Performance Study of a GAA-GAA Coexistence Scheme in the CBRS Band

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***Abstract*—The General Authorized Access (GAA) users in the Citizens Broadband Radio Service (CBRS) band are the lowest priority users who not only have to make sure that they do not cause harmful interference to the higher tier users but also must cooperate with each other to minimize potential interference among themselves. Thus, efficient GAA coexistence scheme is essential for operation of GAA users and to obtain high spectrum utilization. Towards this goal, the Wireless Innovation Forum (WInnForum) has recommended three schemes to facilitate coexistence among the GAA users. To the best of our knowledge, there is no performance study on any of these schemes available in the public domain. In this paper, we study performance of one of these schemes (called Approach 1). We choose two actual locations in the USA around which our study is conducted using actual terrain and land cover data of the continental USA. We evaluate performance of the scheme at different deployment densities, using different propagation models and with different mix of CBRS devices (CBSDs) at those two locations. We provide some interesting insights into the bandwidth allocation process and performance of Approach 1 in terms of mutual interference.**

I. Introduction

The Federal Communications Commission (FCC) in the USA has published the rules for commercial use of the spectrum in the 3.5 GHz band known as Citizens Broadband Radio Service (CBRS) band on a sharing basis [1]. The CBRS band has a three tiered access model. Current incumbents will operate in the highest tier followed by the Priority Access License (PAL) users in the middle tier and the General Authorized Access (GAA) users in the lowest tier. The incumbents must be protected from harmful interference caused by tier-2 (PAL) and tier-3 (GAA) users. PAL users should be protected from interference from GAA users. However, a GAA user cannot expect interference protection from higher tier users as well as from other GAA users in the same tier. Access to the spectrum in this band is managed by Spectrum Access Systems (SASs). As per the rule 47 C.F.R. § 96.35 in [1], GAA users must cooperate with each other to minimize the potential interference and to increase spectrum utilization. In the first phase of deployment in the CBRS band, there will be no PAL users. Hence, only GAA users will share the spectrum with the incumbents. Thus, GAA-GAA coexistence is very criticial to the success of this band. The Wireless Innovation Forum (WInnForum), which is involved in developing standards for operation of systems in the CBRS band has published Technical Reports recommending different schemes to faciliate effective GAA-GAA coexistence that should minimize mutual interference and increase spectrum utlization. The WInnForum has recommended three different schemes for GAA-GAA coexistence in three different Technical Reports [2]–[4]. The design and architecture of these schemes are largely based on discussions and experience of various members of the WInnForum. To the best of our knowledge, there is no performance study on any of these schemes available in the public domain. In this paper, we take up one of those schemes, named *Approach 1*, proposed in [2] and study its performance in different configurations. In the CBRS band, there can be two types of CBRS devices (CBSDs). Category A (CatA) CBSDs transmit at lower power than Category B (CatB) and are typically installed indoors. CatB CBSDs are deployed outdoors. We study the effect of propagation model, deployment density and different population of CatA and CatB CBSDs on the performance of the GAA-GAA coexistence. It is envisioned that operators will group their CBSDs into, what are called, Coexistence Groups (CxGs). The CxGs will be responsible for managing interference among their respective CBSDs. Hence, a SAS will only be responsible for allocating bandwidth to the CxGs.

The main contributions of this work are as follows. The WInnforum does not define any performance metric to evaluate its proposed schemes. We have proposed a few performance metrics, which will be useful for operators and SAS administrators to evaluate the schemes as well as to compare different schemes. To the best of our knowledge, there is no such study on the GAA-GAA coexistence schemes available in the public domain. Consequently, our work should provide insight into the performance of the scheme (Approach 1) proposed in [2] in terms of various deployment parameters and propagation models. We use actual deployment location data and use the WInnForum reference implementation of propagation models [5] which uses actual terrain and land cover data of the continental USA. Hence, our simulation results should be close to what one would expect in practice. As explained later in the paper, in one of our experiments, we deviate from the WInnForum scheme and show how more bandwidth (compared to WInnForum scheme) can be allocated at the cost of higher interference. Results from this experiment suggest that a better scheme can be designed to provide more bandwidth to the CBSDs if they agree to tolerate higher

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
SIRG	Signal to Interference Ratio at a Grid
AIPA	Average Interference Power per unit Area
AIPCCG	Average Interference Power per CBSD per Channel per grid

interference up to a certain threshold.

II. Related Work

Coexistence issues in different wireless bands have been studied in the past. Coexistence challenges for heterogeneous cognitive networks in the TV white space have been discussed in [6]. In this study, coexistence between the secondary users and the incumbents as well as among the secondary users is discussed. Coexistence among secondary users which are heterogeneous in their air interface and MAC protocol is also considered. Coexistence of LTE-licensed assisted access (LTE-LAA) and WiFi in the 5 GHz band has been studied in [7]. Coexistence of LTE-LAA and WiFi in the TV white space has been proposed in [8], [9]. Some of the solutions proposed in the literature are to modify LTE MAC protocol to improve coexistence performance. The above coexistence scenarios are addressed with specific air interface or MAC protocol in mind. However, the GAA-GAA coexistence schemes in the CBRS band proposed by the WInnForum do not assume any particular air interface or MAC protocol. As mentioned earlier, the WInnForum has proposed three approaches to solve the GAA-GAA coexistence problem. Approach 1 [2] treats bandwidth as the only resource and hence, allocates bandwidth to the CBSDs such that interfering CBSDs are assigned different channels to the extent possible. It does not manipulate transmit power of the CBSDs for coexistence purpose. If the deployment is too dense and hence, assigning different channels to interfering CBSDs is not possible, then this scheme allows some CBSDs to be assigned the same channel even if they may interfere with each other. Approach 2 [3] deals with bandwidth and transmit power together and treats them as two types of resources. In dense deployment scenarios, if there are not enough channels to allocate different channels to interfering CBSDs, then less transmit power is allocated to a pair of interfering CBSDs so that intereference between them is mitigated and hence, can be allocated the same channel. Approach 3 [4] tries to maximize the amount of bandwidth allocated to individual CxGs by using a recursive algorithm to a cluster of CBSDs. It first identifies the CBSDs which belong to a CxG and are only connected to (i.e., interfere with) CBSDs which belong to the same CxG. These CBSDs are refered to as *cluster of size 1*. These clusters can be allocated $100\,\%$ of the available bandwidth. Next is to identify CBSDs belonging to cluster of size 2. CBSDs in these clusters belong to one of two CxGs. In this case, $50\,\%$ of available bandwidth is allocated to CBSDs belonging to one CxG and the other $50\,\%$ is allocated to CBSDs belonging to the other CxG. This algorithm is then applied recursively until all CBSDs are covered. A study of impact of propagation models on GAA-GAA coexistence and deployment density is presented in [10].

III. Overview of WInnForum Scheme (Approach 1)

The WInnForum has proposed three different schemes as solutions to GAA-GAA coexistence. In this section, we present salient parts of one of these schemes, named Approach 1 [2], which we have used in our study.

A. CBSD Interference Graph

For the purpose of GAA-GAA coexistence, a CBSD Interference Graph (CIG) is constructed in a deployment area. The vertices in the CIG are the CBSDs. An edge is placed between two CBSDs if either one or both of the CBSDs experience interference from the other CBSD above a given threshold. Edge Weight (EW) between all pairs of CBSDs is computed to determine if an edge should exist between the pair. If the computed EW is above a set Edge Threshold (ET), then an edge is established between the two CBSDs.

1) Edge Weight Calculation: For Edge Weight (EW) calculation, an Interference Metric (IM) between two CBSDs is first computed. IM is a measure of mutual interference between two CBSDs. Depending on the deployment scenario, IM may be computed in *area coordination* or in *point coordination* mode. For example, when CBSDs are deployed as LTE e-NodeB, then it needs to have a coverage area which should be protected from interference. Hence, in this case, IM in area coordination mode should be computed. On the other hand, when two CBSDs are deployed for Fixed wireless service, one CBSD is deployed as the Base Transceiver Station (BTS) and the other is deplyed as a Customer Premise Equipment (CPE) CBSD. They communicate in point-to-point mode and hence, interference at those CBSDs needs to be limited. The point coordination mode is appropriate in this case. In this study, we are interested in CBSD deployment for LTE coverage and hence, focus on area coordination mode.

In area coordination mode, for a pair of CBSDs, say CBSD-1 and CBSD-2, coverage area of each CBSD is computed. Coverage area of a CBSD, for a given transmit power, is the area around the CBSD such that the received signal strength at any point inside the area is above a set threshold. The WInnforum scheme specifies that this threshold should not be less than -96 dB relative to 1 mW (dBm)/10 MHz. The fraction of coverage area of CBSD-1 that overlaps with the coverage area of CBSD-2 is taken as CBSD-1's interference metric IM_1. Similarly, interference metric IM_2 of CBSD-2 is the overlap area expressed as a fraction of its coverage area. Then the EW between CBSD-1 and CBSD-2 is the maximum

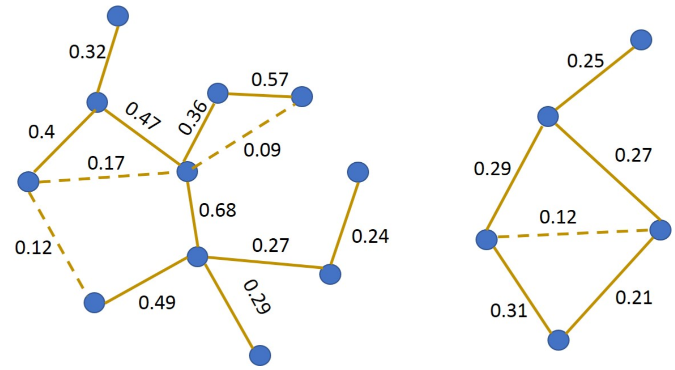

Fig. 1: An Example CBSD deployment with Edge Weights

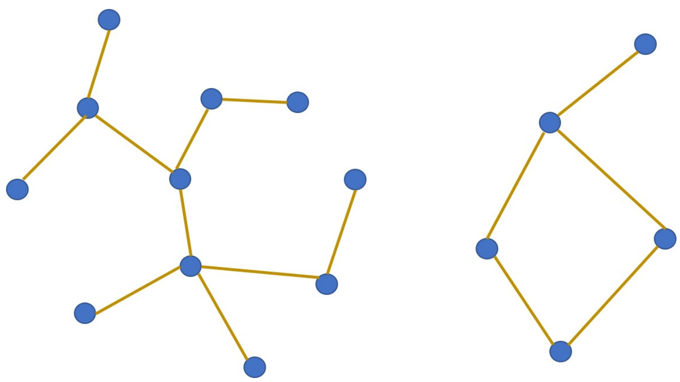

Fig. 2: Example CBSD Interference Graph when ET=0.2

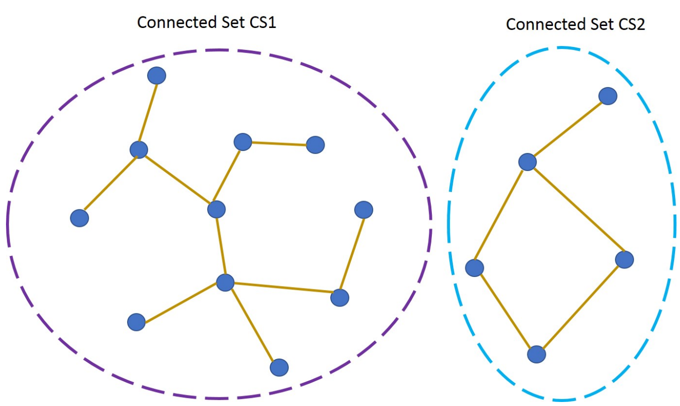

Fig. 3: Example Connected Sets

of IM_1 and IM_2. Note that EW takes a value between 0 to 1. For a given edge threshold (ET), an edge is established between CBSD-1 and CBSD-2 only if the EW is greater than the ET. This procedure is followed for every pair of CBSDs to obtain the CBSD interference graph.

2) Connected Set: Once the CBSD inferference graph is constructed, the next step is to generate *connected set(s)* off of it. A CBSD interference graph may contain one or more connected sets. Any two CBSDs in a connected set are connected directly through an edge or indirectly through other CBSDs in the interference graph. No CBSD within a connected set is connected directly or indirectly to any CBSD outside of the connected set [2].

Fig. 1 shows an example of CBSD Interference Graph when the ET is set to 0.2. In the figure, there is a solid edge between two CBSD if their coverage areas overlap and the EW between them is greater than or equal to the ET. A dashed edge indicates that the coverage areas of the two CBSDs overlap, but the EW is less than the ET. No edge between two CBSDs implies that the coverage area of the two CBSDs do not overlap. After applying edge threshold and removing the dashed edges, we get the CBSD interference graph as shown in Fig. 2. When the conditions of connected set are applied to this interference graph, we get two connected sets CS1 and CS2 as shown in Fig. 3.

3) Coexistence Groups: It is envisioned that operators in this band will create Coexistence Groups (CxGs) to faciliate GAA-GAA coexistence. A CxG consists of a group of CBSDs which will coordinate their own interference within the group. Thus, a SAS is only responsible for the allocation of bandwidth at the CxG level. The operator (or a CxG manager) of a CxG will take the bandwidth allocated to it and assign it to individual CBSDs within the CxG as per its interference management policy. As a result, a connected set will consist of one or more CxGs, i,e., CxGs are subgraphs in a connected set. The CBSDs which do not belong to any CxG are grouped together to form a common CxG (sort of a virtual CxG).

4) Graph Coloring of Connected Sets: The WInnForum scheme proposes a graph coloring approach [11] to allocate GAA bandwidth. The graph coloring starts at the CxG sub graph level. Graph coloring of a CxG involves computing its *chromatic number*. Chromatic number of a CxG is the minimum number of colors required to color the nodes of the CxG such that no two nodes having an edge between them are assigned the same color. Once chromatic number of each CxG inside a connected set is computed, then the *total chromatic number* of the connected set is computed by summing up the chromatic numbers of the CxGs belonging to the connected set. The bandwidth allocation to the CxGs is done as per the following procedure [2].

Let B be the total bandwidth available for the GAA users. Let C_i be the chromatic number of CxG_i. If there are M CxGs in the connected set, then the total chromatic number of the connected set is $C = \sum_{i=1}^{M} C_i$ and the bandwidth allocated to CxG_i is given by

$$BW_i = B \cdot \frac{C_i}{C} \quad (1)$$

Note that the bandwidth allocated to a CBSD is B/C. It is understood that for useful operation, a CBSD should get at least 10 MHz bandwidth. Consequently, if $B/C < 10$ MHz then the ET needs to be increased which will eliminate some edges from the connected set and hence, bring down the value of C. Then the bandwidth allocation process is repeated again. This procedure is repeated until $B/C \geq 10$ MHz.

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: Ratio of CBSD categories deployed in different Areas

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

IV. Experiment and Results

A. Deployment Model

We consider a deployment area of $5\,km \times 5\,km$ in size around Virginia Beach (VB) in the east coast (the center at latitude 36.872227 and longitude -76.023389) and around San Diego (SD) in the west coast (the center at latitude 32.723588 and longitude -117.145319) of the USA.

We chose these two cities because the terrain around these two cities are quite different. The terrain around Virginia Beach is somewhat flat, whereas it is hilly around San Diego. Propagation loss is a function of the terrain profile between transmitter and receiver. Hence, the two chosen cities have quite different propagation characteristics. The coverage area of CBSDs are clipped by the above square deployment area. The deployment area is discretized by dividing it into equal sized grids of size $50\,m \times 50\,m$. CBSDs are uniformly placed around this deployment area as per the deployment density used for a given experiment. The parameters of the CBSDs used in our experiments are shown in Table II. All the CBSDs are assumed to have omnidirectional antennae.

In this study, we have assumed that each CBSD is a singleton CBSD and hence, all the CBSDs in the deployment area form one CxG. Since the FCC rule allows up to 70 MHz (out of total of 150 MHz) for PAL users, we assume that the rest 80 MHz is available for GAA users. We have used -96 dBm/10 MHz as the receive power threshold while computing coverage area of a CBSD.

B. Deployment Configurations

We ran our experiments in two deployment configurations as follows.

- *Config A*: In this configuration, all the deployed CBSDs are chosen to be Category A.

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

- *Config B*: In this configuration, we used a mix of Category A and Category B CBSDs as per Table III.

For each of the above configurations, we ran experiments with different deployment densities and propagation models at the two chosen locations (SD and VB). All the Category A CBSDs in our experiements are considered indoors, whereas all the Category B CBSDs are deployed outdoors.

C. Performance Metrics

The WInnForum does not suggest any performance metrics for evaluating the GAA-GAA coexistence scheme. In this section, we describe the performance metrics used in our evaluations.

- *Signal to Interference Ratio at a Grid (SIRG)*: The signal power at a grid within the coverage area of one or more CBSDs operating on the same channel is the highest received power at the grid from one of these CBSD transmitters. The received power at that grid from all other CBSDs operating on the same channel is considered as interference power. So, the SIRG (for a given channel) is the ratio of signal power to the aggregate Interference power expressed in dB.
- *Average Interference Power per unit Area (AIPA)*: This metric captures the average interference experienced by a receiver while it is inside the coverage area of a CBSD. If there are N_g grids inside the coverage area of a CBSD and I_i is the interference power (in dBm) received at the grid i over a channel assigned to the CBSD, then the AIPA (in dBm) of the CBSD, on that channel is given by

$$AIPA = 10\log_{10}\left(\frac{\sum_{i=1}^{N_g} 10^{I_i/10}}{N_g}\right) \qquad (2)$$

- *Average Interference Power per CBSD per Channel per grid (AIPCCG)*: The AIPCCG is defined as the average interference power (in dBm) per CBSD per channel per grid. Let I_i^j be the interference power (in dBm) received at a grid i on channel j. Let N_g, N_c and N_d be the number of grids, channels and CBSDs in the deployment area respectively. Then AIPCCG is given by

$$AIPCCG = 10\log_{10}\left(\frac{\sum_{j=1}^{N_c}\sum_{i=1}^{N_g} 10^{I_i^j/10}}{N_g \cdot N_c \cdot N_d}\right) \qquad (3)$$

D. Propagation Models

We have evaluated performance of the GAA-GAA coexistence scheme using two different propagation models: 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]. The ITM model, also known as the Longley-Rice model, is a propagation model based on electromagnetic theory, terrain features and radio measurements. The parameters used in the ITM propagation model are given in Table IV. The Hybrid propagation model is a model proposed by the WInnForum and is a hybrid between the ITM and the extended Hata (eHata) model. The eHata model [14] is an extension of the Hata model [15], which is essentially an empirical model based on a series of land-mobile measurements made by Okumura [16] over varied terrain. While the eHata model accounts for clutter loss, the ITM model does not consider clutter loss. The Hybrid propagation model primarily sets its loss equal to the larger of the ITM loss and the eHata loss in urban and suburban area. In the rural area, the propagation loss using the Hybrid model is equal to the loss using the ITM model. Thus, in general, propagation loss using the Hybrid model is higher than or equal to the ITM model.

E. Bandwidth Allocation

In this section, we analyze bandwidth allocated to the CBSDs using the WInnForum GAA-GAA coexistence scheme (Approach 1). The experiments were run for all combinations of locations (San Diego and Virginia Beach), propagation models (ITM and Hybrid), and deployment densities of 3, 10, 30 and 50 $CBSDs/km^2$ for both the CBSD deployment configurations.

We first analyze the BW allocation in San Diego. Fig. 4 and Fig. 5 show the cumulative distribution function (CDF) of BW allocation for different deployment densities and propagation models for Config A and Config B respectively. For both Config A and B, for the ITM model as deployment density increases we generally see better BW allocation to the CBSDs (more CBSDs get more BW). This is counter intuitive. However, in these cases, as deployment density increases, the interference graph becomes more connected leading to a higher chromatic number. If the chromatic number is too high then the BW allocated to the CBSDs goes below 10 MHz and hence, the algorithm increases the ET which results in a lower chromatic number. In some cases, some edges in a connected set may be eliminated so as to create multiple connected sets due to this. Each connected set has the entire available bandwidth at its disposal for allocation to its CBSDs. Hence, the increase in the ET increases the chance of getting more BW for each individual CBSD. An extreme case is when the algorithm has to raise the ET to 1.0 for some of the connected sets (as is the case for the ITM model at density 50 in Config B). In this case, each CBSD becomes a single-CBSD connected set and is assigned the entire available bandwidth. As we will discuss later, this improvement in BW allocation comes at the cost of incurring higher interference. However, in the case of the Hybrid propagation model, as the density increases, there is no clear trend in BW allocation. The way the BW allocation algorithm is designed, when deployment density increases, as described above, the system parameters such as the ET, the number of connected sets, the chromatic number in connected sets change. With so many parameteric changes in the system, it is hard to predict a trend in the BW allocation when the deployment density increases. Comparing BW allocation using the Hybrid vs the ITM propagation model, again, it is hard to conclude which model produces better performance. In Config A, the Hybrid model produces better performance whereas in Config B, the ITM gives better performance. In general, the Hybrid propagation model produces equal or more loss than the ITM. So, one can generally assume to get better BW allocation than the ITM. However, sometimes the ITM model can result in better BW allocation (see in case of Config B) (at the cost of higher interference as we will see later). Comparing performance between Config A and B, we see that if the Hybrid model is used, Config A gives better performance, but if the ITM model is used, then there is no clear winner. Again, this is because there are many system parameters that change when the deployment density increases.

At Virginia Beach (Fig. 6 and Fig. 7), the BW allocation does not vary that much when the deployment density increases, especially for Config B (in which the interference graph is more connected due to higher transmission power of CatB CBSDs). Because of the flat terrain, propagation loss is less compared to SD. Hence, CBSDs quite far away are connected to each other. As a result, degree of vertices is high for low deployment density. As the deployment density increases, the degree of vertices does not increase significantly. Thus, the chromatic number of connected sets, and consequently BW allocation does not increase significantly. Note that chromatic number of a graph is less than or equal to the (maximum vertex degree +1). When the deployment density increases, we see that the BW allocation remains the same or becomes better for both propagation models and for both Config A and B. The reason is same as we discussed before for SD. For other cases, there is no clear trend.

When we compare BW allocation between SD and VB, generally SD has an equal or a better BW allocation for both configurations. This can be attributed to the hilly terrain around SD which leads to more propagation loss which, in turn, leads to less dense connectivity in the connected sets and hence, results in a lower chromatic number.

For both SD and VB, it is hard to draw a trend in the BW allocation across two configurations. As mentioned before, when the deployment density increases, there are multiple system parameters that change. Hence, when using the WInnforum coexistence scheme it is hard to determine which configuration is better in terms of the BW allocation.

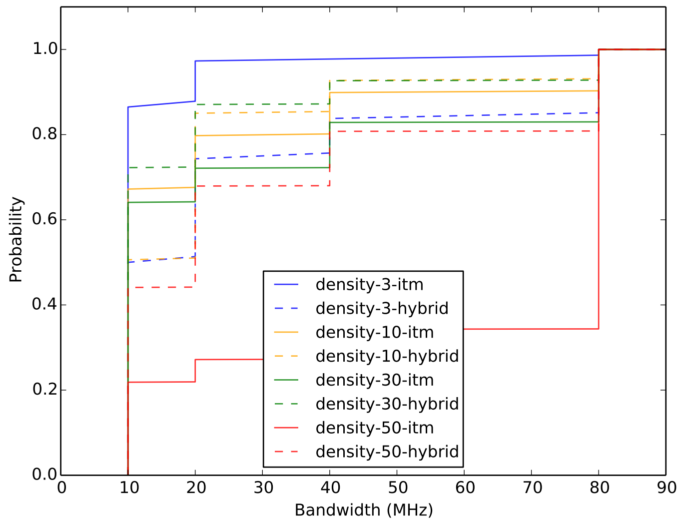

Fig. 4: CDF of Bandwidth Allocated for Config A (San Diego)

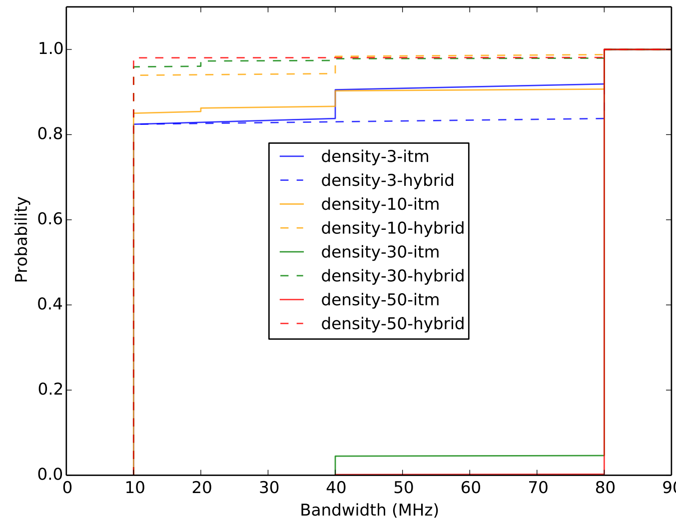

Fig. 5: CDF of Bandwidth Allocated for Config B (San Diego)

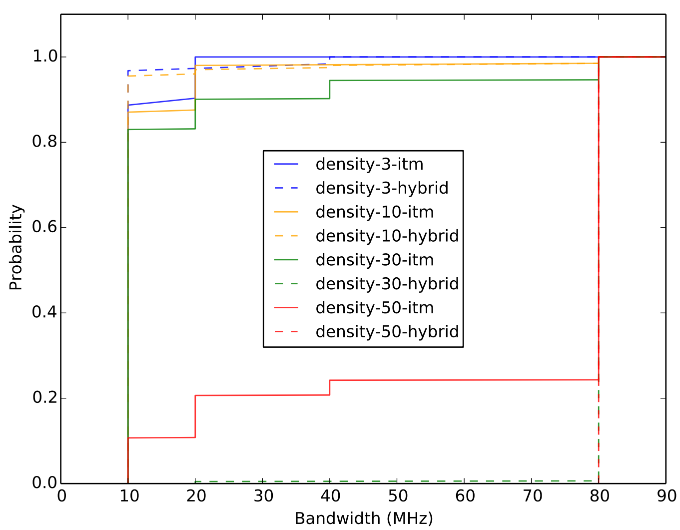

Fig. 6: CDF of Bandwidth Allocated for Config A (Virginia Beach)

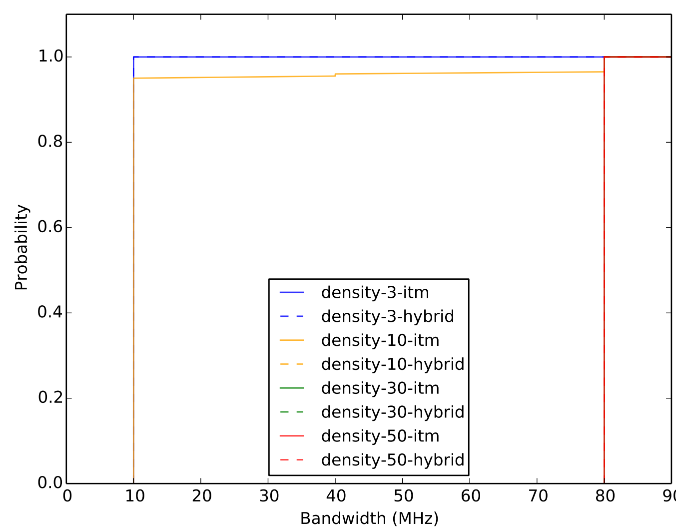

Fig. 7: CDF of Bandwidth Allocated for Config B (Virginia Beach)

F. Performance in terms of AIPA

Fig. 8 and Fig. 9 show the CDF of the AIPA with different propagation models and deployment densities in SD in Config A and Config B respectively for the channel with the worst interference. The corresponding figures for VB are Fig. 10 and Fig. 11. For a given propagation model and a given configuration, as the deployment density increases the AIPA becomes worse for both SD anf VB location. This is quite intuitive. When the deployment density increases, there is more interference due to transmission from higher number of CBSDs which causes the AIPA to increase. Another factor that contributes to the AIPA increase is when the scheme has to increase the ET to allocate a minimum of 10 MHz BW to the CBSDs. As explained in the BW allocation for SD, the ITM model allocates more BW when the deployment density increases, but this is achieved at the cost of increasing the ET which leads to a higher AIPA. We see this increase in the AIPA for the ITM model in SD in Fig. 8 and Fig. 9. In SD, the Hybrid propagation model results in better AIPA than the ITM model in both the configurations. But in VB, the ITM does better than the Hybrid in both the configurations. This is because

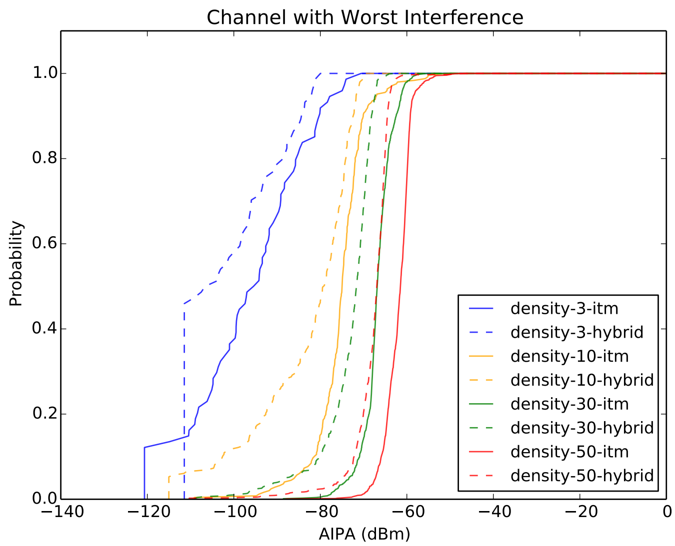

Fig. 8: CDF of AIPA for Config A (San Diego)

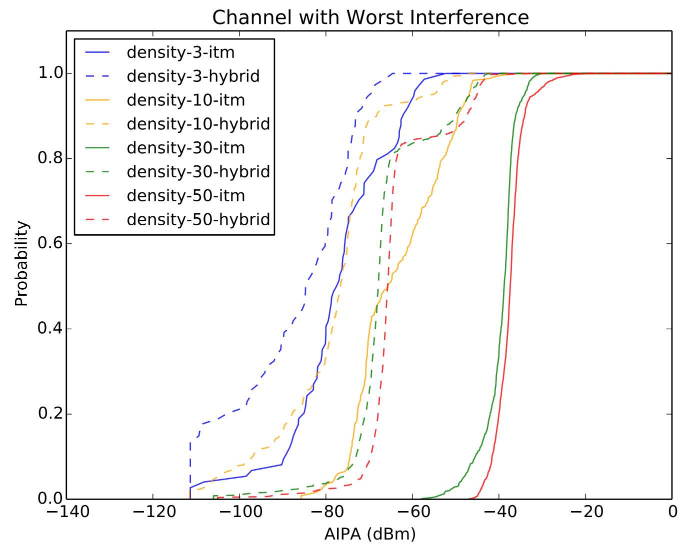

Fig. 9: CDF of AIPA for Config B (San Diego)

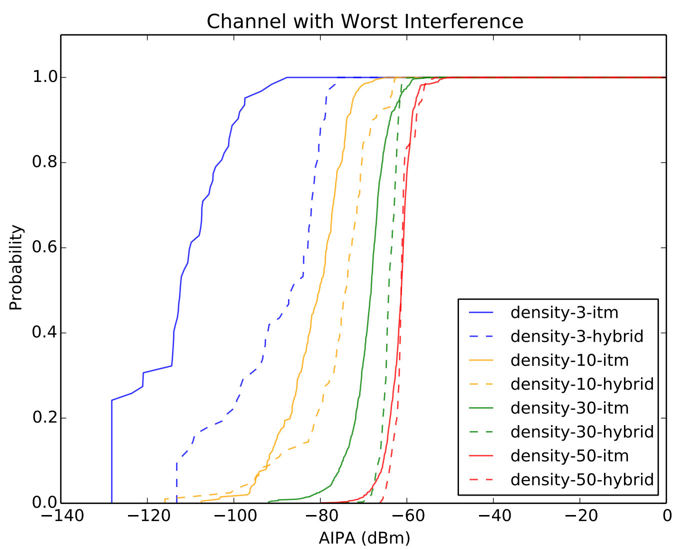

Fig. 10: CDF of AIPA for Config A (Virginia Beach)

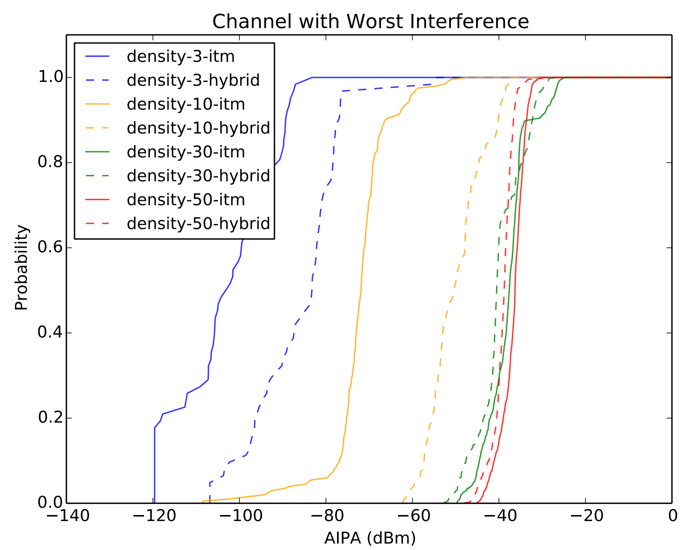

Fig. 11: CDF of AIPA for Config B (Virginia Beach)

of the way the Hybrid model is defined. When the Hybrid model is used in urban and suburban areas, the propagation loss takes on the value provided by the eHata (since its loss is generally more than the ITM in such areas) whereas in rural areas the propagation loss is equal to that provided by the ITM (as per Requirement R2-SGN-04 in [13]). In SD, the majority grids are in urban or suburban area, so that the propagation loss is determined by the eHata model in most cases when the Hybrid model is used, which leads to higher loss. Thus, the AIPA in SD is better for the Hybrid model than when the ITM model is used. In contrast VB has a large rural area. Thus, when the Hybrid model is used, the propagation loss in VB is mostly equal to that calculated by the ITM model. As a result, one would expect the AIPA performance of the ITM and the Hybrid model to be very close to each other. However, as per the implementation of the Hybrid model by the WinnForum (see R2-SGN-04 in [13] and [5]), antenna height of a CBSD cannot be less than 20 m. Due to this requirement, for the CBSDs having height less than 20 m typically its coverage using the ITM would be lower than that using the Hybrid model. Lower coverage area leads to lower interference. Since VB is dominated by rural grids, the ITM provides better AIPA performance than the Hybrid.

For both the locations, the AIPA performance is better for Config A for both the propagation models and for all deployment densities. This is intuitve, since having Cat B

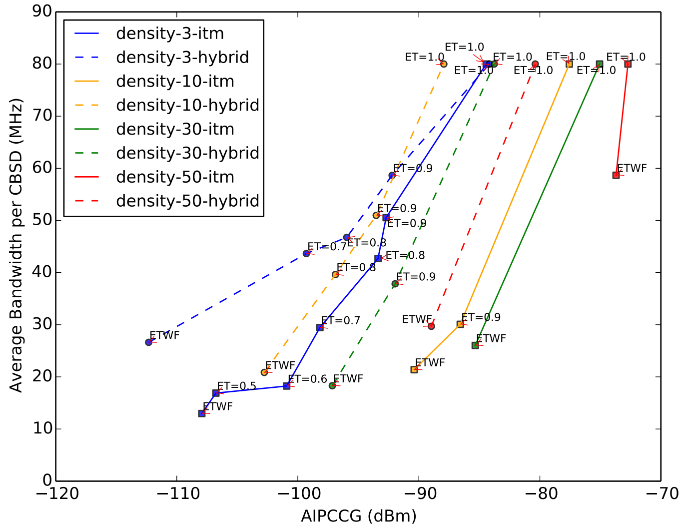

Fig. 12: BW Allocation vs AIPCCG at Different ET in Config A (San Diego)

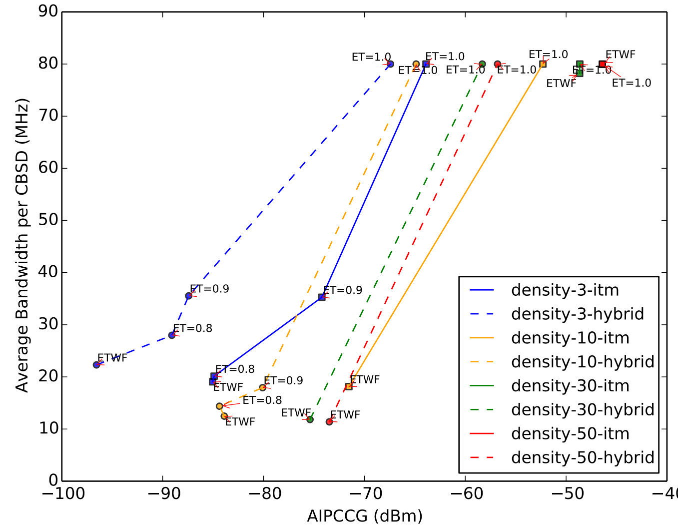

Fig. 13: BW Allocation vs AIPCCG at Different ET in Config B (San Diego)

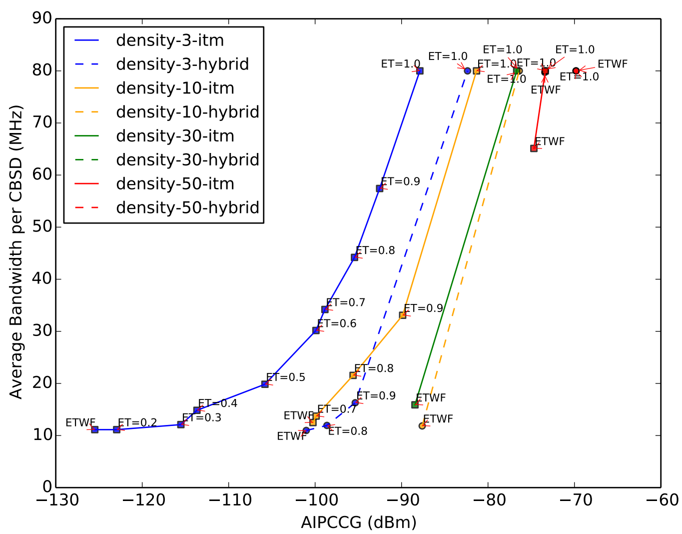

Fig. 14: BW Allocation vs AIPCCG at Different ET in Config A (Virginia Beach)

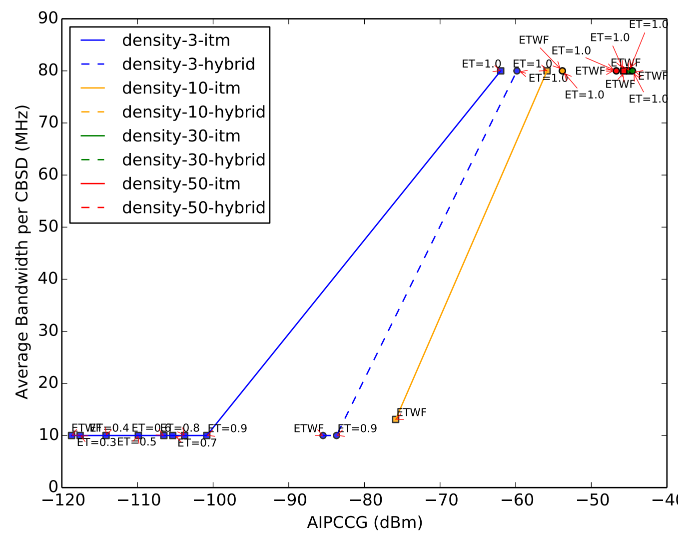

Fig. 15: BW Allocation vs AIPCCG at Different ET in Config B (Virginia Beach)

CBSDs (which have higher transmit power), creates more interference.

G. *Performance of BW Allocation vs AIPCCG*

For this performance measurement, we deviate from the scheme proposed by the WInnForum. In this experiment, we want to observe the effect of allocating higher BW at the cost of higher interference when we go beyond the ET at which the proposed WInnForum scheme would stop. Note that the proposed WInnForum scheme stops increasing the ET of a connected set once the CBSDs in the connected set get at least 10 MHz bandwidth. Figures 12, 13, 14 and 15 show how increase in the ET results in more average BW allocation per CBSD at the cost of interference for the locations SD (Config A and B) and VB (Config A and B) respectively. Note that in this experiment, the CBSDs are allocated actual BW computed for a given ET, i.e., the final BW allocation is not rounded down to multiples of 10 MHz. The points marked as ETWF (WInnForum ET) represents the operating point of the WInnForum Scheme in terms of average BW and AIPCCG. Note that, in general, there will not be a single ET value at this operating point since there could be multiple connected

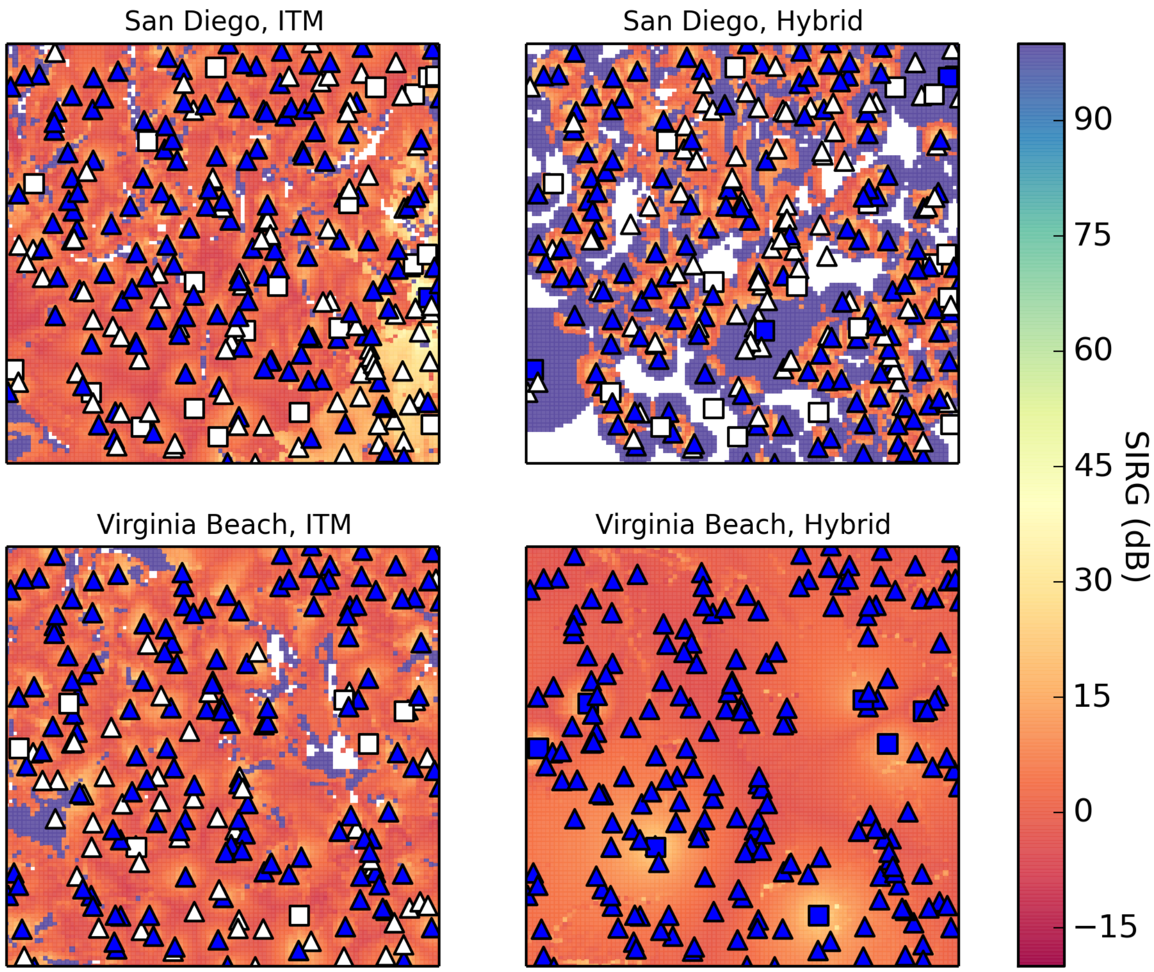

Fig. 16: Heatmap of SIRG of Channel 1, Deployment Density 10, Config B

sets each with its own ET. Hence, we do not provide an ET value at this operating point in the graphs. For a given deployment density, we then continue to increase the ET beyond the corresponding ETWF. The interference metric in this experiment is AIPCCG and its computation is explained in Section IV-C. At both SD and VB location, as expected, when a higher BW is allocated to the CBSDs, the AIPCCG also goes up for all combinations of configurations, propagation models and deployment densities. Also, as the deployment density increases, to get the same BW allocation, the ET needs to be higher and the corresponding AAIPC is also higher. For a given propagation model and a given deployment density, as the ET increases, the CBSDs get more BW at the cost of higher AIPCCG. In SD, the Hybrid propagation model produces a better result than the ITM model for all deployment densities and for both the configurations, i.e., for a given allocated BW, the AIPCCG is lower for the Hybrid model than the ITM model. But in VB, the ITM model produces a better BW allocation than the Hybrid model. This reversal of performance between the two propagation models at the two locations is due to the same reason as explained in the performance in terms of the AIPA.

H. Performance in terms of SIRG

Figure 16 shows the SIRG heatmap in SD and VB for both propagation models in Config B for the most crowded channel (Channel 1). The CBSDs in blue have been allocated channel 1 whereas the CBSDs in white operate on some other channel(s). The color coded scale (in dB) is provided to the right. For both the ITM and the Hybrid propagation models, SD shows better SIRG performance over VB, although the difference is more prominent with the Hybrid model. With the hilly terrain around SD, the Hybrid propagation loss is more in SD than in VB. Hence, there is less interference which leads to a higher SIRG. At SD, using the Hybrid model gives a much better SIRG performance over the ITM. Since SD has lot of urban and suburban areas, the Hybrid model incurs more loss and hence, leads to less interference. At VB, there is no marked difference between the ITM and the Hybrid propagation in terms of SIRG. VB has a vast rural area in which the ITM and the Hybrid model produce almost the same loss. Hence, the SIRG performance using those two models at VB has no significant difference. We have the SIRG performance for other deployment densities and configurations, but we are not able to present them here due to space limitation.

V. Conclusion and Future Work

In this paper, we studied the performance of the proposed WInnForum GAA-GAA coexistence scheme, called Approach 1. Our study looked at the effect of propagation model, deployment density and different mix of CatA and CatB CBSDs on the performance of GAA-GAA coexistence. Our study found that the way WinnForum Approach 1 is designed, performance of the BW allocation is hard to predict. There are multiple system parameters at play while allocating BW (e.g., ET, number of CSs and chromatic number of each CS), which are inter-dependent, making the prediction hard. In terms of the AIPA performance, Config A performs better than Config B. The AIPA performance in SD is better than in VB for the Hybrid model, whereas the ITM model performs better in VB. The way the GAA-GAA coexistence scheme is designed, it is possible to get a better BW allocation at higher deployment densities at the cost of incurring higher interference. The SIRG performance is generally better at locations having hilly terrian (e.g., SD) than at locations having flat land. At a given location, the Hybrid model will generally have a better SIRG performance than the ITM model.

From our study of performance of average BW vs AIPCCG, we feel a better scheme could be to have a target threshold for the SIRG in a deployment area and then allocate the maximum possible BW to CBSDs such that the SIRG does not go below the threshold. We intend to study this scheme further and compare its performance with WInnForum's Approach 1. We would like to analyze the performance of the WInnForum scheme when the CBSD deployment has multiple CxGs to investigate the effect of having CxGs on BW allocation and on interference. We are in the early stage of implementing WInnForum's Approach 3 proposed in [4]. We would like to compare the performance of that scheme with Approach 1.

References

[1] "Citizens Broadband Radio Service," 47 C.F.R. § 96, 2019.

[2] "Operations for Citizens Broadband Radio Service (CBRS); GAA Spectrum Coordination - Approach 1," Document WINNF-TR-2003, Version V1.0.0, May 2019. [Online]. Available: https://winnf.memberclicks.net/assets/work_products/Recommendations/WINNF-TR-2003-V1.0.0%20GAA%20Spectrum%20Coordination-Approach%201.pdf

[3] "Operations for Citizens Broadband Radio Service (CBRS); GAA Spectrum Coordination - Approach 2," Document WINNF-TR-2004, Version V1.0.0, May 2019. [Online]. Available: https://winnf.memberclicks.net/assets/work_products/Recommendations/WINNF-TR-2004-V1.0.0%20GAA%20Spectrum%20Coordination-Approach%202.pdf

[4] "Operations for Citizens Broadband Radio Service (CBRS); GAA Spectrum Coordination - Approach 3," Document WINNF-TR-2005, Version V1.0.0, May 2019. [Online]. Available: https://winnf.memberclicks.net/assets/work_products/Recommendations/WINNF-TR-2005-V1.0.0%20GAA%20Spectrum%20Coordination%20-%20Approach%203.pdf

[5] "Reference models for SAS testing." [Online]. Available: https://github.com/Wireless-Innovation-Forum/Spectrum-Access-System/tree/master/src/harness/reference_models

[6] C. Ghosh, S. Roy, and D. Cavalcanti, "Coexistence challenges for heterogeneous cognitive wireless networks in TV white spaces," *IEEE Wireless Communications*, vol. 18, no. 4, pp. 22–31, 2011.

[7] B. Chen, J. Chen, Y. Gao, and J. Zhang, "Coexistence of LTE-LAA and Wi-Fi on 5 GHz with corresponding deployment scenarios: A survey," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 7–32, 2016.

[8] F. M. Abinader, E. P. Almeida, F. S. Chaves, A. M. Cavalcante, R. D. Vieira, R. C. Paiva, A. M. Sobrinho, S. Choudhury, E. Tuomaala, K. Doppler *et al.*, "Enabling the coexistence of LTE and Wi-Fi in unlicensed bands," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 54–61, 2014.

[9] A. M. Cavalcante, E. Almeida, R. D. Vieira, S. Choudhury, E. Tuomaala, K. Doppler, F. Chaves, R. C. Paiva, and F. Abinader, "Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands," in *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*. IEEE, 2013, pp. 1–6.

[10] Y. Hsuan, "Impacts of Propagation Models on CBRS GAA Coexistence and Deployment Density," in *Invited Presentation, WInnComm*, 2018. [Online]. Available: https://winnf.memberclicks.net/assets/Proceedings/2018/Invited%20Hsuan.pdf

[11] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to algorithms*. MIT press, 2009.

[12] "Irregular Terrain Model (ITM) (Longley-Rice) (20 MHz–20 GHz)." [Online]. Available: https://www.its.bldrdoc.gov/resources/radio-propagation-software/itm/itm.aspx

[13] "Requirements for Commercial Operation in the U.S. 3550–3700 MHz Citizens Broadband Radio Service Band," Wireless Innovation Forum Document WINNF-TS-0112, Version V5.0, Mar. 2018. [Online]. Available: https://workspace.winnforum.org/higherlogic/ws/public/document?document_id=4743&wg_abbrev=SSC

[14] E. Drocella, J. Richards, R. Sole, F. Najmy, A. Lundy, and P. McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology," National Telecommunications and Information Administration, Technical Report TR 15-517, Mar. 2016. [Online]. Available: http://www.its.bldrdoc.gov/publications/2805.aspx

[15] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE transactions on Vehicular Technology*, vol. 29, no. 3, pp. 317–325, 1980.

[16] Y. Okumura, "Field strength and its variability in VHF and UHF land-mobile radio service," *Rev. Electr. Commun. Lab.*, vol. 16, pp. 825–873, 1968.