GAA-GAA Coexistence in the CBRS Band: Performance Evaluation of Approach 3

Weichao Gao, Anirudha Sahoo and Emma Bradford*
National Institute of Standards and Technology
Gaithersburg, Maryland, U.S.A.
Email: {weichao.gao, anirudha.sahoo}@nist.gov, emma.abe.bradford@gmail.com

***Abstract*—The General Authorized Access (GAA) users operate at the lowest priority in the Citizens Broadband Radio Service (CBRS) band. So, they must not cause harmful interference to the higher priority users and must cooperate with each other to minimize mutual interference and increase spectrum utilization. Towards this goal, the Wireless Innovation Forum (WInnForum), a standards body, has recommended three schemes. We study performance of one of the schemes, called Approach 3. To the best of our knowledge, there is no performance study available for Approach 3. WInnForum does not specify any performance metrics to evaluate the schemes. We define few performance metrics for Approach 3 that will be useful for the operators in deciding their operating parameters. We choose two actual locations and use real terrain and land cover data of continental USA in our simulation study. Hence, we expect our results to be similar to practical implementations.**

I. Introduction

The Citizens Broadband Radio Service (CBRS) band in the 3.5 GHz band has recently been opened up by the Federal Communications Commission (FCC) to the commercial operators on a priority based sharing [1]. As per the Part 96 FCC rules, there will be three tiers of users in this band. The current incumbent will operate in tier 1 with highest priority. Priority Access Lincense (PAL) users will be at the middle tier with medium priority, whereas General Authorized Access (GAA) users will be at the lowest tier operating with lowest priority. A higher tier user must be protected against harmful interference from the lower tier users. However, a lower tier user cannot expect interference protection from the higher tier users. Thus, GAA users are not protected from interference from higher tier users. The rule 47 C.F.R. § 96.35 in [1] specifies that GAA users must cooperate with each other to minimize mutual interference and increase spectrum utilization. In addition, in the first phase of deployment in the CBRS band, there will not be any PAL users. Hence, GAA-GAA coexistence plays a very important role in the commercial success of CBRS band.

The Wireless Innovation Forum (WInnForum) is the standardization body responsible for specifying the standards of various aspects of the CBRS system. The WInnForum has come out with three technical reports describing three schemes to address GAA-GAA coexistence. It is widely expected that commercial vendors will adopt one of these schemes as their GAA-GAA coexistence solution. While we have reported performance analysis of one of the schemes, called *Approach 1* [2], there is no such performance analysis available for the other two schemes. In this paper, we present our performance study of the WInnForum proposed GAA-GAA coexistence scheme called *Approach 3* [3]. It is expected that CBRS service providers will group their CBSDs into Coexistence Groups (CxGs). Each CxG will have a CxG manager which will be assigned the task of managing interference among the CBSDs belonging to the CxG.

*The author was at National Institute of Standards and Technology when this work was done.

TABLE I: List of Acronyms

CBRS	Citizens Broadband Radio Service
PAL	Priority Access License
GAA	General Authorized Access
SAS	Spectrum Access System
CBSD	CBRS device
CxG	Coexistence Group
CIG	CBSD Interference Graph
EW	Edge Weight
ET	Edge Threshold
BW	Bandwitdh
IM	Interference Metric
VB	Virginia Beach
SD	San Diego
ITM	Irregular Terrain Model
AMABCC	Average Maximum Allocable Bandwidth of CBSDs in a CxG
CRC	Coverage Ratio of a CxG
RCIAC	Ratio of inter-CxG Interfered Area of a CxG
AAICIGC	Average Aggregate Interference per inter-CxG Interfered Grid of a CxG

The main contributions of this paper are as follows.

- The WInnForum technical report does not specify any performance metrics at the CxG level for Approach 3. WInnForum did not want to enforce any particular performance metrics and hence left them to the implementers and the operators. It only outlines certain principles (e.g., channel quality based on SINR), to be considered while assigning bandwidth to the individual CBSDs [3], which are pertinent to a CxG manager when it allocates BW to its CBSDs. We have defined few performance metrics at the CxG level for Approach 3 which will be helpful for operators to compare performances of CxGs in different deployment configurations.
- There is very little performance study on GAA-GAA coexistence available in the literature. In fact, to the best of our knowledge, this is the first performance evaluation

of Approach 3. Hence, this work provides the very first insight into Approach 3 in terms of its performance to the research community at large.

- Our simulation study uses deployment scenarios in San Diego and Virginia Beach. These two cities are chosen because of their diverse terrain characteristics. Actual terrain and land cover data around these two cities are used by way of using the WInnForum supplied reference implementation of ITM and Hybrid propagation models [4], which use the terrain and land cover data of the continental USA. Hence, we expect our performance results to be close to practical implementations.

II. Related Work

GAA-GAA coexistence architectures in the CBRS band has been studied by the WInnForum. The WInnForum has proposed three different approaches for GAA-GAA coexistence. In these approaches, resources are allocated such that mutual interference is minimized while making sure that the allocation is fair to the CBSDs or CxGs. In Approach 1 [5], bandwidth (BW) is allocated to CBSDs such that CBSDs which potentially could interfere with each other are allocated, to the extent possible, different channels. If the deployment density is too high to achieve the above said criterion for BW allocation, then this approach would allocate the same channel to CBSDs even though they may interfere with each other. While Approach 1 considers BW as the only resource to be allocated, Approach 2 [6] considers BW and transmit power as two resources for allocation. Approach 2 tries to allocate BW at maximum allowed transmit power to CBSDs such that the CBSDs which may potentially interfere with each other are assigned non-overlapping BW. If this is not possible (e.g., due to high deployment density), transmit power is lowered to reduce the number of CBSDs which interfere with each other and then allocate non-overlapping BW to them. Approach 3 [3] tries to maximize BW allocation to CxGs using a recursive clustering approach. A CBSD, which has edges only with CBSDs belonging to the same CxG as itself, is said to belong to cluster size 1. This CBSD is allocated $100\,\%$ BW. A CBSD belonging to cluster size 2 has its edges to CBSDs which are either in its own CxG or belong to exactly one other specific CxG. CBSDs in cluster size 2 are assigned $50\,\%$ of allocable BW. This procedure is applied recursively until BW is allocated to all CBSDs. Performance analysis of Approach 1 has been reported in [2]. But this study did not consider multiple CxGs in the deployment. A simulation study of how different propagation models and deployment densities affect GAA-GAA coexistence is available in [7].

Coexistence issues in other wireless systems have also been studied. Coexistence in the shared spectrum system based on TV white space has been studied in [8]. This study includes coexistence between incumbents and secondary users as well as among secondary users. Coexistence between devices which use different air interfaces and MAC protocols but use the same spectrum has been studied. For example, the authors in [9] have studied coexistence issues between LTE-licensed assisted access (LTE-LAA) and WiFi in the 5 GHz band. In [10], [11] the authors discuss coexistence of LTE-LAA and WiFi but in the TV whitespace spectrum.

III. Overview of WInnForum Scheme: Approach 3

In this section, we give an overview of the Approach 3 [3] proposed by the WInnForum for GAA-GAA coexistence.

A. CBSD Interference Graph

Interference among CBSDs is the main concern with respect to GAA-GAA coexistence. Hence, Approach 3 starts with constructing a CBSD Interference Graph (CIG) in a given deployment area. The CIG consists of CBSDs as vertices and edges between pairs of CBSDs that interfere with each other. Since Approach 3 does not explicitly specify how to determine if an edge exists between two CBSDs, we use *area coordination* based edge creation method specified in [5]. First, we compute the coverage areas of the two CBSDs. The coverage area of a CBSD is calculated based on a propagation model, an omnidirectional antenna model and the CBSD's Equivalent Isotropically Radiated Power (EIRP). The received signal strength around the boundary of coverage is set to -96 dBm/10 MHz. Let us consider two CBSDs, C_1 and C_2. Let the coverage areas of C_1 and C_2 be A_1 and A_2 respectively. Let A be the overlap area. If the coverage areas of the two CBSDs do not overlap, i.e., $A = 0$, then there is no edge between them. Otherwise, the edge weight between them is set to $max(A/A_1, A/A_2)$. An edge is created between C_1 and C_2 if the edge weight is more than a predetermined edge threshold (ET) of the CIG. Note that once the ET is fixed for a deployment area, the CIG does not change.

1) Coexistence Groups: A CIG may consist of one or more Coexistence Groups (CxGs). A CxG consists of a group of CBSDs which manage interference among themselves. Thus, resources are allocated to individual CxGs in the CIG rather than to individual CBSDs. Each CxG typically will have a CxG manager which will then be responsible for allocating resources to individual CBSDs. In Approach 3, one or more subsets of CBSDs inside a given CxG, called clusters, are identified and are allocated BW based on the the cluster size of the subset. This information is passed onto the CxG manager. However, while allocating BW to individual CBSDs, the CxG manager may use different allocation (while not violating the cluster level allocation) to manage interference. Approach 3 essentially makes sure that BW is allocated in such a way that interference among CxGs is minimized.

2) Bandwidth Allocation: WInnForum Aproach 3 allocates BW to each CxG in a CIG. However, a subset of CBSDs (called a *cluster*) in a CxG may be allocated a certain amount of BW and another subset of CBSDs in that CxG may be allocated a different amount of BW as explained below.

Approach 3 uses a recursive clustering method to allocate BW to CxGs. It identifies a set of CBSDs in a given CxG that have edges to other CBSDs belonging to the same CxG as itself. These CBSDs are marked as belonging to cluster size 1. CBSDs in this set are allocated $100\,\%$ of GAA BW. To identify CBSDs

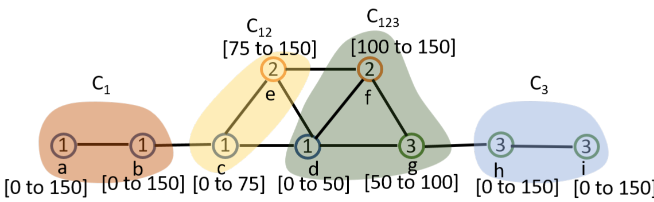

Fig. 1: An example illustrating clustering of CBSDs using Approach 3

belonging to cluster size 2, CxGs are chosen in pairs. For a pair of CxGs, CBSDs belonging to one of the two CxGs which have edges to CBSDs in its own CxG or the other CxG are identified as belonging to cluster size 2. These CBSDs are allocated $50\,\%$ of GAA BW. Similarly, CBSDs belonging to cluster size 3 are allocated $33.33\,\%$ of GAA BW and so on.

We illustrate the method followed in Approach 3 by an example shown in Figure 1. The figure shows the CIG of a CBSD deployment. Circles denote CBSDs. The numbers inside the circles denote the CxG id to which the CBSD belongs. CBSDs a and b belong to CxG1 and are connected to CBSDs which belong to CxG1 only. So, CBSDs a and b belong to cluster of size 1 (denoted as C_1). Same is the case with CBSDs h and i. Thus, they also belong to cluster of size 1 (denoted as C_3). CBSDs c and e are connected to CBSDs which belong to either CxG1 or CxG2. Hence, they belong to cluster of size 2 (denoted as C_{12}). Finally, CBSDs d, f and g are connected to CBSDs belonging to three CxGs, i.e., CxG1, CxG2 and CxG3. Hence, they belong to cluster size of 3 (denoted as C_{123}). These clusters are shown by different colors in the figure. We assume that total available bandwidth is 150 MHz. Hence, clusters C_1 and C_3 get $100\,\%$ or 150 MHz bandwidth. Thus, CBSDs a, b, h and i are assigned 0 MHz to 150 MHz. Cluster C_{12} should be assigned $50\,\%$ bandwidth. So CBSD c is assigned 0 MHz to 75 MHz whereas CBSD e is assigned 75 MHz to 150 MHz. Note that these two CBSDs are assigned $50\,\%$ bandwidth while making sure their bandwidth is non overlapping to ensure that there is no interference between CxG1 and CxG2. Finally, cluster C_{123} should be assigned $33\,\%$ bandwidth and the CBSDs belonging to CxG1, CxG2 and CxG3 in this cluster should be assigned non-overlapping frequency range. BW assigned to CBSD d should overlap with BW assigned to CBSD c (since both of them belong to the same CxG). Similarly, BW assigned to CBSD f should overlap with BW assigned to CBSD e and BW assigned to CBSD g should overlap with BW assigned to CBSD h. Thus, CBSD d is assigned 0 MHz to 50 MHz, CBSD f is assigned 100 MHz to 150 MHz and CBSD g is assigned 50 MHz to 100 MHz. It is worth pointing out that, the CBSD level frequency range allocation illustrated in this example is just one way of assigning frequencies to the CBSDs. In fact, frequency range allocation to CBSDs is a proprietary implementation by individual operators and may take into account different factors as outlined in Section 4.4 of [3].

TABLE II: CBSD Parameters

Area Type	Antenna Height [m] (Above Ground Level)		EIRP [dBm/10MHz]	
	Cat A	Cat B	Cat A	Cat B
Dense Urban	$50\,\%$: 3 to 15 $25\,\%$: 18 to 30 $25\,\%$: 33 to 60	6 to 30	26	40 to 47
Urban	$50\,\%$: 3 $50\,\%$: 6 to 18	6 to 30	26	40 to 47
Suburban	$70\,\%$: 3 $30\,\%$: 6 to 12	6 to 100	26	47
Rural	$80\,\%$: 3 $20\,\%$: 6	6 to 100	26	47

TABLE III: Ratios of CBSD categories deployed in different area types

Area Type	Cat A	Cat B
Dense Urban	$90\,\%$	$10\,\%$
Urban	$90\,\%$	$10\,\%$
Suburban	$90\,\%$	$10\,\%$
Rural	$95\,\%$	$5\,\%$

IV. Simulation Setup

A. Deployment Model

In this study, we choose Virginia Beach (VB) in the east coast and San Diego (SD) in the west coast as our deployment locations. Two square deployment areas of $5\,km \times 5\,km$, one around VB (the center at latitude 36.842 491 and longitude -76.006 384) and the other around SD (the center at latitude 32.723 588 and longitude -117.145 319) are considered. These two locations are chosen because they have a diverse terrain. The area around VB is primarily flat, whereas it is quite hilly around SD. For ease of computation, the deployment area is divided into grids of size $50\,m \times 50\,m$. For a given deployment density, CBSDs are deployed randomly with a uniform distribution in the deployment area. Deployment density is defined as the number of CBSDs per unit area and is expressed in CBSDs per square kilometer. The relative positions of the CBSDs inside the deployment areas in SD and VB are identical. Coverage areas of CBSDs are not allowed to spill over to the outside of the square deployment area. So, if coverage of any CBSD goes outside of the square deployment area, it is clipped by the boundary of the square. CBSDs are assumed to have omnidirectional antennae. The distributions of CBSD antenna height and EIRP are shown in Table II

The total BW of CBRS band is 150 MHz. Out of this, up to 70 MHz can be used by PAL users. Hence, in this study we assume 80 MHz of BW available for GAA use. Received power threshold of -96 dBm/10 MHz is used for computation of coverage area of a CBSD, i.e., the coverage area of a CBSD is such that the received power at any point on the boundary of coverage is -96 dBm/10 MHz.

The deployment has a mix of Category A (Cat A) and Category B (Cat B) CBSDs. The ratio of Cat A and Cat B

TABLE IV: ITM Parameters

Parameter	Value
Polarization	1 (Vertical)
Dielectric constant	25 (good ground)
Conductivity (S/m)	0.02 (good ground)
Mode of Variability (MDVAR)	13 (broadcast point-to-point)
Surface Refractivity (N-units)	ITU-R P.452
Radio Climate	ITU-R P.617
Confidence/Reliability Var. (%)	50/50

CBSDs for each area type is shown in Table III. All Cat A CBSDs are considered to be indoors whereas all Cat B CBSDs are assumed to be outdoors. Note that the deployment parameters shown in the above tables are the same as those used in [2].

B. Propagation Models

We use the Irregular Terrain Model (ITM) (in point to point mode) [12] and the Hybrid model as described in the Requirement R2-SGN-04 in [13] to analyze how these two models impact GAA-GAA coexistence performance. The ITM model is essentially the Longley-Rice model which is based on electromagnetic theory, terrain features and radio measurements. ITM parameters in our experiments are set as per Table IV. The Hybrid propagation model, as the name suggests, is a hybrid between ITM and extended Hata (eHata) [14] model and is proposed by the WInnForum. One limitation of the ITM model is that it does not account for clutter loss. In contrast, Hybrid model does not have this limitation. As per [13], ITM and Hybrid propagation losses are the same in the rural area. But in urban and suburban areas Hybrid propagation loss is the larger of ITM and eHata losses. Hence, the Hybrid propagation loss is generally higher than or equal to the ITM propagation loss.

C. Creation of CxGs

A set of experiments is run with a given number of CxGs. If the number of CxGs is desired to be N_g, then a CBSD is randomly placed into one of the $(N_g - 1)$ CxGs or left as a singleton CBSD. After all the CBSDs are done with placement, all singleton CBSDs are grouped into a *virtual* CxG. Note that in our experiments, relative positions of CBSDs and the grouping of CBSDs into CxGs are identical between the two deployment locations. In this study, we have set the number of CxGs to three and four in each deployment area.

D. Performance Metrics

The WInnForum does not suggest any performance metrics at the CxG level for evaluating the GAA-GAA coexistence scheme Approach 3. That task is left to the implementers and operators. In this section, we define the performance metrics which we think are appropriate and useful to the implementers and operators of a CBRS system. Traditional performance metrics such as throughput and network capacity that are used in wireless networks are not directly useful in this case. Operators in the CBRS band are more concerned about *coverage* and *interference*, since these two directly affect their deployment strategy and users' experience. Hence, the metrics we propose are based on coverage and interference and focus on quantifying the CxG-wise bandwidth allocation, inter-CxG interference, and the quality of bandwidth allocation. It is worth mentioning that the proposed metrics do indirectly affect the network capacity and throughput. The key notations used in the metrics are listed in Table V.

TABLE V: Notations used in performance metrics

CxG:	
N_g	the total number of CxGs in the deployment area
CxG_g	the CxG with index g
CBSD:	
$\mathbb{CBSD}_g$	the set of CBSDs in CxG_g
$\overline{\mathbb{CBSD}}_g$	the set of CBSDs in all the CxGs except those in CxG_g
$\mathbb{CBSD}_{k\overline{g}}$	the set of CBSDs in $\overline{\mathbb{CBSD}}_g$ that interferes with CxG_g at $grid_k$
Grid:	
$grid_k$	the grid with index k
$\mathbb{GRID}$	the set of grids in the entire deployment area
$\mathbb{GRID}_g$	the set of grids covered by the CBSDs in CxG_g
$\mathbb{GI}_g$	the set of grids in $\mathbb{GRID}_g$ that are interfered by the CBSDs from other CxGs
Power:	
rx_{ik}	received power (in dBm) at $grid_k$ from $CBSD_i$
$RX_{k\overline{g}}$	aggregate received power at $grid_k$ from all the CBSDs in $\overline{\mathbb{CBSD}}_g$
P_{th}	received power threshold used to compute coverage of a CBSD
General:	
B	total GAA BW
S_i	size of the cluster that $CBSD_i$ belongs to

1) Bandwidth Allocation:

- *Average Maximum Allocable Bandwidth of CBSDs in a CxG (AMABCC)*: To compute this metric, first Maximum Allocable Bandwidth of a CBSD (MABC) in a given CxG is computed. To compute MABC, the size of the cluster to which a CBSD belongs is computed. Let this cluster size for $CBSD_i$ be denoted as S_i, and let B be the total GAA BW. Then $MABC_i$ of $CBSD_i \in \mathbb{CBSD}_g$ is given by

$$MABC_i = \frac{B}{S_i}. \quad (1)$$

Then the average of MABC among all CBSDs in $\mathbb{CBSD}_g$ is given by

$$AMABCC_g = \frac{\Sigma_{\forall CBSD_i \in \mathbb{CBSD}_g} MABC_i}{|\mathbb{CBSD}_g|}. \quad (2)$$

2) Inter-CxG Interference: The inter-CxG interference has two aspects: the coverage area experiencing interference and the magnitude of interference.

To define the performance metric involving coverage, we first define coverage area of CxG_g. This quantity, denoted by $GRID_g$, represents the area (in terms of grids) covered by the CBSDs belonging to CxG_g. A grid is considered covered by a CxG if the received power from any CBSD in the CxG is greater than or equal to a predefined received power threshold

P_{th} (-96 dBm/10 MHz in our deployment model). Note that the coverage of CBSDs in a CxG may overlap. Hence, $GRID_g$ is essentially the union of coverages of all the CBSDs in the CxG_g. Therefore, $GRID_g$ is given by

$$GRID_g = \bigcup_{CBSD_i \in \mathbb{CBSD}_g} \{grid_k \in \mathbb{GRID} \mid rx_{ik} \geqslant P_{th}\}. \quad (3)$$

where rx_{ik} is the received power at $grid_k$ from $CBSD_i$, and $\mathbb{GRID}$ is the set of all grids in the deployment area. Note that $GRID_g$ is independent of coexistence scheme; it only depends on the configuration of the CBSD deployment and the propagation model used to compute propagation loss.

- *Coverage Ratio of a CxG (CRC)*: This metric presents the fraction of the deployment area covered by a CxG. The CRC of CxG_g is defined as

$$CRC_g = \frac{|GRID_g|}{|\mathbb{GRID}|}. \quad (4)$$

  Although CRC does not directly represent interference performance of Approach 3, it could be a factor while choosing operating parameters in terms of BW and interference. Typically, operators would like to have CRC of its CxG as close to 1.0 as possible.
- *Ratio of inter-CxG Interfered Area of a CxG (RCIAC)*: To define this metric, we first need to define few intermediate terms. In a given CxG CxG_g, a grid $grid_k$ is considered to experience inter-CxG interference if there exists a pair of CBSDs ($CBSD_i$, $CBSD_j$) such that $CBSD_i \in \mathbb{CBSD}_g$ and $CBSD_j \in \overline{\mathbb{CBSD}_g}$, both the CBSDs cover $grid_k$ and the EW between them is below ET. Thus, $\mathbb{CBSD}_{k\overline{g}}$, the set of CBSDs which belong to any CxG other than CxG_g and interferes with CxG_g at $grid_k$, is given by

$$\begin{aligned}\mathbb{CBSD}_{k\overline{g}} = \{&CBSD_j \mid CBSD_i \in \mathbb{CBSD}_g, \\ &CBSD_j \in \overline{\mathbb{CBSD}_g}, rx_{ik} \geqslant P_{th}, \\ &rx_{jk} \geqslant P_{th}, 0 < EW_{ij} \leqslant ET\}.\end{aligned} \quad (5)$$

  Note that in the above equation, $rx_{ik} \geqslant P_{th}$ implies $CBSD_i$ covers $grid_k$, whereas $rx_{jk} \geqslant P_{th}$ implies $CBSD_j$ covers $grid_k$. When the EW between the two CBSDs is non-zero but below ET, as given by the inequality $0 < EW_{ij} \leqslant ET$, there is no edge between the two CBSDs, hence they may be assigned the same frequency range (bandwidth), which may lead to interference at the grids in the common coverage areas of the two CBSDs. Therefore, $\mathbb{GI}_g$, the set of grids in $\mathbb{GRID}_g$ which experience interference due to CBSDs from other CxGs is given by

$$\mathbb{GI}_g = \{grid_k \in \mathbb{GRID}_g \mid |\mathbb{CBSD}_{k\overline{g}}| > 0\}. \quad (6)$$

  For a given CxG, CxG_g, the $RCIAC_g$ is given by

$$RCIAC_g = \frac{|\mathbb{GI}_g|}{|GRID_g|}. \quad (7)$$

  Thus, RCIAC of a CxG is essentially the fraction of grids, out of all the grids covered by the CxG, that are interfered by the CBSDs from other CxGs. Closer the value of its RCIAC to zero, the better is the performance of the CxG.
- *Average Aggregate Interference per inter-CxG Interfered Grid of a CxG (AAICIGC)*: For a given CxG, CxG_g, we denote the aggregate inter-CxG interference at $grid_k$, by $RX_{k\overline{g}}$. $RX_{k\overline{g}}$ is essentially the aggregate received power at $grid_k$ from all CBSDs other than those in CxG_g. Hence, it is (in dBm) given by

$$RX_{k\overline{g}} = 10\log_{10}\Big(\sum_{\forall CBSD_i \in \mathbb{CBSD}_{k\overline{g}}} 10^{rx_{ik}/10}\Big). \quad (8)$$

  $AAICIGC_g$ is the average of $RX_{k\overline{g}}$ over all the grids in $\mathbb{GI}_g$ and hence is (in dBm) defined by

$$AAICIGC_g = 10\log_{10}\Big(\frac{\sum_{\forall grid_k \in \mathbb{GI}_g} 10^{RX_{k\overline{g}}/10}}{|\mathbb{GI}_g|}\Big). \quad (9)$$

  Obviously, the lower the AAICIGC of a CxG, the better is its performance.

V. Performance Results

Before we present our results, it is worth noting that Approach 3 does not prescribe a particular method for frequency range allocation at the CBSD level. Therefore, CRC values reported in our performance results are the maximum possible (i.e., upper bound) CRC values in the corresponding configurations. Similarly, RCIAC and AAICIGC values are the maximum possible (i.e., upper bound) values in the corresponding configurations.

A. Performance in terms of CRC

Figure 2 and Figure 3 show the CRC of one of the CxGs (CxG_0) in different deployment configurations when the total number of CxGs is 3 and 4 respectively. Performance of other CxGs are similar. However, they are not presented to avoid cluttering of the results. It can be observed from the figures that when density of deployment (in number of CBSDs per km^2) is low (e.g., 3), the number of CBSDs in a CxG may not be enough to cover the entire deployment area. For a given location, using Hybrid propagation model always leads to equal or lower coverage than using ITM model. This is due to higher propagation loss incurred by Hybrid model in urban and suburban areas. With respect to locations, in general, the deployment in SD tends to have less coverage than VB due to the hilly terrain which leads to more propagation loss and hence less coverage area for each CBSD. However, when deployment density is 3, the CxG in SD covers more area than in VB when ITM model is used. Recall that although the relative positions of CBSDs are same at both the locations, other parameters such as transmit power and antenna height are randomly chosen based on the area type of the location. In those cases where SD has higher CRC, there is a Cat B CBSD with large height that leads to large coverage area. This, in turn, makes the coverage of the CxG large. It can also be observed that as the number of CxGs increases from three to four, the coverage of the CxG

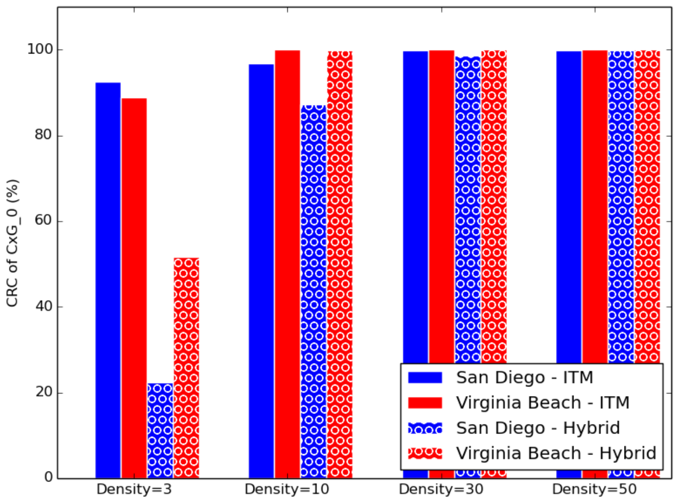

Fig. 2: Coverage Ratio of CxG_0, density in CBSD/km^2 (Number of CxGs = 3)

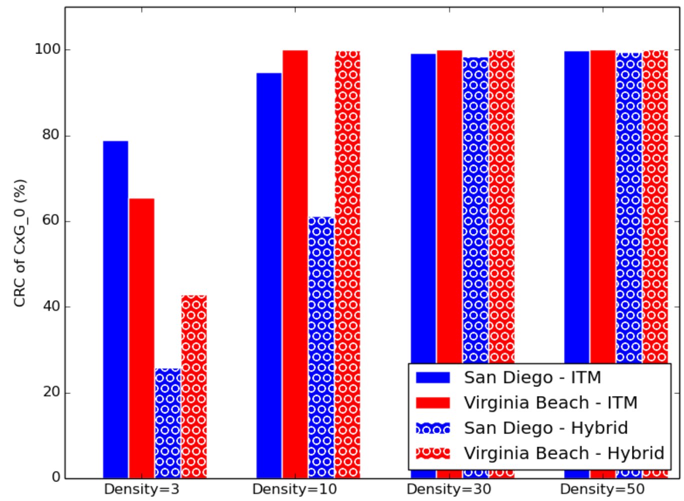

Fig. 3: Coverage Ratio of CxG_0, density in CBSD/km^2 (Number of CxGs = 4)

becomes lower when the deployment density is 3. This is due to the smaller number of CBSDs in each CxG when number of CxGs increases.

B. Performance in terms of AMABCC

Figures 4 and 5 show the AMABCC of CxG_0. It can be observed from the results that increasing the edge threshold improves the AMABCC in low density (e.g., density 3 and 10) deployment. At high densities, however, increasing edge threshold does not affect AMABCC much. At high densities, EWs are high, hence an increase in ET does not change the CIG topology much. Hence, cluster size of each CBSD does not change much and that is why AMBCC does not change much (see Eqn(2)). In terms of the propagation models, at high densities (e.g., density 30 and 50) the two models perform almost the same. At low densities Hybrid model provide slightly more flexibility in terms of increasing ET for more bandwidth, i.e., when ET increases AMABCC increase is slightly more when Hybrid model is used than when ITM is used. This is due to lower coverage when Hybrid model is used which leads to lower cluster sizes. In terms of location, deployment in SD gets more bandwidth (or AMABCC) than VB. Due to hilly terrain, overlap of coverage area of inter-CxG CBSDs is smaller at SD than VB which leads to lower cluster sizes for CBSDs and hence higher AMABCC. However, there is a deviation from this when Hybrid model is used with deployment density is 3. As discussed previously, a Cat B CBSD covers the majority of the area in San Diego making the cluster size high. This leads to lower AMABCC. Finally, as the number of CxGs increases from three to four, for a given configuration AMABCC decreases. This is because with higher number of CxGs, cluster size increases that leads to lower bandwidth. Note that the lower bound of the AMABCC occurs when all the clusters are of size N_g and is given by $1/N_g$ of the total GAA BW (80 MHz in our case), where N_g is the total number of CxGs. This is clear from Figures 4 and 5 when ET equals 0. The upper bound of AMABCC occurs when all clusters are of size one, i.e, when there is no edge between any pair of inter-CxG CBSDs. In this case, AMABCC equals the total GAA BW. This is the case when ET equals 1.0.

C. Performance in terms of RCIAC

Figures 6 and 7 show RCIAC of CxG_0 in different deployment configurations. Note that the inter-CxG interference does not exist when the ET is set to 0. It can be observed that RCIAC increases with the increase of the deployment density as well as the ET. When Hybrid model is used, RCIAC is better (smaller) than using ITM model. This is due to less overlap of CBSD coverage area caused by higher propagation loss between the inter-CxG CBSDs in Hybrid model. In terms of location, we do not see much difference in RCIAC performance between SD and VB. The hilly terrain in SD, due to higher propagation loss, produces smaller coverage area (CAC) as well as smaller interfered area compared to VB. Hence, RCIAC values at the two locations are similar.

D. Performance in terms of AAICIGC

Figures 8 and 9 show the AAICIGC performance of the CxG_0. As mentioned before, the inter-CxG interference does not exist when the edge threshold is 0. It can be observed that AAICIGC increases with the increase of ET. As ET increases, more inter-CxG edges disappear from CIG. This leads to allocating more overlapping BW to inter-CxG CBSDs which causes more interference. The deployment density does not have much impact on the AAICIGC performance. As deployment density increases, the interference power as well as the number of interfered grids increase. Thus, AAICIGC does not vary much

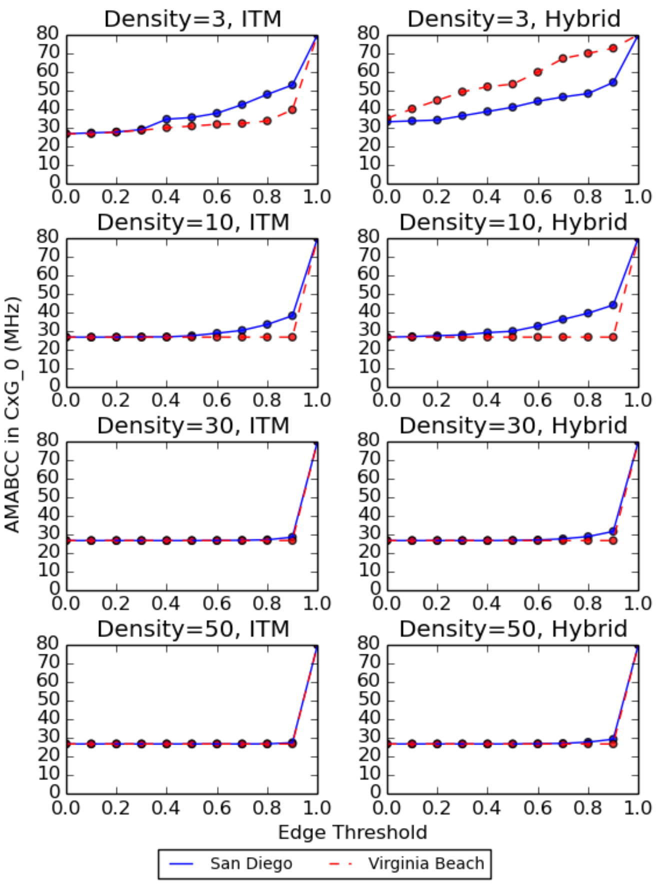

Fig. 4: AMABCC of CxG_0, density in CBSD/km^2 (Number of CxGs = 3)

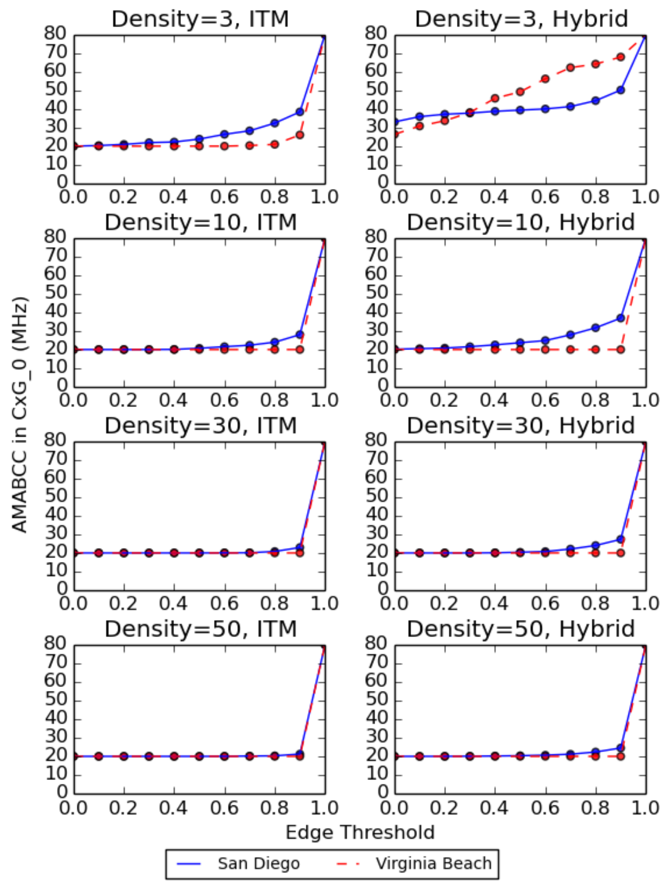

Fig. 5: AMABCC of CxG_0, density in CBSD/km^2 (Number of CxGs = 4)

(see Eqn(9)). At low ET and high deployment density (e.g., ET 0.2 and density 30), AAICIGC performance of Hybrid model is better than that of ITM model. But at high ET, ITM catches up with Hybrid. In terms of location, AAICIGC is higher in SD compared to VB when ET is small, but VB catches up when ET tends towards 1.0. This is because EWs in SD are skewed towards low values due to high propagation loss in hilly terrain. So, at low ET, more edges (which are below the ET) contribute to the interference. In contrast, EWs in VB are skewed toward high values, hence those edges contribute to interference when ET is set to high value closer to 1.0. This skewness of EWs in SD and VB is clear from the distribution of EWs shown in Figure 10.

E. Quality of Bandwidth Allocation

To evaluate the quality of bandwidth allocated to CxGs, one has to juxtapose the results of AMABCC and AAICIGC. At high deployment densities (.e.g, density 30 and 50), increasing ET would not produce higher AMABCC, but AAICIGC would increase rapidly. At low deployment densities, however, increasing ET does increase AMABCC, especially in SD. This comes at the cost of slight increase in AAICIGC. But low densities do not provide full coverage of the deployment area by a given CxG as is evident from the CRC performance. Therefore, these factors should be considered while choosing an operating point for a CxG (i.e., ET and deployment density).

In terms of confidence intervals for our experiments, we are able to get them for all the configurations when deployment densities are 3 and 10 $CBSDs/km^2$. When deployment density is 3, the maximum (across the two locations, two propagation models and all edge thresholds) bound of 95% confidence interval around the mean for AMABCC is ± 0.48 MHz, for RCIAC is $\pm 0.59\%$ and for AAICIGC is ± 1.51 dB. The corresponding numbers when deployment density is 10 are ± 0.35 MHz, ± 0.68 % and ± 1.02 dB respectively. For higher densities, the run time to get the confidence intervals becomes prohibitively long, primarily due to large number of CBSDs in the deployment. Hence, we are not able to report confidence intervals for densities 30 and 50.

VI. Conclusion

In this paper, we evaluated performance of the WInnForum recommended GAA-GAA coexistence scheme called *Approach*

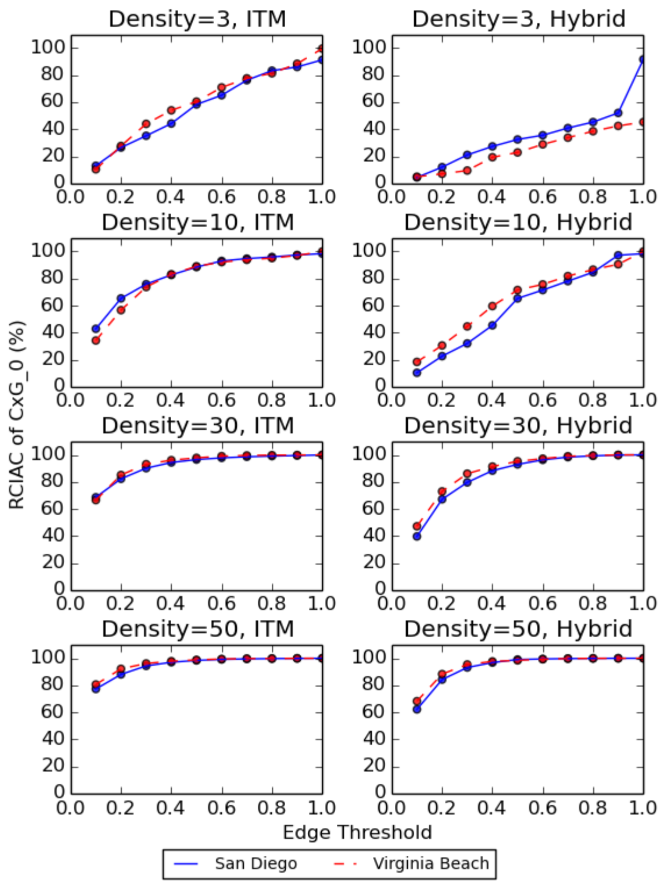

Fig. 6: RCIAC of CxG_0, density in CBSDs/km^2 (Number of CxGs = 3)

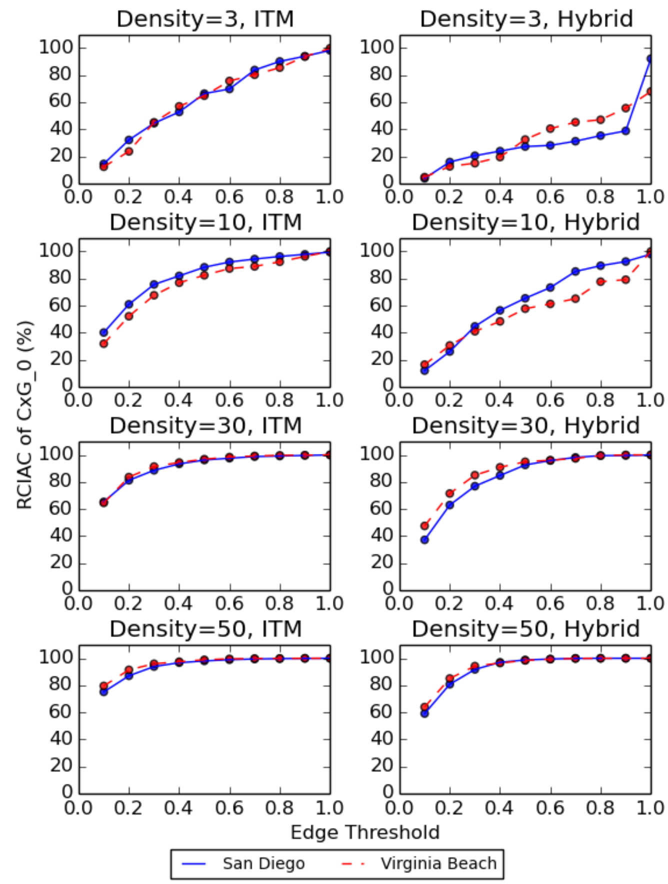

Fig. 7: RCIAC of CxG_0, density in CBSDs/km^2 (Number of CxGs = 4)

3. We looked at its performance with different deployment locations and densities using two different propagation models. If each CxG is required to cover the deployment area (most likely scenarios in metro cities), then deployment density has to be high so that CRC of the CxG is close to $100\,\%$. If CBSDs are uniform randomly distributed among the CxGs (as is done in our experiments), then at a high density deployment, when low ET is chosen, most CBSDs will belong to cluster size of N_g. Thus, a faster approximation to Approach 3 would be to just allocate $1/N_g$ of total GAA BW to each CxG. At the other extreme, if ET is close to 1.0, then an approximation is to allocate total GAA BW to each CxG.

The following are some key takeaways from our experiments. At a high density deployment, BW allocation (AMABCC) does not vary much when ET is increased, but interference increases both in terms of interference power (AAICIGC) and interference area (RCIAC) of CxGs. Hence, a good operating point is to have ET set to a low value. At a high density deployment, if getting more BW is more important, then ET should be set to a high value (e.g., greater than 0.9), but this will incur higher inter-CxG interference. On the other hand, if inter-CxG interference is of more concern than BW, then ET should be set to a low value (close to 0). In fact, ET=0 will produce no inter-CxG interference at the cost of allocating lowest BW to CxGs. These observations can be made from Figures 4 and 8. Note that, in this study we only concentrated on inter-CxG interference. There will be intra-CxG interference which needs to be managed by the respective CxG managers and is beyond the scope of this study.

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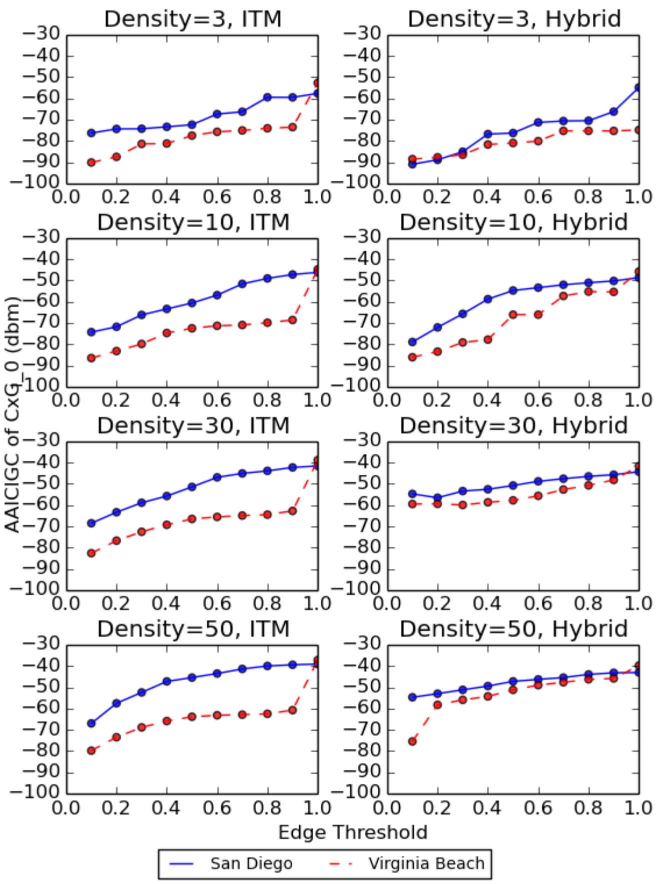

Fig. 8: AAICIGC of CxG_0, density in CBSDs/km^2 (Number of CxGs = 3)

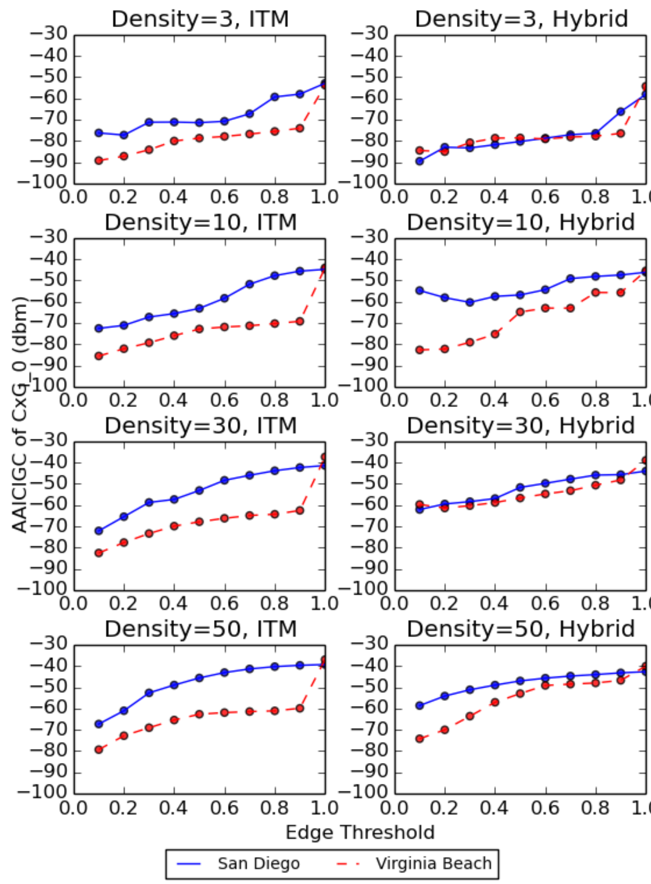

Fig. 9: AAICIGC of CxG_0, density in CBSDs/km^2 (Number of CxGs = 4)

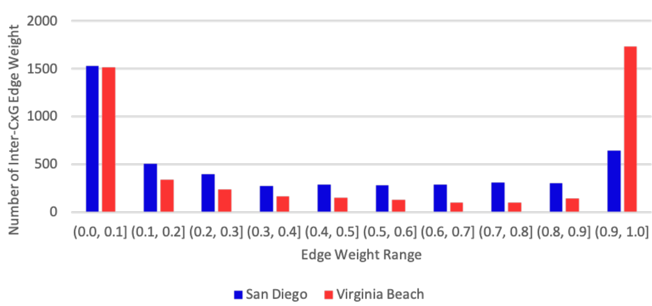

Fig. 10: Distribution of EW of all the CBSDs in CxG_0 (Density=10 CBSDs/km^2, ITM Model, CxGs=4)

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