|\mathcal{F}|]$ decreases dramatically with growing number of multiplexing streams in the conventional scheme, while it decreases much slower for our proposed ones. When $N_s = 18$, the practical scheme with setting I provides 128% more spectrum sharing opportunity than the conventional one.

The resulting per- femtocell capacity calculated as $E[\log_2(1+\gamma_f) \cdot \mathbf{1}(f \in \mathcal{F}_a)]$ is shown in Fig.3. When $N_s = 1$, there is no room for Geo-Aware grouping and so the result is equivalent to the unaware case. With increasing of N_s, the gain over conventional scheme is significant. When $N_s = 18$, the practical scheme with setting I allows femtocells to have capacity 103% higher than the conventional one. The gain in capacity is slightly lower than the gain in sharing probability, because the increased active FBS density causes a bit higher intra-tier interference in femto-tier. The setting I has more strict criterions to count a MU as the neighbor of existing scheduled ones. It allows much higher spectrum sharing probability for FBSs and femtocell capacity.

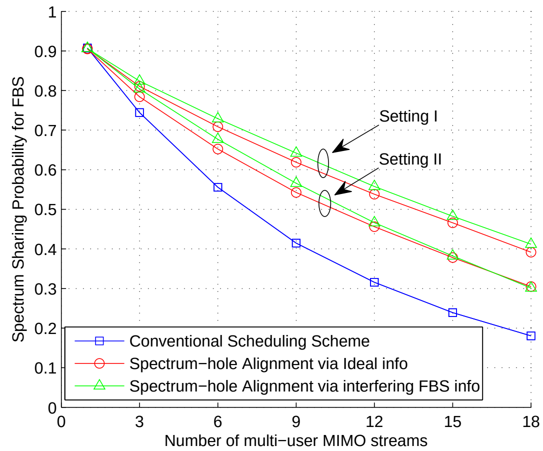


Fig. 2. The spectrum sharing probability of FBS vs. the number of MU-MIMO streams

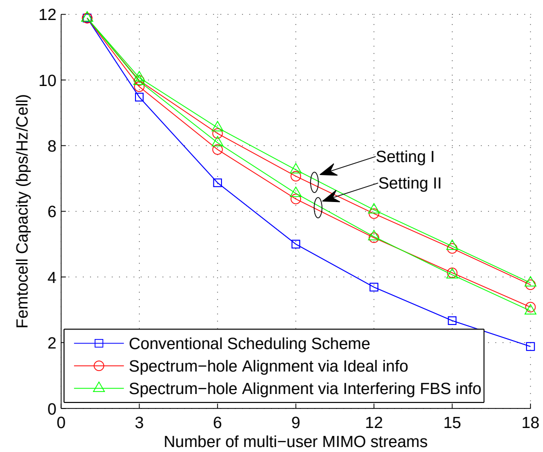


Fig. 3. The impact of MU-MIMO stream number to femtocell capacity

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