Inter-operator Interference Coordination in the Spectrum-Sharing Overlapping Area

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Abstract. With the widespread application of dynamic spectrum access technology, sharing spectrum with the same primary systems by multiple operators will become a common scenario. Serious co-channel interference (CCI) needs to be mitigated if there is no coordination among the operators. In this paper, a cluster-based interference management algorithm is proposed to reduce the inter-operator CCI in the spectrum-sharing overlapping area. The proposed algorithm consists of two major steps: (1) undirected weighted graph-based clustering and spectrum allocation; (2) signal to interference and noise ratio (SINR) margin-based power adjustment. A novel weight is defined and employed in the clustering procedure to take the SINR requirement of each secondary user (SU) into account. Simulation results show that the ratio of satisfied SUs (whose SINR exceeds their SINR thresholds) can be increased while the sum of co-channel interference is significantly reduced. Furthermore, by introducing a third-party agent, direct exchange of sensitive SU information between different operators can be avoided for better privacy protection.

Keywords: Dynamic Spectrum Access (DSA) · Inter-operator interference Spectrum Access System (SAS) · Undirected weighted graph

1 Introduction

Cognitive radio (CR) technology, or more specifically, dynamic spectrum access (DSA) is one of the key technologies to address the spectrum shortage problem. In the DSA systems, a spectrum management mechanism named as spectrum access system (SAS) is proposed to authorize and manage the spectrum access with the goal of better spectrum utilization [1]. SAS can serve as "an information and control clearinghouse for the band-by-band registrations and conditions of use that will apply to all users with access to each shared Federal band under its jurisdiction" [1]. How to use the limited

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spectrum more efficiently is also the key to successfully apply CR to the fifth-generation (5G) mobile communication systems. With the widespread application of DSA technology, spectrum sharing with the same primary systems by multiple operators will be inevitable.

In the inter-operator spectrum sharing system, also known as the co-primary spectrum sharing system [2], multiple secondary users (SUs) controlled by different SASs coexist with the same primary system (PS) or these SUs share the same spectrum pool. In this case, SASs may be developed by different operators or spectrum policies, resulting in various coexistence scenarios. The common issue to be addressed is the serious inter-operator co-channel interference (CCI) if the SUs belonging to different SASs share the same spectrum without any coordination. Given the quality of service (QoS) requirement of PU, how to mitigate the CCI and increase the number of allowable SUs through the cooperation among SASs is the major issue investigated in this paper.

In this paper, a cluster-based interference management algorithm is proposed, which consists of two major steps: (1) undirected weighted graph-based clustering and spectrum allocation; (2) signal to interference and noise ratio (SINR) margin-based power adjustment. The major contributions of this work are summarized as follows.

(1) A clustering-based spectrum allocation and power adjustment algorithm is proposed to ensure the coexistence of SUs in the spectrum sharing overlapping area of different operators;
(2) A novel weight is defined and employed in the clustering procedure, which takes the SINR requirement of each SU into account;
(3) A new parameter termed as "*SINR margin*" is introduced into the power adjustment procedure to avoid the unnecessary power waste and further reduce the CCI in the spectrum-sharing overlapping area;
(4) A public SAS, which could be an authorized "third-party" agent, is proposed to avoid the direct exchange of sensitive information between SASs for better privacy and security.

Note that the proposed scheme is different from the well-known medium access control (MAC) protocol-carrier sense multiple access with collision avoidance (CSMA/CA). CSMA/CA is a contention-based MAC protocol, while the proposed scheme enables simultaneous transmissions in the same channel and takes the QoS requirements of the spectrum-sharing SUs into account.

The remainder of this paper is organized as follows. In Sect. 2, we briefly summarize the existing work on user clustering and inter-operator interference management. Section 3 provides an overview of the multiple SASs-based spectrum sharing systems and the CCI model. Section 4 discusses the clustering procedure and the clustering-based spectrum allocation. Section 5 discusses the power adjustment procedure based on the newly proposed SINR margin. Simulation results are presented in Sect. 6. Finally, Sect. 7 concludes the paper.

2 Related Works

In this section, literature survey consists of the following three parts: (1) general interference management approaches; (2) clustering-based spectrum allocation and interference management; and (3) inter-operator interference management.

Generally speaking, interference management algorithms can be designed from different domains such as time, space, frequency, and power. Classical interference mitigation approaches in spectrum sharing systems mainly include the precoding algorithm, interference avoidance algorithm and transmit power control algorithm. Precoding algorithm is an interference suppression algorithm by designing the proper precoding matrix according to the specific criteria [3]. Because of the dependence on the spatial freedom, precoding algorithm is applied to the multiple input multiple output (MIMO) systems. Block diagonalization, minimum mean square error (MMSE), signal to the interference leakage and interference (SLNR) maximization and interference alignment are the most commonly used precoding algorithms [4–7]. Interference avoidance algorithms result in the minimum distance between co-channel users to avoid the interference. In [14], the authors design the primary exclusion zone to avoid the PU's interference caused by the SUs and the secondary exclusion zone to avoid the CCI between the co-channel SUs. However, setting the minimum distance between users will lead to lower spatial utilization of the spectrum. Transmit power control method is also a simple but effective interference suppression method by limiting the transmit power [8]. However, sometimes the transmit power might be too low to satisfy the QoS requirement of users.

Various methods for clustering-based spectrum allocation or interference management are also investigated. In [9], a graph-based clustering resource allocation scheme is proposed. However, the interference graph in [9] only contains the interference relationship. In other words, the information conveyed from the graph in [9] is whether there exists interference between two users. The diverse QoS requirements of the users cannot be inferred from the interference graph. As a result, the graph-based clustering resource allocation scheme may not be able to meet the different QoS requirements of the users. A graph-based two-step resource allocation scheme is proposed in [10]. The first step is clustering the users based on the interference graph, and the second step is to allocate the resources within the cluster. Clustering-based interference alignment shows excellent performance in interference management except for the channel information dependence and antenna limitation [11]. The undirected weighted graph in [11] also takes the path loss experienced by the desired signal and co-channel interference into consideration to better reflect the impact of interference.

Inter-operator interference management is different from the intra-operator interference management. Coordination between different operators is necessary, especially in the spectrum-sharing overlapping areas. Resource allocation with concurrent learning for heterogonous long term evolution (LTE) small cells is proposed in [12], which is a dynamic resource allocation scheme with a distributed two-level learning procedure. However, the convergence speed of learning is quite a drawback. In [13], a hierarchical game approach for multi-operator spectrum sharing is proposed to avoid the inter-operator interference. A Kalai-Smorodinsky bargaining game among leaders and a Stackelberg game between operators and mobile users are employed in this approach. The co-primary spectrum sharing scenario is a new spectrum access mode to enable two or more operators to share spectrum resource with the same primary system [2]. In [2], each operator accesses the shared spectrum pool in a non-orthogonal manner with asymmetric power levels to solve the inter-operator interference. But such approach is suitable for the operators with the same priority in spectrum sharing. In summary, the above-mentioned three papers treat the SUs equally, and the various QoS requirements from different users are not considered yet in the proposed algorithms. How to design an interference coordination algorithm with consideration of the various QoS requirements in the spectrum-sharing overlapping area is the major problem to be addressed in this paper. More specifically, the U.S. Federal Communications Commission has proposed a dynamic spectrum management framework for a Citizen Broadband Radio Service (CBRS) governed by SAS [15]. Coexistence of CBRS networks offered by different operators is such an application scenario.

3 System Scenario and Interference Model

In this section, the system scenario of SAS-based spectrum sharing systems with multiple operators is presented and the co-channel interference model is discussed.

3.1 System Scenario

As shown in the Fig. 1, two SAS operators (namely, SAS_1 and SAS_2) coexist with the same PS, and each SAS is in charge of multiple SUs. Each SU consists of a pair of transmitter and receiver. In this paper, "Public SAS" is introduced as an authorized "third-party" agent to coordinate the SASs and exchange necessary information in between. With the "Public-SAS", exchange of sensitive SU information between SASs can be avoided, thus protecting the SUs' privacy.

3.2 Interference Model

As Fig. 1 shows, the management areas of SAS_1 and SAS_2 are overlapped. Serious CCI may exist if there is no coordination between the SASs. The CCI at the i-th SU receiver is defined as follows:

$$I_i = \sum_{j \in A} P_j d_{ij}^{-\alpha_{ij}} \tag{1}$$

where I_i is the CCI of the i-th SU receiver; A is the index set of all co-channel SU transmitters in the overlapping area; P_j is the transmit power of the j-th SU; d_{ij} is the distance between the i-th SU receiver and the j-th SU transmitter; α_{ij} is the path loss exponent corresponding to the radio link between the i-th SU receiver and j-th SU transmitter.

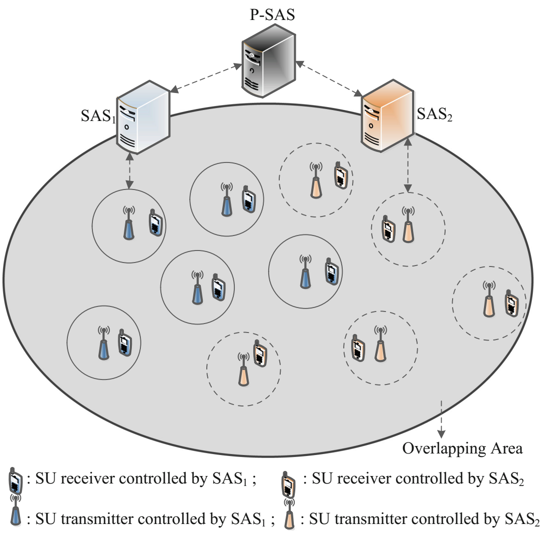

Fig. 1. Inter-operator interference coordination in the spectrum-sharing overlapping area. Note: "P-SAS" is the proposed third-party agent to coordinate the different SASs.

The SINR of a satisfied SU should be no less than its SINR threshold, i.e., $SINR \geq SINR_{th}$. The main problem to be solved is how to increase the ratio of satisfied SUs and reduce the CCI in the overlapping area of different SASs.

The SINR of the i-th SU is calculated by

$$SINR_i = 10\lg\left(\frac{P_{\max i} d_{ii}^{-\alpha_{ii}}}{\sum_{j\in A} P_{\max j} d_{ij}^{-\alpha_{ij}} + N_0}\right) \tag{2}$$

where $SINR_i$ is the SINR of the i-th SU receiver; P_{maxi} is the maximum transmit power of the i-th SU transmitter; d_{ii} is the distance between the i-th SU receiver and the i-th SU transmitter; α_{ii} is the path loss exponent corresponding to the radio link between the i-th SU receiver and i-th SU transmitter; A is the index set of all co-channel SU transmitters in the overlapping area; P_{maxj} is the maximum transmit power of the j-th SU; d_{ij} is the distance between the i-th SU receiver and the j-th SU transmitter; α_{ij} is the path loss exponent corresponding to the radio link between the i-th SU receiver and j-th SU transmitter; N_0 is the noise power of the i-th SU receiver.

4 Clustering-Based Spectrum Allocation

In this section, the undirected weighted graph is firstly introduced, and then an undirected weighted graph-based clustering procedure is proposed. Finally, the clustering-based spectrum allocation method is introduced.

4.1 Undirected Weighted Graph

As shown in Fig. 2, the undirected weighted graph G = (V, E, W) consists of all secondary systems (SS) in the spectrum-sharing overlapping area, and each SS consists of a pair of SU transmitter and SU receiver. V is the set of vertices and each vertex is corresponding to a SS. E is the set of edges between two SSs. W is the weight set, i.e., W = $\{w_{ij}\}$.

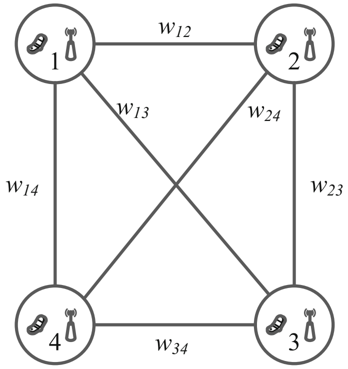

Fig. 2. Undirected weighted graph considering four spectrum-sharing secondary systems

The weight (w_{ij}) can be defined in different ways. The weight defined by (3) reflects the relative interference level to the desired signal. Bigger weight represents the relatively weaker interference. Considering the SUs usually have different QoS requirement, e.g., SINR threshold, the weight in (3) treats the SUs equally. This observation motivated us to define a novel weight which takes the SUs' different QoS requirements into consideration. The newly proposed weight is defined by (4). The weight in (4) is normalized by each SU's SINR threshold, therefore, the weight can reflect the relative interference to the desired signal as well as the SINR requirement. Generally, bigger weight indicates relatively smaller interference.

$$w_{ij} = \frac{P_{\max i} d_{ii}^{-\alpha_{ii}}}{P_{\max j} d_{ij}^{-\alpha_{ij}}} + \frac{P_{\max j} d_{jj}^{-\alpha_{jj}}}{P_{\max i} d_{ji}^{-\alpha_{ji}}}, \tag{3}$$

$$w_{ij} = \frac{P_{\max i} d_{ii}^{-\alpha_{ii}}}{P_{\max j} d_{ij}^{-\alpha_{ij}} SINR_{thi}} + \frac{P_{\max j} d_{jj}^{-\alpha_{jj}}}{P_{\max i} d_{ji}^{-\alpha_{ji}} SINR_{thj}}, \tag{4}$$

where w_{ij} is the weight between the i-th SU pair and the j-th SU pair; $SINR_{thi}$ is the SINR threshold of the i-th SU receiver; $SINR_{thj}$ is the SINR threshold of the j-th SU receiver; the definitions of the other parameters are the same as (2).

4.2 Undirected Weighted Graph-Based Clustering Approach

As shown in Figs. 3 and 4, in order to take the SUs' different QoS requirements (more specifically, SUs' SINR requirements) into account, a clustering procedure is proposed. In some sense, the undirected weighted graph-based clustering procedure can be viewed as a greedy algorithm. The most demanding SU, which has the highest SINR threshold in the un-clustered set, is selected as the first cluster member. Then, select the other members in an order such that the sum of weights remains the largest.

To explain the proposed clustering procedure, a step-by-step illustration is shown in Fig. 3 and discussed as follows. In Fig. 3, as a simple example, there are 4 SSs in the un-clustered set. To establish the first cluster, i.e., Cluster-1, the SINR thresholds of these four SSs are compared and then pick out the most demanding SS, i.e., the SS with the maximal SINR threshold as the first member of Cluster-1. For this example, SS_1 has the highest SINR threshold. Therefore, SS_1 is selected as the first cluster member of Cluster-1. Next, the weights between SS_1 and the other three SSs, i.e., $\{w_{12}, w_{13}, w_{14}\}$, are calculated. Assuming w_{13} is the largest weight among w_{12}, w_{13} and w_{14}, the SS_3 is picked out and put into Cluster-1. Then, the SINR of all SSs in Cluster-1 (i.e., SS_1 and SS_3) are estimated and compared against their corresponding SINR thresholds. If every SS in the Cluster-1 meets its SINR threshold, it confirms that SS_3 can be successfully put into Cluster-1; otherwise, when there is additional channel available, a new cluster (Cluster-2) can to be created to accommodate SS_3. For this example, SS_3 can be successfully put into Cluster-1.

Repeat the same procedure for the remaining SSs in the un-clustered set. The sum of weights between SS_2 and the SSs in Cluster-1 are calculated (i.e., $w_{12} + w_{23}$), which is then compared with the sum of weights between SS_4 and the SSs in Cluster-1 (i.e., $w_{14} + w_{34}$). Assuming $w_{12} + w_{23} > w_{14} + w_{34}$, SS_2 is picked out and put into Cluster-1. The SINR of all SS in Cluster-1 (i.e., SS_1, SS_3, and SS_2) are estimated again and compared against their corresponding SINR thresholds. If all SSs in the Cluster-1 still meet their SINR thresholds, SS_2 can be successfully put into Cluster-1. Otherwise, as long as there is additional available channel, a new cluster needs to be created. Finally, check whether the last SS left in the un-clustered set can be successfully put into Cluster-1. For this example, a new cluster (i.e., Cluster-2) needs to be created to accommodate SS_4. Note: when there is no additional channel available for creating a new cluster, the SSs left in the un-clustered set might be put into the last cluster.

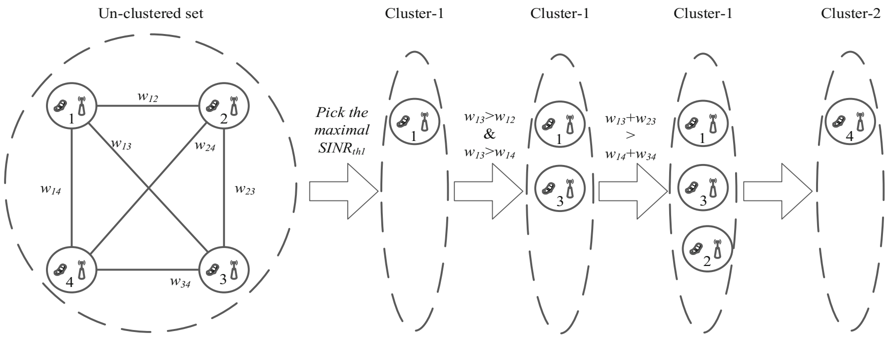

Fig. 3. Illustration of the proposed clustering procedure

In the proposed clustering procedure, each SS's SINR requirement and the interference between different SSs are considered altogether. In this way, the number of satisfied SSs can be increased while reducing the sum of co-channel interference.

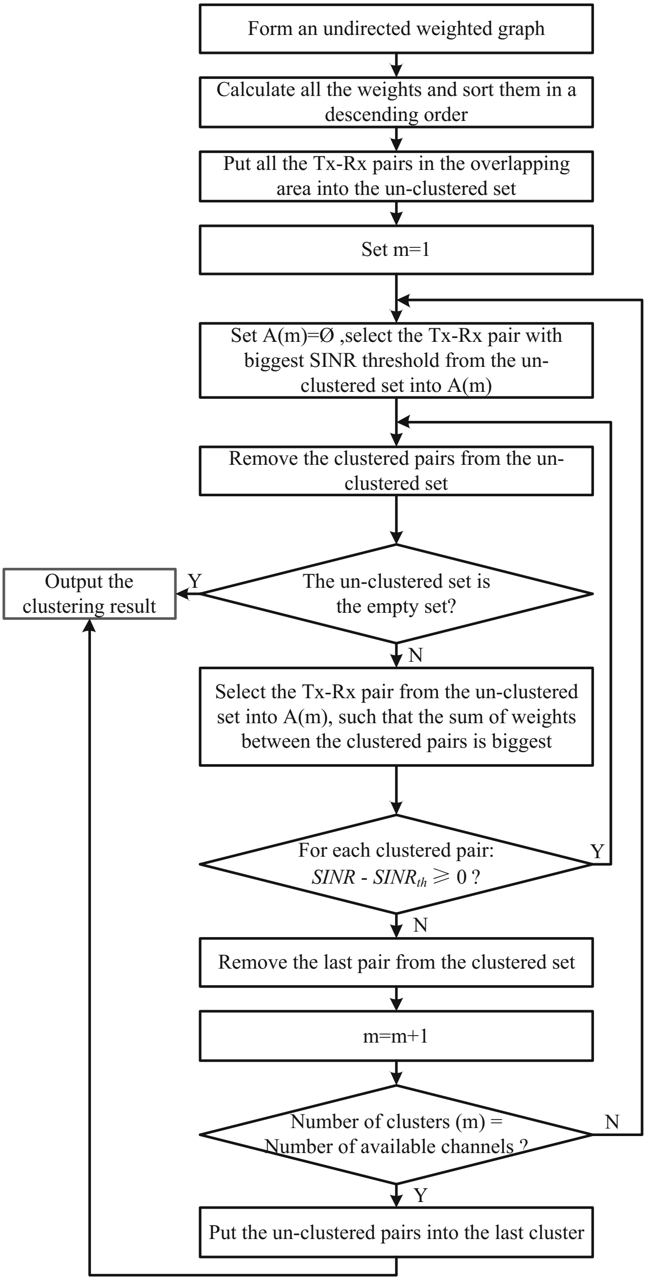

Fig. 4. Flowchart of the proposed clustering-based spectrum allocation scheme

4.3 Clustering-Based Spectrum Allocation Method

Spectrum allocation is based on the clustering result. As the SUs in the same cluster have relatively low interference, SUs in the same cluster can share the same spectrum whereas SUs in different clusters should use different spectrum. SUs are marked by the corresponding cluster index, therefore, SASs can allocate available spectrum to each SU based on its associated cluster index.

The flowchart of the proposed clustering-based spectrum allocation scheme is shown in Fig. 5. Predefined events, such as the change of SINR threshold, may trigger the start of interference coordination by sending the event indicator. An SAS, say, SAS_1, in the overlapping area sends the related information to the public-SAS for clustering. The public-SAS process the received information and then collects the needed information from other SAS, say, SAS_2. Each SAS allocates spectrum to each SU according to the received cluster information from the public-SAS. It's worth noting that the received cluster information of each SAS doesn't contain any user information of the other SASs, thus protecting the privacy of user information.

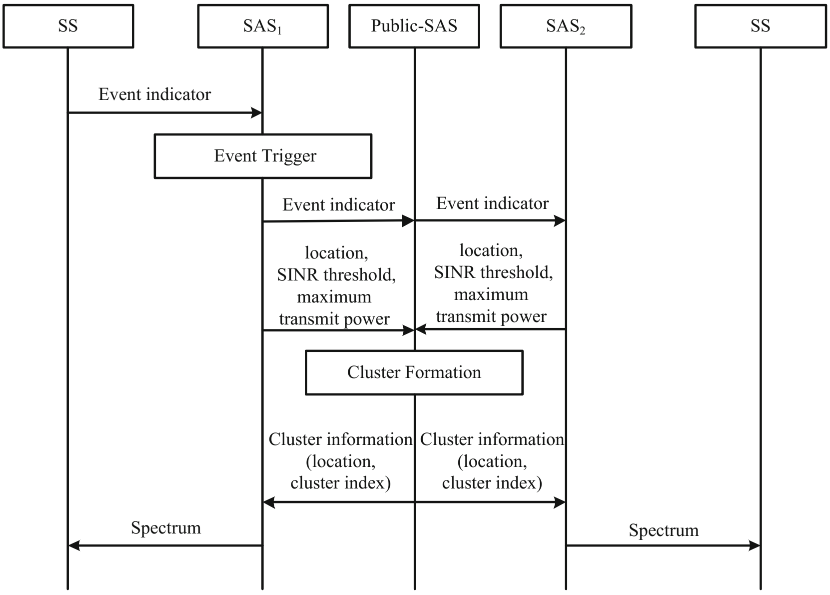

Fig. 5. Flowchart of the proposed clustering-based spectrum allocation scheme. Note that "Public-SAS" is the proposed third-party agent to coordinate the different SASs in the overlapping areas.

5 Power Adjustment Procedure

Once the clustering-based spectrum allocation is completed, power adjustment can be applied to further reduce the sum of CCI.

SINR margin is a newly proposed parameter, which is defined as the difference between the actual SINR and the SINR threshold. In a cluster, it is possible that the actual SINR of some SUs are much bigger than their SINR thresholds. Based on such observation, SINR margin-based power adjustment approach is proposed to reduce the unnecessary SINR margin. By decreasing the transmit power of SU, SINR margin can be reduced to the SINR margin threshold.

SINR margin can be determined for each cluster. For example, when we set the SINR margin threshold to be 0 dB, it means that each SU needs to reduce the transmit power until the SINR of an SU is equal to its SINR threshold.

The flowchart of the clustering-based spectrum allocation and power adjustment scheme is shown in the Fig. 6. After clustering and spectrum allocation, SINR margin threshold of each cluster is determined according to the information of cluster members. And then SUs should reduce their transmit power until its SINR margin is equal to the SINR margin threshold.

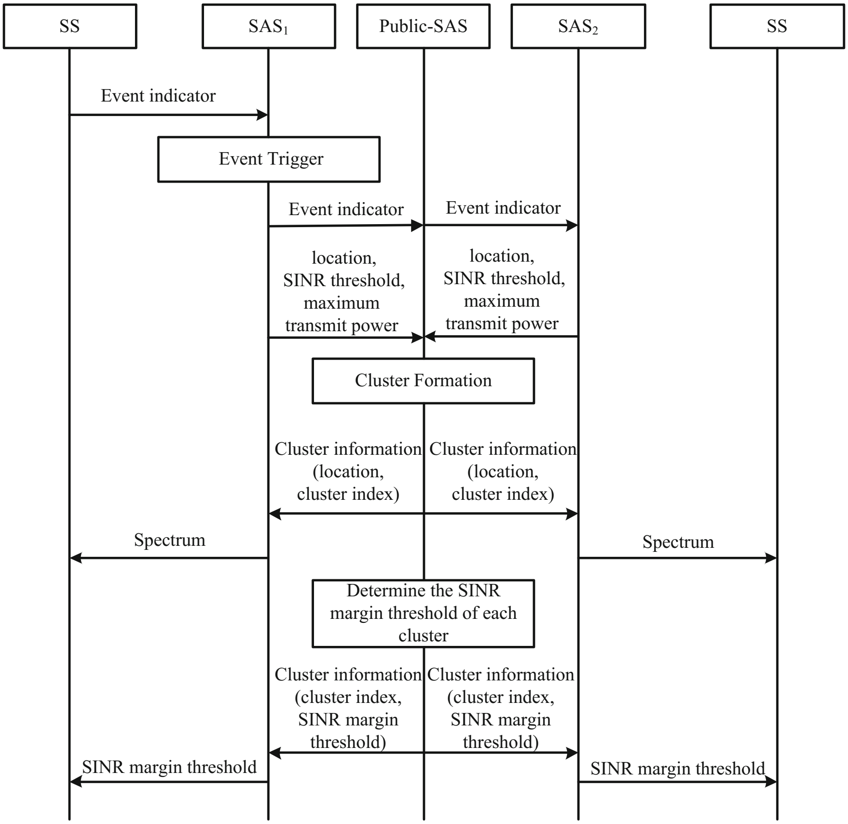

Fig. 6. Flowchart of the proposed clustering-based spectrum allocation and power adjustment scheme. Note that "Public-SAS" is the proposed third-party agent to coordinate the different SASs in the overlapping areas.

6 Performance Simulations

Simulations are conducted to evaluate the performance of the proposed algorithms.

6.1 Simulation Scenario

In the simulation, 12 SSs belonging to different SASs coexist in an area of 100 m × 100 m. For a given time instance, it is assumed that there is only one pair of SU transmitter and receiver in each SS. SSs in the spectrum sharing overlapping area are small cells with various SINR requirements, and the radius of each SS is assumed to be 20 m. The transmitter is at the cell center and the receiver is at the cell edge.

6.2 Simulation Parameters

Major simulation parameters are listed in Table 1. The SINR thresholds of 12 SUs are different from each other, ranging from 9 dB to 20 dB with a step size of 1 dB.

Table 1. List of simulation parameters

Symbol	Definition	Value
N_p	Number of secondary systems (SU Tx-Rx pairs)	12
N_c	Number of available channels	3
NF	Noise figure of SU receiver	5 dB
$SINR_{th}$	SINR threshold	9 dB–20 dB
P_{max1}	Maximum transmit power of the former 6 SUs	3 dBm
P_{max2}	Maximum transmit power of the latter 6 SUs	0 dBm
$\alpha_{ii} = \alpha_{jj}$	Path loss exponent	2.5
$\alpha_{ij} = \alpha_{ji}$	Path loss exponent	3.5
$SINR_{th\_margin}$	$SINR$ margin threshold	0 dB

6.3 Ratio of Satisfied SUs

In this simulation, we only change the random locations of the 12 SUs in 10000 simulation runs, and get the ratio of satisfied SUs (i.e., $SINR \geq SINR_{th}$). As shown in Table 2, the ratio of satisfied SUs can be increased with the proposed weight setting and it can be further increased with the power adjustment.

Table 2. Ratio of satisfied SUs

Algorithm in use	Sequential Coloring [9]	Using the proposed clustering procedure with the existing weight as defined by (3) (without power adjustment)	Using the proposed clustering procedure with the proposed weight as defined by (4) (without power adjustment)	Using the proposed clustering procedure with the proposed weight as defined by (4) (with power adjustment)
Ratio of satisfied SUs	82%	84%	95%	96%

6.4 Comparison of the CDF of SINR

In this simulation, SU_1 has the highest SINR requirement, i.e., 20 dB. In Fig. 7, the SINR cumulative distribution function (CDF) curve corresponding to SU_1 is plotted. As shown in Fig. 7, in sense of probability of satisfying the SINR threshold, the proposed weight scheme results in better performance than the existing weight. The probability of failing to meet the SINR requirement is about 6% with the sequential coloring algorithm when using the existing weight, while it is reduced to 0% when adopting the proposed weight setting. In addition, the SINR values are more concentrated after applying the power adjustment.

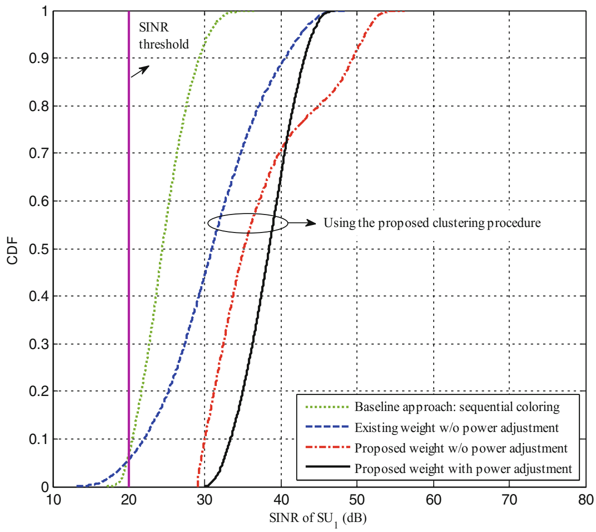

Fig. 7. CDF of SINR of SU_1

6.5 Sum of Co-channel Interference

In this simulation, the sum of co-channel interference is defined by (5).

$$I_{sum} = \sum_{m=1}^{Nc} \sum_{i,j \in C_m} P_j d_{ij}^{-\alpha_{ij}} \tag{5}$$

where C_m represents the m-th cluster; N_c is total number of the clusters in the overlapping area; P_j is the transmitting power of the j-th SS; d_{ij} is the distance between the transmitter in the j-th SS to the receiver in the i-th SS; α_{ij} is the path loss exponent between the transmitter in the j-th SS to the receiver in the i-th SS.

Figure 8 shows the sum of co-channel interference when using different algorithms. Simulation results demonstrate that the proposed weight leads to better performance in terms of sum interference as compared to the traditional weight. Furthermore, the sum of interference can be further reduced with the power adjustment according to the SINR margin.

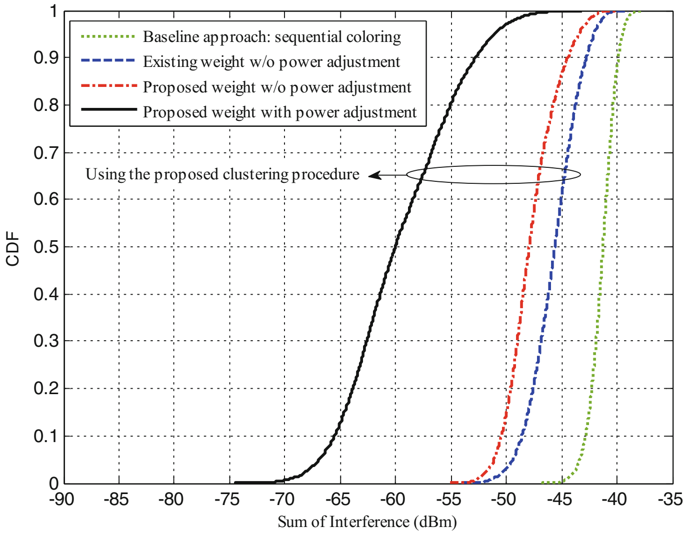

Fig. 8. CDF of the sum of interference

7 Conclusion

In this paper, the inter-operator interference in the overlapping area of different SASs is addressed without directly exchanging SUs' sensitive information between SASs. A clustering-based spectrum allocation and power adjustment scheme is proposed to improve the ratio of satisfied SUs while reducing the sum of co-channel interference. In the clustering procedure, a novel weight is defined and employed in the undirected weighted graph, which takes each SU's SINR requirement into account. Furthermore, the SINR margin-based power adjustment is employed to further reduce the sum interference. Simulation results, such as the ratio of satisfied SUs, the CDF of SINR and the sum interference, demonstrate the effectiveness and advantages of the proposed algorithm. The proposed scheme is also applicable to scenarios with mobile SUs. The only difference is that the clustering algorithm needs to be conducted periodically in response to the topology changes due to UE mobility. Given the limited number of available channels, when the number of SUs keeps increasing, not all SUs' QoS requirements could be satisfied through clustering and power adjustment. Further interference management (such as interference alignment) can be applied within each cluster to accommodate even more SUs, which is worthy investigation in the future.

References

1. PCAST Report to the President. Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth. Executive Office of the President and President's Council of Advisors on Science and Technology, July 2012
2. Yu, Q., Wang, J., Yang, X., Zhu, Y., Teng, Y., Kari, H.: Inter-operator interference coordination for co-primary spectrum sharing in UDN. China Commun. **12**, 104–112 (2015)
3. Jung, M., Hwang, K., Choi, S.: Interference minimization approach to precoding scheme in MIMO-based cognitive radio networks. IEEE Commun. Surv. Tutor. **15**(8), 789–791 (2011)
4. Lee, K.-J., Lee, I.: MMSE based block diagonalization for cognitive radio MIMO broadcast channels. IEEE Trans. Multimedia **10**(10), 3139–3144 (2011)
5. Park, J., Lee, B., Shim, B.: A MMSE vector precoding with block diagonalization for multiuser MIMO downlink. IEEE Trans. Commun. **60**(2), 569–577 (2012)
6. Sun, C., Ge, J., Bao, X., Shi, X.: A leakage-based precoding scheme for cognitive multiuser MIMO systems. In: IEEE 4th International Conference on Intelligent Networking and Collaborative Systems, Salerno, pp. 562–565 (2012)
7. Xu, Y., Mao, S.: Distributed interference alignment in cognitive radio networks. In: IEEE 22nd International Conference on Computer Communications and Networks (ICCCN), Nassau, pp. 1–7 (2013)
8. Yeh, S., Shilpa, T., Nageen, H., Kerstin, J.: Power control based interference mitigation in multi-tier networks. In: IEEE GLOBECOM Workshops, Miami, USA, pp. 701–705 (2010)
9. Zhang, Q., Zhu, X., Wu, L., Sandrasegaran, K.: A coloring-based resource allocation for OFDMA femtocell networks. In: IEEE Wireless Communications and Networking Conference (WCNC), pp. 673–678 (2013)
10. Pateromichelakis, E., Shariat, M., Quddus, A., Tafazolli, R.: Dynamic clustering framework for multi-cell scheduling in dense small cell networks. IEEE Commun. Lett. **17**(9), 1802–1805 (2013)
11. Chen, S., Cheng, R.S.: Clustering for interference alignment in a multiuser interference channel. In: Proceedings of the IEEE VTC, Yokohama, Japan, pp. 1–5, May 2012
12. Bikov, E., Ghamri-Doudane, Y., Botvich, D.: Smart resource allocation with concurrent learning scheme for heterogeneous LTE small cell networks. In: IEEE Global Communications Conference (GLOBECOM), San Diego, California, USA (2015)
13. Zhang, H., Xiao, Y., Cai, L.X., Niyato, D., Song, L., Han, Z.: A hierarchical game approach for multi-operator spectrum sharing in LTE unlicensed. In: IEEE GLOBECOM, San Diego, California, USA (2015)
14. Tefek, U., Lim, T.J.: Interference management through exclusion zones in two-tier cognitive networks. IEEE Trans. Wireless Commun. **15**(3), 2292–2302 (2016)
15. Sohul, M.M., Yao, M., Yang, T., Reed, J.H.: Spectrum Access System for the Citizen Broadband Radio Service. IEEE Commun. Mag. **53**(7), 18–25 (2015)