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Resource Allocation in Moving and Fixed General Authorized Access Users in Spectrum Access System

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ABSTRACT Spectrum access system (SAS) is a spectrum sharing framework proposed to share the spectrum between the incumbent users and the citizen broadband radio service devices, i.e. Priority access users and general authorized access (GAA) users. In this paper, we propose an interfering angle based method for the joint resource (channel and transmit power) allocation problem to the mobile and fixed GAA users. With mobile GAA users, the set of GAA users that can hear each other will change at different time instants making the resource allocation problem more challenging. The resource allocation of fixed and mobile GAA users is done considering coexistence with priority users, as well as coexistence between mobile and fixed GAA users. For the conflict-free resource allocation to fixed and mobile GAA users, we propose to use the maximum allowed transmit power for the beams of fixed GAA users that lie within the interference range of mobile GAA users. The simulation results show improved capacity from our proposed method while satisfying a predetermined interference constraint.

INDEX TERMS Spectrum access system, citizen broadband radio service devices, moving general authorized access users, resource allocation, interference mitigation.

I. INTRODUCTION

With the increasing demand in capacity, regulatory bodies have proposed spectrum sharing standards that allow the use of underutilized spectrum by the secondary users. The Federal Communication Commission (FCC) has proposed the use of the spectrum band 3550 to 3700 MHz by small cells also known as citizen broadband radio services which are primarily owned by federal users and non-federal satellite services. Spectrum Access System (SAS) has different priority of users who are Incumbent Access (IA) users, Priority Access Licensee (PAL) users and General Authorized Access (GAA) users. IA users have the highest priority, and they receive interference protection from citizen broadband radio service devices (CBSDs).

PAL users can access the spectrum by competitive bidding up to seven 10 MHz channels in a census tract. IA and PAL users receive interference protection, and GAA users receive no interference protection from the other tiers of users. GAA users can access throughout 150 MHz. PAL and GAA citizen broadband radio service devices need to report their location coordinates along with the other transmission characteristics to SAS to protect the incumbents from the harmful interference. In SAS to protect PAL users the Root Mean Square (RMS) interference from GAA users at the PAL protection area should be at or below the −80 dBm when integrated over a 10 MHz bandwidth [1], [2].

Environmental Sensing Capability (ESC) senses the federal users and provide information to the SAS based on which PAL users are allocated channel. In SAS to maximize the spectrum utilization, the PAL channel can be accessed by GAA users located outside the PAL protection area. To ensure the interference criteria at the PAL protection area is satisfied channel allocation for GAA users depends on the location of GAA users.

There is a significant increase in the mobile data traffic and to accommodate the growing moving data traffic moving

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small cells have been proposed in the literature. We consider two types of GAA users in this study, i.e. fixed GAA (FGAA) users and mobile GAA (MGAA) users. FGAA users have fixed locations, and MGAA users are installed in vehicles. In this study, we consider MGAA users are installed in trains and they move in fixed paths, i.e. train tracks. We define the carrier sensing range as the range in which other GAA users can hear a transmitting GAA user. Dense deployment of GAA users may result in overlapping carrier sensing ranges with neighboring GAA users. GAA users can interfere with each other when the overlapped GAA users transmit in the same channel at the same time.

In this work, we present the conflict-free coexistence between PAL users, FGAA users and MGAA users. For the conflict-free co-channel coexistence we consider four different categories of interferences which are listed below:

- Interference between PAL user and FGAA /MGAA user.
- Interference between FGAA user and FGAA user.
- Interference between FGAA user and MGAA user.
- Interference between MGAA user and MGAA user.

With a large number of small cells deployment, there is a significant increase in the overlapped coverage area. The user equipment (UE) in the overlapped area receives interference which reduces the network performance. The conflict-free resource management scheme is essential since interference would reduce network performance.

A. RELATED WORKS

Resource allocation is a well-investigated topic in a fixed small cell [3]–[9]. In [3] an iterative approach for the joint subchannel and transmit power allocation was proposed for the femtocells. In [4] the subchannel and power allocation problem for the cognitive small cells is studied using cooperative Nash bargaining game theory, where the cross-tier interference mitigation, minimum outage probability requirement, imperfect CSI and fairness in terms of minimum rate requirement are considered. Capacity aware channel allocation is presented in [5] for cognitive radios with only one interfering secondary user from the interfering set allocated to the same channel at the same time. In [6] to improve the spectrum utilization, interference alignment along with frequency clustering is proposed for the cognitive radio system. Resource allocation is done in a cognitive radio network in [7] with primary users cooperation by allowing only one secondary user to access the channel at a time. In [8] the authors provide an overview of the FCC regulation for citizen broadband radio services and utilize the listen before talk for the coexistence of GAA users. A super radio formation algorithm has been proposed in [9] for citizen broadband radio services utilizing a Wi-Fi like carrier sensing mechanism.

The resource allocation in a moving small cells has been investigated in [10]–[12]. In [10], [11] resource blocks and power are allocated to moving small cells to enhance the network service quality restricting one resource block to only one user at a certain time. However, in these studies, interference to fixed small cells is not considered for the resource allocation; conflicts between fixed and mobile small cells need to be addressed properly for the conflict-free resource allocation. In [12] resource allocation schemes for the fixed and mobile small cell users are reviewed, and their studies show that further studies need to be done to avoid interference to nearby fixed cells from the moving cells.

Traditional channel allocation schemes [3]–[9] avoid allocating the same channel to users that can interfere with each other. The GAA users that can hear each other can detect the other GAA users transmission. However, hidden GAA users interfere with each other causing the network performance degradation. Therefore, to reduce the interference between GAA users and to allocate multiple GAA users to the same channel in case of spectrum scarcity we propose a novel resource allocation scheme that considers the overlapping coverage area.

B. CONTRIBUTIONS AND ORGANISATION

In literature, mobile small cells are considered to improve the quality of service. However, mobility adds an additional challenge to the resource allocation problem. The main contributions of this paper are shown as follows:

- To the best of our knowledge for the first time joint channel and transmit power allocation is done jointly for the mobile and fixed GAA users, taking in the consideration the interfering set of GAA users that are changing continually with the mobility of MGAA users.
- In this work, we propose the interference angle based resource allocation method to allocate both MGAA and FGAA users with overlapping areas to the same channel at the same time.
- To maximize the GAA network capacity, we propose a conflict-free channel allocation constraint, i.e. the maximum allowed transmit power to the beams of the FGAA users that are within the carrier sensing range of the MGAA users.
- Interference aware resource allocation algorithm is proposed that considers not only the interference protection to PAL users protection area but also ensures the self coexistence between GAA users. We predict the interference between FGAA users and MGAA users as well as between MGAA users based on their mobility pattern.

The remainder of this paper is organized as follows. In section II the system model is presented and the problem formulation for joint channel and transmit power allocation are presented in section III. Simulation results and discussion are shown in section IV, followed by the conclusion in section V.

The notation that will be used in this paper is summarized in Table 1.

II. SYSTEM MODEL

In this work, we consider a GAA network that consists of F FGAA users and M MGAA users, and P PAL users as shown in Figure 1. We denote FGAA users by i, $i \in \mathcal{F} = \{1, \ldots, F\}$, MGAA users by j, $j \in \mathcal{M} = \{1, \ldots, M\}$ and PAL users by m,

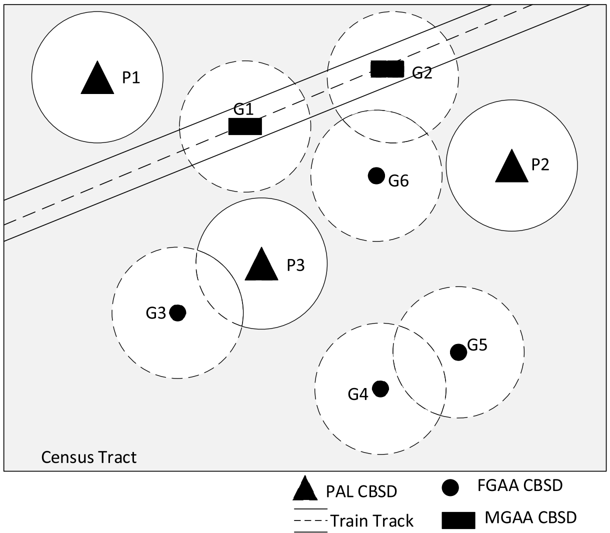

FIGURE 1. Illustration of PAL, FGAA, MGAA users interference scenarios in a census tract.

TABLE 1. Symbols and definitions.

Symbol	Definition
$\mathcal{P}$	Set of PAL users
$\mathcal{C}$	Set of PAL Channels
$\mathcal{F}$	Set of FGAA users
$\mathcal{M}$	Set of MGAA users
B_i	Total number of beams of the ith FGAA user
i	FGAA user index
j	MGAA user index
m	PAL user index
c	PAL channel user index
$\hat{\mathcal{U}}_i$	Set of UEs that lie in the overlapped area
$\mathcal{U}_i^*$	Set of UEs that do not lie in the overlapped area
T	Total number of time slots
S	Superset of all the FGAA users that can hear each other
S^*	Superset of all the MGAA users that can hear each other
r_i^c	Carrier sensing range of the ith FGAA user when transmitting on the cth channel
$d_{i,j}(t)$	Distance between the ith FGAA user and the jth MGAA user at a certain time t
$Pt_{i,b}^c$	Transmit power for a set of beams that lie in the interfering angle
Pt_{i,b^*}^c	Transmit power for a set of beams that do not lie in the interfering angle
α_i^c	Indication function for the ith FGAA user channel allocation
β_j^c	Indication function for the jth MGAA user channel allocation
$\mathcal{S}_{\mathcal{N}}(t)$	Set of FGAA user and MGAA user that can hear each other at a certain time

$m \in \mathcal{P} = \{1, ..., P\}$. In SAS, PAL users use dedicated PAL channels denoted as c, $c \in \mathcal{C} = \{1, ..., C\}$. We consider a scenario in which $(F + M) >> C$.

In this study, we considered that the MGAA users are located in the trains. Trains move on a fixed track with a uniform speed; hence the mobility is deterministic [10]. We estimate the position of the MGAA users using the information of the MGAA user's velocity. We assume that MGAA users are equipped with an omnidirectional antennas and the FGAA users are equipped with smart antenna with switch beam systems with multiple beams to maximize the spectrum reuse in the GAA network [15]–[17]. We denote the beam of the ith FGAA user as b_i, $b_i \in \mathcal{B}_i = \{1, ..., B_i\}$ where B_i is the number of beams of the ith FGAA user.

In SAS, PAL channel is considered busy inside of the PAL protection area. And GAA users outside the PAL protection area can utilize the channel while satisfying the interference constraint at the PAL protection area. In Figure 1, MGAA user G1 can use all the PAL channels while satisfying the interference constraint to PAL users. FGAA user G3 and PAL user P3 cannot transmit on the same channel at the same time to protect the PAL user from harmful interference. Also, FGAA users G4 and G5 would cause harmful interference to each other when transmitting on the same channel. Similarly, UEs associated with MGAA user G2 and FGAA user G6 interfere with each other in the overlapped area.

In this work, we divide the time into T time slots and each time slot is denoted by t. The interference between FGAA user and FGAA user is constant. However, the other three possible interferences involving MGAA user vary over time due to the mobility.

The channel gain from the ith GAA user to the uth user equipment (UE) on the pth PAL channel is given by:

$$h_{u,i}^p = 10^{-\frac{L_{i,u}^{dB}}{10}} \times \zeta_{u,i} \times \Gamma_{u,i}, , \quad \forall u = 1, 2, .., U \tag{1}$$

where $L_{i,u}$ is the pathloss between the ith GAA user and the uth GAA end user, $\zeta_{u,i}$ is the shadowing coefficient and is modeled as a correlated lognormal distribution, and $\Gamma_{u,i}$ is the Rayleigh distributed fading coefficient.

III. PROBLEM FORMULATION

Interference pattern between the FGAA users and MGAA users is time-dependent due to the mobility of the MGAA users. The Signal to Interference plus Noise Ratio (SINR) at uth receiver of the ith FGAA user over the cth channel in time t is given by:

$$\gamma_u^c(t) = \frac{Pt_i^c(t)h_{u,i}^c(t)}{P_N + \sum_{o\in\mathcal{F}\setminus\{i\}} Pt_o^c(t)h_{u,o}^c(t) + \sum_{j\in\mathcal{M}} Pt_j^c(t)h_{u,j}^c(t)} \tag{2}$$

where $Pt_i^c(t)$ is the transmit power of the ith FGAA users on the cth channel in time t, $\sum_{o\in\mathcal{F}\setminus\{i\}} Pt_o^c(t)h_{o,u}^c$ is the interference on the uth user equipment from other transmitting FGAA users and $\sum_{j\in\mathcal{M}} Pt_j^c(t)h_{j,u}^c(t)$ is the interference on the uth user equipment (UE) from the jth transmitting MGAA users.

Similarly, $\gamma_v^c(t)$ is defined for UE v_j of the jth MGAA user.

$$\gamma_v^c(t) = \frac{Pt_j^c(t)h_{v,j}^c(t)}{P_N + \sum_{i\in\mathcal{F}} Pt_i^c(t)h_{v,i}^c(t) + \sum_{k\in\mathcal{M}\setminus\{j\}} Pt_k^c(t)h_{v,k}^c(t)} \tag{3}$$

The downlink capacity per GAA user for the jth MGAA user when transmitting on the cth channel at a certain time t

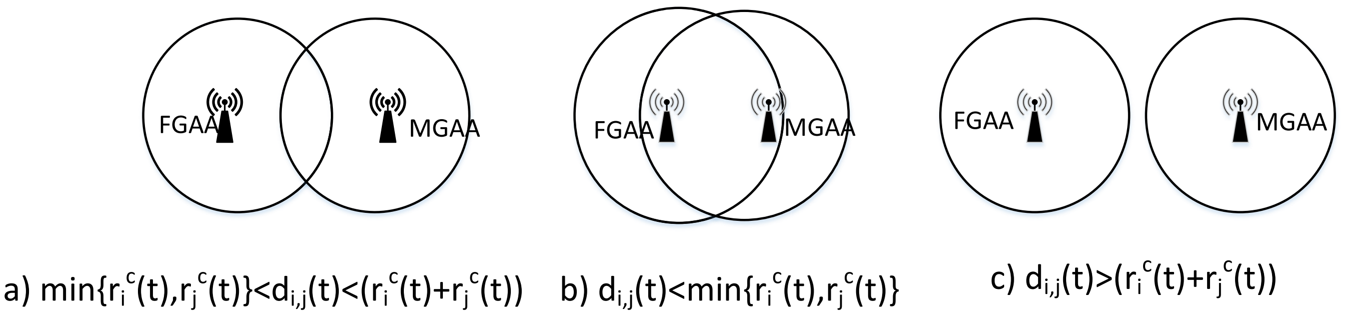

FIGURE 2. Impact of MGAA users interference to FGAA users a) MGAA users and FGAA users cannot hear each other, but UE in overlapped area are interfered b) MGAA users and FGAA users can hear each other, i.e. they are within the carrier sensing range c) MGAA user and FGAA user do not interfere with each other.

is given by

$$C_j^c(t) = \frac{1}{|\mathcal{V}_j|}\sum_{v=1}^{|\mathcal{V}_j|}\log_2\left(1+\gamma_v^c(t)\right) \tag{4}$$

where $|\mathcal{V}_j|$ is the total number of user equipment (UE) in the jth MGAA user. Similarly, for the ith FGAA user $C_i^c(t) = \frac{1}{|\mathcal{U}_i|}\sum_{u=1}^{|\mathcal{U}_i|}\log_2\left(1+\gamma_u^c(t)\right)$, where $|\mathcal{U}_i|$ is the total number of UE in the ith FGAA user.

According to FCC documents, the nodes can hear each other if the received signal strength is 6 dB above the noise floor [20], [22]. Considering that GAA users are transmitting with the maximum allowed transmit power we find the carrier sensing range of both FGAA users and MGAA users as [19]:

$$r_i^c = 10^{\left(\left(10\log_{10}\left(\frac{P_{max}}{Pr}\right)-46.4-20\times\log_{10}0.2f\right)/20\right)} \tag{5}$$

where r_i^c is the carrier sensing range of the ith FGAA user when transmitting on the cth channel, P_{max} is the FCC allowed maximum transmit power, $Pr(dB) = (N_{fl}+6)$ is the received power threshold for GAA users to hear each other, and N_{fl} is the noise floor in dBm.

The impact of MGAA users interference to the FGAA users is shown in Figure 2. The first type of conflict is the one in which MGAA user is hidden from FGAA user, i.e. FGAA user and MGAA user cannot hear each other as shown in Figure 2(a). MGAA users are hidden if the distance between the ith FGAA user and the jth MGAA user at a certain time t, i.e. $d_{i,j}(t)$ is smaller than $(r_i^c(t)+r_j^c(t))$ but larger than $\min\{r_i^c(t), r_j^c(t)\}$. In the overlapped area, the UEs that are associated with the ith FGAA user and the jth MGAA user are interfered. In this work, for the first type of conflict where FGAA users and MGAA users are hidden from each other we propose the interfering angle based resource allocation to ensure the self coexistence between mobile and fixed GAA users. The second type of conflict as shown in Figure 2(b) is the one in which MGAA user and FGAA user can hear each other, i.e. $d_{i,j}(t) \le \min\{r_i^c(t), r_j^c(t)\}$. For the second type of conflict, we consider that only users from the set that can hear each other can transmit on the same channel at the same time. Similarly, in a scenario as shown in Figure 2(c) FGAA users and MGAA users do not interfere with each other. When $d_{i,j}(t) > (r_i^c(t)+r_j^c(t))$ both FGAA users and MGAA users can use the same channel at the same time while satisfying the FCC proposed interference threshold.

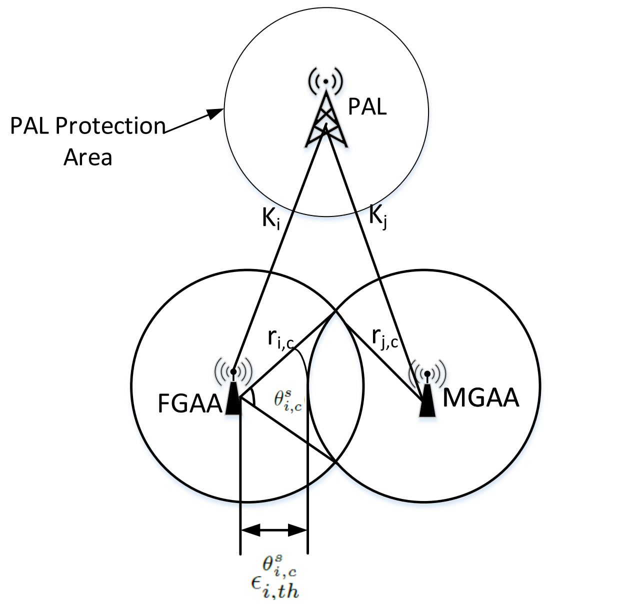

FIGURE 3. Illustration of FGAA user and MGAA user with overlapped area. K_i and K_j points in PAL protection area to find the RMS interference from GAA users.

A. INTERFERING ANGLE BASED MAXIMUM ALLOWED FGAA TRANSMIT POWER CONSTRAINT

Due to the mobility, the MGAA users can be in the interference range of FGAA users for a certain time. $\theta_{i,c}(t)$ is the interfering angle on the ith FGAA user from the jth MGAA user at time t as shown in Figure 3, and is given by

$$\theta_i^c(t) = 2\cos^{-1}\left(\frac{d_{i,j}^2(t)+r_i^c(t)^2-r_j^c(t)}{2r_i^c(t)d_{i,j}(t)}\right) \tag{6}$$

where $d_{i,j}(t)$ is the distance between the ith FGAA user and the jth MGAA user at a certain time t.

In this work, we propose the interfering angle based resource allocation to the ith FGAA user, $\forall i \in \mathcal{F}$ during the time the ith and jth GAA users are in the carrier sensing range. For the conflict-free channel allocation to FGAA users and MGAA users, the carrier sensing range threshold of the ith

FGAA user in $\theta_i^c(t)$ angle should be:

$$\epsilon_{i,th}^{\theta_i^c}(t) = d_{i,j}(t) - r_j^c(t) \tag{7}$$

To ensure the self-coexistence between the FGAA users and MGAA users, FGAA users need to satisfy the following constraint in $\theta_i^c(t)$ angle.

$$10^{\left(\left(10\log_{10}\left(\frac{Pt_i^{\theta_i^c}(t)}{Pr}\right)-46.4-20\times\log_{10}\frac{f}{5.0}\right)/20\right)} \leq \epsilon_{i,th}^{\theta_i^c}(t) \tag{8}$$

where the left-hand side of equation (8) is the carrier sensing range of the ith FGAA user, and $Pt_i^{\theta_i^c}(t)$ is the transmit power of the ith FGAA user in $\theta_i^c(t)$ angle.

Let $\mathcal{B}_i^{\hat{c}}(t)$ is the set of beams that lies in the interfering angle $\theta_i^c(t)$ when $\min\{r_i^c(t), r_j^c(t)\} < d_{i,j}(t) < (r_i^c(t)+r_j^c(t))$. For the conflict-free resource allocation to FGAA users and MGAA users, we propose a method to find the maximum allowed transmit power to the $\mathcal{B}_i^{\hat{c}}(t)$ set of beams. The maximum allowed transmit power for the bth beam, $\forall b \in \mathcal{B}_i^{\hat{c}}(t)$ of the ith FGAA user can be determined by solving equation (8) which is given by:

$$P_{max}^{\theta_{i,b}^c}(t) = Pr \times 10^{\frac{L^{dB}(\epsilon_{i,th}^{\theta_i^c}(t))}{10}} \tag{9}$$

where $L^{dB}(\epsilon_{i,th}^{\theta_i^c}(t))$ is the path loss for the ith GAA for the $\epsilon_{i,th}^{\theta_i^c}(t)$ distance.

The maximum allowed transmit power for the $\mathcal{B}_i^{\hat{c}}(t)$ set of beams that lies in the interfering angle $\theta_{i,c}(t)$ for the ith FGAA user is given by:

$$0 \leq Pt_{i,b}^c \leq P_{max}^{\theta_i^c}, \quad \forall b \in \mathcal{B}_i^{\hat{c}}(t) \tag{10}$$

The maximum allowed transmit power constraint for the jth MGAA user and the b^*th beam of the ith FGAA user that does not lie in the $\theta_{i,c}(t)$ angle is given by:

$$0 \leq Pt_{i,b^*}^c, \quad Pt_j^c \leq P_{max}, \ \forall b^* \in \mathcal{B}_i \backslash \mathcal{B}_i^{\hat{c}}(t) \tag{11}$$

Using the interfering angle based maximum allowed transmit power constraint for FGAA users, both FGAA users and MGAAs user can transmit at the same time on the same channel. With our proposed method the FGAA user coverage area will be divided into three parts, one part where the beams transmit power is unchanged, the other part with reduced transmit power for the beams in the presence of MGAA user and a small area with no coverage. The downlink capacity per user for the FGAA user from our proposed method is

$$C_i^c(t) = \frac{1}{\mathcal{U}_i^*}\sum_{u^*=1}^{|\mathcal{U}_i^*|}\log_2\left(1+\gamma_{u^*}^c(t)\right) + \frac{1}{\hat{\mathcal{U}}_i}\sum_{\hat{u}=1}^{|\hat{\mathcal{U}}_i|}\log_2\left(1+\gamma_{\hat{u}}^c(t)\right) \tag{12}$$

where $\mathcal{U}_i^*$ are the UEs that lie in the area with no transmit power changes, $\hat{\mathcal{U}}_i$ are the UEs that lie in the area with changed transmit power, and $\left(\mathcal{U}_i^* + \hat{\mathcal{U}}_i\right) \leq \mathcal{U}_i$.

Lemma 1: Our proposed method of resource allocation for FGAA users and MGAA users is conflict-free.

FGAA user and MGAA user interfere with each other if the coverage area overlaps, i.e. $d_{i,j} < r_j^c(t) + r_i^c(t)$. *In our proposed method to ensure the conflict-free channel allocation, the maximum allowed transmit power is allocated to the beams of FGAA users that lie in interfering angle such that* $\epsilon_{i,th}^{\theta_i^c}(t) = d_{i,j}(t) - r_j^c(t)$.

B. INTERFERENCE PROTECTION TO PAL USERS

In SAS, to ensure that PAL protection criteria are satisfied, the channel is considered as busy for GAA users inside the PAL protection area; however the PAL channel can be utilized by GAA users beyond the PAL protection area, i.e.

$$d_{i,m} > R_m \tag{13}$$

where R_m is the radius of the mth PAL user protection area.

To satisfy the above conditions, we find the set of FGAA users, i.e. $\hat{\mathcal{F}}$ and the set of MGAA users, i.e. $\hat{\mathcal{M}}$ that satisfy the condition $d_{i,m} > R_m$ and $d_{j,m}(t) > R_m$.

To protect PAL users from harmful interference, the Root Mean Square (RMS) interference from GAA users $\forall i \in \mathcal{F}, \ j \in \mathcal{M}$ at the PAL protection area should be less than the FCC proposed interference threshold. Let K_i, be the nearest point at the mth PAL protection area from the ith GAA user as shown in Figure 3. The point in the PAL protection area with the shortest distance from the GAA user receives the maximum interference. RMS interference at the mth PAL protection area is given by:

$$I_{K_{i,j}}^m = \frac{1}{T}\int_0^T \left(\sum_{i=1}^{F^*(t)} Pt_{i,b^*}^c(t)h_{i,m}(t) + \sum_{j=1}^{M^*(t)} Pt_j^c(t)h_{j,m}(t)\right)dt \tag{14}$$

where b^* is the beam in the direction of the mth PAL user, $F^*(t)$ is the total number of transmitting FGAA users at a certain time, and $M^*(t)$ is the total number of transmitting MGAA users at the certain time. $\frac{1}{T}\int_0^T \left(\sum_{i=1}^{F^*(t)} Pt_{i,b^*}^c(t)h_{i,m}(t)\right)dt$ is the RMS interference to mth PAL user from transmitting FGAA users, and $\frac{1}{T}\int_0^T \left(\sum_{j=1}^{M^*(t)} Pt_j^c(t)h_{j,m}(t)\right)dt$ is the RMS interference to mth PAL user from transmitting MGAA users.

To protect the mth PAL user from the GAA users harmful interference, RMS interference at the PAL protection area should be less than the FCC predetermined interference threshold, i.e. I_{th}.

$$I_{K_{i,j}}^m \leq I_{th}, \quad \forall j \in \mathcal{M}, \ \forall i \in \mathcal{N} \tag{15}$$

In this work, we have considered multiple PAL users allocated to the same channel. To ensure FCC proposed interference criteria are satisfied the RMS interference from GAA users should be less than the interference threshold at all the PAL users protection areas allocated to the same channel.

C. SELF COEXISTENCE BETWEEN GAA USERS CONSTRAINT

In this work, to ensure the self coexistence between GAA users that can hear each other we consider three different types of coexistence, i.e. coexistence between FGAA users, coexistence between MGAA users and the coexistence between FGAA users and MGAA users.

Let $\alpha_i^c(t)$ denote the indication function for FGAA users channel allocation.

$$\alpha_i^c(t) = \begin{cases} 1, & \text{if } i\text{th FGAA user is allocated to } c\text{th channel} \\ 0, & \text{Otherwise} \end{cases} \tag{16}$$

The FGAA users do not interfere with each other if $d_{i,o}(t) > (r_i^c + r_o^c), \forall i, o \in \mathcal{F}, i \neq o$. Let $\mathcal{S}_\mathcal{F}$ denote the set of FGAA users that satisfy the carrier sensing range condition $d_{i,o}(t) \leq \min\{r_i^c, r_o^c\}, \forall i, o \in \mathcal{F}, i \neq o$, where $d_{i,o}$ is the distance between the ith and oth FGAA user. To ensure the self coexistence between FGAA users that can hear each other, only one user from set $\mathcal{S}_\mathcal{F}$ can transmit at a particular time in the same channel, i.e.

$$\sum_{i=1}^{|\mathcal{S}_\mathcal{F}|} \alpha_i^c(t) \leq 1, \quad \alpha_i^c(t) \in \{0, 1\}, \ \forall i \in \mathcal{S}_\mathcal{F} \tag{17}$$

Let $\beta_j^c(t)$ denotes the indication function for MGAA users channel allocation at certain time.

$$\beta_j^c(t) = \begin{cases} 1, & \text{if } j\text{th MGAA user is allocated to } c\text{th channel} \\ 0, & \text{Otherwise} \end{cases} \tag{18}$$

For the MGAA users, their position and distance between the MGAA users can be determined due to the deterministic mobility. MGAA users do not interfere with each other if $d_{j,k}(t) > (r_j^c + r_k^c), \forall j, k \in \mathcal{M}, j \neq k$. With mobility the interfering set of MGAA users changes rapidly; let $\mathcal{S}_\mathcal{M}(t)$ denote the set of MGAA users that satisfy the carrier sensing range condition $d_{j,k} \leq \min\{r_j^c, r_k^c\}, \forall j, k \in \mathcal{M}, j \neq k$. Similarly, to ensure the self coexistence between MGAA users they must satisfy the following constraint:

$$\sum_{j=1}^{|\mathcal{S}_\mathcal{M}(t)|} \beta_j^c(t) \leq 1, \quad \beta_j^c(t) \in \{0, 1\}, \ \forall j \in \mathcal{S}_\mathcal{M}(t) \tag{19}$$

Let $\mathcal{S}_\mathcal{N}(t)$ denote the set of FGAA users and MGAA users that satisfy the carrier sensing range condition $d_{i,j}(t) \leq \min\{r_i^c, r_j^c\}, \forall i, j \in \mathcal{N}$, where $\mathcal{N} = \mathcal{F} \cup \mathcal{M}$. For the ith FGAA user and the jth MGAA user in set $\mathcal{S}_\mathcal{N}(t)$, only one user, from the set that can hear each other, can access the channel at a particular time.

$$\mathbb{I}_{i,j}^c = \begin{cases} 1, & \text{if } d_{i,j}(t) \leq \min\{r_i^c, r_j^c\} \\ 0, & \text{Otherwise} \end{cases} \tag{20}$$

$$\sum_{i=1}^{|\mathcal{S}_\mathcal{N}(t)|} \alpha_i^c(t)\mathbb{I}_{i,j}^c + \sum_{j=1}^{|\mathcal{S}_\mathcal{N}(t)|} \beta_j^c(t)\mathbb{I}_{i,j}^c \leq 1, \quad \forall i, j \in \mathcal{S}_\mathcal{N}(t) \tag{21}$$

D. INTERFERING ANGLE BASED RESOURCE ALLOCATION

Interference pattern between the FGAA and MGAA users is time-dependent due to the mobility of the MGAA users. We formulate the optimization problem of the joint channel and transmit power allocation to both MGAA and FGAA users considering the mobility of the MGAA users to maximize the GAA network capacity as shown below:

$$\begin{aligned}
\max \ & \sum_{i=1}^{|\hat{\mathcal{F}}|} \alpha_i^c(t) C_{i,c}(t) + \sum_{j=1}^{|\hat{\mathcal{M}}|} \beta_j^c(t) C_{j,c}(t) \\
\text{s.t. } & C1 : \alpha_i^c(t) \in \{0, 1\}, \quad \forall i \in \mathcal{S}_\mathcal{F}, \ \forall \mathcal{S}_\mathcal{F} \in S \\
& C2 : \sum_{i=1}^{|\mathcal{S}_\mathcal{F}|} \alpha_i^c(t) \leq 1 \\
& C3 : \beta_j^c(t) \in \{0, 1\}, \quad \forall j \in \mathcal{S}_\mathcal{M}(t), \ \forall \mathcal{S}_\mathcal{M}(t) \in S^* \\
& C4 : \sum_{j=1}^{|\mathcal{S}_\mathcal{M}(t)|} \beta_j^c(t) \leq 1 \\
& C5 : \sum_{i=1}^{|\mathcal{S}_\mathcal{N}(t)|} \alpha_i^c(t)\mathbb{I}_{i,j}^c + \sum_{j=1}^{|\mathcal{S}_\mathcal{N}(t)|} \beta_j^c(t)\mathbb{I}_{i,j}^c \leq 1 \\
& C6 : 0 \leq Pt_{i,b}^c \leq P_{max}^{\theta_i^c}, \quad \forall b \in \mathcal{B}_i^{\hat{c}}(t) \\
& C7 : 0 \leq Pt_{i,b^*}^c, \quad Pt_j^c \leq P_{max}, \ \forall b^* \in \mathcal{B}_i \backslash \mathcal{B}_i^{\hat{c}}(t) \\
& C8 : I_{K_{i,j}}^m \leq I_{th}, \quad \forall j \in \mathcal{M}, \ \forall i \in \mathcal{N}
\end{aligned} \tag{22}$$

where S and S^* are the supersets of all the users that can hear each other for FGAA and MGAA users respectively. $\alpha_i^c(t)$ and $\beta_j^c(t)$ are the binary variables that indicate if the cth channel is allocated to the ith FGAA user and the jth MGAA user respectively. To ensure the conflict-free resource allocation for FGAA users and MGAA users for the first type of conflict as shown in Figure 2, constraint $C6$ and $C7$ is used in the optimization equation (22). For the second type of conflict to ensure only one user, from the set that can hear each other, can access the PAL channel at the particular time $C1$, $C2$, $C3$, $C4$ and $C5$ is used in our proposed work. Constraint $C8$ is to ensure that the PAL users are protected from the harmful interference.

The above problem (22) is a mixed integer linear optimization problem which has a higher computational complexity [13]. To reduce the computational complexity, we separate the problem (22) into a two-phase suboptimal problem, i.e. channel allocation phase and transmit power allocation phase.

Lemma 2: Our proposed method increases the spectrum utilization compared to the traditional resource allocation methods. In traditional methods, in a scenario where the area is overlapped at a certain time only one user from the users with overlapped area can transmit at the same time at the same channel, i.e. area of transmission at a particular channel at the particular time will be $\pi r_{i,c}^2(t)$ *or* $\pi r_{j,c}^2(t)$.

Overlapped area, i.e. the area of interference is given by:

$$IA_{i,j}(t)= r_{i,c}^2(t)\cos^{-1}\left(\frac{d_{i,j}^2(t)+r_{i,c}^2(t)-r_{j,c}^2(t)}{2r_{i,c}(t)d_{i,j}(t)}\right)$$
$$+r_{j,c}^2(t)\cos^{-1}\left(\frac{d_{i,j}^2(t)-r_{i,c}^2(t)+r_{j,c}^2(t)}{2r_{j,c}(t)d_{i,j}(t)}\right)-\frac{1}{\sqrt{2}}$$
$$\sqrt{(2r_{j,c}^2(t)(r_{i,c}^2(t)+d_{i,j}^2(t))+(r_{i,c}^2(t)-d_{i,j}^2(t))^2-r_{j,c}^4(t))} \tag{23}$$

Area with no transmission can be calculated using area of sector and overlapped area which is given by:

$$SA_{i,j}(t)=\frac{1}{2}r_{i,c}^2(t)\theta_{i,c}^s(t)-\left(\frac{1}{2}\epsilon_{i,th}^{\theta_{i,c}^s,2}(t)\theta_{i,c}^s(t)+IA_{i,j}(t)\right) \tag{24}$$

Area of transmission from proposed method is $\left(\pi r_{i,c}^2(t)+\pi r_{j,c}^2(t)-SA_{i,j}(t)\right)$ which is greater than the area of transmission from traditional method, i.e. $\pi r_{i,c}^2(t)$ or $\pi r_{j,c}^2(t)$.

1) CHANNEL ALLOCATION FOR FGAA USERS AND MGAA USERS

Assuming GAA users are transmitting with the maximum transmit power, the channel allocation problem can be formulated as integer linear programming as shown below:

$$\begin{aligned}
\max\ & \sum_{i=1}^{|\hat{\mathcal{F}}|}\alpha_i^c(t)C_{i,c}(t)+\sum_{j=1}^{|\hat{\mathcal{M}}|}\beta_j^c(t)C_{j,c}(t)\\
\text{s.t. } & \alpha_i^c(t)\in\{0,1\},\quad \forall i\in\mathcal{S}_{\mathcal{F}},\ \forall\mathcal{S}_{\mathcal{F}}\in S\\
& \sum_{i=1}^{|\mathcal{S}_{\mathcal{F}}|}\alpha_i^c(t)\leq 1\\
& \beta_j^c(t)\in\{0,1\},\quad \forall j\in\mathcal{S}_{\mathcal{M}}(t),\ \forall\mathcal{S}_{\mathcal{M}}(t)\in S^*\\
& \sum_{j=1}^{|\mathcal{S}_{\mathcal{M}}(t)|}\beta_j^c(t)\leq 1\\
& \sum_{i=1}^{|\mathcal{S}_{\mathcal{N}}(t)|}\alpha_i^c(t)\mathbb{I}_{i,j}^c+\sum_{j=1}^{|\mathcal{S}_{\mathcal{N}}(t)|}\beta_j^c(t)\mathbb{I}_{i,j}^c\leq 1
\end{aligned} \tag{25}$$

For the optimization problem (25) the left-hand side of the constraint is a unimodular matrix, and the right hand side is an integer. The proof in [14] shows that as a result of the unimodular property the optimal solution of integer linear programming is optimal for the problem.

2) TRANSMIT POWER ALLOCATION FOR FGAA USERS AND MGAA USERS

Based on the above channel allocation for GAA users, transmit power is allocated to FGAA users and MGAA users by solving the following convex optimization equation:

$$\begin{aligned}
\max\ & \sum_{i=1}^{|\hat{\mathcal{F}}|}\alpha_i^c(t)C_{i,c}(t)+\sum_{j=1}^{|\hat{\mathcal{M}}|}\beta_j^c(t)C_{j,c}(t)\\
\text{s.t. } & 0\leq Pt_{i,b}^c\leq P_{max}^{\theta_i^c},\quad \forall b\in\mathcal{B}_i^{\hat{c}}(t)\\
& 0\leq Pt_{i,b^*}^c,\quad Pt_j^c\leq P_{max},\ \forall b^*\in\mathcal{B}_i\backslash\mathcal{B}_i^{\hat{c}}(t)\\
& I_{K_{i,j}}^m\leq I_{th},\quad \forall j\in\mathcal{M},\ \forall i\in\mathcal{N}
\end{aligned} \tag{26}$$

Theorem 3: The objective function of the optimization equation (26) to maximize the GAA network capacity is concave and (26) with the constraints of transmit power and RMS interference to PAL protection area is convex problem.

Proof: The proof is provided in Appendix. □

To find the optimal transmit power allocation, we simplify the above objective equation using i^* where $i^*\in\mathcal{N}$, $\mathcal{N}=\mathcal{F}\bigcup\mathcal{M}$. The simplified objective equation is

$$C_{i^*}^c(t)=\frac{1}{|\mathcal{U}_{i^*}|}\sum_{i^*=1}^{|\mathcal{N}|}\sum_{u=1}^{|\mathcal{U}_{i^*}|}\log_2\left(1+\frac{Pt_{i^*}^c(t)h_{i^*,u}(t)}{I_{i^*,o}^c(t)}\right) \tag{27}$$

where $I_{i^*,o}^c(t)=P_N+\sum_{o\in\mathcal{N}\backslash\{i^*\}}Pt_o^c(t)h_{o,u}(t)$. In our proposed method, transmit power is allocated for each time slot t, and the timeframe is divided into N_T number of time slots, i.e. we need to solve the problem N_T times to find the optimal transmit power for GAA users for each time slot.

Based on the above proof, we obtain the optimal solution of (26) by using the Karush-Kuhn-Tucker (KKT) conditions. The Lagrangian of the above optimization equation with objective function $C_{i^*}^c(t)$ for time t and the non-negative Lagrange multiplier λ which can be found using the interference constraint is given by:

$$\begin{aligned}
\mathcal{L}=&\frac{1}{|\mathcal{U}_{i^*}|}\sum_{i^*=1}^{|\mathcal{N}|}\sum_{u=1}^{|\mathcal{U}_{i^*}|}\log_2\left(1+\frac{Pt_{i^*}^c(t)h_{i^*,u}(t)}{I_{i,o}^c(t)}\right)\\
&-\lambda\left(\sum_{i=1}^{F^*(t)}Pt_{i^*}^c(t)h_{i,m}(t)+\sum_{j=1}^{M^*(t)}Pt_j^c(t)h_{j,m}(t)-I_{th}\right)
\end{aligned} \tag{28}$$

According to the Kuhn Tucker conditions we get:

$$\frac{\partial\mathcal{L}}{\partial Pt_{i^*}^c}=\frac{\left(h_{i^*,u}(t)\right)^{-1}}{\ln(2)\left(I_{i,o}^c(t)+Pt_{i^*}^{\hat{c}}(t)h_{i,u}(t)\right)}-\lambda h_{i,m}(t)=0 \tag{29}$$

The optimal transmit power of the i^*th GAA user on the cth channel is given by:

$$Pt_{i^*}^{\hat{c}}(t)=h_{i^*,u}(t)^{-1}\left(\left(\ln(2)\lambda h_{i,m}(t)\right)^{-1}-I_{i,o}^c(t)\right) \tag{30}$$

The transmit power is time dependent as the sets of GAA users that can hear each other will change due to the mobility of the MGAA users.

The Lagrange multiplier λ is calculated using (30) and using the Karush-Kuhn-Tucker condition, i.e.

$$\lambda\left(\sum_{i=1}^{F^*(t)}Pt_{i^*}^c(t)h_{i,m}(t)+\sum_{j=1}^{M^*(t)}Pt_j^c(t)h_{j,m}(t)-I_{th}\right)=0$$

3) FGAA USERS AND MGAA USERS RESOURCE ALLOCATION ALGORITHM

In the proposed algorithm, i.e. Algorithm 1, joint transmit power and channel allocation method is proposed for FGAA users and MGAA users. Algorithm 1 has the computational complexity of ($\mathcal{O}(|\mathcal{F}||\mathcal{M}||\mathcal{C}|)$.

Algorithm 1 Interfering Angle Based Method for GAA Users Resource Allocation

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Input: P_{max}, I_{th}
for FGAA i, $i = \{1, ..., |\mathcal{F}|\}$ **do**
  for MGAA j, $j = \{1, ..., |\mathcal{M}|\}$ **do**
    for PAL channel c, $c = \{1, ..., |\mathcal{C}|\}$ **do**
      Calculate the carrier sensing range, i.e. r_i^c and r_j^c using P_{max} in (5) for both FGAA and MGAA users.
      Find the interfering angle using $\theta_i^c(t) = 2\cos^{-1}\left(\frac{d_{i,j}^2(t)+r_i^c(t)^2-r_j^c(t)}{2r_i^c(t)^2 d_{i,j}(t)}\right)$
      Find the sets of overlapping GAA users and the interfering angle using (6).
      Find $\mathcal{B}_i^{\hat{c}}(t)$ set of beams that lies in $\theta_i^c(t)$.
      Find the maximum transmit power, i.e. $P_{max}^{\theta_{i,b}^c}(t)$ for $\mathcal{B}_i^{\hat{c}}(t)$ set of beams using (9).
      Considering all GAA are transmitting with P_{max} we find the set of GAA users that can transmit at the same time using
$$\text{maximize} \quad \sum_{i=1}^{|\hat{\mathcal{F}}|} \alpha_i^c(t) C_{i,c}(t) + \sum_{j=1}^{|\hat{\mathcal{M}}|} \beta_j^c(t) C_{j,c}(t)$$
$$\text{subject to} \quad C1, C2, C3, C4, C5$$
      Find $\mathcal{U}_i^*$ and $\hat{\mathcal{U}}_i$ using the location information.
      Find the transmit power allocation ensuring the PAL protection criteria is satisfied using
$$\text{maximize} \quad \sum_{i=1}^{|\hat{\mathcal{F}}|} \alpha_i^c(t) C_{i,c}(t) + \sum_{j=1}^{|\hat{\mathcal{M}}|} \beta_j^c(t) C_{j,c}(t)$$
$$\text{subject to} \quad C6, C7, C8$$
      Find the optimal transmit power using $Pt_{i*}^{\hat{c}}(t) = h_{i*,u}(t)\left(\left(\ln(2)\lambda h_{i,m}(t)\right)^{-1} - I_{i,o}^c(t)\right)$
    end for
  end for
end for
Output: $\alpha_i^c(t)$, $\beta_j^c(t)$, $Pt_{i,b}^c$, Pt_j^c

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IV. NUMERICAL RESULTS

We consider a scenario in which there are 2 PAL channels with 3 PAL users allocated to each PAL channel. In this work, we consider 15 FGAA users randomly located within a range of 500 meters, and 4 MGAA users travelling in a fixed path. We randomly locate 6 GAA UEs for each GAA user. All the results are computed in MATLAB. For the simulations, we used the FCC proposed maximum allowed transmit power of 24 dBm, RMS interference threshold of -80 dBm, and the central frequency of 3.6 GHz. In this work, we consider that the train is moving at 60 km/hr. We consider a PAL protection area of 50m and time slot of 1 second each.

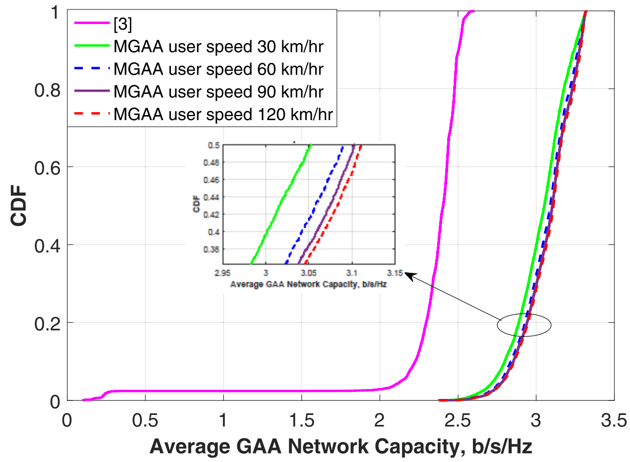

FIGURE 4. **Average GAA network capacity considering MGAA users with different speed compared to [3].**

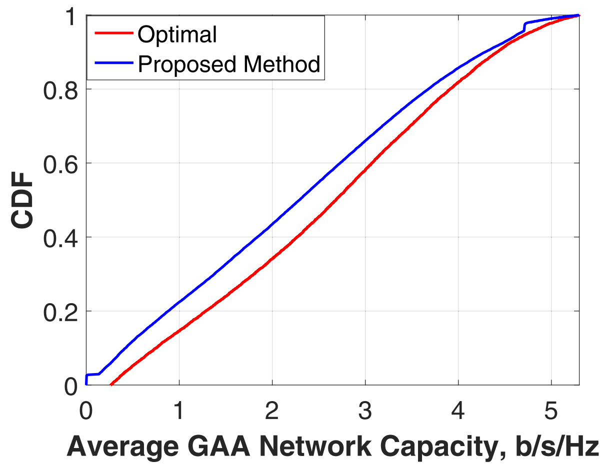

FIGURE 5. **Comparison of our proposed method with optimal for the test case with 2 FGAA and 1 MGAA users.**

Figure 4 shows the cumulative distribution function (CDF) of the average GAA capacity from our proposed method with MGAA users at 30km/hr, 60km/hr, 90km/hr, 120km/hr compared to [3]. In [3] only one conflicting user can transmit at a particular time, however in our proposed method both MGAA user and FGAA user from the same interfering set can transmit at the same time using our proposed maximum allowed transmit power in the interfering angle. If the speed of the vehicle is lower, the MGAA user will be in the same interference set with FGAA user for a longer time, i.e. FGAA user needs to transmit with reduced transmit power for that time period. Hence, the average GAA user capacity increases as the speed increases. If FGAA user and MGAA user are in the same interfering set GAA users need to ensure the interference protection to PAL users protection area as well as to ensure the conflict-free resource allocation among GAA users.

To find the optimal solution for the above joint channel and transmit power allocation is very difficult with a large number of GAA users. To compare our proposed method with the optimal solution, we consider a simple scenario

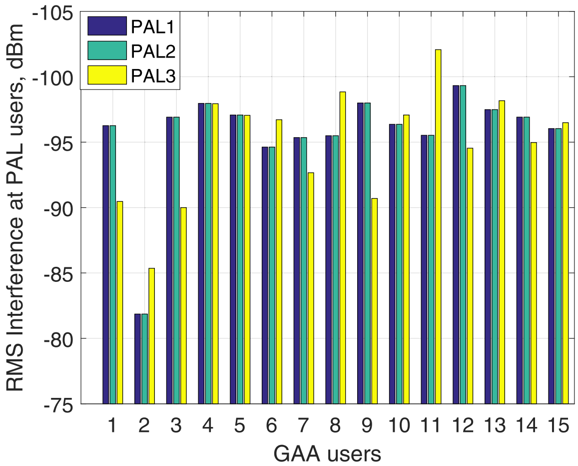

FIGURE 6. RMS Interference from GAA user to multiple PAL users protection area allocated to the same PAL channel.

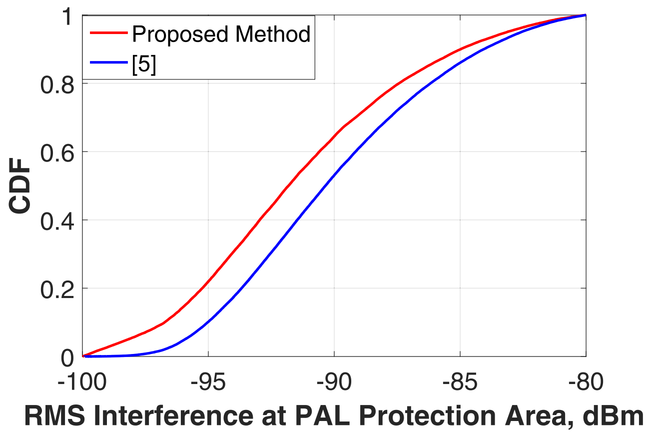

FIGURE 7. Root mean square interference at PAL protection area from our proposed method and [5].

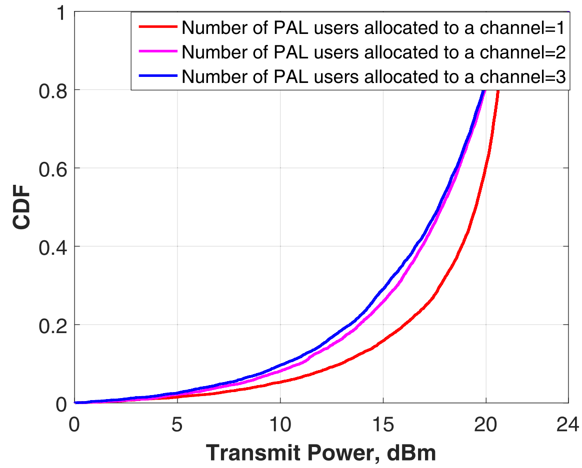

FIGURE 8. Transmit Power allocation of GAA users with different number of PAL users in the same channel.

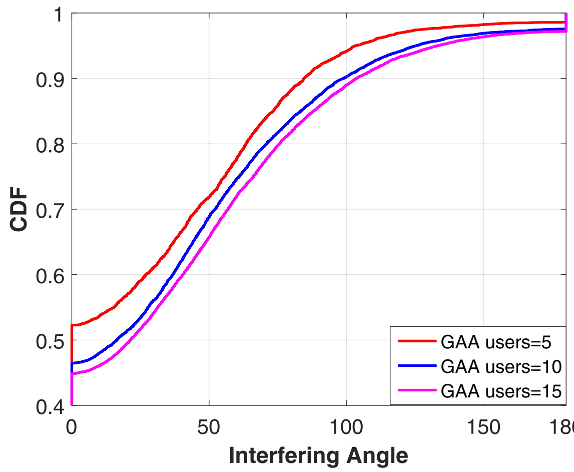

FIGURE 9. Interfering angles for different number of GAA users.

with 2 FGAA users and 1 MGAA user with 1 UE for all GAA users. Figure 5 shows the comparison of our proposed method to the optimal solution. We can observe an average decrease of 19.68% in our proposed method as compared to the optimal solution.

In SAS RMS interference from a GAA user to the PAL protection area should be -80 dBm to protect the PAL users from harmful interference. In this work we consider 3 PAL users allocated to a single PAL channel, and to protect the PAL users GAA users need to ensure the RMS interference protection at all the PAL protection area is satisfied. Figure 6 shows that the RMS interference from GAA users to PAL protection area is below the predetermined threshold of -80 dBm.

Figure 7 shows the comparison of our proposed method to [5]. In [5] only one conflicting user is allocated to a channel at a particular time; however in our proposed method using interfering angle based resource allocation both FGAA user and MGAA user are allocated to the same PAL channel at the same time due to which RMS interference is more from our proposed method. The result shows that both the methods satisfy the FCC criteria to protect the PAL users from harmful interference, however RMS interference from our proposed method is greater than [5].

Figure 8 shows the transmit power allocation to GAA users based on the number of PAL users allocated to the PAL channel. The result shows that less transmit power is allocated to GAA users as the number of PAL users increases. As the number of PAL users increases GAA users need to ensure that the interference criteria are satisfied to all the PAL users.

Figure 9 shows the interfering angle between GAA users, i.e. the overlapping angle for the different number of GAA users. The result shows that as the number of GAA users increases the interfering angle between GAA users also increases. Hence, for the dense deployment of small cells, the overlapping area increases significantly causing network performance degradation due to interference.

Figure 10 shows the comparison between transmit power allocation of GAA users with and without considering the conflicts between GAA users. Most of the resource allocation method [20], [22] only considers the interference to

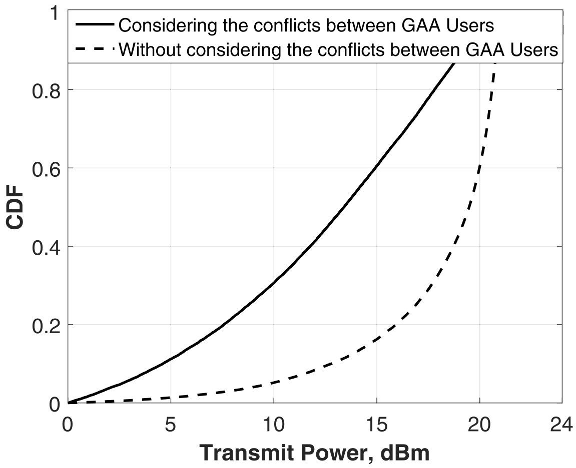

FIGURE 10. Transmit power with and without considering the conflicts.

primary users. However, in our proposed transmit power allocation method we consider the hidden node problems to reduce the interference between GAA users. The results show that transmit power allocation is reduced when considering the overlapping area; however our proposed method considers the conflicts between GAA users and interference protection to PAL users.

V. CONCLUSION

In this paper, we proposed an interfering angle based joint channel and transmit power allocation method to MGAA and FGAA users considering coexistence to PAL users as well as self-coexistence between FGAA users and MGAA users. The maximum allowed transmit power in the interfering angle is proposed that ensures the conflict-free channel allocation to both MGAA users and FGAA users on the same channel at the same time. The simulation results show that the average GAA capacity can be maximized from the proposed method while satisfying the interference constraint at the PAL protection area.

APPENDIX
PROOF OF THEOREM III.3.

To prove the convexity of optimization equation (26), we need to prove that the objective function is concave with respect to α_i^c and Pt_i^c.

Firstly we define,

$$f_1(\alpha_i^c, Pt_i^c) = \alpha_i^c C_i^c \tag{31}$$

The objective function is the sum of $f_1(\alpha_i^c, Pt_i^c)$ for all the GAA users i.e. $i \in \mathcal{F}$ allocated to the PAL channel.

From (26) we get,

$$f_1(\alpha_i^c, Pt_i^c) = (\alpha_i^c \log_2 \left(1 + Pt_i^c h_{i,u}(\alpha_i^c I_{i,o}^c)^{-1}\right) \tag{32}$$

According to [23] f_1 is concave if Hessian matrix H is a negative semidefinite matrix. Hessian matrix H of f_1 can be arranged as [24]:

$$H = \begin{bmatrix} \frac{\partial^2 f}{\partial(\alpha_i^c)^2} & \frac{\partial^2 f}{\partial \alpha_i^c \partial Pt_i^c} \\ \frac{\partial^2 f}{\partial Pt_i^c \partial \alpha_i^c} & \frac{\partial^2 f}{\partial (Pt_i^c)^2} \end{bmatrix} \tag{33}$$

$$H = \begin{bmatrix} -\frac{1}{\ln 2}\frac{\left(Pt_i^c h_{i,u}\right)^2}{\alpha_i^c\left(\alpha_i^c I_{i,o}^c + Pt_i^c h_{i,u}\right)^2} & \frac{1}{\ln 2}\frac{Pt_i^c (h_{i,u})^2}{\left(\alpha_i^c I_{i,o}^c + Pt_i^c h_{i,u}\right)^2} \\ \frac{1}{\ln 2}\frac{Pt_i^c (h_{i,u})^2}{\left(\alpha_i^c I_{i,o}^c + Pt_i^c h_{i,u}\right)^2} & -\frac{1}{\ln 2}\frac{\alpha_i^c (h_{i,u})^2}{\left(\alpha_i^c I_{i,o}^c + Pt_i^c h_{i,u}\right)^2} \end{bmatrix} \tag{34}$$

The eigenvalues of (34) are

$$-\left(\frac{1}{\ln 2}\frac{Pt_i^c h_{i,u}^2}{\left(\alpha_i^c I_{i,o}^c + Pt_i^c h_{i,u}\right)^2}\right)^2$$

and

$$-\left(\frac{1}{\ln 2}\frac{h_{i,u}^2\left((Pt_i^c)^2 + (\alpha_i^c)^2\right)}{\alpha_i^c\left(\alpha_i^c I_{i,o}^c + Pt_i^c h_{i,u}\right)^2}\right) - \left(\frac{1}{\ln 2}\frac{Pt_i^c h_{i,u}^2}{\left(\alpha_i^c I_{i,o}^c + Pt_i^c h_{i,u}\right)^2}\right)^2$$

For H to be a negative semidefinite matrix, it should be a Hermitian matrix with nonpositive eigenvalues. Hermitian matrix is a square matrix where $H = H^T$, H^T is the transpose of the H matrix. From (34) we can verify that H is a negative semidefinite matrix, i.e. Hermitian matrix with nonpositive eigenvalue and f_1 is concave. Similarly, $f_2(\alpha_j^c, Pt_j^c)$ is concave and the sum of two concave function, i.e. $\left(f_1(\alpha_i^c, Pt_i^c) + f_2(\alpha_j^c, Pt_j^c)\right)$ is concave [23]. The inequality constraint in optimization equation (26) is convex, so the feasible set of the objective equation is convex and the optimization equation (26) is a convex problem [25]. The optimization problem (26) is a convex optimization problem as it also satisfies the proof in [25], [26] for Problem 2.

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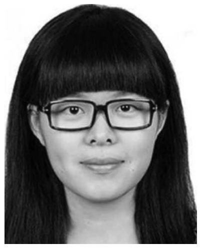

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