INTERFERENCE MANAGEMENT FOR HETEROGENEOUS NETWORKS WITH SPECTRAL EFFICIENCY IMPROVEMENT

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ABSTRACT

SE is a key characteristic of cellular communication systems. With the explosive growth of mobile data traffic in future wireless networks, the improvement of SE is necessary and it has been the main target in the 3rd Generation Partner Project standard. Considering this, a small cell solution is put forward and widely regarded as a promising technique to enhance SE by deploying low power cells (micro/pico/femto cells) in macrocells. However, with this mechanism cell gains can be severely limited by high inter-cell interference due to the densely deployed small cells. To address this problem, we first browse the major interference management techniques such as interference cancellation, interference coordination, coordinated multipoint transmission and reception, and interference alignment. Then we analyze the challenges when processing interference in a small cell architecture, and we explore the corresponding solutions. Finally, we design a scheme for interference mitigation from both the signaling and data transmission point of views. For the former, power constraint is employed. For the latter, a joint cross-tier and intra-tier interference mitigation sub-scheme is utilized. With this method, cross-tier interference can be alleviated by hybrid spectrum sharing, while intra-tier interference is avoided with orthogonal spectrum allocation. Besides, two methods are employed for exchanging information required in interference mitigation: wireless broadcast channel and UE-assisted relay. Simulations show that our proposed scheme achieves considerable improvement in SE compared to traditional schemes.

INTRODUCTION

In recent years, the demand for higher data rates has increased rapidly due to the wide use of mobile devices such as smart phones, tablets, and others. To satisfy this demand, various approaches have been proposed. Carrier aggregation (CA) allows flexible expansion of bandwidth through simultaneous utilization of multiple carriers. 3GPP Long Term Evolution (LTE) Release 10 supports improved multiple-input multiple-output (MIMO) operation as 8×8 downlink (DL) MIMO and 4×4 uplink (UL) MIMO to improve throughput. However, these technologies fail to provide significant enhancements as they are reaching the theoretical limits. Such techniques may not be optimal either, especially under low signal-to-interference plus noise ratio (SINR) conditions [1].

On the other hand, a small cell solution has become a promising tool and had begun to attract researchers' attention. A small cell consists of a number of low power nodes such as micro/pico/femto base stations (BSs) deployed in a macrocell, and the integrated architecture is called a heterogeneous network (HetNet). A recent report issued by Informa Telecoms & Media shows that 98 percent of mobile operator respondents believe small cells are essential for the future of their networks [2]. Reference [3] mentions that the new architecture is able to increase the spectrum utilization by 23.5 percent.

For operators, due to the high price and scarcity of spectrums, allocating a portion of spectrum to small cells might be impossible. Hence, they prefer a co-channel deployment scheme. Under this scheme, new issues involving cross-tier/intra-tier interference arise and have become the common focus in HetNet [4]. Cross-tier interference happens between cells belonging to different tiers. To reduce the heavy burden of the macrocell and to improve spectral efficiency, cell expansion [1] has been implemented, which motivates some macro users (MUEs) to migrate to small cells. However, under this scheme, DL interference generated by macrocells could be harmful to these migrating users. Similarly, if femto base stations (FBSs) are in closed subscriber group (CSG) mode, nearby MUEs are prevented from access. In this case, MUEs may receive a stronger signal from CSG FBSs and their normal transmission may be disturbed. When considering UL transmission, MUEs located far from the macro base stations (MBSs) intend to emit stronger signals for successful transmission, here they become the

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The basic concept of interference cancellation is to regenerate the interfering signals through various coding methods and then subtract them from the desired signal based on a special mechanism. Two classical ways of IC used extensively in wireless networks are pre-IC and post-IC.

source of interference to cell-edge users of neighboring small cells. Intra-tier interference is generated by nodes of the same tier. Consider that small cells are densely deployed, the interference can be strong if the spectrum is not carefully arranged. The above discussion shows that interference is a complex issue in HetNets. It should also be noted that interference is a negative factor [5] to SINR. Since the decrease of SINR can lower the value of SE, highly efficient interference management is necessary for a successful co-channel deployment in HetNet.

With the goal of enhancing spectral efficiency, this article focuses on interference management (IM) techniques for HetNet. In the past, four main techniques have been investigated: interference cancellation, coordination, CoMP, and interference alignment. The first technique is commonly used in 2G/3G systems, and it can achieve higher capacity through utilizing the interference in the signal detection process. The second technique is applied to LTE/LTE-A, and it performs adaptive resource partitioning in frequency and power to eliminate interference among cells. CoMP can be achieved by coordinating multi-points. Interference alignment manages interference by aligning multiple interference signals within a reduced dimensional subspace at each receiver. Although much work has been done, when considering the characteristics of HetNet such as self-organization, FBSs have no X2 interface and control channels have serious interferenc, there are challenges in the design of IM schemes.

This article provides an overview and analysis of existing interference management techniques. Furthermore, challenges in HetNet when employing IM techniques are presented and the corresponding solutions are proposed. Then we propose our scheme for interference mitigation and conduct simulations of the scheme.

OVERVIEW OF INTERFERENCE MANAGEMENT TECHNIQUES

Interference management techniques have attracted researchers' attention for many years. In the following we give a general introduction of the commonly used techniques and also show their influence on SE.

INTERFERENCE CANCELLATION

The basic concept of interference cancellation (IC) is to regenerate the interfering signals through various coding methods and then subtract them from the desired signal based on a special mechanism. Two classical ways of IC used extensively in wireless networks are pre-IC (represented by dirty paper coding (DPC)) and post-IC (commonly employed with successive interference cancellation (SIC)). To approach the Shannon capacity, SIC is combined with Orthogonal Frequency Division Multiplexing (OFDM), called SIC-OFDM. This technique is implemented at the receiver; a receiver will decode the interference sequentially using a successive decoder and every user is decoded by treating other interfering users as noise.

From the characteristics of IC, we know that the related techniques are complex, which makes them less suitable for UEs but more appropriate for base stations (macrocell/smallcell BSs). Hence IC is mostly used for UL interference management. Reference [6] employs SIC combining with resource allocation and designates a common channel for MUEs and femtocell users (FUEs). The gain reported in that paper is over 200 percent in sum rate. In relay-assisted HetNet, spectral efficiency can reach 2.2 bps/Hz.

INTERFERENCE COORDINATION

In 3GPP R8, intercell interference coordination (ICIC) is first introduced as an efficient technique to constrain the intercell interference. The core concept is to coordinate the resource distribution (i.e. frequency and power) in nearby cells to guarantee cell edge users' (CEUs') transmissions. Various approaches have been studied such as power control, spectrum partition supported partial frequency reuse (PFR), and softer frequency reuse (SFR). All these scheduling algorithms are static and are possible to guarantee fairness and throughput for CEUs. However, from the SE perspective, they are less optimal compared to adaptive fractional frequency reuse (AFFR). AFFR is a flexible method with which frequency reuse factor (FRF) can be adjusted according to femtocell location or other dynamic information. FRF revealing the property of SE is the proportion of spectrums allocated to the cell-edge users. For example, FRF = 3 means that one third of the spectrum band is allocated for CEUs. With AFFR, a higher FRF value can be obtained than other schemes [7]. In a macro/femto scenario, AFFR is applied to mitigate interference among multiple femtocells. The femto gateway takes the charge of analyzing the effect of mutual interference among femtocells with interference graph modeling. The result shows that higher system SE can be obtained on the order of 20 percent and users can reach 4~5 bps/Hz on average.

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Besides frequency and power, spatial resource can also be utilized for coordination. Coordinated multipoint transmission and reception (CoMP), initially proposed in R10, is another promising technique similar to ICIC. One classic scheme to achieve CoMP is joint processing (JP)/joint transmission (JT), which is regarded as an advanced downlink solution and mainly focuses on achieving spectral efficiency in LTE-A. Recent research [8] has shown that the DL JP/JT technique outperforms zero forcing (ZF) algorithms within macro/pico networks. The spectral efficiency achieved by the system is 3.8 bps/Hz per user and 0.046 per cell edge user under JP/JT, compared to 0.03 gained by ZF. One of the current issues with implementing JP/JT is multi-user MIMO (MU-MIMO). Since more overhead will be generated in densely deployed scenarios, the cost and complexity of the mechanism may be higher.

INTERFERENCE ALIGNMENT

Interference alignment (IA) is another efficient technique to handle interference at high signal to noise ratio (SNR). The advantage of this

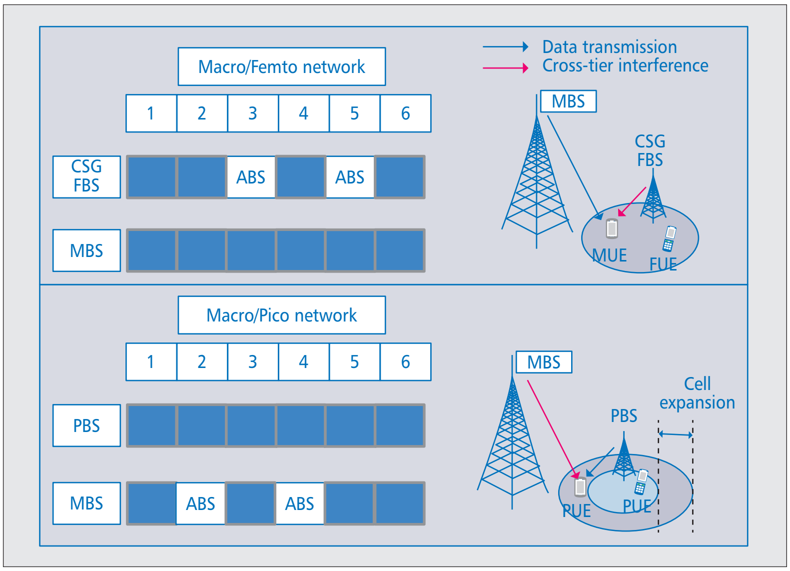

Figure 1. Coordination of ABSs.

technique is that each user is capable of reaching higher degrees of freedom (DoF). DoF measures how much of the sum rate may be increased with the improvement of SNR. In the view of IA, the receiver's subspace is divided into useful subspace (USS) and interference subspace (ISS). The core of this technique is to align the interfere signal to the ISS at the receiver and then enable the separation of useful signal from the interference. In other words, IA regulates the interference falling into a particular signal subspace and leaves the residual subspace interference free. An appropriate pre-encoder is designed at the transmitter with the purpose of preprocessing signals.

CHALLENGES AND SOLUTIONS

When considering the characteristics of the HetNet architecture, several challenges emerge along with the employment of interference management techniques, for example, the design of an intelligent interference management scheme to accommodate HetNet's self organization property, Inter-BS exchange when no X2 interface is installed on the FBS, and the management of interference on the control channels. In the following section, we give a detailed description of the challenges and the corresponding solutions.

DESIGN OF AN INTELLIGENT INTERFERENCE MANAGEMENT SCHEME

Some cells, especially femtocells, are distributed in a random pattern because they are widely installed and deployed by end users without network planning and can be turned on and off at any time. This feature requires that the network has the functionality of auto-configuration, auto-optimization, and auto-healing. With auto-configuration, femtocells can configure themselves when entering or leaving a cell. Auto-optimization usually aims to satisfy system demand through monitoring the surrounding environment and carefully adjusting wireless parameters. Auto-healing plays an important role in guaranteeing the network robustness: some users may fall into a coverage hole when nodes withdraw from the network because of dysfunction. If this happens, other nodes locating nearby should offset their power and execute compensation mechanisms to provide service for the users. On the basis of the forgoing analysis, intelligence is a crucial factor in HetNets in the context of self-organization. Hence, it is a challenge to find an intelligent interference management scheme.

One related scheme is self-organized power control with which FBSs or MBSs can automatically adjust their power with the goal of minimizing mutual interference between cells. Another promising technique is cognitive radio (CR). CR provides an active way for FBSs to perceive the environment and offers opportunistic access for FUEs [9]. Through spectrum sensing, CR is able to calculate the received interference on each spectrum within the sensing frame. If the value exceeds a certain threshold, the spectrum is identified as being busy and no FBS intends to occupy it. Otherwise, FBSs will compete for the spectrum in an opportunistic way. To further exploit the distributed property of the CR-based macro/femto heterogeneous networks, game theory is utilized [10, 11]. Game theoretical models are employed to model the actions of FBSs or MBSs. To enhance the spectrum efficiency, FBSs or MBSs can constantly update their interference management strategies based on the information acquired by cognitive radio technology.

INTER-BS EXCHANGE

When mitigating interference with coordination schemes, the X2 interface defined in R8 is essential for macrocells and picocells (relays) to carry interference coordination signals such as overload indicator (OI), relative narrowband transmit power (RNTP), and high interference indicator (HII). With OI, the information of which resource blocks (RBs) are seriously interfered is transmitted to nearby cells. RNTP is used to notify neighboring cells the threshold of power on specified RBs. HII can inform CEUs which RBs will be occupied. However, since no X2 interface is installed on FBSs, signaling exchange is unavailable and macro/femto or femto/femto coordination cannot be implemented. One possible solution is based on backhaul; however, delay may cause new problems. To overcome this issue, UE-assisted relaying, over-the-air broadcasting, and CR are investigated [12].

INTERFERENCE MANAGEMENT FOR CONTROL CHANNELS

In the HetNet scenario, more cells may suffer co-channel interference and hence have lower SINR. The low SINR threatens not only the data channels but also the control channels. When signaling transmission is severely disturbed, users may declare radio link failure. In such a case they may experience service outage under unreliable control channels. Considering this problem, an efficient interference mitigation scheme on control channels is important.

In some work, interference alignment is applied to address the above problem. Besides,

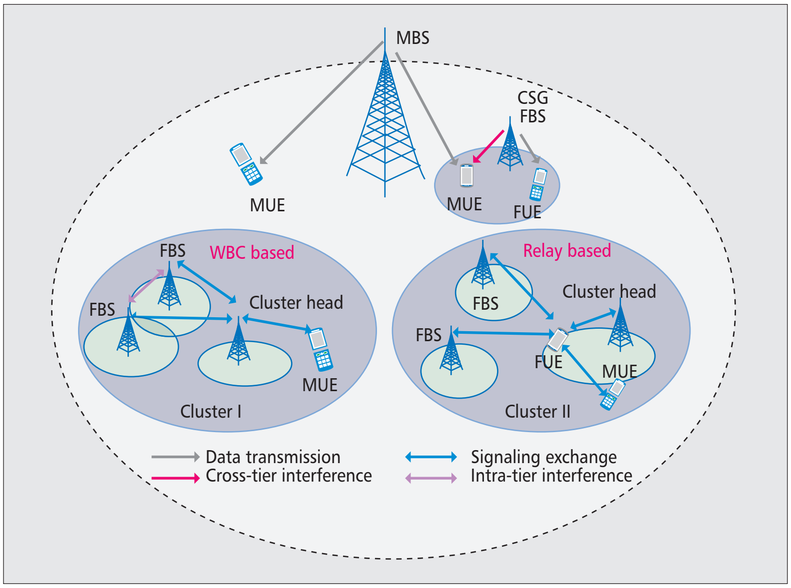

Figure 2. The network scenario.

an enhanced inter-cell interference coordination (eICIC) technique has been developed by 3GPP LTE-Advanced. This technique is aimed at coordinating the blanking of subframes in the time domain by utilizing almost blank subframes (ABSs). With this method, there is no interference on conflict subframes so that signaling transmissions can be successful. 3GPP R11 applies ABSs to two HetNet scenarios, macro/pico networks and Macro/femto networks, respectively. As illustrated in Fig.1, for CSG FBSs, assume their DL signals cause serious interference to neighboring MUEs on slots 3 and 5. In this case, to avoid disturbing MUEs' transmission, the corresponding slots of FBSs are configured with ABSs. Similarly, if a pico base station (PBS) intends to exchange signaling on slots 2 and 4, to prevent serious DL interference generated from MBS, PBS should inform MBS about the order of the slots and enable MBS to configure ABSs on these slots. The property of ABSs-related-schemes is evaluated in [13], and the results show that almost all users in the network can reach the spectral efficiency of 3.5 bps/Hz by using ABSs. On the contrary, for a network without employing ABSs, only about 8 percent of users can achieve the same level.

THE INTERFERENCE MITIGATION SOLUTION

To improve spectral efficiency, we design an effective scheme from the view of signaling transmission and data transmission in a macro/femto heterogeneous network. The signaling part is based on eICIC. The difference from previous work is that we apply power control to conflict slots for interference mitigation instead of deploying ABSs. For data transmission, we design a joint cross-tier and intra-tier interference mitigation scheme (JCIM) to process interference, and hybrid spectrum sharing is employed. The key idea is as follows:

- Initially femtocells are classified to several clusters (e.g. cluster I and II as illustrated in Fig. 2) according to their geographic locations, and one FBS is randomly selected as the cluster head.
- The cluster head is responsible for exploring the surrounding environment and exchanging the related information with other FBSs (illustrated in section B).
- With the information, interference mitigation is achieved through power control for signaling transmissions and by JCIM for data transmissions.

In the paradigm shown in Fig. 2, we consider a two-tier network consisting of one macrocell, several clusters of FBSs, and a set of MUEs and FUEs. Define the MUE set as $\mathcal{M}$ and the FBS set as $\mathcal{N}$; MUEs and FBSs are randomly distributed within the macrocell. Denote the spectrum set as $\mathcal{F}$ and assume each FBS can serve only one FUE. Within each FBS cluster, the head exploits the surrounding environment with the period of T_s frames and each acquisition is implemented in the first frame. Then in the next frame, the head calculates the spectrum allocation matrix and transmits it back to FBSs in the same cluster. The remaining $T_s - 2$ frames are used for data transmissions and receptions.

DESCRIPTION ABOUT THE INTERFERENCE MITIGATION SCHEME

As shown below, our interference mitigation scheme consists of two sub-schemes.

Interference Mitigation for Signaling Transmissions: We intend to employ eICIC to alleviate interference on control channels. However, with eICIC when conflict occurs the spectrum is unavailable, which further decreases the spectral efficiency. To address this problem, we apply power control in the following way. When the FBS plans to transmit signaling, first it checks the scheduling information of the control channels. Subsequently, FBS calculates the power level on the same channel obeying the rule that the accumulated interference can be tolerated by the MUE.

Interference Mitigation for Data Transmissions: To deal with the interference produced by data transmission, we design a joint cross-tier and intra-tier interference mitigation scheme (JCIM). In this scheme, FBSs and MBS share the spectrums in a hybrid mode and meanwhile cross-tier interference can be alleviated. For intra-tier interference, it can be averted through orthogonal spectrum allocation.

The Hybrid Mode: This hybrid mode concept was initially mentioned for spectrum sharing in cognitive radio. Traditionally, spectrum sharing consists of three modes: underlay, overlay, and hybrid. With underlay, spectrum access allows the coexistence of secondary users (SUs) and primary users (PUs) under the premise that interference to PUs is within the limit. This approach is achieved through imposing restricted transmission power constraints on SUs. Different from spectrum underlay, the overlay strategy focuses more on when and where spectrums are vacant and SUs can occupy them. Although much research has shown that the two strategies can enhance spectrum efficiency separately, the hybrid mode shows better performance because it combines the benefits of both overlay and underlay [14]. The details of hybrid mode spectrum sharing is as follows. If the SU locates far from the PU, its transmission may not interfere with PU and then the SU can utilize PU's spectrum through an overlay way. If the SU is near the PU, for the sake of avoiding unacceptable interference to the PU, the SU's access is allowed in an underlay mode.

In macro/femto based HetNets, femtocells are deployed underlaying the macrocell, and this framework is similar to a cognitive radio network that arranges SUs underlaying PUs. The features of HetNet, such as random deployment of FBSs and mandating no modifications of existing macrocells [10], motivate people to treat FBSs as SUs and MBS as PUs. Accordingly, hybrid spectrum sharing can be applied to our network.

DETAILS OF INFORMATION EXPLORATION AND EXCHANGE

The cluster head is responsible for collecting environment information. Since FBSs are transparent to MBS, the problems arise subsequently regarding what information is required and how to acquire that information. We need the following information:

- Scheduling information (shown in Table 1), including which spectrum is occupied by MUEs, the locations of these MUEs, and the interference tolerance on the spectrum.
- Information related to FBSs (shown in Table 2), containing the positions of FBSs and the channel gains for FUEs.

Table 1 shows one example of the scheduling information of MBS. In a scenario with four MUEs and four FBSs, four spectrums are available wireless resources. MUE_i means spectrum f_i is occupied by i^{th} MUE, which also implies that spectrum f_i is dedicated to i^{th} MUE. λ_1 and λ_2 denote the maximum tolerating interference on f_1 and f_2, respectively. In other words, accumulated power received by MUE_1 and MUE_2 from FBSs should be lower than the two values. In addition, in the third line the third flag is set to 1, which means that spectrum f_3 is vacant and FUEs can transmit signal according to their own demand. 0 implies that interference on spectrum f_4 is too high and no FUE is allowed to use it. The remaining values are equalized to 1, which means the spectrums are not occupied by the corresponding MUEs and their neighboring FBSs are free to use them. The fourth column denotes the locations of MUEs, and the fifth column gives the channel gain from MUE to MBS. Table 2 shows the information about FBSs, where h_i represents the channel gain from FUE to FBS, and (c_i, d_i) denotes the location of FBSs.

After determining which information should be obtained, the next question is how to acquire it. Considering no X2 interface is installed on FBS, direct interaction between BSs (cluster head with MBS or other FBSs) is impossible. Here, two mechanisms can be applied: wireless broadcast channels (WBC) and UE-assisted relaying (UER), as shown in cluster I and cluster II of Fig. 2.

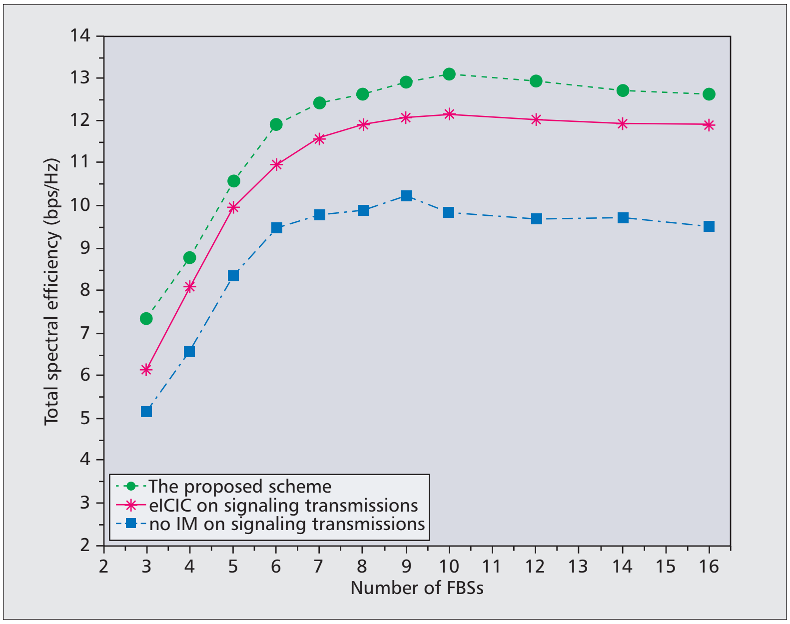

Figure 3. Comparison of different interference mitigation schemes on signaling transmission.

Wireless Broadcast Channels: With this rule, information exchange can be realized by broadcasting. MBS broadcasts its scheduling information to FBSs. FBSs transmit information including positions and channel gains (illustrated in Table II) to the cluster head through broadcast channels.

UE-Assisted Relaying: Employing this method, information interaction is completed by relay. FBSs obtain information (shown in Table 1) about MUEs with a handshake. Then one FUE is selected as the donor to complete the task of relaying information to the cluster head. The selection of donor depends on the relay selection method [15].

GENERATION OF SPECTRUM ALLOCATION SET

As information has been gathered and shared, JCIM can be realized by spectrum allocation which intends to achieve significant improvement of overall spectral efficiency in terms of system utility. The objective function is designed as follows:

$$
\begin{aligned}
&\{\Omega^*\} = \arg\max U \\
&U = U_{\mathcal{M}} + U_{\mathcal{N}} \\
&U_{\mathcal{M}} = \sum_{i\in\mathcal{M}} \log \ 1+\frac{p_i g_i}{\sum_{j\in\mathcal{N}} x_{i,j} p_j h_{i,j} + N_0} \\
&U_{\mathcal{N}} = \sum_{j\in\mathcal{N}} \log \ 1+\frac{p_j h_j}{\sum_{i\in\mathcal{M}} x_{i,j} p_i h_{i,j} + N_0} \\
&\sum_{k\in\mathcal{F}} rho_{j,k} \le 1
\end{aligned}
\tag{1}
$$

where $\Omega^* = \{rho_{j,k}\}$ is the optimal spectrum allocation set, $rho_{j,k}$ is the spectrum allocation factor. $rho_{j,k} = 1$ denotes that the k^{th} spectrum is

	f_1	f_2	f_3	f_4	Location	Gain
MUE_1	λ_1	1	1	1	(a_1, b_1)	g1
MUE_2	1	λ_2	1	1	(a_2, b_2)	g2
MUE_3	1	1	1	1	(a_3, b_3)	g3
MUE_4	1	1	1	0	(a_4, b_4)	g4

Table 1. Scheduling information.

	FBS_1	FBS_2	FBS_3	FBS_4
Location	(c_1, d_1)	(c_2, d_2)	(c_3, d_3)	(c_4, d_4)
Gain	h_1	h_2	h_3	h_4

Table 2. Information related to FBS.

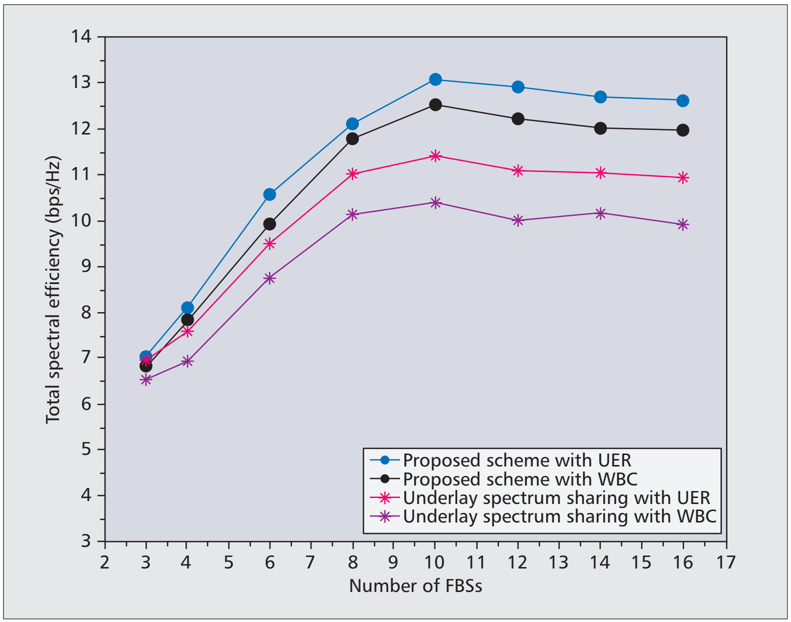

Figure 4. Spectral efficiency under different information exchange methods.

allocated to the j^{th} FBS, and $rho_{j,k} = 0$ means no spectrum is allocated to the j^{th} FBS. The inequation is designed to eliminate intra-tier interference, which means one spectrum can only be allocated to a single FBS. p_j is the power of FBS_j and is determined by the parameters shown in Table 1. If FBS_j located near MUE_1 intends to utilize f_1, the power level can be $\lambda_1/(h_{i,j})$. $U_{\mathcal{M}}$ and $U_{\mathcal{N}}$ are the spectral efficiency of MUEs and FBSs, respectively. Since in our assumption each FBS can support one FUE, $U_{\mathcal{N}}$ can also be regarded as the spectral efficiency of all FUEs. $h_{i,j}$ is the channel gain between i^{th} MUE and j^{th} FBS. p_i represents the transmission power of MUE. N_0 denotes the variances of the noise. $\chi_{i,j}$ is the spectrum sharing factor and the value of 1 means that the j^{th} FBS utilizes the same spectrum as the i^{th} MUE.

The formulated problem is an assignment problem and can be solved by the Hungarian algorithm. With this algorithm, a stable one-to-one matching between FBSs and spectrums can be achieved by an iterative procedure. The computing complexity is on the order of $O(n^3)$, where n is the number of FBSs.

SIMULATION RESULTS

We evaluated the performance of the proposed scheme, and the results as presented in Fig. 3 and Fig. 4. We consider a HetNet scenario with one MBS supporting three MUEs. The service radius for FBSs is $10m$ and the number of FBSs located within the MBS coverage varies between 2~16. The noise $N_0 = -9dB$.

Lines plotted in Fig. 3 compare the spectral efficiency (calculated by function (1)) between the proposed scheme and the method with eICIC on signaling transmissions, as well as the mechanism without any IM on signaling transmissions. Results show that our scheme outperforms the other two and obtains higher SE. Moreover, the scheme with IM on control channels can achieve higher SE than that with no IM. This usually happens in a crowded heterogeneous scenario where FBSs' signaling transmissions may be disturbed by interference. Furthermore, the subsequent data transmissions can be interrupted, which leads to lower SE. It is also obvious that as the increment of the number of FBSs, spectral efficiency first increases quickly and then becomes slow until reaching an acme. This is because as more FBSs join in the scenario, spectrum resource becomes scarce and the interference becomes larger, and the utilization rate of spectrum is lowed.

Figure 4 shows the influence of different information exchange methods including UER and WBC on spectral efficiency. The results show that UER is superior to WBC, because when utilizing WBC, only specialized channels can be employed for information exchange. In a crowded scenario, the channel may not be available and interference management fails to perform well. What makes it different is that UER can exploit vacant channels adaptively and establish more stable links for information exchange. The lines with spheres denote the proposed scheme employing JCIM, while the lines with stars represent the scheme utilizing underlay spectrum sharing for data transmissions. The former performs better than the latter, demonstrating that our proposed scheme achieves better spectral efficiency.

CONCLUSION

Small cell architecture is widely regarded as a promising technique to improve spectral efficiency. In this architecture, a large amount of small cells are deployed in a macrocell. It is an important issue to deal with the severe inter-cell interference generated by densely deployed small cells. In this article, first we gave a summary of the major interference mitigation techniques such as cancellation, coordination, and alignment. Then we analyzed challenges of interference management in small cell architecture and discussed several existing schemes for the challenges. For the macro/femto scenario, we studied interference mitigation from two points of view: signaling and data. We utilized power control to alleviate interference on signaling, and we designed JCIM for data transmission. Using our scheme, the cross-tier interference can be alleviated by hybrid spectrum sharing; the intra-tier interference is avoided with orthogonal spectrum allocation. Our simulation results showed the advantage of the proposed scheme.

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REFERENCES

[1] D. Lopez *et al.*, "Enhanced Intercell Interference Coordination Challenges in Heterogeneous Networks," *IEEE Wireless Commun.*, vol. 18, no. 3, Jun. 2011, pp. 22–30.

[2] "http://www.smallcellforum.org/newsstory-98-percent-of-mobile-operators-say-small-cells-essential-for-future-of-networks," Dec. 2012.

[3] W. Ni and I. Collings, "A New Adaptive Small-Cell Architecture," *IEEE JSAC*, vol. 31, no. 5, May. 2013, pp. 829–39.

[4] N. Saquib *et al.*, "Interference Management in OFDMA Femtocell Networks: Issues and Approaches," *IEEE Wireless Commun.*, vol. 19, no. 3, Jun 2012, pp. 86–95.

[5] G. Boudreau *et al.*, "Interference Coordination and Cancellation for 4G Networks," *IEEE Commun. Mag.*, vol. 47, no. 4, Apr. 2012, pp. 74–81.

[6] B. Kaufman *et al.*, "Femtocells in Cellular Radio Networks with Successive Interference Cancellation," *Proc. IEEE ICC*, 2011, pp. 1–16.

[7] H. Lee *et al.*, "Mitigation of Inter-Femtocell Interference with Adaptive Fractional Frequency Reuse," *Proc. IEEE ICC*, 2010, pp. 1–5.

[8] M. Shoeb *et al.*, "Coordinated Multi-Point Algorithms In Pico Based Heterogeneous Networks," *Proc. 14th Int'l. Conf. Advanced Communication Technology* (ICACT), 2012, pp. 37–40.

[9] L. Huang *et al.*, "Cognitive Femtocell Networks: An Opportunistic Spectrum Access for Future Indoor Wireless Coverage," *IEEE Wireless Commun.*, vol. 20, no. 2, Apr. 2013, pp. 44–51.

[10] S. Cheng *et al.*, "On Exploiting Cognitive Radio to Mitigate Interference in Macro/Femto Heterogeneous Network," *IEEE Wireless Commun.*, vol. 18, no. 3, Jun. 2011, pp. 40–47.

[11] W. Lai *et al.*, "Game Theoretic Distributed Dynamic Resource Allocation with Interference Avoidance In Cognitive Femtocell Networks," *Proc. IEEE WCNC*, 2013, pp. 7–10.

[12] T. Zahir *et al.*, "Interference Management in Femtocells," *IEEE Commun. Surveys & Tutorials*, vol. 15, no. 1, First Quarter. 2013, pp. 293–311.

[13] S. Kshatriya *et al.*, "On Interference Management Based on Subframe Blanking in Heterogeneous LTE Networks," *Proc. Fifth International COMSNETS Conf.*, 2013, pp. 1–7.

[14] V. Chakravarthy *et al.*, "A Novel Hybrid Overlay/Underlay Cognitive Radio Waveform in Frequency Selective Fading Channels," *IEEE 4th Int'l. Conf. CROWNCOM*, 2009, pp. 1–6.

[15] X. Ping and L. Lihua *et al.*, "Cooperative Spectrum Sharing Protocol with Best Secondary User Selection," *J. Beijing University of Posts and Telecommun.*, vol. 8, no. 10, May. 2013, pp. 27–32.

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