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Resource Management for LTE-U Based Small Cell Systems*

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As the development of wireless communication techniques, more and more related intelligent personal devices have been invented to link with wireless networks, i.e. tablets, smart watches, and unmanned ground vehicular. Driven by this, the wireless data will explode continuously as predicted in [1]. The monthly global data traffic will be 49 exabytes by 2021, and annual traffic will exceed half a zettabyte. The number of mobile-connected devices per captia will reach 1.5 by 2021. The *fourth generation* (4G) wireless communication systems can not meet such demands due to the limited licensed frequency spectrum resource. To deal with such challenge, one key and long term solution is to enlarge the reuse of the licensed frequency bands. Correspondingly, the ultra dense small cellular systems have been proposed in the *fifth generation* (5G) wireless communication systems to realize the effective frequency spectrum reuse on licensed bands [2]. As a result, the spectrum is successfully reused so that the *spectral efficiency* (SE) and system capacity can be improved to an extreme extend. Furthermore, the distance to the end users becomes shorter which will improve the *quality of service* (QoS).

However, deploying small cell into the conventional cellular systems is not straight forward due to the co-channel interference brought by the frequency reuse. Without dealing with such interference, the SE may not improve, but jeopardized. Conventionally, cellular systems employ centralized scheduling schemes to manage the system resources mainly including transmission power and frequency spectrum. When deploying *multiple small base stations* (SBSs) into the conventional cellular systems, it is impractical to still use the centralized resource management schemes. On one hand, the communication between the *macro base station MBS* and SBSs is constrained due to the limited backhaul resources between the small cell and macro cell systems. Secondly, the communication between the MBS and SBSs will bring tremendous signaling overhead, which is hard to be realized in practice. Therefore, the successful deployment of small cell systems to improve the SE on licensed bands is fully dependent on how to design a distributed or decentralized effective resource management scheme.

Authors in [3] and [4] have investigated if a given licensed frequency resource should be dedicated, shared or partly dedicated and partly shared between the MBS and SBSs. The co-channel interference has been investigated in dense small cell systems and two interference mitigation method have been proposed in [5] based on the resource partition in time and frequency domain. In [6], the impairment to the *small cell users* (SUEs) due to the co-channel interference is investigated. Then, the conditions to the universal frequency reuse are derived. A dynamic cell muting scheme has been proposed in [7], where some frequency resuse at certain small cells are muted for the interference mitigation to the other small cells. From a different direction, a user-centric interference nulling scheme [8] has been proposed, where a user initiates the suppression of the interference of some neighboring SBSs according to their distances to the user. When considering the distributed structure of the small cell systems, the mean-field game theory has been applied to design a distributed interference mitigation scheme in [9]. In [10], the game theoretic method is combined with the graph theory to model the system and design a corresponding decentralized interference coordination scheme. None-cooperative game theory is applied to design a distributed power allocation method to coordinate the interference among SBSs, where the Nash Equilibrium can be reached. The above mentioned works have only considered the licensed bands.

Another way to break the frequency spectrum shortage barrage on licensed bands is to exploit the unlicensed bands dominated by Wi-Fi systems[11]. There is over 400 MHz unlicensed spectrum for public since the *Federal Communications Commission* (FCC) has released an additional 295 MHz bandwidth in the 5 GHz *Unlicensed National Information Infrastructure* (U-NII) band. With low *operational expenditure* (OPEX) charges, Wi-Fi system have been the dominant player on all unlicensed bands in 2.4 and 5 GHz [12]. However, SE in Wi-Fi systems is low since there is no resource management schemes in Wi-Fi systems as efficient as the one in cellular systems. In contrast, *long-term evolution* (LTE) used in cellular systems has more efficient resource management and error control techniques. Therefore, enabling the small cell systems on the unlicensed bands, named as *LTE-unlicensed* (LTE-U), can not only alleviate spectrum scarcity, but also improve the SE on the unlicensed bands. One of the critical challenges for the LTE-U system is how to deal with interference to the existing Wi-Fi users and ensure harmonious coexistence.

According to above analysis, we will design one distributed resource management scheme for the LTE-U based small cell systems to maximize the SE on licensed bands and guarantee harmonious coexistence with Wi-Fi systems on unlicensed bands, while satisfying SUEs' and *macro-*

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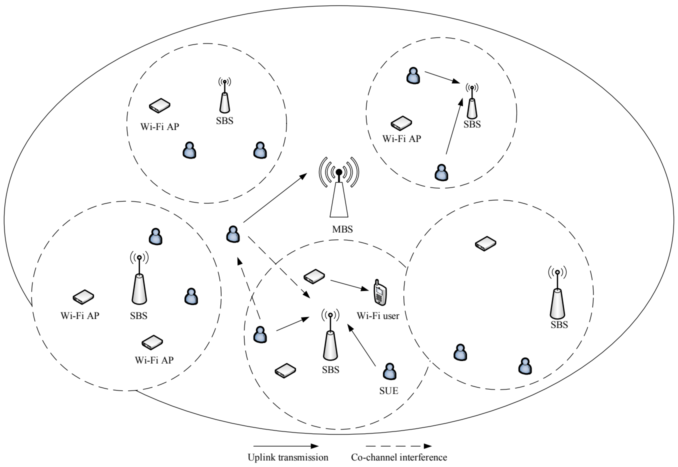

Fig. 1. System model.

cell users MUEs' *quality of service* (QoS) requirement. For the distributed scheme, there exists not or very limited information exchange between the MBS and SBSs.

We study the system where S SBSs, denoted by the set $\mathcal{S}$ reuse the uplink frequency spectrum of the MBS and share unlicensed band with multiple Wi-Fi APs, as shown in Fig. 1. Each SBS, s, shares unlicensed bands with W_s Wi-Fi APs, denoted by sets $\mathcal{W}_s,\ s \in \mathcal{S}$, to serve uplink transmission of K_s *small cell users* (SUE)s, denoted by sets $\mathcal{K}_s,\ s \in \mathcal{S}$. The *Orthogonal Frequency Division Multiple Access* (OFDMA) is employed in the system by which the licensed band is equally divided into N subchannels denoted by set $\mathcal{N}$.

A. Achievable Data Rates

When the SBS s reuses subchannel n to serve SUE k, the achievable data rate is given by

$$r_{s,k,n} = c_{s,k,n} B^{(L)} \log\left(1 + \frac{p_{s,k,n} h_{s,k,n}}{(I_{s,k,n} + N_0)\, c_{s,k,n}}\right), \quad (1)$$

where $c_{s,k,n}$ is the time sharing factor of SUE k on subchannel n and satisfies $0 \leqslant \sum_{k\in\mathcal{K}_s}\sum_{n\in\mathcal{N}} c_{s,k,n} \leqslant 1$, $r_{s,k,n} = 0$ if $c_{s,k,n} = 0$, $B^{(L)}$ is the bandwidth of each subchannel, $p_{s,k,n}$ is the transmission power of SUE k on subchannel n, $h_{s,k,n}$ is the channel gain between the SUE k and SBS s on subchannel n, $I_{s,k,n}$ is the interference from the macro cell user and SUEs of other small cells, N_0 is the noise power. Therefore, the total uplink transmission rate on the licensed channel achieved at the SBS s is given by

$$r_s^{(tot)} = \sum_{k\in\mathcal{K}_s}\sum_{n\in\mathcal{N}} r_{s,k,n}. \quad (2)$$

On the other hand, when the SBS s shares the unlicensed channel with Wi-Fi AP m to serve SUE k, its achievable data rate is given by

$$\hat{r}_{s,k,m} = B_k^{(U)} \beta_{s,k,m} \log\left(1 + \frac{\hat{p}_{s,k,m}\hat{h}_{s,k,m}}{\hat{N}_0})\right), \quad (3)$$

where $\hat{p}_{s,k,m}$ is the transmission power of SUE k on unlicensed channel, $\hat{h}_{s,k,m}$ is the channel power gain on unlicensed channel m between the SBS s and SUE k, $\beta_{s,k,m}$ is the time fraction allocated to SUE k on unlicensed channel at the SBS s, $B_m^{(U)}$ is the bandwidth of unlicensed channel used by Wi-Fi AP m. Then, the sum data rate obtained at the SBS on the unlicensed band is given by

$$\hat{r}_s^{(tot)} = \sum_{k\in\mathcal{K}_s}\sum_{m\in\mathcal{W}_s} \hat{r}_{s,k,m}. \quad (4)$$

Based on (4) and (2), the total data rate achieved at the SBS is written as

$$R_s^{(tot)} = r_s^{(tot)} + \hat{r}_s^{(tot)}. \quad (5)$$

B. Interference on licensed band

As we indicated in (1), each SUE served by the SBS s will experience the interference, $I_{s,k,n}$, when s reuses the licensed channel n, with the MBS and other SBSs, which is given by

$$I_{s,k,n} = \sum_{i\in\mathcal{S}, i\neq s}\sum_{j\in\mathcal{K}_i} p_{i,j,n}\tilde{h}_{i,j,k,n} + \sum_{l\in\mathcal{K}_M} \tilde{p}_{l,n} g_{l,k,n}, \quad (6)$$

where $p_{i,j,n}$ is the transmission power of SUE j served by SBS i on subchannel n, $\tilde{h}_{i,j,k,n}$ is the interference channel power gain from SUE j to SUE k, $\mathcal{K}_M$ is the set of users served by the MBS, $\tilde{p}_{l,n}$ is the transmission power of user l served by the MBS on channel n. In our work, we assume that the $\tilde{p}_{l,n},\ \forall l \in \mathcal{K}_M$ is fixed and the interference from macro cell users are treated as a Gaussian noise at the SBS since the interference channel power gains $g_{l,k,n},\ \forall l \in \mathcal{K}_M,\ k \in \mathcal{K}_s,\ n \in \mathcal{N}$ are unknown at each SBS.

On the other hand, the interference experienced at the MBS on subchannel n is given by

$$\widetilde{I}_n = \sum_{s\in\mathcal{S}}\sum_{k\in\mathcal{K}_s} p_{s,k,n}\widetilde{g}_{s,k,n}, \quad (7)$$

where $\widetilde{g}_{s,k,n}$ is the interference channel power gain on subchannel n from the kth SUE served by SBS s to the MBS. When SBSs reuse the licensed bands with the MBS, the co-channel interference brought to the MBS should not exceed a threshold.

C. Collision probability on unlicensed band

Different from the licensed bands, unlicensed frequency spectrum is usually shared in *time division multiple access* (TDMA) mode. The small cell and Wi-Fi systems can not use the unlicensed channels simultaneously. Therefore, the collision will occur when they access the same unlicensed channel at the same time. Collision probability is directly related to the $\sum_{s\in\mathcal{S}}\sum_{k\in\mathcal{K}_s}\beta_{s,k,m}$, which is the time fraction used by SBSs on unlicensed channel m. To reduce the influence to the Wi-Fi systems and guarantee the harmonious coexistence, the time fraction used by SBSs on each unlicensed channel m should be constrained.

D. Problem formulation

In the paper, our aim is to maximize the SE on licensed bands, which is defined as

$$f_{se} = \frac{\sum\limits_{s\in\mathcal{S}} r_s^{(tot)}}{B^{(L)}}. \tag{8}$$

Since $B^{(L)}$ is fixed, maximizing f_{se} is equal to maximize $\sum\limits_{s\in\mathcal{S}} r_s^{(tot)}$ on licensed bands.

With the licensed and unlicensed bands, each SBS needs to guarantee that the data rate requirement of it served SUEs is satisfied. Therefore, we have the following constraint

$$\sum_{n\in\mathcal{N}} r_{s,k,n} + \sum_{m\in\mathcal{M}} \widehat{r}_{s,k,m} \geqslant \overline{r}_{s,k},\ \forall s\in\mathcal{S},\ \forall k\in\mathcal{K}_s, \tag{9}$$

where the left section of the inequality is the total achievable data rate of SUE k, $\overline{r}_{s,k}$ is the data rate requirement of SUE k. Secondly, the total transmission power of each SUE k is limited, which is expressed as

$$\sum_{n\in\mathcal{N}} p_{s,k,n} + \sum_{m\in\mathcal{W}_s} \widehat{p}_{s,k,m} \leqslant \overline{p}_{s,k},\ \forall s\in\mathcal{S},\ \forall k\in\mathcal{K}_s, \tag{10}$$

where $\overline{p}_{s,k}$ is the transmission power limit of SUE k served by the SBS s.

When reusing the licensed bands at the SBSs, the co-channel interference brought to the MBS should be constrained as we explained in Section B. Then, the third constraint should be

$$\widetilde{I}_n \leq \overline{I}_n,\ \forall n\in\mathcal{N}, \tag{11}$$

where $\overline{I}_n$ is the co-channel interference constraint to the MBS on subchannel n.

To guarantee the harmonious coexistence with the Wi-Fi system, the time fraction used by SBSs on each unlicensed channel m should be limited to

$$\sum_{s\in\mathcal{S}}\sum_{k\in\mathcal{K}_s} \beta_{s,k,m} \leqslant \overline{\beta}_m,\ \forall s\in\mathcal{S},\ \forall m\in\mathcal{W}_s, \tag{12}$$

where $\overline{\beta}_m$ is the upper bound on the utilization of unlicensed channel m.

Based on above analysis, an optimization is formulated as follows.

$$\max_{\mathbf{p},\widehat{\mathbf{p}},\mathbf{c},\boldsymbol{\beta}} \left\{ \sum_{s\in S} r_s^{(tot)} \right\}, \tag{13}$$

subject to
(9), (10), (11), (12), and

$$\begin{aligned} &\beta_{s,k,m} \geq 0,\ p_{s,k,n} \geq 0,\ \widehat{p}_{s,k,m} \geq 0, \\ &\forall s\in\mathcal{S},\ k\in\mathcal{K}_s,\ n\in\mathcal{N},\ m\in\mathcal{W}_m, \end{aligned} \tag{13a}$$

where $\mathbf{p}$ represents the S power allocation matrices of S SBSs to their SUEs on licensed subchannels, and each of them has $K_s \times N$ dimensions, $\widehat{\mathbf{p}}$ is the power allocation matrices of S SBSs to their SUEs on unlicensed channels, and each of them has $K_s \times W_s$ dimensions, $\mathbf{c}$ is to represent S matrices of time sharing factor of SUEs served by S SBSs on subchannels, and each of them has $K_s \times N$ dimensions, $\boldsymbol{\beta}$ denotes S matrices to represent the time fraction allocated to SUEs on unlicensed channel, an each of them has $K_s \times W_s$ dimension.

Obviously, it is impractical for the MBS to take care of the power and spectrum allocation strategy for each SBS because the interference channel information of all SUEs is impossible to be obtained at the MBS. Therefore, each SBS needs to work autonomously on its own power and spectrum management with the aim to maximize the SE on licensed bands. As a result, a corresponding distributed scheme needs to be designed.

One optional way is to use the game theoretical method to design the scheme where each SBS is modeled as a player [13]. If using the non-cooperate game to model the scheme, there is no information exchange among the SBSs, which means the co-channel interference mitigation is not well handled. On the other hand, if cooperate game is applied to model the method, there is a certain amount of information exchange among the SBSs and SE is able to be improved comparing to the non-cooperative game. Another alternative game theoretical model which can be applied to our model is the Stackelberg game model [14]. By using Stackelberg model, the MBS can be treated as a leader, and SBSs are modeled as followers. Then, by pricing the co-channel interference, the SBSs can compete for the licensed spectrum with the help of unlicensed bands. But, it is well known that the performance of game model is relative low and it has pretty slow convergence speed. If the interference from the macro cell user and SUEs of other small cells could be approximately evaluated in advance and treated as the noise, the object function (8) will become convex. Then we can use the primal-dual method [15], [16] to design the distributed constrained optimization algorithm to solve the problem (13) with a better convergence speed and performance.

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