Interference Mitigation and Resource Allocation in Cognitive Radio-Enabled Heterogeneous Networks

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***Abstract*—In this paper, we propose an effective interference mitigation scheme to address the resource allocation problem in Heterogeneous networks (HetNets), where cognitive radio technology are employed to identify physical resource blocks (PRBs) that cause light interference to the users served by the macrocell. A stochastic scheduling algorithm is proposed to mitigate the cross-tier and the intra-tier interference by allocating different portions of the PRBs probabilistically, based on which an efficient algorithm is developed to work out the optimal resource allocation for un-planned femtocells with low computational load. Analysis and numerical results show our proposed scheduling scheme can keep the cross-tier and the intratier interference under control. Moreover, our proposed resource allocation algorithm for the femtocells achieves a significant capacity gain. Since the proposed interference mitigation scheme requires nonexistence of macro-femto backhaul coordination and no modifications of existing macrocells, it is promising for applications in the LTE-Advanced cellular systems that employ HetNets.**

I. Introduction

Advances in communication signal processing make cellular wireless systems achieve near optimal performance which is determined by information theoretic capacity limits. As a result, advanced network topology seems to be the possible way to obtain more capacity gains of wireless cellular systems. Heterogeneous network (HetNet), where low-power, lower-cost and plug-and-play femtocells are employed in the coverage range of a traditional macrocell and share the same radio spectrum with the macrocell, is deemed as a promising paradigm to improve spectral efficiency per unit area, as well as satisfy high traffic demands in densely populated areas [1, 2]. HetNets exploit the fact that the traffic demand in a cellular network is not uniform, which makes it possible to deploy low-power access points, such as femtocells, to obtain higher data rates with given power budgets. Furthermore, such low-power femtocells can also eliminate coverage holes in the macro-only system and improve capacity in hot-spots, enhancing system performance dramatically.

However, the plug-and-play nature of femtocells allows subscribers to install them autonomously, which leads to unpredictable interference to the users served by the macrocell and other femtocells. Interference in a two-layer HetNet on the downlink can be typically classified into two categories: cross-tier interference and intra-tier interference. The former is interference between femtocells and macrocells; the latter is the interference between neighboring femtocells [3].

Interference management in HetNets has been attracted attention in both academia and industry. In a Long Term Evolution (LTE)-Advanced system, interference management is referred as enhanced intercell interference coordination, and interference mitigation techniques can be classified into the following two categories [4]: Interference coordination, which ensures orthogonality between mutual interfering transmitted signals in the following domains: time-frequency, location/space or antenna spatiality; Interference cancellation, which employs coding techniques such as sphere decoding or dirty paper coding, to allow the user who suffers heavy interference to actively cancel interfering signals from the desired one. Some promising interference management schemes are investigated in recent years. In [5], a joint user association and interference coordination scheme is proposed, which focus on cell splitting, range expansion, semi-static resource negotiation on third-party backhaul connections, and fast dynamic interference management for QoS via over-the-air signaling in HetNets. In [6], a stochastic frequency-domain scheduling algorithm is proposed to seek the avoidance of cross-tier and intra-tier interference, which can achieve a good tradeoff between full-range spectrum allocation and orthogonal spectrum allocation.

As a widely investigated spectrum sharing technique, cognitive radio is also introduced to mitigate interference in HetNets [7, 8]. In [9], a cognitive interference management scheme for heterogeneous networks with macrocells and femtocells is proposed, where the macro/femtocells are allocated resources (in time and frequency) and transmission opportunities by considering their potential to cause interference among users. In [10], spectrum resource allocation in an LTE downlink system is considered, where femtocells are assumed to incorporate cognitive capabilities and aim to maximize the spectrum utility by utilizing the unoccupied frequencies while minimizing interference to the macrocell in a spectrum overlay LTE system. A game-theoretic framework is developed to address the resource blocks allocation problem in femtocells. In [11], an extensive analysis on interferences due to different interfering sources within cognitive empowered femtocell networks is given, based on which a stochastic dual control approach is introduced for dynamic sensing coordination,

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aiming to achieving efficient interference mitigation without involving global and centralized control efforts. In [12], a distributed game-theoretic resource allocation mechanism is also developed whereby users autonomously decide which subchannel in which coalition to join for an LTE network.

The cognitive radio enabled femtocell gives an attractive perspective for interference management and resource allocation in HetNets. However, there are challenges for practical applications. First, network state information is usually required to exchange between macrocell and femtocells, while macro-femto backhaul coordination is not allowed according to LTE-Advanced specification; second, complex cognitive function is required for some proposed resource allocation schemes, which is also difficult for a low-cost femtocell to implement. In this paper, we propose a new interference mitigation and resource allocation scheme for cognitive radio-enabled HetNets where only simple cognitive function is necessary and the coordination between macrocell and femtocell is not required.

The rest of this paper is organized as follows. In Section II, heterogeneous network model is illustrated, as well as operation modes of the macrocell and femtocells. In Section III, we give the interference mitigation analysis results and the resource allocation algorithm in details. Numerical results are given in Section IV with discussions. Conclusion and future work are presented in Section V.

II. System Model

Consider a HetNet where M femtocells operate within the coverage of a macrocell. The macrocell and the femtocell are also called as eNB and HeNB in LTE-Advanced systems, respectively. There are K mobile stations (denoted as FMSs thereafter), which are served by the HeNB. The eNB serves multiple mobile stations (denoted as MMSs thereafter). The set of MMSs laid within the coverage area of the sth HeNB is denoted as $\mathcal{L}_s = \{1, 2, \cdots, L_s\}$, which can be taken as indoor MMSs. Correspondingly, other MMSs are outdoor MMSs. Both the macrocell and femtocells adopt OFDM. The smallest radio resource unit that can be assigned to a mobile station is known as a physical resource block (PRB), which is composed of successive subcarriers over OFDM symbols. We denote $\mathcal{N} = \{1, 2, \ldots, N_{max}\}$ as the set of indexes of the total available PRBs.

The indoor MMSs may suffer heavy interference if the PRBs used by them are reused by the femocell users. As a result, the HeNB should avoid using the PRBs occupied by indoor MMSs to mitigate cross-tier interference. In other words, the femtocells need to be aware of the radio resource usage state of the macrocell to keep the performance of the MMSs from degeneration. Inspired by the cognitive radio technology developed in past decade, cognitive radio-enabled HeNBs are introduced to identify available resource and adapt to HetNet environments. Denote $\mathcal{N}_{\text{ocp}}[i]$ as the set of the PRBs which are occupied by the MMSs and $\mathcal{N}_{\text{nocp}}[i]$ is the complementary set of $\mathcal{N}_{\text{ocp}}[i]$, i.e. $\mathcal{N}_{\text{ocp}}[i] \cup \mathcal{N}_{\text{nocp}}[i] = \mathcal{N}$. Both of them can be obtained by sensing the radio environment.

In the macrocellular downlink, an eNB partitions the set $\mathcal{N}$ at scheduling time interval i into two mutually exclusive subsets: $\mathcal{N}_{\text{IM}}[i]$ and $\mathcal{N}_{\text{OM}}[i]$. The spectral resources with indexes in subset $\mathcal{N}_{\text{IM}}[i]$ are reserved for the indoor MMSs and they are referred as indoor PRBs. While the spectral resources with indexes in subset $\mathcal{N}_{\text{OM}}[i]$ are reserved for the outdoor MMSs and they are referred as outdoor PRBs. Both sets $\mathcal{N}_{\text{IM}}[i]$ and $\mathcal{N}_{\text{OM}}[i]$ can be further partitioned into two mutually exclusive subsets at each scheduling time interval i: $\mathcal{N}_{\text{IM-ocp}}[i]$ and $\mathcal{N}_{\text{IM-nocp}}[i]$, $\mathcal{N}_{\text{OM-ocp}}[i]$ and $\mathcal{N}_{\text{OM-nocp}}[i]$, respectively. If an indoor PRB is occupied by the indoor MMSs, its index is in set $\mathcal{N}_{\text{IM-ocp}}[i]$. Otherwise, the indoor PRB is unoccupied by the indoor MMSs, its index is in set $\mathcal{N}_{\text{IM-nocp}}[i]$. Similarly, an outdoor PRB's index is in set $\mathcal{N}_{\text{OM-ocp}}[i]$ if it is occupied by the outdoor MMSs, otherwise, its index is in set $\mathcal{N}_{\text{OM-nocp}}[i]$. Note that the "occupied" case is defined as the received interference power of a resource block exceeds a certain threshold. For a practical LTE-Advanced system, the intralayer interference mitigation between adjacent macrocells can be controlled using the intercell interference coordination techniques as suggested in standardization. In this paper, we investigate how to mitigate the interference between the macrocell and the femtocells, and the interference among femtocells.

III. Our Proposal for Interference Mitigation and Resource Allocation

A. Stochastic Resource Block Scheduling

For the femtocell downlink, we define $M_f[i]$ as the number of PRBs that a HeNB requires in downlink at scheduling interval i. Moreover, we assume that each cognitive radio-enabled HeNB schedules PRBs independently. This assumption is in reasonable for an LTE-Advanced femtocell deployment, as an agile information exchange protocol is not define between femtocells. The HeNB with cognitive abilities can sense the received interference power from the marco-network on each resource block. If the sensing is perfect, the spectral efficiency can be significantly improved without interfering with the macrocell. In practice, however, the spectrum sensing is not perfect owing to the complex signal fading in wireless environment and limited sensing time. Imperfect sensing will cause sensing errors, such as misdetection and false alarm. These sensing errors will lead to interference among macrocells and femtocells. Additionally, in the absence of coordination in the femtocell layer, the best scheduling policy is to simply select the required number of PRBs randomly within the full range of available resources. If there is no sensing errors, it is obviously that $\mathcal{N}_{\text{ocp}}[i] = \mathcal{N}_{\text{IM-ocp}}[i] \cup \mathcal{N}_{\text{OM-ocp}}[i]$ and $\mathcal{N}_{\text{nocp}}[i] = \mathcal{N}_{\text{IM-nocp}}[i] \cup \mathcal{N}_{\text{OM-nocp}}[i]$. In Table I, we give the sensing error probabilities.

Denote $N_{\text{IM-ocp}}[i]$, $N_{\text{IM-nocp}}[i]$, $N_{\text{OM-ocp}}[i]$ and $N_{\text{OM-nocp}}[i]$ as the number of the indoor PRBs occupied by indoor MMSs, the number of the indoor PRBs that remain unoccupied, the number of the outdoor PRBs occupied by outdoor MMSs and the number of the outdoor PRBs that remain unoccupied,

TABLE I: sensing error probabilities

Indoor / Outdoor	Actual Status	Sensing Error Probability
$\mathcal{N}_{\text{IM}}[i]$	$\mathcal{N}_{\text{IM-ocp}}[i]$	$P(\mathcal{N}_{\text{ocp}}[i]\vert\mathcal{N}_{\text{IM-ocp}}[i]) = 1 - P1$
		$P(\mathcal{N}_{\text{nocp}}[i]\vert\mathcal{N}_{\text{IM-ocp}}[i]) = P1$
	$\mathcal{N}_{\text{IM-nocp}}[i]$	$P(\mathcal{N}_{\text{ocp}}[i]\vert\mathcal{N}_{\text{IM-nocp}}[i]) = P2$
		$P(\mathcal{N}_{\text{nocp}}[i]\vert\mathcal{N}_{\text{IM-nocp}}[i]) = 1 - P2$
$\mathcal{N}_{\text{OM}}[i]$	$\mathcal{N}_{\text{OM-ocp}}[i]$	$P(\mathcal{N}_{\text{ocp}}[i]\vert\mathcal{N}_{\text{OM-ocp}}[i]) = 1 - P3$
		$P(\mathcal{N}_{\text{nocp}}[i]\vert\mathcal{N}_{\text{OM-ocp}}[i]) = P3$
	$\mathcal{N}_{\text{OM-nocp}}[i]$	$P(\mathcal{N}_{\text{ocp}}[i]\vert\mathcal{N}_{\text{OM-nocp}}[i]) = P4$
		$P(\mathcal{N}_{\text{nocp}}[i]\vert\mathcal{N}_{\text{OM-nocp}}[i]) = 1 - P4$

respectively. These parameters satisfy

$$\begin{aligned} N_{\text{IM-ocp}}[i] + N_{\text{IM-nocp}}[i] &= N_{\text{IM}}[i] \\ N_{\text{OM-ocp}}[i] + N_{\text{OM-nocp}}[i] &= N_{\text{OM}}[i] \end{aligned} \tag{1}$$

where $N_{\text{IM}}[i]$ and $N_{\text{oM}}[i]$ are the numbers of the elements of $N_{\text{IM}}[i]$ and $N_{\text{OM}}[i]$, respectively. The sensing error probabilities satisfy the following equations:

$$\begin{cases} N_{\text{IM-ocp}}[i](1-P1) + N_{\text{IM-nocp}}[i]P2 + \\ N_{\text{OM-ocp}}[i](1-P3) + N_{\text{OM-nocp}}[i]P4 = X_{ocp} \\ N_{\text{IM-ocp}}[i]P1 + N_{\text{IM-nocp}}[i](1-P2) + \\ N_{\text{OM-ocp}}[i]P3 + N_{\text{OM-nocp}}[i](1-P4) = X_{nocp} \end{cases} \tag{2}$$

where X_{ocp} and X_{nocp} are the numbers of the elements of $\mathcal{N}_{\text{ocp}}[i]$ and $\mathcal{N}_{\text{nocp}}[i]$, respectively, according to the sensing result. According to (1) and (2), we can calculate $N_{\text{IM-ocp}}[i]$, $N_{\text{IM-nocp}}[i]$, $N_{\text{OM-ocp}}[i]$ and $N_{\text{OM-nocp}}[i]$.

The result of this resource assignment process is stored in set $\mathcal{M}_f[i] \in \mathcal{N}$. In our stochastic algorithm, the elements of set $\mathcal{M}_f[i]$ are selected iteratively in $M_f[i]$ steps (i.e. one PRB index per iteration). Particularly, the probabilities of choosing a PRB in subset $\mathcal{N}_{\text{IM}}[i]$ or $\mathcal{N}_{\text{OM}}[i]$ depend on the iteration index j and are dictated by

$$P_{IM}^{(j)} = \frac{N_{\text{IM-nocp}}^{(j)}[i]}{N_{\text{IM-nocp}}^{(j)}[i] + \omega N_{\text{OM-nocp}}^{(j)}[i]} \tag{3}$$

$$P_{OM}^{(j)} = \frac{\omega N_{\text{OM-nocp}}^{(j)}[i]}{N_{\text{IM-nocp}}^{(j)}[i] + \omega N_{\text{OM-nocp}}^{(j)}[i]} \tag{4}$$

where $N_{\text{IM-nocp}}^{(j)}[i]$ and $N_{\text{OM-nocp}}^{(j)}[i] - j + 1$ denote the number of PRBs that remain unoccupied (Released in the schedule time interval) in subsets $\mathcal{N}_{\text{IM}}[i]$ and $\mathcal{N}_{\text{OM}}[i]$ prior to the execution of the jth iteration of the algorithm. The subset selection with probabilities (3) and (4) at each iteration is biased by factor

$$\frac{P_{IM}^{(j)}}{P_{OM}^{(j)}} = \frac{N_{\text{IM-nocp}}^{(j)}[i]}{\omega N_{\text{OM-nocp}}^{(j)}[i]} \tag{5}$$

where the parameter ω can be any value in the interval $[1, \infty]$. The spectrum assignment schemes with the two extreme values of ω are following: The case that $\omega = 1$ means a full-range spectrum allocation in the total available spectrum N_{max}. In this situation, the intratier interference among femtocells is minimized, whereas the cross-layer interference between macrocell and femtocell is maximized. The case that $\omega = \infty$ represents an orthogonal spectrum assignment between macrocell and femtocells. In this case, the intratier interference among femtocells is maximized, whereas cross-layer interference between eNBs and HeNBs is avoided. Depending on the number of indoor MMSs, the stochastic algorithm will be able to provide different spectrum sharing options between macrocell and femtocells by employing the parameter ω.

B. Resource Allocation in Femtocells

Denote Ω_m as the set of PRBs allocated to the mth femto network by using stochastic resource block scheduling as mentioned in Section III. Assume that N PRBs are allocated to the mth femto network. Define the signal-to-interference plus noise power ratio (SINR) of the kth FMSs in an HeNB on the nth PRB as

$$H_{k,n} = \frac{p_{k,n} g_{k,n}^H}{\Gamma(N_0 B + p_e g_{k,n}^e)}, \tag{6}$$

where $p_{k,n}$ is the kth FMS's transmission power on the nth PRB. $g_{k,n}^H$ is the power gain of the kth FMS from the HeNB on the nth PRB, $g_{k,n}^e$ is the power gain of the kth FMS from the eNB on the nth PRB, p_e is the transmission power of the eNB, N_0 is the PSD of additive white Gaussian noise, Γ is the SNR gap and can be represented as $\Gamma = -\frac{\ln(5BER)}{1.5}$ for an uncoded MQAM with a specified BER [13]. The transmission rate of the kth FMS on the nth PRB is

$$r_{k,n} = \log(1 + H_{k,n}). \tag{7}$$

The bandwidth of the nth PRB spans from $f_0 + (n-1)B$ to $f_0 + nB$, where f_0 is the starting frequency. There are L indoor MMSs that lie within the coverage area of the HeNB. The interference introduced to the lth indoor MMS by FMSs' access on the nth PRB with unit transmission power is given by

$$I_{n,l} = \int_{f_0+(n-1)B}^{f_0+nB} g_{n,l}^e \phi_n(f) df, \tag{8}$$

where $g_{n,l}^e$ is the power gain from the HeNB to the lth indoor MMS's receiver on the nth PRB. $\phi_n(f)$ is the Power Spectrum Density (PSD) of the PRB used by an FMS, which can be expressed as $\phi_n(f) = T_s(\frac{\sin \pi f T_s}{\pi f T_s})^2$, where T_s is OFDM symbol duration.

Our target is to maximize the throughput of a femtocell while keeping the interference to the MMSs under specified thresholds. The optimization problem can be formulated as

$$\begin{aligned} &\max_{p_{k,n}} \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_m} \rho_{k,n} r_{k,n} \\ s.t.\quad &\text{C1}: \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_m} \rho_{k,n} r_{k,n} \geq R_{min} \\ &\text{C2}: \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_m} \rho_{k,n} p_{k,n} \leq P_t \\ &\text{C3}: \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_m} \rho_{k,n} p_{k,n} I_{n,l} \leq I_l^{th}, \forall l \\ &\text{C4}: p_{k,n} \geq 0, \forall k, n \\ &\text{C5}: \rho_{k,n} \in \{0, 1\}, \forall k, n \\ &\text{C6}: \textstyle\sum_{k=1}^{K} \rho_{k,n} = 1, \forall n, \end{aligned} \tag{9}$$

TABLE II: Heuristic PRB Allocation Algorithm

Algorithm: Heuristic PRB Allocation Algorithm

$\mathcal{K} = \{1, \cdots, K\}$, Calculate $H_{ij}, C_i = 0, \forall i \in \mathcal{K}, \forall j \in \Omega_m$.
for $k \in \mathcal{K}$
  $[max\_value,\ j'] = \arg max\{H_{k,j}\}, \forall j \in \Omega$
  $[second\_max\_value,\ jj'] = \arg max\{H_{k,j}\}, \forall j \in \Omega, j \neq j'$
  $C_i = max\_value - second\_max\_value$.
endfor
while $\Omega \neq \varnothing$
  Sorting $\{C_i\}$ in decreasing order.
  $i' = \arg max\{H_{k,j}\}, \forall j \in \Omega, \Omega = \Omega \setminus i'$.
endwhile

where $\rho_{k,n}$ can only be either 1 or 0, indicating whether the nth PRB is used by the kth FMS or not, P_t is the power limit of the HeNB and I_l^{th} is the interference power threshold of the lth indoor MMS. C1 is the throughput requirement of the femtocell. C2 and C3 are the power limitation and the interference constraint, respectively. C4 is intuitive. C5 and C6 indicate that the PRBs are not shared among FMSs.

Suppose that each possible assignment of an FMS is evaluated by a pseudo-cost function $C(i)$. The desirability of an FMS to obtain a PRB is measured by the difference between the second smallest and the smallest values of the PRBs. An FMS is assigned a PRB in decreasing order based on the difference. Our proposed algorithm is described in Table II.

Given a PRB assignment of the FMSs, the power allocation problem can be rewritten as

$$\begin{aligned} &\max_{p_{k,n}} \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} r_{k,n} \\ s.t.\quad &\text{C1}: \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} r_{k,n} \geq R_{min} \\ &\text{C2}: \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} p_{k,n} \leq P_t \\ &\text{C3}: \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} p_{k,n} I_{n,l} \leq I_l^{th}, \forall l \\ &\text{C4}: p_{k,n} \geq 0, \forall k, n, \end{aligned} \tag{10}$$

where Ω_k is the set of PRBs allocated to the kth FMS.

Eq.(10) defines a convex optimization problem and can be solved by barrier method [14]. The logarithmic barrier function is

$$\begin{aligned} \phi(\mathbf{x}) = \; & -\log(\textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} r_{k,n} - R_{min}) \\ & -\log(P_t - \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} p_{k,n}) \\ & -\sum_{l=1}^{L} \log(I_l^{th} - \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} p_{k,n} I_{n,l}) \\ & -\textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} \log p_{k,n}. \end{aligned} \tag{11}$$

where $\mathbf{x} = (p_1, p_2, \cdots, p_N)$. Notice that the subscript k can be omitted now as it has been determined for a given PRB allocation assignment. Denote

$$f(\mathbf{x}) = \textstyle\sum_{k=1}^{K} R_k, \tag{12}$$

where $R_k = \sum_{n\in\Omega_k} r_{k,n}$, the optimal solution of (10) can be approximated by solving the following unconstrained minimization problem

$$\min \psi_t(\mathbf{x}) = -tf(\mathbf{x}) + \phi(\mathbf{x}) \tag{13}$$

where $t \geq 0$ is a parameter to control the accuracy of solution. This is an unconstrained minimization problem that can be solved efficiently by Newton method.

The Newton step at $\mathbf{x}$, denoted by $\Delta\mathbf{x}_{nt}$, is given by

$$\nabla^2\psi_t(\mathbf{x})\Delta\mathbf{x}_{nt} = -\nabla\psi_t(\mathbf{x}) \tag{14}$$

where $\nabla^2\psi_t(\mathbf{x})$ and $\nabla\psi_t(\mathbf{x})$ are the Hessian and the gradient of $\psi_t(\mathbf{x})$, respectively. The computational complexity of the barrier method mainly lies in the computation of Newton step that needs matrix inversion. In order to reduce the computational cost, we exploit the structure of the (10) and develop a fast algorithm to calculate the Newton step with lower complexity. Denote

$$\begin{aligned} f_0 &= P_t - \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} p_{k,n}, \\ f_1 &= \textstyle\sum_{k=1}^{K} \sum_{n\in\Omega_k} r_{k,n} - R_{min}, \\ g_l &= I_l^{th} - \sum_{k=1}^{K} \sum_{n=1}^{N} p_{k,n} I_{n,l}, \quad l = 1, 2, \cdots, L. \end{aligned} \tag{15}$$

The Hessian of $\psi_t(\mathbf{x})$ is

$$\begin{aligned} \nabla^2\psi_t(\mathbf{x}, z) = & \begin{bmatrix} D_1 & & & \\ & D_2 & & \\ & & \ddots & \\ & & & D_N \end{bmatrix} \\ & + \frac{\nabla f_0 \nabla f_0^T}{f_0^2} + \frac{\nabla f_1 \nabla f_1^T}{f_1^2} + \sum_{l=1}^{L} \frac{\nabla g_l \nabla g_l^T}{g_l^2} \\ & = D + \sum_{i=1}^{M} F_i F_i^T. \end{aligned} \tag{16}$$

where $D = \text{diag}(D_1, D_2, \cdots, D_N)$ and $M = L + 2$ with

$$D_n = (t + \frac{1}{f_1})\frac{H_{k,n}^2}{(1 + p_{k,n}H_{k,n})^2} + \frac{1}{p_{k,n}^2}. \tag{17}$$

F_i are all vectors with N elements,

$$F_i = \begin{cases} \frac{\nabla f_0}{f_0}, & i = 1 \\ \frac{\nabla f_1}{f_1}, & i = 2 \\ \frac{\nabla g_l}{g_l}, & l = 1, \cdots, L, i = l + 2. \end{cases} \tag{18}$$

Theorem 1: The equation (10) can be solved with a complexity of $O(M^2N)$.

The proof is placed in Appendix. If we solve the (10) via standard convex optimization technique, it generates a complexity of $O(N^3)$. Since $M \ll N$ for practical wireless systems, our proposed algorithm has a significant advantage to solve the resource allocation problem that should be tackled in an online manner.

TABLE III: Simulation parameters.

System Parameters	Radius of Macrocell	500 m (LTE-A)
	Carrier frequency	2 GHz
	Total Bandwidth	100 MHz
	Thermal Noise PSD	-174 dBm/Hz
Shadowing	Shadow Fading	Log-normal
eNB Parameters	Transmit Power	46 dBm
	Antenna Gain	14 dBi
	Noise Figure	7 dB
HeNB Parameters	Transmit Power	10 dBm
	Noise Figure	7 dB
M(F)MS Parameters	Maximum Transmit Power	23 dBm
	Anternna Gain	0 dBi
	Noise Figure	7dB

IV. System Simulation And Discussion

Consider an LTE-Advanced network where an eNB is located at the center of a circle with radius of $500m$. And one HeNB with 2 FMSs is overlaid in the coverage of the eNB. There are 2 outdoor MMSs and 2 indoor MMSs within the cell of macrocell and femtocell respectively. A dual-stripe building model [15] is adopted to evaluate the performance of our proposed algorithms. The simulation parameters are listed in Table III. The distance dependent path loss attenuation varies according to the characteristics of the evaluated links which are summarized as follows:

1. eNB to outdoor MMS

$$PL(d) = 15.3 + 37.6log_{10}(d). \tag{19}$$

We use a single-slope model to characterize the path loss attenuation in this situation, where d is the distance between the eNB to the outdoor MMS.

2. eNB to indoor MMS / FMS

$$PL(d) = 15.3 + 37.6log_{10}(d) + L_{ow}, \tag{20}$$

where d is the distance between the eNB to the indoor MMS/FMS and L_{ow} is the penetration loss in the external walls of the building.

3. HeNB to FMS

$$\begin{aligned} PL(d) = \; & 38.46 + 20log_{10}(d) + 0.7d_{2D} \\ & +qL_{iw} + 18.3n^{(\frac{n+2}{n+1}-0.46)}, \end{aligned} \tag{21}$$

where d is the distance between the HeNB to the FMS, d_{2D} is the indoor distance of the link, L_{iw} is the penetration loss in the internal walls of the building, $q(n)$ denotes the number of penetrated walls (floors).

Fig.1-2 show the cumulative distribution functions (CDFs) of the downlink throughput of the indoor MMSs and the FMSs, respectively. From Fig.1 we can see that the proposed stochastic scheduling algorithm leads to a capacity reduction for the indoor MMSs comparing with the orthogonal spectrum reuse strategy. It can be explained intuitively. For the stochastic scheduling algorithm, some PRBs that used by the MMSs can be reused by the FMSs, which introduces much interference to the MMSs and results in the capacity reduction of the MMSs. However, as can be seen in Fig.2, the FMSs can benefit from the stochastic scheduling algorithm because some FMSs may have high channel gains over these PRBs used by MMSs. Furthermore, we can see the proposed algorithm achieves a tradeoff compared with the orthogonal spectrum reuse and the full range spectrum one.

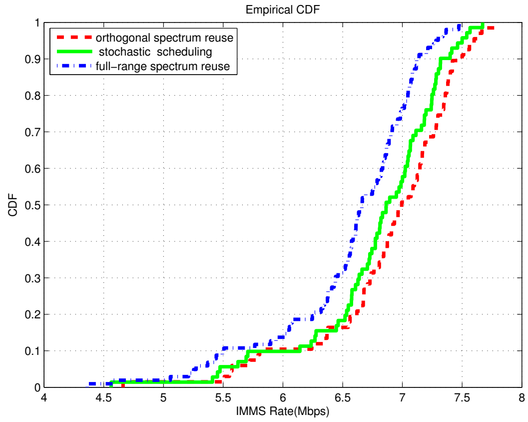

Fig. 1: The Empirical CDF of Transmission Rate of indoor MMSs.

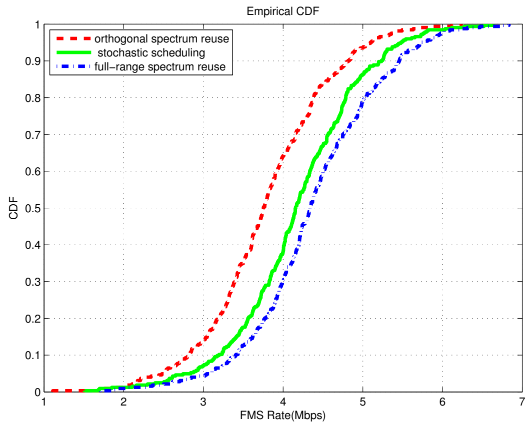

Fig. 2: The Empirical CDF of Transmission Rate of FMSs.

Fig.3 shows the sum capacity of the indoor MMSs and FMSs with different settings of sensing error probabilities. For a give ω, the sum capacity varies in a narrow range for different sensing error probabilities, which means the sum capacity is not sensitive to the changes of sensing error.

V. Conclusion

In this paper, we proposed a cognitive radio-enabled interference mitigation scheme for heterogeneous networks. Given a simple and feasible cognitive function, we presented an effective resource block scheduling algorithm that can reduce cross-tier and intra-tier interference with no requirements of macro-femto backhaul coordination, as well as no modifications of existing macrocells. Furthermore, we also developed an efficient algorithm for resource allocation in femtocells, which can get the optimal solution with much lower complexity compared to standard methods.

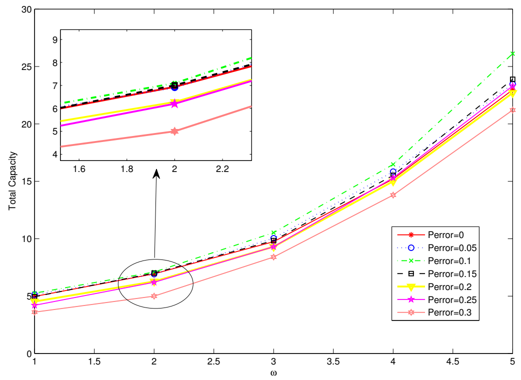

Fig. 3: Sum Capacity of indoor MMSs and FMSs vs sensing error.

APPENDIX

A. Proof of Theorem 1

Proof: Rewrite the KKT system (14) as follows,

$$\Lambda_0 \Delta\mathbf{x} = F_0, \tag{22}$$

where $\Lambda_0 = \nabla^2 \psi_t$ and $F_0 = -\nabla\psi_t$. According to Eq.(16), Λ_0 can be written as

$$\Lambda_0 = D + \sum_{i=1}^{M} F_i F_i^T, \tag{23}$$

which can be decomposed into M equations,

$$\Lambda_i = \Lambda_{i+1} + F_{i+1}F_{i+1}^T, i = 0, 1, \cdots, M-1, \tag{24}$$

By exploiting the structure of Λ_i's, we give an M-step procedure to compute the Newton step.

First, use Eq.(24) to decompose Λ_0, $\Lambda_0 = \Lambda_1 + F_1F_1^T$. Denote two intermediate variables as the solutions of the following two sets of linear equations, $\Lambda_1 v_1^1 = F_0$ and $\Lambda_1 v_2^1 = F_1$. Then $\Delta\mathbf{x}$ can be obtained by $\Delta\mathbf{x} = v_1^1 - \frac{F_1 v_1^1}{1+F_1 v_2^1} v_2^1$. So we can figure out $\Delta\mathbf{x}$ if obtaining the two new variables v_1^1 and v_2^1.

Continue the procedure, decompose Λ_1 with $\Lambda_1 = \Lambda_2 + F_2F_2^T$. Then the two variables introduced in step 1 can be updated by solving the following three sets of linear equations, $\Lambda_2 v_i^2 = F_{i-1}, i = 1, 2, 3$, where v_1^2, v_2^2 and v_3^2 are other intermediate variables.

For the mth step, decompose Λ_{m-1} with $\Lambda_m = \Lambda_m + F_mF_m^T$. We can update the m variables introduced in Step $m-1$ by $v_i^{m-1} = v_i^m - \frac{F_m^T v_i^m}{1+F_m v_{m+1}^m} v_{m+1}^m, i = 1, 2, \cdots, m$, which is obtained by solving the following $m+1$ sets of linear equations, $\Lambda_m v_i^m = F_{i-1}, i = 1, 2, \cdots, m+1$.

Continue the procedure to the Mth step, and there are $M+1$ matrix systems $\Lambda_M v_i^M = F_{i-1}, i = 1, 2, \cdots, M+1$. Form the derivation process, we can find that the m variables $v_i^{m-1}, i = 1, 2, \cdots, m$ in the $(m-1)$th Step can be obtained by the $m+1$ variables $v_i^m, i = 1, 2, \cdots, m+1$ in the mth Step. Thus, if we figure out the $M+1$ variables $v_i^M, i = 1, 2, \cdots, M+1$, $\Delta\mathbf{x}$ will be indirectly obtained. Obviously, an M-step reverse procedure is necessary after we solve the $M+1$ matrix systems in the Mth Step.

The process to solve the matrix equation $\Lambda_M v_i^M = F_{i-1}$ is following. According to the analysis in Section IV, we have $\Lambda_M = D$. Unify these equations into the following equation:

$$\begin{bmatrix} D_1 & & & \\ & D_2 & & \\ & & \ddots & \\ & & & D_N \end{bmatrix} v = g. \tag{25}$$

Since D is a diagonal matrix, we can easily obtained

$$v_i = D_i^{-1} g_i, i = 1, \ldots, N. \tag{26}$$

Thus the computational complexity of solving the $M+1$ matrix systems is $O(MN)$. Then an M-step reverse iteration can be implemented to figure out the $\Delta\mathbf{x}$. The total computational cost of our proposed fast barrier method is $O(M^2N)$. ■

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