Macro- and Femtocell Interference Mitigation in OFDMA Wireless Systems

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***Abstract*—We conceive an interference mitigation scheme, for twin-layer networks for protecting the macrocell-users, from the interference imposed by the femtocells as well as for mitigating the interference amongst femtocells. Femtocells are capable of finding the available sub-bands using cognitive radio techniques, where the lowest interference is observed by the nearby macrocell-users. A sub-channel allocation algorithm is developed with the aid of graph-theoretic approaches for optimizing the femtocell throughput in dense femtocells deployment scenarios. The femto-users are grouped into different clusters for suppressing the interference amongst them. Each cluster is assigned a unique sub-channel by using the classic cluster-coloring approach. Adaptive power allocation is performed among the femtocells for further enhancing the system throughput and the attainable performance is quantified.**

***Index Terms*—Femtocell, graph coloring, OFDMA, cognitive radio.**

I. INTRODUCTION

Owing to the poor indoor coverage-penetration by macrocells, it may not be feasible to meet the requirements of high data-rate services for macro-users. An efficient remedy is to employ femtocell base stations (fBS), which are popular short-range, low-cost/low power and user-installed access points, capable of communicating with the cellular network over a broadband wireline connection [1]. Furthermore, fBSs are capable of reducing the traffic load imposed on macro base stations (mBS), thus potentially reducing the infrastructure cost.

However, the employment of fBSs also has several technical challenges [1]. The closed subscriber group (CSG) scheme, which only allows subscribing users to access the network will inject interference upon the macro-users roaming in the vicinity. Additionally, the interference of one femtocell to other femtocells nearby is relatively serious as well. Usually, the interference management between macrocells and femtocells brings new problems. In [2], the interference appearing in twin-layer networks (the femtocell and macrocell layers) is modeled as *cross-layer* and *co-layer* interference. The resource allocation approaches of femtocells were designed for example in [3-5] for handling both cross-layer and co-layer interference. Both uncoordinated and coordinated resource assignment algorithms were developed in [3], while a recalled Q-learning based interference coordination scheme was proposed in [4-5] for two layer networks. However, the aforementioned contributions neglected the practical fact that it is hard to coordinate between mBSs and fBSs, owing to the requirements of scalability, security and the availability of backhaul bandwidth. Furthermore, the number of user-installed fBSs is typically unknown. The schemes proposed in [6] and [7] assigned dedicated spectrum to femtocells for eliminating the cross-layer interference for the downlink (DL) and uplink (UL), respectively. Suitable femtocellular resource allocation mechanisms were investigated in [8-10] for maximizing the throughput or spectral efficiency in sparse fBS deployment scenarios. A range of cognitive radio (CR) aided cross-layer interference mitigation schemes was conceived in [8-9], while a game theoretic approach was employed in [10]. The weighted sum-rate of twin-layer network was maximized in [11] for a delay-tolerant scenario, which however imposed a high information exchange rate between the mBSs and fBSs.

The employment of the fractional frequency reuse (FFR) strategy is capable of mitigating the interference amongst inter-cells [12]. Generally, the cell edge users suffer from lower data rates because of the increased path-loss and inter-cell interference [13]. Therefore, the FFR strategy has found favour in twin-layer networks in multi-macrocell environments [14-15]. An optimal fetmocellular spectrum access algorithm was proposed in [14], which were based on adopting the FFR strategy. In [15], FFR was employed for suppressing the co-channel interference in twin-layer WiMax networks.

If the fBS of twin-layer networks relies on CR functions, it becomes capable of exhibiting an increased flexibility and autonomy [16-17]. Graph-theory was used as a powerful mathematical tool for mitigating the interference in twin-layer networks by the authors of [18-19].

In this paper, a novel interference coordination scheme is proposed for the macrocells and femtocells involved in twin-layer networks. The inter-macrocell interference is reduced by employing a FFR scheme. With CR sensing techniques,

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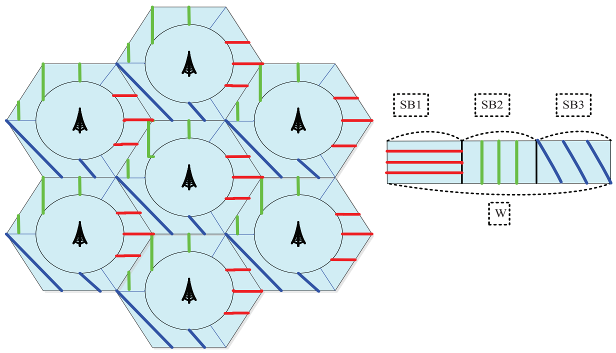

Fig. 1. FFR based seven-cell cellular networks.

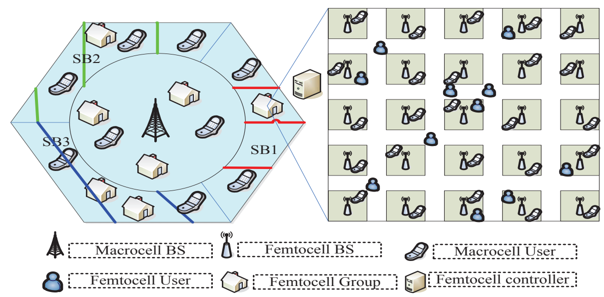

Fig. 2. The femtocell networks in the coverage of the macrocell network.

femtocells become capable of finding the available sub-bands, in which the lowest interference is imposed by the nearby macro-users, thus minimizing the cross-layer interference. Furthermore, a graph-coloring aided sub-channel allocation algorithm is developed for coordinating the co-layer interference as well as for maximizing the femtocells' throughput.

The rest of the paper is organized as follows. Sec. II describes our system model, while Sec. III presents the proposed interference mitigation scheme conceived for twin-layer networks operating in multi-macrocell scenarios. Our simulation results are provided in Sec. IV, while Sec. V concludes this paper.

II. System Model

In this paper, we consider the DL of an orthogonal frequency division multiple access (OFDMA) system with M hexagonal grid macrocells and F femtocells in each macrocell. As illustrated in Fig. 1, an FFR scheme is employed in the macrocell, where the whole bandwidth associated with the macrocell edge regions is divided into 3 sub-bands (SBs). We assume that each mBS can schedule DL-transmissions in all the sub-channels at any time instant. One sector is assigned to a single SB containing N_{sc} sub-channels, which are available for supporting both the cell-center and the corresponding cell-edge macrocell-users. At each time instant, albeit multiple sub-channels are potentially available for a macrocell-user, it merely utilizes at most one sub-channel.

A dense femtocell scenario is shown in Fig. 2. As an example, twenty-five femtocells compose one femtocell group under the coordination of a centralized femtocell controller. Each femtocell group is distributed randomly and uniformly within the macro-cell's coverage area. We assume that at most one femtocell-user is active within the coverage of the fBS at the time-instant considered.

We assume furthermore that the channel is slowly time-varying and obeys the Rayleigh multipath fading distribution. There are three types of wireless links in the two-tier networks: the outdoor-to-outdoor link, the indoor-to-indoor link and the outdoor-to-indoor link. We assume that there is perfect synchronization between all cells in the system. In addition to Rayleigh fading, we consider both path-loss and shadowing. Hence, our propagation model is described as:

$$P_r = P_t \cdot A \cdot G \cdot S, \tag{1}$$

where P_t and P_r represent the transmit and receive powers, respectively, A is the antenna gain, S is the shadowing gain, and G denotes the path-gain of a link, which is a function of the distance R between the user and BS. Without loss of generality, we denote the index of the serving mBS by 0. The instantaneous received signal-to-interference noise ratio (SINR) of macrocell-user k over the n-th sub-channel can be expressed as:

$$\gamma_{k,0,n}^{(m)} = \frac{P_{k,0,n}^{(m)} A_{k,0,n}^{(m)} G_{k,0,n}^{(m)} S_{k,0,n}^{(m)}}{{\Phi_1}^{(m)} + {\Phi_2}^{(m)} + \sigma_{n,k}^2}, \tag{2}$$

where

$${\Phi_1}^{(m)} = \sum_{l=1, l\neq 0}^{M} P_{k,l,n}^{(m)} A_{k,l,n}^{(m)} G_{k,l,n}^{(m)} S_{k,l,n}^{(m)}, \tag{3}$$

and

$${\Phi_2}^{(m)} = \sum_{j=1}^{M\times F} \beta_j^n P_{k,j,n}^{(f)} \mathrm{A}_{k,j,n}^{(f)} G_{k,j,n}^{(f)} S_{k,j,n}^{(f)}, \tag{4}$$

with $P_{k,l,n}^{(m)}$ and $P_{k,j,n}^{(f)}$ denote the transmit signal powers over the n-th sub-channel of mBS l and fBS j, respectively; $A_{k,l,n}^{(m)}$ and $A_{k,j,n}^{(f)}$ denote the overall antenna gains for mBS l and fBS j, respectively; $G_{k,l,n}^{(m)}$ and $G_{k,j,n}^{(f)}$ represent the corresponding path gains; $S_{k,l,n}^{(m)}$ and $S_{k,j,n}^{(f)}$ denote the corresponding shadowing gains, and $\sigma_{n,k}^2$ is the noise power of zero mean complex-valued additive white Gaussian noise (AWGN). Here, β_j^n describes the indicator function of resource allocation. If $\beta_j^n = 1$, sub-channel n is assigned to femtocell j; otherwise $\beta_j^n = 0$.

The achievable instantaneous data rate of macrocell-user k over the n-th sub-channel is given by:

$$R_{k,0,n}^{(m)} = B\log_2(1 + \gamma_{k,0,n}^{(m)}), \tag{5}$$

where B denotes the bandwidth of a sub-channel.

Similarly, the SINR of femto-user i, which is served by fBS 0 over the n-th sub-channel is expressed as

$$\gamma_{i,0,n}^{(f)} = \frac{P_{i,0,n}^{(f)} \mathrm{A}_{i,0,n}^{(f)} G_{i,0,n}^{(f)} S_{i,0,n}^{(f)}}{\Phi_1^{(f)} + \Phi_2^{(f)} + \sigma_{n,i}^2}, \tag{6}$$

where

$$\Phi_1^{(f)} = \sum_{l=1}^{M} P_{i,l,n}^{(m)} \mathrm{A}_{i,l,n}^{(m)} G_{i,l,n}^{(m)} S_{i,l,n}^{(m)}, \tag{7}$$

and

$$\Phi_2^{(f)} = \sum_{j=1, j\neq 0}^{M\times F} \beta_j^n P_{i,j,n}^{(f)} \mathrm{A}_{i,j,n}^{(f)} G_{i,j,n}^{(f)} S_{i,j,n}^{(f)}. \tag{8}$$

The corresponding instantaneous data rate of femtocell-user i is written as:

$$R_{i,0,n}^{(f)} = B \log_2(1 + \gamma_{i,0,n}^{(f)}). \tag{9}$$

III. Proposed Interference Mitigation Algorithm

In order to protect the macro-users, which are active within the femtocell's coverage, from the strong interference of femtocells as well as to mitigate the interference amongst femtocells, and finally to maximize the throughput of femtocell groups, we propose a novel interference mitigation scheme associated with both macrocells and femtocells. The proposed scheme is implemented with the aid of CR sensing techniques, while simultaneously using the classic graph coloring method. We assume that the mBSs transmit equal powers over all sub-channels, while the fBSs may adjust their transmit powers to adapt to the practical environment.

A. CR-based Interference Mitigation Scheme

The fBS is capable of determining which particular SB is 'free' using CR sensing. Consequently, the cross-layer imposed by the interference fBS upon those macro-users, who are active in its coverage can be significantly mitigated. If an fBS detects any macrocell-users utilizing some of the sub-channels, it immediately abandons the SBs, which include those sub-channels. If all the SBs have been deemed to be 'busy', the fBS exploits that particular SB, which undergoes the lowest interference. In our contribution, the fBS detects the macro-user's UL signals, which may be more effective in practice. We assume that the DL and UL transmissions operate over the same sub-channels.

According to the energy-detection based CR approach, the signal observed at the fBS is expressed as:

$$y(x) = h(x)s(x) + w(x), \tag{10}$$

where $s(x)$ is the signal transmitted by the macrocell-user, $h(x)$ is the channel's gain from the macrocell-user to fBS, $w(x)$ is the AWGN sample, and x is the sample index. The average received energy is given by [20],

$$Y(X) = \frac{1}{X} \sum_{x=0}^{X-1} |y(x)|^2, \tag{11}$$

where X is the total number of samples. The goal of channel sensing is to distinguish between the following two hypotheses:

$$H_0 : y(x) = w(x), \tag{12}$$

$$H_1 : y(x) = h(x)s(x) + w(x). \tag{13}$$

Two probabilities are very important in the energy detection: the probability of detection P_D and the probability of false alarm P_F. The decision concerning the occupancy of sub-channels by nearby macrocell-users can be obtained by comparing the decision metric Y against a threshold λ. For simplicity, we assume that the time-bandwidth product is an integer number, denoted by m. Then P_D can be calculated by [21]

$$P_D = \Pr(Y > \lambda \,|H_1) = Q_m(\sqrt{2\gamma}, \sqrt{\lambda}), \tag{14}$$

where γ is the signal-to-noise ratio (SNR) and $Q_m(\cdot,\cdot)$ is the generalized Marcum Q-function defined as follows,

$$Q_m(a,b) = \int_b^{\infty} \frac{x^m}{a^{m-1}} e^{-\frac{x^2+a^2}{2}} I_{m-1}(ax)dx, \tag{15}$$

with $I_{m-1}(\cdot)$ being the modified Bessel function of the $(m-1)$th order. Furthermore P_F can be written as

$$P_F = \Pr(Y > \lambda \,|H_0) = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)}, \tag{16}$$

where $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are the complete and incomplete gamma functions, respectively.

Therefore, the detection probability and the false alarm probability for each SB $\alpha \in \{1,2,3\}$ can be expressed as,

$$Q_D^{SB\alpha} = 1 - \prod_{n=1}^{N_{sc}} (1 - P_{D,n}^{SB\alpha}), \tag{17}$$

$$Q_F^{SB\alpha} = 1 - \prod_{n=1}^{N_{sc}} (1 - P_{F,n}^{SB\alpha}), \tag{18}$$

where $P_{D,n}^{SB\alpha}$ and $P_{F,n}^{SB\alpha}$ denote the detection probability and false alarm probability over the n-th sub-channel in SB_α, respectively.

Again, the fBSs determine the 'states' of SBs with the aid of CR-based sensing, where the detection threshold λ is an important parameter. The higher the detection threshold, the more 'safe' to use a related subband, but this may result in an increased missing probability. In practice, we may control the detection threshold value, depending on the specific scenario considered. Since the CR techniques substantially improve the attainable spectral efficiency, an enhanced system throughput may be achieved.

B. Graph-based Sub-channel Allocation Algorithm

A graph-based sub-channel allocation algorithm is developed for mitigating the co-layer interference between the femtocells of a given femtocell group and for maximizing the throughput of each femtocell group. Due to the relatively low distance between fBS and its femtocell-user, they are assumed to have the same path-loss, thus they are assigned the same indices in this algorithm. The throughput maximization problem for a femtocell group may be written as

$$\begin{aligned} \max_{\beta,\mathbf{p}} & \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{I}}\sum_{n\in\hat{N}} \beta_i^n\beta_j^n B\log_2(1+\frac{p_i}{\sum\limits_{j\neq i} p_j G_{ji}+\delta}) \\ \text{s.t.} \quad & \sum_{n\in\hat{N}} \beta_i^n \leqslant 1, \forall i\in\mathcal{I} \\ & \sum_{n\in\hat{N}} \beta_j^n \leqslant 1, \forall j\in\mathcal{I} \\ & 0\leqslant p_i \leqslant P^{\max}, \beta_i^n\in\{0,1\}, \forall i\in\mathcal{I}, \forall n\in\hat{\mathcal{N}} \\ & 0\leqslant p_j \leqslant P^{\max}, \beta_j^n\in\{0,1\}, \forall j\in\mathcal{I}, \forall n\in\hat{\mathcal{N}}, \end{aligned} \tag{19}$$

where $\mathcal{I}$ and $\hat{\mathcal{N}}$ denote the set of fBSs in a femtocell group and the set of all available sub-channels within a femtocell group, respectively. Furthermore the cardinality of the set $\hat{\mathcal{N}}$ is N, $\mathbf{p}=\{p_i\}$ with p_i being the transmit power of fBS i, G_{ji} represents the total path-loss (including both shadowing and fast fading) between fBS j and fBS i, $P^{\max}$ denotes the maximum transmit power of fBS and δ is the corresponding noise power. Naturally, it is hard to derive the closed-form solution for the problem (19). However, if either the sub-channel selection or the power allocation is fixed, the problem becomes straightforward. In the following, we first decompose the sub-channel assignment problem into two phases: clustering phase and coloring phase, followed by determining the optimized power allocation among the fBSs within the same femtocell group.

Clustering Phase:

The clustering problem may be mapped to the MAX k-CUT problem of graph-theory. However, there is a difference between the traditional problem and our current problem, since our premise is that the number of clusters is fixed to N.

We assume that the femtocells using the same SBs in the same femtocell groups construct an interference graph $\mathcal{G}=(\mathcal{V},\mathcal{E},\mathcal{W})$, where $\mathcal{V}=\{v_1,v_2,\ldots,v_L\}$ is the vertex set, with L being the number of vertices in the graph, and each vertex represents an fBS. Note that all fBSs' vertices in the set $\mathcal{V}$ use the same SB. Furthermore, $\mathcal{E}=\{e_1,e_2,\ldots,e_H\}$ is the edge set, where H is the number of edges in the graph, and each edge represents the path-loss between fBSs. $\mathcal{W}=\{w_1,w_2,\ldots,w_L\}$ is a set of weights corresponding to the vertices. A larger weight implies having a larger sum of the path loss values. The color of the nodes represents the available sub-channels, and a color pool of the interference graph relies on which particular SBs can be used by the corresponding interference graph. We denote the color pool by $\mathcal{C}=\{c_1,c_2,\ldots,c_{N_{sc}}\}$, where N_{sc} is the number of colors available for all femtocells in the same SB. Note that each cluster corresponds to at most one sub-channel, which may be reused among the femtocells within this cluster.

As a first step, we classify the femtocells, which utilize the same SB into a single graph. A femto-user reports the path-loss information associated with all the neighboring fBSs to its serving fBS. Then, all the fBS members of the femtocell group report the associated path-loss as well as the indices of the favorite SBs to the femtocell controller.

Next, we form clusters, assuming that the weight of a cluster is the sum of the weights corresponding to the vertices in this cluster. Let us denote the weight of cluster k by W_k. During the cluster forming process, a new vertex always joins a specific cluster, which has the lowest weight among all clusters.

The weight of node $i\in\mathcal{V}$ can be expressed as:

$$w_i=\sum_j \mathcal{T}_{ij}, \tag{20}$$

where $\mathcal{T}_{ij}$ represents the path loss between the neighboring fBS j and fBS i, which share the same SB.

The cluster forming process is detailed in Algorithm 1.

Algorithm 1 : Cluster Forming Algorithm

Initialize $\mathcal{G}=(\mathcal{V},\mathcal{E},\mathcal{W})$
    $W_k=0,\ \ k=1,\cdots,N_{sc}$
for $v=1$ to L **do**
    if There are several clusters having the same lowest weight, **then**
        Choose a cluster randomly, which has the lowest weight for the node v
    else
        Migrate node v to the specific cluster k, which has the lowest weight
    end if
    Update the weight of cluster k,
    $W_k=W_k+w_v$
end for

Given the clustering approach of Algorithm 1, any two femtocells incurring strong mutual-interference, will be placed into different clusters, which utilize orthogonal sub-channels. Hence, the interference between femtocells is mitigated.

Coloring Phase:

The sub-channel assignment is performed with the aid of coloring the clusters, while maximizing the throughput of each femtocell group. The coloring phase may be characterized as:

$$\begin{aligned} \beta^* &= \arg\max_{\beta_l^n} \sum_{l\in L}\sum_{n\in\bar{\mathcal{N}}} \beta_l^n B\log_2(1+\gamma_l^n) \\ \text{s.t.} & \quad \sum_{n\in\bar{\mathcal{N}}} \beta_l^n \leqslant 1, \forall l\in\mathcal{L}, \end{aligned} \tag{21}$$

where $\bar{\mathcal{N}}$ denotes the specific set of the sub-channels with cardinality $\bar{N}$, which are used by the vertices involved, γ_l^n denotes the SINR of femtocell l over the n-th sub-channel. $\mathcal{L}$ is a set of vertices in the graph with cardinality L

The cluster coloring phase is detailed in Algorithm 2.

Power Adjustment:

Let us now consider the allocation of power among the fBSs within a femtocell group for the sake of further improving the attainable throughput. Given the aforementioned algorithms,

Algorithm 2 : Cluster Coloring Algorithm

Initialization: Order all the clusters in the ascending order of their weight.
for $k = 1$ to $\bar{N}$ **do**
  Find the suitable color c for cluster k according to (21)
  Remove the color c from the color pool
end for

we have derived an effective sub-channel assignment solution for all femtocells in the femtocell group. Conditioned on a certain sub-channel assignment solution, it becomes straightforward to derive an effective power adjustment matrix by solving (19). Hence we rewrite the problem of maximizing the throughput of a femtocell group, given a certain sub-channel selection matrix as:

$$\begin{aligned} &\max_{\mathbf{p}} \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{I}}\sum_{n\in\hat{\mathcal{N}}} \beta_i^n\beta_j^n B\log_2(1+\frac{p_i}{\sum\limits_{j\neq i} p_j G_{ji}+\delta}) \\ &\text{s.t.}\quad 0\leqslant p_i\leqslant P^{\max}, \forall i\in\mathcal{I} \\ &\qquad\quad 0\leqslant p_j\leqslant P^{\max}, \forall j\in\mathcal{I}, \end{aligned} \tag{22}$$

where $\mathbf{p}$ is the vector of transmit powers in the fBSs.

If a fBS is the one and only member in a cluster, it will be assigned the maximum transmit power $P^{\max}$, whereas if a cluster contains several fBSs, they will be allocated the specific transmit powers required for reaching the best performance. The proposed scheme protects macro-users from cross-layer interference and additionally coordinates the co-layer interference imposed on adjacent fBSs.

IV. Simulation Results

In this section, the performance of the proposed scheme is evaluated using simulations. The scheduler of a mBS uses the Round Robin (RR) scheduling algorithm, while the allocator of a fBS employs the proposed coloring-based sub-channel allocation algorithm. Our simulation parameters are provided in Table I, where we assume the detection threshold λ to be the specific value, which guarantees a detection probability of 0.99 at 10dB SNR.

The cumulative distribution function (CDF) of the macro-users's SINR is illustrated in Fig. 3. The proposed scheme achieves higher macro-users SINRs in contrast to the conventional random resource allocation, and almost the same performance of the traditional CR-based schemes [22]. This implies that both the proposed method and the traditional CR-based method effectively mitigate the cross-layer interference imposed, thus the macro-users are better protected than in the conventional random allocation scheme.

The CDF of the femto-users' SINR is seen in Fig. 4. In contrast to the random and traditional CR-based allocation schemes, the proposed scheme achieves significantly better performance owing to the interference coordination between adjacent fBSs of the same femtocell group. Although the traditional CR-based scheme also mitigates the cross-layer interference, it neglects the co-layer interference between adjacent femtocell. Fig.5 portrays the spectral efficiency of the three schemes. As expected, the proposed scheme provides a higher spectral efficiency than the other two schemes.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
The coverage radius of macrocell R_m	500 m
The coverage radius of femtocell R_f	10 m
The distance between adjacent femto BSs $d_{f_{BS}}^{f_{BS}}$	5 m
The radius of interior region	200 m
N_{sc}	10
N_{SB}	3
mBS transmit power	46 dBm
fBS transmit power	20 dBm
Femtocell group per macrocell	10
Macro-user per macrocell	30
The penetration loss of walls L_{wp}	10 dB
Path loss mBS-macrouser R(m)	L=15.3+37.6log10(R)
Path loss fBS-femtouser serving link R(m)	L=38.46+20log10(R)+0.7(R)
Path loss otherwise R(m) (q is the number of walls)	L=15.3+37.6log10(R)+qL_{wp}

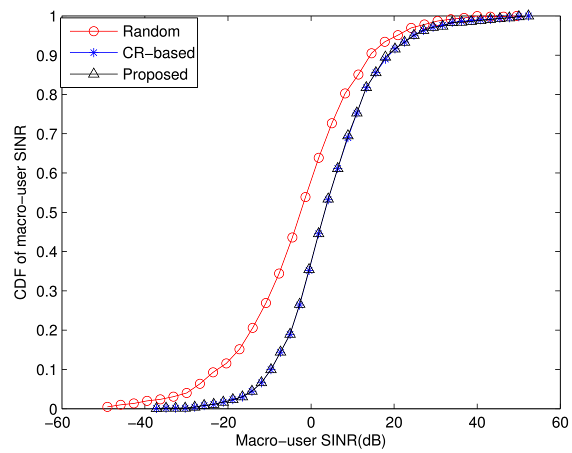

Fig. 3. CDF of macrocell-user's SINR

V. Conclusions

A novel interference coordination scheme was proposed for dense twin-layer femtocell networks. The cross-layer interference between the macrocell and femtocells was significantly mitigated with the aid of CR-based spectrum sensing techniques. A graph coloring aided sub-channel allocation algorithm was developed for coordinating the co-layer interference between femtocells. The power allocation among the femtocells of a group was adapted in order to take into account the network dynamics.

References

[1] V. Chandrasekhar, J. G. Andrews and A. Gatherer, "Femtocell Networks: A Survey," *IEEE Communications Magazine*, Vol. 46, No. 9, pp. 59-67, Sept. 2008.

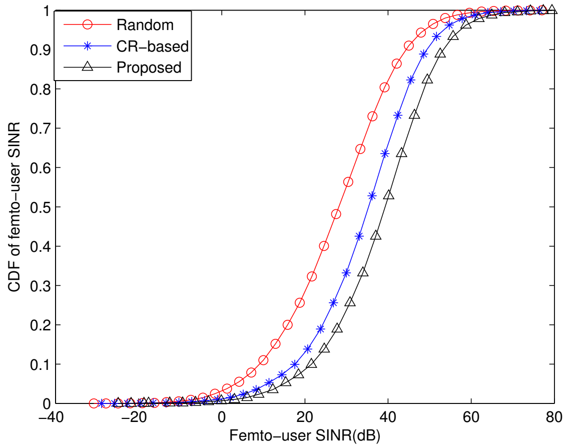

Fig. 4. CDF of femtocell-user's SINR

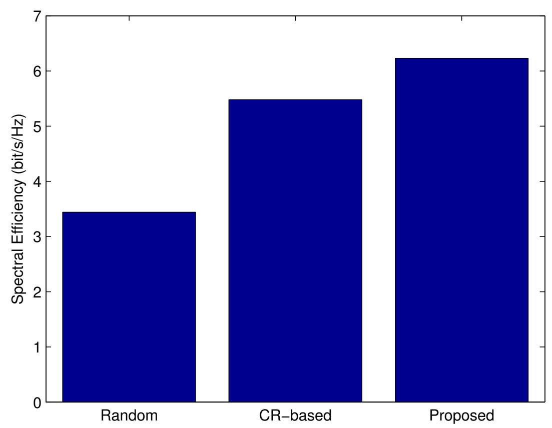

Fig. 5. Spectral efficiency of three schemes

[2] D. Lopez-Perez, A. Valcarce, G. de la Roche and J. Zhang, "OFDMA Femtocells: A Roadmap on Interference Avoidance," *IEEE Communications Magazine*, Vol. 47, No. 9, pp. 41-48, Sept. 2009.

[3] Y. Shi and A. B. MacKenzie, "Distributed Algorithms for Resource Allocation in Cellular Networks with Coexisting Femto- and Macrocells," *IEEE GLOBECOM*, pp. 1-6, Dec. 2011.

[4] M. Bennis and D. Niyato, "A Q-learning Based Approach to Interference Avoidance in Self-Organized Femtocell Networks," *IEEE GLOBECOM*, pp. 706-710, Dec. 2010.

[5] A. Galindo-Serrano, L. Giupponi and M. Majoral, "On Implementation Requirements and Performances of Q-Learning for Self-Organized Femtocells," *IEEE GLOBECOM*, pp. 231-236, Dec. 2011.

[6] Y. Shi, A. B. MacKenzie, L. A. DaSilva, K. Ghaboosi and M. Latva-aho, "On Resource Reuse for Cellular Networks with Femto- and Macrocell Coexistence," *IEEE GLOBECOM*, pp. 1-6, Dec. 2010.

[7] Y. Sun, R. P. Jover and X. Wang, "Uplink Interference Mitigation for OFDMA Femtocell Networks," *IEEE Transactions on Wireless Communications*, Vol. 11, No. 2, pp. 614-625, Feb. 2012.

[8] G. W. O. Da Costa, A. F. Cattoni, V. A. Roig and P. E. Mogensen, "Interference Mitigation in Cognitive Femtocells," *IEEE GLOBECOM*, pp. 721-725, Dec. 2010.

[9] S. Kaimaletu, R. Krishnan, S. Kalyani, N. Akhtar and B. Ramamurthi, "Cognitive Interference Management in Heterogeneous Femto-Macro Cell Networks," *IEEE ICC*, pp. 1-6, June 2011.

[10] M. Bennis and S. M. Perlaza, "Decentralized Cross-Tier Interference Mitigation in Cognitive Femtocell Networks," *IEEE ICC*, pp. 1-5, June 2011.

[11] A. Agustin, J. Vidal, O. Munoz-Medina and J. R. Fonollosa, "Decentralized Weighted Sum Rate Maximization in MIMO-OFDMA Femtocell Networks," *IEEE GLOBECOM*, pp. 270-274, Dec. 2011.

[12] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang and S. Vrzic, "Interference coordination and cancellation for 4G networks," *IEEE Communications Magazine*, Vol. 47, No. 4, pp. 74-81, April 2009.

[13] S. H. Ali and V. C. M. Leung, "Dynamic Frequency Allocation in Fractional Frequency Reused OFDMA Networks," *IEEE Transactions on Wireless Communications*, Vol. 8, No. 8, pp. 4286-4295, Aug. 2009.

[14] Z. Zhao, F. Zheng, A. Wilzeck and T. Kaiser, "Femtocell Spectrum Access Underlaid in Fractional Frequency Reused Macrocell," *IEEE ICC*, pp. 1-6, June 2011.

[15] S. Yeh, S. Talwar, S. Lee and H. Kim, "WiMAX femtocells: A Perspective on Network Architecture, Capacity, and Coverage," *IEEE Communications Magazine*, Vol. 46, No. 10, pp. 58-65, Oct. 2008.

[16] S. M. Cheng, W. C. Ao, F. M. Tseng and K. C. Chen, "Design and Analysis of Downlink Spectrum Sharing in Two-tier Cognitive Femto Networks," *IEEE Transactions on Vehicular Technology*, Vol.61, No.5, pp. 2194-2207, June 2012.

[17] K. A. Meerja, P. H. Ho and B. Wu, "A Novel Approach for Co-Channel Interference Mitigation in Femtocell Networks," *IEEE GLOBECOM*, pp. 1-6, Dec. 2011.

[18] Y. J. Chang, Z. Tao, J. Zhang and C. C. J. Kuo, "A Graph-based Approach to Multi-Cell OFDMA Downlink Resource Allocation," *IEEE GLOBECOM*, pp. 1-6, Dec. 2008.

[19] H. Li, X. Xu, D. Hu, X. Tao, P. Zhang, S. Ci and H. Tang "Clustering Strategy Based on Graph Method and Power Control for Frequency Resource Management in Femtocell and Macrocell Overlaid System," *Journal of Communications and Networks*, Vol. 13, No. 6, pp. 664-677, Dec. 2011.

[20] Y. Zheng, X. Xie and L. Yang, "Cooperative Spectrum Sensing Based on Blind Source Separation for Cognitive Radio," *ICFIN*, pp. 398-402, Oct. 2009.

[21] A. Ghasemi, E. S. Sousa, "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments," *DySPAN*, pp. 131-136, Nov. 2005.

[22] D. C. Oh, H. C. Lee and Y. H. Lee, "Cognitive Radio Based Femtocell Resource Allocation," *ICTC*, pp.274-279, Nov. 2010.