Interference Management with Block Diagonalization for Macro/Femto Coexisting Networks

Uk Jang, Keeseong Cho, Won Ryu, and Ho-Jin Lee

A femtocell is a small cellular base station, typically designed for use in a home or small business. The random deployment of a femtocell has a critical effect on the performance of a macrocell network due to co-channel interference. Utilizing the advantage of a multiple-input multiple-output system, each femto base station (FBS) is able to form a cluster and generates a precoding matrix, which is a modified version of conventional single-cell block diagonalization, in a cooperative manner. Since interference from clustered-FBSs located at the nearby macro user equipment (MUE) is the dominant interference contributor to the coexisting networks, each cluster generates a precoding matrix considering the effects of interference on nearby MUEs. Through simulation, we verify that the proposed algorithm shows better performance respective to both MUE and femto user equipment, in terms of capacity.

Keywords: Femtocells, interference mitigation, CoMP, coexisting networks.

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I. Introduction

Utilizing femtocells for mobile operations to improve indoor coverage and provide high data rate services in a cost effective manner in the 4th generation networks and beyond is viewed as a promising option [1]-[8]. Typically, femtocells are connected to the Internet and a cellular operator's network via a DSL router or cable modem. Since the coverage of femtocells is not manually optimized by the cellular operator and deployment is generally in a plug-and-play manner, macrocells may have to share the same resources with femtocells, unless appropriate mitigation methods are utilized. Therefore, interference issues may arise in the downlink of coexisting macro-femto networks. The Femto Forum previously published a report [2] that evaluates extreme cases of macro-femto interference based on both co-channel and adjacent channel deployment. In a downlink, each macro user equipment (MUE) suffers from strong interference from nearby femtocells, which is a critical performance factor for MUEs. However, priority should generally be given to macrocells rather than to femtocells. Therefore, the important aspect in a coexisting network is that the performance of MUEs must be maintained even though a large number of femtocells may be deployed on top of a macrocell. To address interference problems, researchers have recently considered power control methods, interference mitigation techniques, and resource partitioning [5]-[8]. Unfortunately, most previous works on interference mitigation in coexisting networks focus on the case of each femto base station (FBS) being equipped with a single transmit antenna.

Multiple-input multiple-output (MIMO) is a promising wireless transmission technology that deploys multiple antennas at both ends of a communication link to increase the

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data rate or enhance reliability without using additional power, bandwidth, or time slots [9]. It has been shown that the capacity of MIMO-BC [9] can be achieved by applying dirty-paper coding (DPC) at the transmitter. However, since DPC is not practical due to its complexity, to avoid such complexity, a simple precoding scheme of downlink transmit beamforming (DL-Tx-BF) that can support multiple users simultaneously, called space division multiple access (SDMA), has been an active area of research for many years [10]-[20]. The basic idea is that a careful selection of weight vectors can mitigate co-channel interference among different user streams. The main advantage of DL-Tx-BF is that the whole complexity burden is placed on the transmitting end, assuming the availability of full or limited channel state information, while the complexity of the mobile receiver remains as low as possible. Additionally, coordinated multiple point transmission (CoMP) (also referred to as co-MIMO, collaborative MIMO, network MIMO, etc.) is proposed to increase cell-edge user performance in an interference-limited environment for LTE-Advanced and IEEE802.16m. The conventional multi-user-MIMO, with single-cell processing, forms a MIMO interference channel, whose spatial degrees of freedom are determined by the number of transmit antennas at each base station (BS). If neighboring BSs are able to cooperatively schedule their transmissions, the entire network may obtain the total number of spatial degrees of freedom proportional to the number of cooperative BSs. Therefore, co-MIMO is able to provide excellent performance gain, an important issue in wireless communication [15]-[19].

In this paper, we propose block diagonalization (BD) with an antenna selection algorithm to maintain the performance of both MUE and femto user equipment (FUE) simultaneously over a macro-femto coexisting network. Using the CoMP-joint processing and transmission (CoMP-JPT) [15], each FBS joins one cluster member and serves its users in a cooperative manner. The proposed precoding matrix design with antenna selection at each clustered FBS is modified from a conventional single-cell BD, for which we consider the femto to macro interference suppression.

II. System Model for Coexisting Networks

1. Network Structure

Consider a multi-user downlink channel with K_M MUEs and a single macro base station (MBS). Each MBS has N_T^M antennas, and each MUE has N_R antennas. Closed-access F femtocells are randomly distributed over the cell boundary of the macrocell coverage area. There are F FBSs, among which each FBS has a single FUE. Each FBS and FUE has N_T^F and N_R antennas, respectively. For simplicity, co-channel interference from neighboring macrocell transmissions is ignored.

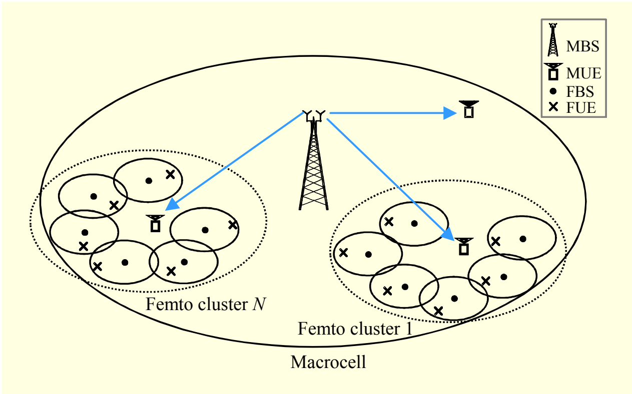

Fig. 1. Macro-femto coexisting network with clustered femtocells.

Let us consider a scenario in which FUEs are served by a cluster of cooperative FBSs. Since it is impractical to coordinate across all the FBSs, we propose dividing the network into a number of femto clusters, where the c-th cluster contains F_c femtocells, as shown in Fig. 1. To coordinate interference mitigation, each cluster should be formed close to the MUE. By coordinating the FBSs within the same cluster, it is possible to increase the number of spatial degrees of freedom, which will be used to mitigate the FBS-to-MUE interference, using the proposed algorithm.

2. Strategies for Interference Mitigation

In coexisting macro/femto networks, five possible types of interference exist: 1) inter-MUE interference, 2) MBS to FUE interference, 3) clustered-FBS to MUE interference, 4) inter-cluster interference, and 5) inter-femto interference.

A. Inter-MUE Interference

Since every MUE uses the same frequency band, inter-MUE interference exists. Inter-MUE interference can easily be canceled by a conventional BD [13] at each MBS.

B. MUE to FUEs Interference

This is the dominant interference from the perspective of FUE over coexisting macro/femto networks, if femtocells are located near an MBS. However, since we assumed that the femtocells are randomly generated at the cell boundary, it is not a main contributor in this system.

C. Clustered FBSs to MUEs Interference

If femtocells are randomly generated near MUEs, MUEs can suffer a severe interference from the clustered-FBSs. Since the severity of the interference can increase as the number of femtocells increases, we propose an antenna selection algorithm with BD at clustered-FBSs for interference mitigation.

D. Inter-cluster Interference

To remove the inter-cluster interference, in this system, each clustered-FBS will use fractional frequency reuse by exchanging proper information through the backhaul.

E. Inter-femto Interference

This is not a main interference contributor for a small number of femtocells in a macrocell since this interference is relatively smaller due to low transmit power at the FBSs and penetration losses. However, as the number of femtocells increases, the amount of inter-femto interference will increase significantly. To cancel inter-femto interference, coordinated FBSs form a "clustered-FBS," in which all propagation links (including interfering channels) are exploited to carry useful data. This is the dominant interference from the perspective of FUE over coexisting macro/femto networks if femtocells are located near an MBS. However, since we assumed that the femtocells are randomly generated at the cell boundary, it is not a main contributor in this system.

3. Notation

Throughout this paper, we use the following notations. Let $\mathbf{A}^T$, $\mathbf{A}^H$, and $\mathbf{A}^{-1}$ denote the transpose, the complex conjugate transpose, and the pseudo-inverse of matrix **A**, respectively. The Frobenius norm of $m\times n$ matrix **A** is $\|\mathbf{A}\|_F = \sqrt{\mathrm{Tr}(\mathbf{A}\mathbf{A}^H)}$, where Tr() is a trace operation.

III. Signal Model and Problem Formulation

1. Signal Model for MUE

To exploit the signal model for MUEs with BD, let $\mathcal{U}_M = \{1,\ldots,K_M\}$ denote a set of MUEs in a macrocell. The transmit vector symbol of the *k*-th MUE is denoted by a vector $\mathbf{x}_{M,k} \in \mathbb{C}^{L_{M,k}\times 1}$. The received signal at the *k*-th MUE ($k \in \mathcal{U}_M$) is given by

$$\mathbf{y}_{M,k} = \mathbf{H}^M_{M,k}\mathbf{M}_{M,k}\mathbf{x}_{M,k} + \underbrace{\mathbf{H}^M_{M,k}\sum_{l\in\mathcal{U}_M, l\neq k}\mathbf{M}_{M,l}\mathbf{x}_{M,l}}_{\text{Inter-MUE interference}} + \underbrace{\sum_{c=1}^{C}\mathbf{H}^c_{M,k}\sum_{n\in\mathcal{U}_c}\mathbf{M}_{c,n}\mathbf{x}_{c,n}}_{\text{Interference from clustered-femtocell}} + \mathbf{n}_{M,k},$$

where

- $\mathbf{H}^M_{M,k} \in \mathbb{C}^{N_R\times N_T^M}$ denotes the channel matrix from the MBS to the *k-th* MUE.
- $\mathbf{n}_{M,k} \in \mathbb{C}^{N_R\times 1}$ is the addictive white Gaussian noise vector with zero mean and covariance matrix $\mathbb{E}(\mathbf{n}_{M,k}\mathbf{n}^H_{M,k}) = \sigma_n^2\mathbf{I}$.
- $\mathbf{M}_{M,k} \in \mathbb{C}^{N_T^M\times L_{M,k}}$ is a precoding matrix for the *k*-th MUE, which is a cascade of two precoding matrices $\mathbf{B}_{M,k}$ and $\mathbf{D}_{M,k}$ for BD, that is, $\mathbf{M}_{M,k}$=$\mathbf{B}_{M,k}\mathbf{D}_{M,k}$, where $\mathbf{B}_{M,k}$ removes the inter-MUE interference and $\mathbf{D}_{M,k}$ is used for parallelizing and power allocation, where $\mathbb{E}(\mathbf{D}_{M,k}\mathbf{x}_{M,k}\mathbf{x}^H_{M,k}\mathbf{D}^H_{M,k})=\mathbf{Q}_{M,k}$ is the transmit covariance matrix.
- C is the total number of clusters in a macrocell.
- F_c is the total number of FBSs in the *c*-th cluster.
- $\mathcal{U}_c$ is the set of FUEs for the *c*-th cluster.
- $\mathbf{H}^c_{M,k} \in \mathbb{C}^{N_R\times F_c\cdot N_T^F}$ is the aggregate channel matrix from the *c*-th cluster to the *k*-th MUE. $\mathbf{H}^c_{M,k} = [\mathbf{H}^{(1)}_{M,k},\cdots,\mathbf{H}^{(f)}_{M,k}]$, where $\mathbf{H}^{(f)}_{M,k} \in \mathbb{C}^{N_R\times N_T^F}$ is a channel matrix from the *f*-th FBS to the *k*-th MUE.
- $\mathbf{M}_{c,n} \in \mathbb{C}^{F_c\cdot N_T^F\times \tilde{L}_{c,n}}$ is a precoding matrix for the *n*-th FUE in the *c*-th cluster, which is a cascade of two precoding matrices $\mathbf{B}_{c,k}$ and $\mathbf{D}_{c,k}$ for BD, that is, $\mathbf{M}_{c,k} = \mathbf{B}_{c,k}\mathbf{D}_{c,k}$, where $\mathbf{B}_{c,k}$ removes the inter-FUE interference, and $\mathbf{D}_{c,k}$ is used for parallelizing and power allocation, where $\mathbb{E}(\mathbf{D}_{c,k}\mathbf{x}_{c,k}\mathbf{x}^H_{c,k}\mathbf{D}^H_{c,k})=\mathbf{Q}_{c,k}$ is the transmit covariance matrix. $\mathbf{M}_{c,n} = [(\mathbf{M}^{(1)}_n)^H, (\mathbf{M}^{(2)}_n)^H, \cdots, (\mathbf{M}^{(f)}_n)^H]^H$, where $\mathbf{M}^{(f)}_n \in \mathbb{C}^{N_T^F\times\tilde{L}_{c,n}}$ is a precoding matrix for the *n*-th FUE at the *f*-th FBS.
- $\mathbf{x}_{c,n} \in \mathbb{C}^{\tilde{L}_{c,n}\times 1}$ is a transmitted vector for the *n*-th FUE in the *c*-th cluster.

The element of the channel vector is [15]

$$\mathbf{H}^\gamma_{\delta,k} = \begin{bmatrix} h^\gamma_{\delta,k}(1,1) & \cdots & h^\gamma_{\delta,k}(1,N_T^\gamma) \\ \vdots & \ddots & \vdots \\ h^\gamma_{\delta,k}(N_R,1) & \cdots & h^\gamma_{\delta,k}(N_R,N_T^\gamma) \end{bmatrix},$$

where $$h^\gamma_{\delta,k}(i,j) = \sqrt{\alpha\frac{1}{(d^\gamma_{\delta,k})^\beta}}\sqrt{s^\gamma_{\delta,k}(i,j)}z^\gamma_{\delta,k}(i,j),$$

where $\gamma,\delta \in \{M,c\}$, $d^\gamma_{\delta,k}$ is the distance between the MBS (or FBS) and the *k*-th MUE (or FUE), α is the median of the mean path gain at a reference distance $d = 1$ km, β is the path loss exponent, $s^\gamma_{\delta,k}(i,j)$ is a log-normal shadow fading random variable, where $10\log s^\gamma_{\delta,k}(i,j)$ is a zero-mean 6 dB standard deviation Gaussian random variable, and $z^\gamma_{\delta,k}(i,j)$ represents Rayleigh fading and is a zero-mean unit variance complex Gaussian random variable.

2. Signal Model for FUE

Regarding FUEs, there are three types of interference: 1) intra-cluster interference, 2) interference from other clusters, and 3) interference from an MBS. For antenna selection, we consider antenna selection matrices $\mathbf{R}_{c,k}^{H} \in \mathbb{R}^{\tilde{L}_{c,k} \times N_R}$ that are formed by taking $\tilde{L}_{c,k}$ rows from $\mathbf{I}_{N_R}$ [14], which means the k-th FUE selects $\tilde{L}_{c,k} (\leq N_R)$ antennas (or streams) to use. After antenna selection matrix $\mathbf{R}_{c,k}^{H}$ is applied to the received signal, the post-processed received signal at the k-th FUE in the c-th cluster ($k \in \mathcal{U}_c$) is given by

$$\begin{aligned}\mathbf{y}_{c,k} = & \underbrace{\mathbf{R}_{c,k}^{H}\mathbf{H}_{c,k}^{c}\mathbf{M}_{c,k}\mathbf{x}_{c,k}}_{\text{Desired signal}} + \underbrace{\mathbf{R}_{c,k}^{H}\mathbf{H}_{c,k}^{c}\sum_{l\neq k}\mathbf{M}_{c,l}\mathbf{x}_{c,l}}_{\text{Intra-cluster interference}} \\ & + \underbrace{\mathbf{R}_{c,k}^{H}\sum_{\hat{c}=1,\hat{c}\neq c}^{C}\mathbf{H}_{c,k}^{\hat{c}}\sum_{n\in\mathcal{U}_{\hat{c}}}\mathbf{M}_{\hat{c},n}\mathbf{x}_{\hat{c},n}}_{\text{Interference from other clusters}} \\ & + \underbrace{\mathbf{R}_{c,k}^{H}\mathbf{H}_{c,k}^{M}\sum_{m\in\mathcal{U}_M}\mathbf{M}_{M,m}\mathbf{x}_{M,m}}_{\text{Interference from MBS}} + \mathbf{R}_{c,k}^{H}\mathbf{n}_{c,k}, \end{aligned} \quad (1)$$

where $\mathbf{H}_{c,k}^{M} \in \mathbb{C}^{N_R \times N_T^M}$ denotes the channel matrix from the MBS to the k-th FUE in the c-th cluster and $\mathbf{H}_{c,k}^{\hat{c}} \in \mathbb{C}^{N_R \times F_c \cdot N_T^F}$ denotes the channel matrix from the $\hat{c}$-th cluster to the k-th FUE of the c-th cluster. $\mathbf{H}_{c,k}^{\hat{c}} = [\mathbf{H}_{c,1}^{(\hat{c})}, \cdots, \mathbf{H}_{c,k}^{(\hat{c})}]$, where $\mathbf{H}_{c,k}^{(\hat{c})} \in \mathbb{C}^{N_R \times N_T^F}$ is a channel matrix from the $\hat{c}$-th FBS to the k-th FUE in the c-th femtocell.

3. Block Diagonalization at MBS

In a downlink MIMO broadcast channel, BD is one of the solutions for canceling inter-user interference. The main idea of BD is to choose the precoding matrix $\mathbf{B}_{M,k}$ such that

$$\mathbf{H}_{M,l}^{M}\mathbf{B}_{M,k} = 0, \quad \forall l \neq k \in \mathcal{S}_M. \quad (2)$$

Equation (2) indicates that the precoding matrix $\mathbf{B}_{M,k}$ has to be chosen such that the subspace spanned by its columns lies in the null space of $\mathbf{H}_{M,l}^{M} (\forall l \neq k \in \mathcal{S}_M)$. Each precoding matrix satisfying the zero-interference constraint (2) can be determined on an orthonormal basis for the left null space of the matrix formed by stacking all $\{\mathbf{H}_{M,l}^{M}\}_{\forall l\neq k\in\mathcal{S}_M}$ matrices together.

We can define the aggregate interference channel matrix for selected MUE $k \in \mathcal{S}_M$ as

$$\widehat{\mathbf{H}}_{M,k} = [(\mathbf{H}_{M,1}^{M})^H \ldots (\mathbf{H}_{M,k-1}^{M})^H, (\mathbf{H}_{M,k+1}^{M})^H \ldots (\mathbf{H}_{M,\hat{K}}^{M})^H]^H.$$

In this case, the zero-interference constraint forces $\mathbf{B}_{M,k}$ to lie in the null space of $\widehat{\mathbf{H}}_{M,k}$. Let us define the singular value decomposition (SVD) of $\widehat{\mathbf{H}}_{M,k}$ as

$$\widehat{\mathbf{H}}_{M,k} = \widehat{\mathbf{U}}_{M,k}[\widehat{\mathbf{\Lambda}}_{M,k}\mathbf{0}_{\hat{L}_{M,k}\times(N_T^M-\hat{L}_{M,k})}][\widehat{\mathbf{V}}_{M,k}^{(1)}\widehat{\mathbf{V}}_{M,k}^{(0)}]^H,$$

where $\hat{L}_{M,k}$ is the rank of $\widehat{\mathbf{H}}_{M,k}$, $\widehat{\mathbf{U}}_k$ is the left singular vector matrix of $\widehat{\mathbf{H}}_{M,k}$, and $\widehat{\mathbf{\Lambda}}_{M,k} = \mathrm{diag}(\lambda_{1,k}, \ldots, \lambda_{\hat{L}_{M,k},k})$ is the $\hat{L}_{M,k} \times \hat{L}_{M,k}$ diagonal matrix containing singular values. Matrices $\widehat{\mathbf{V}}_{M,k}^{(1)}$ and $\widehat{\mathbf{V}}_{M,k}^{(0)}$ denote the right singular matrices, each consisting of the singular vectors corresponding to the first $\hat{L}_{M,k}$ non-zero singular values and the last $N_T^M - \hat{L}_{M,k}$ zero singular values, respectively. Since the key idea of BD is that the columns of $\widehat{\mathbf{V}}_{M,k}^{(0)}$ form the basis for the null space of $\widehat{\mathbf{H}}_{M,k}$, we can choose the precoding matrix $\mathbf{B}_{M,k}$ as

$$\mathbf{B}_{M,k} = \left(\widehat{\mathbf{V}}_{M,k}^{(0)}\right)_{(1:N_T^M-\hat{L}_{M,k})}.$$

After inter-user-interference is completely canceled at the MBS, the effective channel of the k-th MUE after the BD process is $\mathbf{H}_{M,k}^{\text{eff}} = \mathbf{H}_{M,k}^{M}\mathbf{B}_{M,k} \in \mathbb{C}^{L_{M,k}\times L_{M,k}}$. Since the k-th MUE receives its own data stream without inter-MUE interference, the methodology for designing an appropriate decoder is exactly the same as single-user MIMO cases, which means the SVD of $\mathbf{H}_{M,k}^{\text{eff}}$ is $\mathbf{H}_{M,k}^{\text{eff}} = \mathbf{U}_{M,k}\mathbf{\Lambda}_{M,k}\mathbf{V}_{M,k}^{H}$.

We can take $\mathbf{D}_{M,k} = \mathbf{V}_{M,k}\mathbf{Q}_{M,k}^{\frac{1}{2}}$, where the $\mathbf{V}_{M,K}$ are the right singular vectors corresponding to non-zero singular values and $\mathbf{Q}_{M,k}^{\frac{1}{2}}$ denotes a diagonal matrix whose elements scale the power transmitted into each of the columns of $\mathbf{V}_{M,K}$. Finally, the aggregate precoder of the k-th MUE $\mathbf{M}_{M,K}$ is given by

$$\mathbf{M}_{M,k} = \left(\widehat{\mathbf{V}}_{M,k}^{(0)}\right)_{(1:N_T^M-\hat{L}_{M,k})}\mathbf{V}_{M,k}\mathbf{Q}_{M,k}^{\frac{1}{2}}.$$

There exist $N_{M,k}^{I}$ effective co-channel interferers from the clusters and the post-processed received signal at the k-th MUE can be rewritten as

$$\mathbf{y}_{M,k} = \mathbf{H}_{M,k}^{\text{eff}}\mathbf{D}_{M,k}\mathbf{x}_{M,k} + I_{M,k} + \mathbf{n}_{M,k},$$

$$\text{where} \quad I_{M,k} = \underbrace{\sum_{c=1}^{C}\mathbf{H}_{M,k}^{c}\sum_{n\in\mathcal{U}_c}\mathbf{M}_{c,n}\mathbf{x}_{c,n}}_{\text{Interference from clusters}},$$

where $I_{M,k} \in \mathbb{C}^{L_{M,k}\times 1}$ is the co-channel interference from clustered-FBSs.

IV. Precoding Matrix Design at Clustered FBS

To significantly mitigate the clustered-FBS-to-MUE interference, the precoding matrices for the FUEs have to lie in the null space of the interference channel to the MBS. The following *Lemmas* help in understanding the main concept of mitigating the clustered-FBS-to-MUE interference.

Lemma 1: Without antenna selection, the maximum number of streams that can be supported simultaneously at the c-th clustered-FBS under a zero-interference constraint is bounded by $F_c \cdot N_T^F$.

Proof: Let $\mathcal{S}_c$ be the set of selected FUEs in the *c*-th cluster. The maximum number of streams that can be supported simultaneously ($L_{\max}$) is bounded by [13]

$$L_{\max} \le \sum_{k\in\mathcal{S}_c} \text{rank}(\mathbf{H}^c_{c,k}) = \sum_{k\in\mathcal{S}_c} L_{c,k} = F_c N_T^F. \quad \square$$

From Lemma 1, although a clustered-FBS can choose the maximum $F_c \cdot N_T^F$ streams that can be supported simultaneously according to Lemma 1 by conventional BD, a clustered-FBS can select less than $F_c \cdot N_T^F$ streams for their FUEs using a joint antenna/user selection algorithm [14].

Lemma 2: If a clustered-FBS uses $L'_{\max}\left(\le F_c \cdot N_T^F\right)$ streams for their FUEs with antenna selection, the residual degrees of freedom (ρ) can be used to null the clustered-FBS-to-MUE interference and are bounded by $F_c \cdot N_T^F - L'_{\max}$.

Proof: From Lemma 1, there are $F_c \cdot N_T^F$ streams that can be simultaneously supported if a clustered-FBS does not apply antenna selection. If a clustered-FBS only uses $F_c \cdot N_T^F - \rho$ streams for their FUEs by antenna selection, the maximum number of ρ streams that can be supported simultaneously at the clustered-FBS is bounded by

$$\rho = L_{\max} - \sum_{k\in\mathcal{S}_c} \text{rank}(\mathbf{R}^H_{c,k}\mathbf{H}^c_{c,k}) = L_{\max} - \sum_{k\in\mathcal{S}_c} \tilde{L}_{c,k}$$
$$\le F_c \cdot N_T^F - L'_{\max}.$$

Therefore, the number of degrees of freedom needed to null the clustered-FBS-to-MUE interference is bounded by $\rho \le F_c \cdot N_T^F - L'_{\max}$. The maximum number of degrees of freedom to cancel the interference is $F_c \cdot N_T^F - L'_{\max}$ at a clustered-FBS. $\square$

To obtain precoding matrices that satisfy the null space constraint, each clustered-FBS stacks channels for the FUEs located at the *c*-th cluster ($\mathbf{R}^H_{c,k}\mathbf{H}^c_{c,k}, k \in \mathcal{S}_c$) and interfering channels for the *n*-th MUE located near the *c*-th cluster ($\mathbf{H}^c_{M,n}, n \in \mathcal{S}_M$) as follows:

$$\mathbf{H}_c = [(\mathbf{R}^H_{c,1}\mathbf{H}^c_{c,1})^H, \cdots, (\mathbf{R}^H_{c,K_c}\mathbf{H}^c_{c,K_c})^H, (\mathbf{H}^c_{M,n})^H]^H. \quad (3)$$

If $\text{rank}(\mathbf{H}^c_{M,n}) = N_R$, $n \in \mathcal{S}_M$, that is, $\rho = N_R$, then $L'_{\max} = F_c \cdot N_T^F - N_R$, which is an upper bound. By Lemma 2, the clustered-FBS uses $F_c \cdot N_T^F - N_R$ streams to serve the FUEs, and the number of $\rho = N_R$ degrees of freedom is used to cancel the interference in the MUE.

The aggregate interference channel for the *k*-th FUE in the *c*-th cluster is

$$\hat{\mathbf{H}}_{c,k} = \Big[(\mathbf{R}^H_{c,1}\mathbf{H}_{c,1})^H, \cdots, (\mathbf{R}^H_{c,k-1}\mathbf{H}_{c,k-1})^H, \cdots,$$
$$(\mathbf{R}^H_{c,k+1}\mathbf{H}_{c,k+1})^H, \cdots, (\mathbf{R}^H_{c,K_c}\mathbf{H}_{c,K_c})^H, (\mathbf{H}_{c,n})^H\Big]^H. \quad (4)$$

If we apply SVD for $\hat{\mathbf{H}}_{c,k}$ in (4), the aggregate interference channel is decomposed as

$$\hat{\mathbf{H}}_{c,k} = \hat{\mathbf{U}}_{c,k}[\hat{\mathbf{\Lambda}}_{c,k}\mathbf{0}_{\bar{L}_{c,k}\times(F_C N_T^F - \bar{L}_{c,k})}][\hat{\mathbf{V}}^{(1)}_{c,k}\hat{\mathbf{V}}^{(0)}_{c,k}]^H,$$

where $\bar{L}_{c,k}$ is the rank of $\hat{\mathbf{H}}_{c,k}$, $\hat{\mathbf{U}}_{c,k}$ is the left singular vector matrix of $\hat{\mathbf{H}}_{c,k}$, and $\hat{\mathbf{\Lambda}}_{c,k} = \text{diag}(\lambda_{1,k}, \ldots, \lambda_{\bar{L}_{c,k},k})$ is the $\bar{L}_{c,k} \times \bar{L}_{c,k}$ diagonal matrix containing singular values. Matrices $\hat{\mathbf{V}}^{(1)}_{c,k}$ and $\hat{\mathbf{V}}^{(0)}_{c,k}$ denote right singular matrices consisting of singular vectors corresponding to the first $\bar{L}_{c,k}$ non-zero singular values and last $F_C N_T^F - \bar{L}_{c,k}$ zero singular values, respectively. Since the key idea of BD is that the columns of $\hat{\mathbf{V}}^{(0)}_{c,k}$ form the basis for the null space of $\hat{\mathbf{H}}_{c,k}$, we can choose the precoding matrix $\mathbf{B}_{c,k}$ as

$$\mathbf{B}_{c,k} = \left(\hat{\mathbf{V}}^{(0)}_{c,k}\right)_{(1:F_c N_T^F - \bar{L}_{c,k})}.$$

After inter-FUE interference is completely canceled, the effective channel of the *k*-th FUE after the BD process is

$$\mathbf{H}^{\text{eff}}_{c,k} = \mathbf{R}^H_{c,k}\mathbf{H}^c_{c,k}\mathbf{B}_{c,k} \in \mathbb{C}^{\tilde{L}_{c,k}\times\tilde{L}_{c,k}} = \mathbf{U}_{c,k}\mathbf{\Lambda}_{c,k}\mathbf{V}^H_{c,k}.$$

We can take $\mathbf{D}_{c,k} = \mathbf{V}_{c,k}\mathbf{Q}^{\frac{1}{2}}_{c,k}$, where $\mathbf{V}_{c,k}$ represents the right singular vectors corresponding to non-zero singular values, and $\mathbf{Q}^{\frac{1}{2}}_{c,k}$ denotes a diagonal matrix whose elements scale the power transmitted into each column of $\mathbf{V}_{c,k}$. Finally, the aggregate precoder of the *k*-th FUE $\mathbf{M}_{c,k}$ is given by

$$\mathbf{M}_{c,k} = \left(\hat{\mathbf{V}}^{(0)}_{c,k}\right)_{(1:F_c N_T^F - \bar{L}_{c,k})}\mathbf{V}_{c,k}\mathbf{Q}^{\frac{1}{2}}_{c,k}.$$

The received signal of the *k*-th FUE $\mathbf{y}_{c,k}$ in (1) is rewritten as

$$\mathbf{y}_{c,k} = \mathbf{H}^{\text{eff}}_{c,k}\mathbf{D}_{c,k}\mathbf{x}_{c,k} + \mathbf{R}^H_{c,k}\left(I_{c,k} + \mathbf{n}_{c,k}\right),$$

$$I_{c,k} = \underbrace{\sum_{\hat{c}=1,\hat{c}\neq c}^{C} \mathbf{H}^{\hat{c}}_{c,k}\sum_{n\in\mathcal{U}_{\hat{c}}}\mathbf{M}_{\hat{c},n}\mathbf{x}_{\hat{c},n}}_{\text{Interference from other clusters}} + \underbrace{\mathbf{H}^M_{c,k}\sum_{m\in\mathcal{U}_M}\mathbf{M}_{M,m}\mathbf{x}_{M,m}}_{\text{Interference from MBS}},$$

where $I_{c,k} \in \mathbb{C}^{\tilde{L}_{c,k}\times 1}$ is the co-channel interference from other clusters and the MBS.

V. Proposed Algorithm

The important actions to execute at the clustered-FBS are to select i) the member and size of the cluster, ii) the interference channel to the MUE ($\mathbf{H}^c_{M,n}, n \in \mathcal{S}_M$) in (4), and iii) the receive antennas for the selected FUEs using the antenna selection algorithm.

1. Home eNodeB Management System

The number of the HeNBs may be very large and located at a private residence that is not accessible for onsite maintenance. Therefore, it is essential that management functionality be defined, including considerations for multi-vendor environments. The HeNB will be managed by the Home eNodeB Management System (HeMS) through the so-called type 1 interface [4], based on TR-069, as defined by Broadband Forum. The HeMS is able to have functions as follows [4]: 1) The HeMS configures the HeNBs using the TR-069 CPE WAN Management Protocol; 2) HeMS shall have remote access to the HeNB to start/stop the radio transmission on the frequencies specified by HeMS; 3) HeMS shall maintain the configuration data of the HeNB; 4) When the HeNB is initially powered up and connected to the HeMS, HeMS shall send the initially needed configuration data to the HeNB; and 5) The HeMS shall specify which parameters it needs to be notified of when the HeNB changes their values through auto-configuration. The HeNB shall notify the HeMS of changes in the values of any such auto-configured parameters.

Each HeNB is able to collect performance data and send it to the HeMS through the type 1 interface. Hence, the HeMS is able to perform the proposed algorithms using proper information, which means HeMS functions as a central controller.

2. Algorithms

For the antenna selection algorithm, let $\mathcal{A}_k^c = (1,\cdots,N_R)_k$ be the index of antennas for the k-th FUE and $\mathcal{A}^c = \{\mathcal{A}_1^c,\cdots,\mathcal{A}_k^c\}$, $k \in \mathcal{U}_c$ be the set of antenna indices for the FUEs in the c-th cluster. Let $\mathcal{A}^c(i_k, j_p) = \mathcal{A}^c - \{(i)_k,(j)_p\}$ denote the set of selected antenna indices for the FUEs in the c-th cluster; this means that the i-th antenna of the k-th user and the j-th antenna of the p-th user are deactivated by the antenna selection.

For the case of N_R=2, F_c=5, for example, $\mathcal{A}^c(1_1,2_2,2_3,(1,2)_5) = \{(2)_1,(1)_2,(1)_3,(1,2)_4\}$ means that the first antenna of the first FUE, the first antenna of the second FUE, the second antenna of the third FUE, and the first and second antennas of the fifth FUE are deactivated.

Since the antenna selection matrix $\mathbf{R}_{c,k}^H$ is formed by taking $L_{c,k}$ rows from $\mathbf{I}_{N_R}$ [14], in this example, the antenna selection matrix for the k-th FUE in the c-th cluster will be determined as follows:

$$\mathbf{R}_{c,1}^H = [0 \quad 1], \quad \mathbf{R}_{c,2}^H = \mathbf{R}_{c,3}^H = [1 \quad 0],$$

$$\mathbf{R}_{c,4}^H = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{R}_{c,5}^H = \mathbf{0}.$$

First, we can determine the members and size of cluster using the following algorithm.

Algorithm 1 (A1): Determine member FBSs and size of cluster

Initialization: $\mathcal{F}_c = \phi, \forall c$.

Step 1: The k-th MUE feeds the interference signal strength from the f-th FBS, that is, norm of interference channel $\|\mathbf{H}_{M,k}^{(f)}\|_F$, back to the f-th FBS.

Step 2: The f-th FBS selects the MUE that has the largest interference channel norm as

$$\eta_f = \arg_k \max \|\mathbf{H}_{M,k}^{(f)}\|_F, \forall k \in \mathcal{S}_M .$$

Step 3: The f-th FBS feeds η_f back to HeMS.

Step 4: The HeMS selects the member of the c-th cluster.

$$\mathcal{F}_c = \{f \mid c = \eta_f, \forall f\}, \forall c.$$

Step 5: The HeMS determines the size of the c-th cluster.

$$F_c = |\mathcal{F}_c| .$$

Let $k^* \in \mathcal{S}_M$ be the selected MUE at the c-th cluster, the aggregate channel at the c-th cluster in (3) can be rewritten as

$$\mathbf{H}_c(k^*) = [(\mathbf{R}_{c,1}^H\mathbf{H}_{c,1}^c)^H,\cdots,(\mathbf{R}_{c,K_c}^H\mathbf{H}_{c,K_c}^c)^H,(\mathbf{H}_{M,k^*}^c)^H]^H . \qquad (5)$$

After the HeMS decides the member FBSs and size of the cluster, each clustered-FBS has to select the FUEs to be served and to determine its antenna selection matrix for the selected FUEs. The number of $\rho = N_R$ degrees of freedom is used to cancel the interference affecting the k-th MUE, and the total number of antennas for the selected FUEs in the c-th cluster is less than or equal to $N_T^F \cdot F_c - \rho$. For $\mathcal{U}_c$, let $\mathcal{S}_c \subset \{1,\cdots,\hat{K}_c\}$ be the set of selected FUEs with $\tilde{L}_{c,k} \ge 1$ ($|\mathcal{S}_c| = \lceil (N_T^F \cdot F_c - \rho)/N_R \rceil = \hat{K}_c$, where $\lceil \bullet \rceil$ is the ceiling operation).

Algorithm 2 (A2): Antenna selection at the HeMS

Step 1: Without an antenna selection ($\mathbf{R}_{c,k}^H = \mathbf{I}_{N_R}$, $\forall c,k$ and $\rho = 0$), a clustered-FBS can select the number of $\lceil (N_T^F \cdot F_c - \rho)/N_R \rceil$ FUEs to be supported simultaneously. Then,

$$\mathcal{A}^c = \{\mathcal{A}_1^c,\cdots,\mathcal{A}_k^c\},$$

$$k \in \mathcal{S}_c, |\mathcal{S}_c| = \lceil (N_T^F \cdot F_c - \rho)/N_R \rceil.$$

Step 2: for n=1: ${}_{F_c N_R}\mathrm{C}_\rho$

Step 2-1: Temporarily deactivate the number of $\rho = N_R$ receive antennas among the $F_c \cdot N_R$ antennas.

$$\mathcal{A}_n^c = \mathcal{A}^c(\underbrace{i_k,\cdots,j_p}_{\rho=N_R})$$

Step 2-2: Using $\mathcal{A}_n^c$, determine $\mathbf{R}_{c,k}^H, k \in \mathcal{S}_c$.

Step 2-3: With $\mathbf{R}_{c,k}^H$, generate a precoding matrix using (4).

Step 2-4: Calculate the sum capacity of FUEs in the c-th cluster,

$$\mathcal{C}(\mathcal{A}_n^c) = \sum_{k \in \mathcal{S}_c} \mathcal{C}_{c,k} .$$

Step 2-5: n=n+1, go back to Step 2.

Step 3: Determine the set of the selected antennas.

$$n^* = \arg_n \max \mathcal{C}(\mathcal{A}_n^c), \quad \hat{\mathcal{A}}^c = \mathcal{A}_{n^*}^c ,$$

where ${}_nC_k$ is the combination operation, that is, ${}_nC_k = n!/(k!(n-k)!)$.

Generating precoding matrix for the k-th FUE in the c-th cluster, the HeMS considers both $\mathbf{H}_{M,k^*}^c$ and $\mathbf{R}_{c,k}^H \mathbf{H}_{c,k}^c, k \in \mathcal{S}_c$ related to $\hat{\mathcal{A}}^c$. Using (5), the aggregate interference channel for the k-th FUE in the c-th cluster in (4) can be rewritten as,

$$\widehat{\mathbf{H}}_{c,k}(\hat{\mathcal{A}}^c, k^*) = [(\mathbf{R}_{c,1}^H \mathbf{H}_{c,1}^c)^H, \cdots, (\mathbf{R}_{c,k-1}^H \mathbf{H}_{c,k-1}^c)^H, \cdots, (\mathbf{R}_{c,k+1}^H \mathbf{H}_{c,k+1}^c)^H, \cdots, (\mathbf{R}_{c,K_c}^H \mathbf{H}_{c,K_c}^c)^H, (\mathbf{H}_{M,k^*}^c)^H]^H . \quad (6)$$

If the precoding matrix is obtained by BD with (6), intra-clustered (inter-femto) interference and interference from a clustered-FBS affecting the k^*-th MUE can be effectively canceled and mitigated, respectively.

A brief outline of the interactions between HeMS and HeNBs can be shown as follows:

- Each FUE selects the MUE that has the largest interference channel norm and feeds its index (η_f) back to HeMS (A1_Step 1 through A1_Step 3).
- The HeMS can determine the member of each cluster ($\mathcal{F}_c$) and cluster size (F_c) using η_f (A1_Step 4 and A1_Step 5).
- The HeMS determines the set of the selected antennas ($\hat{\mathcal{A}}^c$) using A2.
- The HeMS generates the precoding matrix for the FUEs in the cluster using BD with (6).
- The precoding matrix for the FUEs will be delivered to each FBS.

VI. Simulation Results

A numerical analysis is performed to investigate the effectiveness of the proposed clustered interference mitigation scheme. The simulation parameters are defined in Table 1, and the MIMO channel models are mainly drawn from 3GPP standardization [20]. The path loss models shown in Table 2 are based on [2], [8]. The wall loss values are the lower values in [2], based on the assumption that all the macro UEs are outside and each femtocell (both the FBS and FUE) is inside a house, meaning different femtocells are in different houses.

Table 1. Simulation parameters.

Parameters	Value
Macrocell layout	Hexagonal grid, single macrocell
Femtocell layout	Circular grid, multiple femtocell
Macrocell radius	1 (normalized value)
Femtocell radius	0.03 (normalized value)
# of Tx antennas of MBS	$N_T^M = 8$
# of Tx antennas of FBS	$N_T^M = 2$
# of Rx antennas of MUE/FUE	$N_R = 2$
# of MUEs in a macrocell	$\|\mathcal{U}_M\| = 20$
# of FUE in a cluster	$\|\mathcal{U}_c\| = F_c$
Tx power of MBS	1 (normalized value)
Tx power of FBS	0.001 (normalized value)
Min inter-femto distance	0.1 (normalized value)
Min FBS-MUE distance	0.1 (normalized value)
Location of MUE or FUE	$\geq$ 0.7 (normalized value)

Table 2. Path loss models based on [2], [8] (L_{ow} is outer wall loss and R is distance in meter).

Link	Path loss (dB)
MBS ↔ MUE	$15.3 + 37.6\log_{10}(R)$
MBS ↔ FUE	$15.3 + 37.6\log_{10}(R) + L_{ow}, L_{ow} = 10$
FBS ↔ FUE (serving link)	$15.3 + 37.6\log_{10}(R) + 0.7R$
FBS ↔ FUE (interfering link)	$15.3 + 37.6\log_{10}(R) + L_{ow}, L_{ow} = 20$
FBS ↔ MUE	$15.3 + 37.6\log_{10}(R) + L_{ow}, L_{ow} = 10$

1. Capacity of MUE

- **Capacity 1** (without femtocells): There is no interference from femtocells since there are no femtocells.
- **Capacity 2** (proposed scheme with clustered femto): In the proposed scheme, when a precoding matrix is generated, the c-th clustered-FBS considers the selected interfering channel to the k^*-th MUE, $\mathbf{H}_{M,k^*}^c$. Let Ω_k be the set of clusters that select the k-th MUE, that is,

$$\Omega_k = \{c \mid k = k^* \text{ of } \mathbf{H}_c(k^*), \forall k^*\} \text{ and } |\Omega_k| = \hat{C},$$

where $\mathbf{H}_c(k^*)$ is defined in (5). At the k-th MUE, the interference from Ω_k is mitigated effectively due to the proposed precoding matrix design with the antenna selection at Ω_k. However, there is a large number of effective co-channel interferers from the $\Omega_j, j \neq k$ clusters.

- **Capacity 3** (selfish BD at femtocells): In the presence of femtocells in a macrocell, each MUE is exposed to high

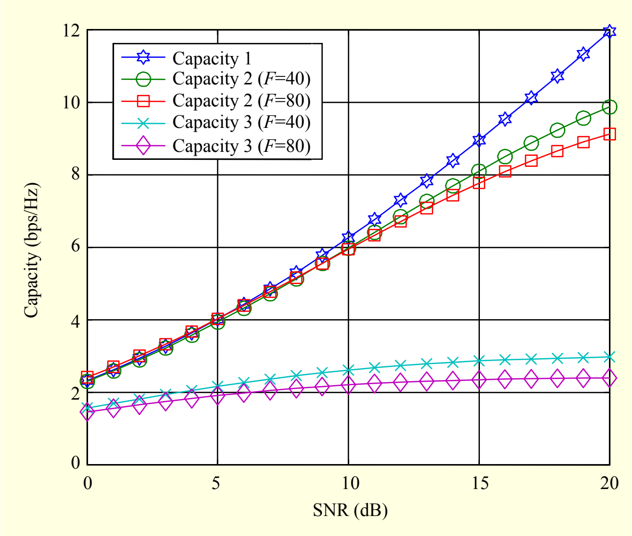

Fig. 2. Capacity of MUE with $\rho = N_R = 2$ according to SNR.

interference from all of the activated FBSs.

Figure 2 compares the capacity of the MUE for different systems. If the MBS performs a conventional BD process without femtocells in a macrocell, the capacity of the MUE (Capacity 1) is much higher than that of a coexisting network in a high SNR region (interference-limited region). This is not surprising because there is no interference from FBSs. However, for the coexisting network, the capacity of the MUE (Capacity 3) greatly decreases in interference-limited regions since each MUE is exposed to high interference from all of the activated FBSs when femtocells are operating in a selfish manner. Compared to selfish BD at FBSs, performing antenna selection and beamformer design using our proposed scheme (Capacity 2) increases the capacity dramatically. As shown in Fig. 2, the performance gap between Capacity 2 and Capacity 3 is very large, which can be interpreted using the amount of interference as follows: If we use the proposed algorithm, the *k*-th MUE only receives the interference from widespread (far apart) clustered-FBSs $(\Omega_j, j \neq k)$ operating at the same frequency. This means that clustered-FBS-to-MUE interference in the nearby MUE (interference from the clusters of Ω_k) would be completely eliminated due to the proposed precoding matrix design at Ω_k. It states that clustered-FBSs located at the near MUE (Ω_k) are dominant interference contributors over the coexisting networks since the interference from widespread clustered-FBSs $(\Omega_j, j \neq k)$ is relatively less due to the low transmit power at the FBSs and the penetration loss. Figure 2 also shows that as the system environment becomes interference-limited, the effect of residual interference from clustered-FBSs becomes a critical factor. As the number of femtocells increases, the system capacity of the MUE decreases since the number of interferers increases in a macrocell. Compared to non-coexisting networks, performance degradation is inevitable in an interference-limited region. The biggest advantage of our proposed algorithm is that both the MBS and the MUE are able to be operated without changing any transmit-receive components/functions, while the capacity of the MUE can be effectively maintained due to the proposed interference management algorithm.

2. Capacity of FUE

• **Capacity 4** (selfish BD at femtocells): If each femtocell operates in a selfish manner, each FUE suffers from strong interference: MUE interference and inter-femto interference.

• **Capacity 5** (proposed clustered femto): If femtocells form clusters using the proposed algorithm, the inter-femto interference is completely canceled, which means all propagation links (including interfering channels) are exploiting useful data. Unfortunately, the inter-cluster interference will remain if all clusters use the same frequency. To reduce the inter-cluster interference, we consider the frequency reuse as follows:

i) Case 1 (without frequency reuse): In this case, all clusters operate on the same frequency band, which means the MBS and the FBSs use the same frequency band. Although this case has high spectral efficiency, the sum capacity of FUEs might degrade due to a large amount of inter-cluster interference.

ii) Case 2 (with frequency reuse): In this case, all clusters operate on different frequency bands. The HeMS has to determine which frequency band is used for each cluster. Although this case shows low spectral efficiency due to the reduced bandwidth utilization ($1/C$), the gain in sum-capacity of FUEs achieved by inter-cluster interference mitigation may be greater than attained using whole frequency bands.

Remark: Since each cluster uses a different frequency band, the reuse factor might be very high if there is a large number of femtocells in a macrocell. We acknowledge that the performance could be further improved by a proper frequency planning algorithm at HeMS; that is, if two clusters are very far apart from each other, they should be able to reuse the same frequency without causing any problems. Therefore, presenting a new frequency planning algorithm in future work will prove to be very useful.

Figure 3 plots the capacity of the FUE versus the total number of femtocells in a macrocell for different FBS schemes. The effects of clustering and frequency reuse are as follows:

1) Effect of Clustering: If each FBS forms a cluster and each clustered-FBS performs BD using the proposed algorithm, each FBS provides each FUE with an inter-femto interference-free channel through properly designed linear precoding matrices. However, for the proposed scheme, the total number of streams

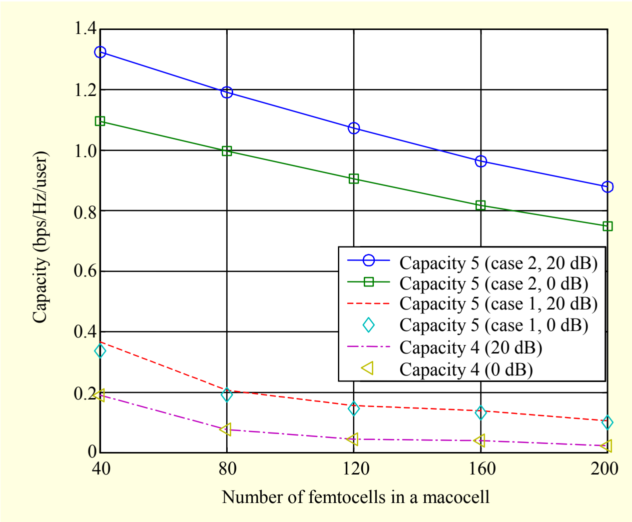

Fig. 3. Capacity of FUE with $\rho = N_R = 2$ according to the different number of femtocells in a macrocell.

that each clustered-FBS supports simultaneously must be reduced, since the number of $\rho = N_R = 2$ degrees of freedom is used to eliminate interference from clusters affecting the MUE. Therefore, there is a trade-off between the number of streams that each cluster supports simultaneously and inter-femto interference mitigation in terms of capacity.

2) Effect of Frequency Reuse across Clustered-FBSs: If the total number of available bandwidths is 1, each femtocell can only utilize a number of frequency channels corresponding to a bandwidth of $1/C$. In the case of performing frequency reuse across clustered-FBSs, all clusters must utilize different frequencies, and there is no inter-cluster interference. However, since the bandwidth utilization will be reduced, there is a trade-off between the spectral efficiency and inter-femto interference mitigation in terms of the FUE capacity.

Interesting results are shown in Fig. 3, in which "clustering with proposed antenna selection algorithm" always guarantees a better performance in terms of capacity at the FUEs. It is obvious that if each FBS forms a cluster and performs the proposed antenna selection algorithm in a cooperative fashion, multiple FBSs collaborate to change the interfering signal into a desired signal in the downlink; that is, inter-femto interference will completely vanish (the capacity of the MUE is also guaranteed). Because of this advantage, the capacity of the clustered-FBS without frequency reuse (Capacity 5_case 1) is higher than that of the non-clustered-FBS (Capacity 4). This suggests that for the femtocell networks, using the degrees of freedom to mitigate interference coming from closely located femtocells (inter-femto interference) might demonstrate a better performance than using it to schedule more streams (that is, increasing desired signal power), in terms of the capacity at the FUE. This can be interpreted as the inter-femto

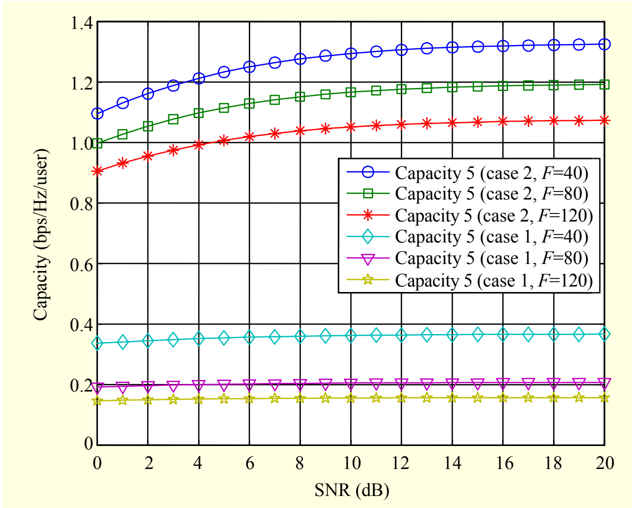

Fig. 4. Capacity of FUE with $\rho = N_R = 2$ according to SNR.

interference being able to hamper the performance of the FUE in femtocell networks. Besides, the cluster-based proposed scheme without frequency reuse is significant on that account, since it guarantees performance of both the MUE and the FUE simultaneously. To increase capacity for both the MUE and the FUE, we have considered the proposed antenna selection algorithm with frequency reuse. If each clustered-FBS operates on a different frequency, the capacity of the FUE increases dramatically. Even though each cluster has fewer streams and uses only partial bandwidth, mitigating interference from other clusters is probably a more critical factor; hence, the cluster-based antenna selection algorithm with frequency reuse shows better performance. Because the capacities of both the MUE and the FUE are guaranteed simultaneously, clustering with frequency reuse (Capacity 5_case 2) is our desired solution. As a result, we can conclude the following:

- From the perspective of an FUE, inter-cluster interference is a main interference contributor in femtocell networks.
- Reducing inter-femto interference is more effective than scheduling more streams simultaneously (Capacity 5_case 1 > Capacity 4).
- Even though each cluster uses only partial bandwidth due to the frequency reuse, the clustering and antenna selection algorithm with frequency reuse to mitigate inter-cluster interference shows better performance than the case without frequency reuse (Capacity 5_case 2 > Capacity 5_case 1).

The capacity of the algorithms to evaluate the proposed clustering scheme with frequency reuse as a function of SNR is compared with that of a clustering scheme without frequency reuse, with F = 40, 80, 120, which is plotted in Fig. 4. Even though each cluster has fewer streams and uses only partial bandwidth, clustering with frequency reuse might guarantee a higher capacity compared with the case of clustering without frequency reuse at a whole SNR region due to the mitigated inter-cluster interference, which is the most critical factor in a femtocell network.

VII. Conclusion

In this paper, we proposed a beamforming solution in which FBSs cooperate to determine signals to be transmitted on a downlink. The proposed algorithm is tightly related to CoMP, which has been proposed for emerging communication standards, such as LTE-Advanced and IEEE802.16m. In the proposed algorithm, by performing clustering-based antenna selection and beamformer design at clustered-FBSs in a cooperative fashion, the capacity of the MUE can be guaranteed. Additionally, simulation results indicate that inter-femto interference is a main interference contributor for the femtocell networks. Clustering with frequency reuse is the best solution to achieve better performance from the perspective of both the MUE and the FUE, and the performance of the proposed algorithm could be further improved by a proper frequency planning algorithm at HeMS. Although this paper offered an initial contribution to the literature concerning coexisting cellular networks, more research is necessary, particularly in the real communication environments.

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