A Practical Approach to Placing Coastal Sensors for Spectrum Sharing in the 3.5 GHz Band

Thao T. Nguyen, Anirudha Sahoo, and Timothy A. Hall
National Institute of Standards and Technology
Gaithersburg, Maryland, U.S.A.
Email: {ttn1, ans9, tim.hall}@nist.gov

***Abstract*—Commercial-federal spectrum sharing in the 3.5 GHz band requires an Environmental Sensing Capability (ESC) system, consisting of sensors deployed along the coasts, to detect federal incumbent shipborne radar in order to protect it from harmful interference from commercial users. The coastal waters where the radar needs protection from interference are divided into a chain of contiguous polygons called Dynamic Protection Areas (DPAs). The sensor(s) associated with each DPA must cover that DPA completely but should minimize any excess coverage on land, in neighboring DPAs, and out at sea. Thus, placement of sensors and their operating parameters are determined by solving this coverage problem. We use existing tower sites as candidate locations for the sensors and the Irregular Terrain Model (ITM) in point-to-point mode to compute the path loss. We present an algorithm for computing the locations and operating parameters of the sensors such that the excess area, and thus the probability of false alarm, is minimized.**

I. Introduction

The problem of spectrum scarcity has been addressed by spectrum-sharing technologies. Proposals have come from academia, such as Mitola et al. regarding spectrum sharing in 5G networks [1], from the private sector, e.g., Nokia's newsletter article on spectrum sharing [2], and also from government agencies. For example, in response to a 2010 Presidential Memorandum to free up 500 MHz of spectrum, the U.S. National Telecommunications and Information Administration (NTIA) has identified a number of bands in use by the Federal government as potentially suitable for commercial broadband service [3]. As part of this model, a new service called the Citizens Broadband Radio Service (CBRS) has been proposed to increase spectrum utilization and allow commercial access to the 3.5 GHz band currently used by Naval shipborne radar and other incumbents.

The 3550 MHz to 3700 MHz CBRS band in the U.S. has a three-tiered access model managed by a Spectrum Access System (SAS) with the assistance of an Environmental Sensing Capability (ESC). The first tier is called Incumbent Access (IA) and includes authorized Federal users. It is protected from harmful interference caused by users in any other tier. The second tier is called Priority Access (PA) and includes providers of residential, business, and mobile broadband services that use small cell technologies. It will operate with strict Quality of Service (QoS) guarantees and interference protection. The third tier is called General Authorized Access (GAA) and consists of general public access on an opportunistic non-interfering basis. PA (Tier 2) and GAA (Tier 3) devices are collectively referred to as CBRS devices (CBSDs).

Incumbent Navy shipborne radar will be protected through a contiguous chain of offshore polygonal regions called Dynamic Protection Areas (DPAs), defined along the coasts of the U.S. At any point in time, a DPA is either in an activated or a deactivated state on any channel in the band. A DPA is activated when the incumbent is detected inside its area by the ESC sensor(s) covering it, and it is deactivated otherwise. When a DPA is activated, the SAS will notify a sufficient number of CBSDs to vacate the channel so that the aggregate interference falls below a protection threshold of -144 dBm/10 MHz [4]. In the NTIA draft used in this paper, which was the latest publicly released version at the time of submission [5], there are 14 non-overlapping coastal DPAs covering the West coast and 26 non-overlapping DPAs covering the East and Gulf coasts of the contiguous United States (CONUS). Excepting those DPAs protecting U.S. Navy ports, all coastal DPAs begin at 10 km out from the shore and vary in shape and area from one another.

An ESC operator must deploy sensors along the coast in such a manner that each DPA is fully covered (or monitored), thus ensuring that the radar signal is detected when the radar is anywhere inside the DPA. The relevant factors in deployment are the number of sensors assigned to a DPA, the location, antenna height, antenna pattern, and detection threshold of each sensor. Full coverage of each DPA is necessary in order to prevent the incumbent from experiencing harmful interference anywhere inside the DPA. However, excess coverage, which can exist either out at sea (outside of any DPA) or in a neighbor DPA, is a problem. Detecting the presence of an incumbent outside of a DPA results in a higher probability of false alarm and unnecessary suspension of CBSD transmissions. This reduces spectrum utilization by commercial operators even though their continued operation would not result in harmful interference to the incumbent. This paper presents a method to determine location, orientation and operating parameters of the ESC sensors such that the DPAs are maximally covered while making sure that unnecessary suspension of CBSDs in the wake of a DPA activation is minimized.

This paper is structured as follows. Section II reviews related work in the literature. In Section III, we formulate the problem, present our approach and define our algorithm. In

Section IV, we describe the models and assumptions used in our analysis. Results are presented in Section V. Finally, Section VI summarizes our contributions and results and discusses future work.

II. Related Work

The problem we are solving falls under the general category of sensor coverage problems. These have been extensively studied in many fields and applications, but generally address the question, "how well do the sensors monitor the physical space?" [6], which often reduces to "is every location of interest, whether defined as a continuous area [7]–[9] or a set of points [10], [11], covered by one or more sensors?" Much of the literature considers omnidirectional sensors, with the coverage area of an individual sensor being a circle, assuming propagation loss is the same in all directions. ESC sensors, however, will be deployed along the coast and must cover an area out at sea. Thus, sensors equipped with directional antennae pointing at computed azimuth angles are more suitable to our application, resulting in a coverage problem similar to that in [12], Sec. 6.2.

An abstract, piecewise linear representation of the coastline and the area to be covered was used in [13] to find the optimal non-uniform (i.e., not equidistant) placement of sensor nodes. They solve for the minimum number of sensors using a sequential convex programming algorithm for both redundant and non-redundant coverage. Similarly, a simple technique for uniform placement of ESC sensors is proposed in [14], assuming a linear coastline with a parallel line in the water representing radar detection distance. In our work here, we use an actual map of the coastline and a DPA database, and we use a greedy algorithm to solve our optimization problem. Maps of the U.S. coastlines and realistic CBSD deployments are used in [15] and [16] to compute aggregate interference from CBSDs to the radar receiver and to estimate an interference contour at sea. The result was in turn used to determine non-uniform sensor locations and their detection thresholds. We formulated sensor placement as a *set cover* problem and solved using a greedy approach for both redundant and non-redundant coverage. However, we assumed omni-directional antennae and covered discrete points along the interference contour. In this paper, we use directional antennae and attempt to cover the entire area within a given DPA.

All of the work discussed above ([13]–[16]) was published before DPAs were introduced. Thus, instead of covering a set of DPAs, they covered either a large coastal area (e.g., entire East or West coast of the U.S.) [13], [14] or specific points along the boundary of an area to be protected from harmful interference [15], [16]. Since those approaches deal with a single large area, rather than a set of smaller connecting areas like DPAs, they are not concerned with excess coverage into any neighboring coverage areas or any false alarms that result from this. Therefore, a direct performance comparison of those schemes with ours is not possible.

Our previous work [17] considered the problem of excess area and used an earlier set of DPAs defined by the NTIA. We formulated the problem as a generalized coverage problem where an ESC sensor covers a geometric shape called a required coverage area (RCA). We considered circle coverage (i.e., an omnidirectional antenna) as well as coverage by a set of antenna patterns and used the Irregular Terrain Model (ITM) in area mode [18] as our propagation model. In this paper, we use the ITM point-to-point mode. We also use the locations of existing towers along the coastal U.S. as candidate ESC sites, rather than a set of equidistant points along the shoreline.

III. Methodology

A. Problem Formulation

As mentioned earlier, to protect a DPA, one or more ESC sensors need to be deployed along the coast such that the sensor(s) can detect radar signal at any point inside the DPA. The deployment has to consider location, antenna pattern and azimuth of the ESC sensors to achieve maximum or full coverage of the DPA. Since the DPA polygon and the ESC coverage area cannot match exactly, the sensors will detect some excess area outside of the DPA. This excess area represents unnecessary activation of the DPA and thus results in unnecessary suspension of transmission for some CBSDs.

The goal is to deploy ESC sensors such that it maximizes the detection coverage area inside the DPA while minimizing the excess area covered by the ESC sensor. Since protecting radar from harmful interference is more important than extraneous detection from the excess area, the first objective of maximizing the coverage area of the DPA has higher precedence than minimizing the excess area. Therefore, our problem can be treated as a two-stage optimization as follows. In the first stage, for a given DPA dpa, a set of locations loc, antenna patterns $pattern$ and azimuths az, find a set of one or more sensor placement tuples $(loc, pattern, az)$ that provide maximum coverage of the DPA. Then, in the second stage, choose the tuple that has the minimum excess area among all the set of tuples found in the first stage.

Therefore, our problem can be formulated as follows. For a DPA, given a set of locations, beamwidths, azimuths and detection thresholds, find a set of one or more sensor placement tuples that maximizes coverage of the DPA and has the minimum excess area among all the set of tuples that give the same maximum coverage. Since we do not want any location to have multiple sensors, no two tuples should have the same location.

B. Approach

We use the ITM point-to-point mode, which is currently adopted as a reference model by the CBRS industry standard [19], to compute propagation loss in our study. The ITM model is essentially an implementation of the Longley-Rice model that predicts long term median propagation loss over irregular terrain in the frequency range 20 MHz to 20 GHz [18]. To apply the ITM point-to-point model, we discretize areas into a set of grid points. We first find the set of sensor placement tuples that maximizes the number of points detected by the sensor. The well-known *set cover* problem, which is

NP-complete [20], can be reduced to this problem. We take the brute force approach to solve this part. Since standards [4] require that a DPA be fully monitored, we assume that the required number of the points covered by the ESC sensors is all the points inside the DPA. We begin with one location at a time and identify the tuple(s) which cover all DPA points. If at least one tuple can detect all the points, then we stop. Otherwise, we take all possible combinations of two locations at a time. For each such combination, we gather the tuple pairs that detect all the DPA points. If at least one such pair exists, then we stop, otherwise we take all possible combinations of three locations at a time and repeat the same process. For our application this brute force approach is computationally not that expensive, since for a DPA, there will be only a few candidate locations, which are the existing tower locations. Moreover, the complexity of this algorithm may not be a major concern since it will be run offline prior to ESC deployment.

At the end of the above process, we will have a set of tuples that provides $100\ \%$ coverage of the DPA. Of those tuples, we choose the one that has the minimum excess area. Note that this final choice could be a set of one or more tuples depending on how many locations are chosen to provide full coverage of the DPA.

C. Algorithm

We design Algorithm 1 based on the above approach to solve the ESC sensor placement problem. The main inputs to the algorithm are radar parameters, ITM parameters, a set of DPA polygons of a U.S. coast, tower locations to be considered for sensor placement, a set of antenna patterns, and a minimum detection threshold.

Fig. 1 is used to explain the working of our algorithm. The algorithm first creates a polygon called *dpa_union_polygon* by taking the union of all the DPA polygons in each coast. This polygon is shown in violet red in Fig. 1. To bring excess area into the geometry, the dpa_union_polygon is dilated by a width of *dilation_width*. The dilated polygon, called *dilated_dpa_union*, is the annular polygon around the dpa_union_polygon. The annular area between the outer edge of dpa_union_polygon and dilated_dpa_union, which is in the sea, is called *excess_sea_polygon* and is shown in shaded green in Fig. 1. Likewise, the annular area between the inner edge of dpa_union_polygon and dilated_dpa_union that is mostly on land is called *excess_land_polygon*, shown in shaded yellow. Using a certain grid size, the polygonal areas dpa_union_polygon, excess_sea_polygon and excess_land_polygon are discretized to generate 3 sets of points *all_protected_points*, *excess_sea_points* and *excess_land_points*, respectively.

For a given DPA, a set of candidate locations along the coast is selected (Line 9). Using the ITM point-to-point propagation loss model over water, the maximum detection radius is computed based on radar parameters, sensor location, sensor height and the sensor's minimum detection threshold (Line 10). For a given candidate sensor location, the maximum detection

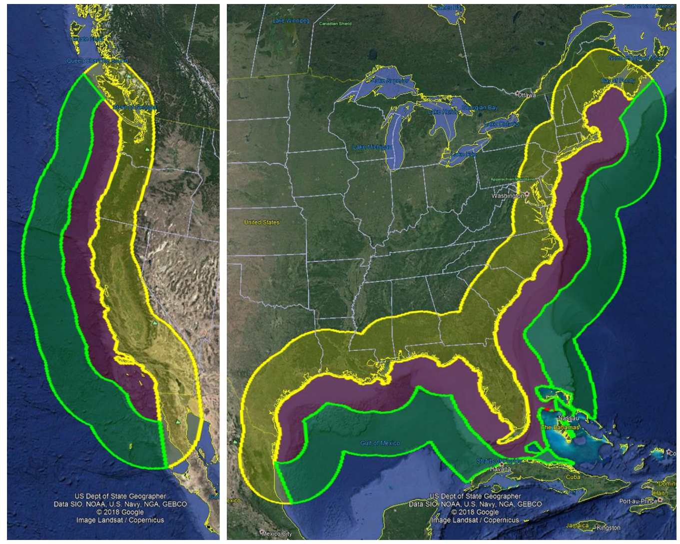

Fig. 1. Land (in shaded yellow), union DPAs (in shaded violet red), and sea (in shaded green) regions.

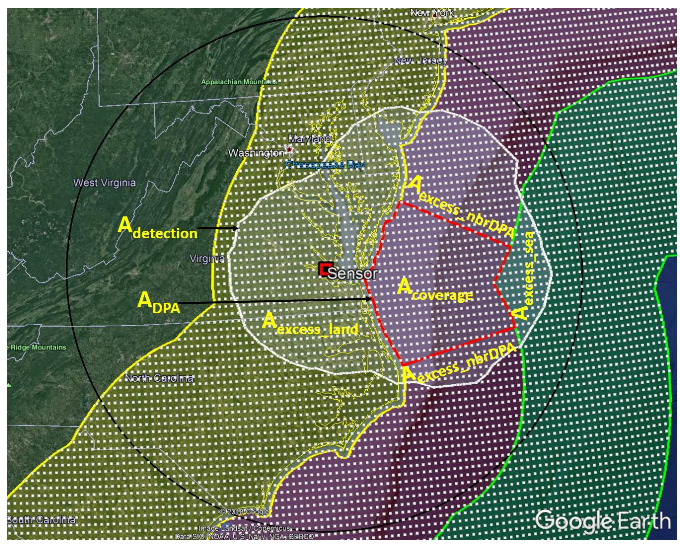

Fig. 2. Illustration of detection and excess areas.

circle is drawn using the maximum detection radius as shown in Fig. 2. All points inside the circle, called $points\_of\_interest$ will be used to estimate the detection coverage of the sensor $A_{detection}$ at that location.

Let A_{DPA} be the total area of the DPA covering all points inside and on the DPA polygon. We define the area that is inside both the DPA and the detection coverage area as $A_{coverage} = A_{DPA} \cap A_{detection}$. The area that is outside the DPA but inside its detection coverage area is defined as $A_{excess} = \overline{A_{DPA}} \cap A_{detection}$. We further divide the excess area A_{excess} of a DPA into three components: a) excess area overlapping with its neighboring DPAs (A_{excess_nbrDPA}), b) excess area extending out to sea (A_{excess_sea}), and c) excess area covering the sea and land region along the shoreline (A_{excess_land}). These areas are illustrated in Fig. 2.

For a given antenna pattern and a given azimuth, the Received Signal Strength (RSS) from each point, which belongs to the set $points\_of\_interest$, to the sensor location is computed (Line 18). Out of those points, the ones which can be detected are identified and the corresponding areas are computed (Lines 21 to 29).

We denote the weights associated with excess areas in neighboring DPAs, sea, and land as $w_{excess\_nbrDPA}, w_{excess\_sea}, w_{excess\_land}$, respectively. Thus, the total weighted excess area can be computed as follows.

$$A_{excess} = w_{excess\_nbrDPA} * A_{excess\_nbrDPA} + w_{excess\_sea} * A_{excess\_sea} + w_{excess\_land} * A_{excess\_land} \quad (1)$$

After all the results are computed, the set of tuples of $(loc, pattern, az)$ for which the maximum DPA coverage is achieved are identified (Line 32). Among those tuples the one with minimum weighted excess area is chosen as the final solution (Line 33).

To keep the description of our algorithm simple, we have not shown the part of the algorithm that tests different combinations of multiple sensor locations for DPA coverage. For our dataset, it so happens that all the DPAs can be provided 100 % coverage by just one sensor per DPA. If this is not the case for some other datasets, the algorithm presented here should have an outer loop to take different combinations of multiple sensor locations to find the final solution.

IV. Model

In this section, we present the models and assumptions used in our analysis. Table I lists all important technical parameters of the radar, ESC sensor, and ITM propagation model.

The operational parameters of the radar can be found in [22], [23], while the technical parameters of an ESC sensor are available in [16], [24]. We utilize the antenna pattern specified in CBRS standards [4] for the ESC sensor antenna pattern. Thus, using the method outlined in [25], the mathematical model for computing ESC antenna gain is as follows:

$$G_{ESC}(\theta) = G_{ESC\_peak} - \min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, \quad A_H\right] \quad (2)$$

where $G_{ESC}(\theta)$ is the sensor antenna gain (dBi) at the off-axis angle θ, $-180^\circ \leq \theta \leq 180^\circ$, G_{ESC_peak} is the ESC peak antenna gain (dBi), θ_{3dB} is the 3-dB beamwidth of the antenna (degree), and $A_H = 20$ dB is the maximum attenuation. We use the ITM point-to-point mode to compute the propagation loss between the radar and the ESC sensor [18], [26]. In addition to those parameters listed in Table I, the ITM point-to-point mode requires terrain profile as inputs to the model. We leverage the CBRS standard reference implementations of the antenna pattern and propagation model [19] as well as the terrain elevation data used for SAS testing [27].

Given the locations of a shipborne radar and an ESC sensor, the received signal strength at the ESC antenna output (Line 18 in Algorithm 1) can be computed as follows:

$$RSS = P_{radar} + G_{peak\_radar} - L_{i\_radar} - PL + G_{ESC}(\theta) - L_{i\_ESC} \quad (3)$$

TABLE I
Technical Parameters.

Shipborne Radar-1 Parameter	**Value**
Transmitted Power to Ant. (dBm)	90
Peak Antenna Gain (dBi)	32
Transmit/Receive Bandwidth (MHz)	1
Center Frequency (MHz)	3650
Antenna Height (m)	50
Insertion/Cable Losses (dB)	2
ESC Sensor Parameter	**Value**
Antenna Directivity/Patterns	3GPP
3-dB Beamwidth (degree)/ Peak Ant. Gain (dBi)	(90,15), (60,16), (45,17), (30,18)
Receive Bandwidth (MHz)	1
Center Frequency (MHz)	3650
Min. Detection Theshold (dBm/MHz)	-89
Antenna Height (m)	import from database [21] subject to min=10 and max=100
Insertion/Cable Losses (dB)	2
ITM Point-to-Point Parameter	**Value**
Polarization	1 (Vertical)
Dielectric constant	81 (Sea Water)
Conductivity	5 (Sea Water)
Surface Refractivity (N-units)	350 (Maritime, Over Sea)
Radio Climate	7 (Maritime, Over Sea)
Mode of Variability	3 (Broadcast)
Terrain Irregularity (m)	0 (Flat/Smooth Water)
Transmitter Siting Criteria	2 (Very Careful)
Receiver Siting Criteria	0 (Random)
Confidence/Reliability Var. (%)	50/50
Miscellaneous	**Value**
Grid Spacing (km)	10

where P_{radar} is the transmit power of the radar (dBm), G_{peak_radar} is the peak antenna gain of the radar (dBi), L_{i_radar} is the radar transmitter insertion loss (dB), PL is the median path loss between the radar transmitter and ESC receiver (dB), $G_{ESC}(\theta)$ is the ESC antenna gain in the direction of the radar (dBi), L_{i_ESC} is the ESC receiver insertion loss (dB). Note that given the azimuth of the sensor, angle θ is the angle that radar transmitter subtends relative to the boresight of the ESC sensor antenna. The ESC sensor can detect the radar if the received signal strength at the ESC sensor is above its detection threshold.

V. Experiment and Results

We ran our algorithm on the set of DPAs published in [5]. We used the tower locations and tower heights published by American Tower [21] as candidate sensor locations and antenna heights, respectively. The results presented in this section were obtained by setting all three weights, $w_{excess\_nbrDPA}, w_{excess\_sea}, w_{excess\_land}$, to 1.

A. ESC Detection Coverage

We implemented the algorithm described in Section III to determine sensor locations and estimate their detection

Algorithm 1: Calculate sensor locations, antenna parameters, and performance metrics for all DPAs in a given U.S. coast

Input: $radar\_pars$: radar parameters including transmit power, bandwidth, main beam attenna gain, height, and insertion loss.
itm_p2p_pars: ITM point to point propagation parameters.
$tower\_locs$: a set of tower locations used as candidate locations for ESC sensors.
$min\_det\_threshold$: minimum detection threshold of ESC sensors.
$ant\_patterns$: a set of sensor antenna patterns, each having a tuple of (beam_width, peak_gain).
az_step: step size of change in azimuth.
$dpa\_polygons$: a set of polygons, each representing a coastal DPA.
$dilation\_width$: width used to dilate the combined DPA polygon to cover land and sea areas.
$grid\_size$: grid size.
$w\_excess\_sea, w\_excess\_land, w\_excess\_nbrDPA$: weighting factors applied to excess areas over sea, land, and neighboring DPAs, respectively.

Output: Results for each DPA including sensor location (C_out), antenna pattern ($pattern\_out$), azimuth (az_out), probability of detection coverage ($P\_coverage$), probability of false alarms from neighboring DPAs (P_fa_nbrDPA) and out in the sea (P_fa_sea).

```
dpa_union_polygon ← ⋃(dpa ∈ dpa_polygons); /* union of consecutive DPA polygons along the coast */
dilated_dpa_union ← DilatePolygon(dpa_union_polygon, dilation_width); /* dilate DPA union polygon */
grid_points ← GenerateGrid(dilated_dpa_union, grid_size); /* generate points within dilated polygon */
(excess_land_polygon, excess_sea_polygon) ← FormLandSeaPolygon(dpa_union_polygon, dpa_union_polygon); /* form excess
    land/sea polygons, adjacent to DPA union polygon, over land/sea areas */
(all_protected_points, excess_land_points, excess_sea_points) ←
    GetPoint(grid_points, dpa_union_polygon, excess_land_polygon, excess_sea_polygon); /* get all protected/land/sea
    points inside DPA union/land/polygon, respectively */
foreach dpa ∈ dpa_polygons do
    A_dpa ← ComputeArea(dpa); /* compute area of DPA */
    dpa_points ← GetDPAPrtnPoint(dpa, all_protected_points); /* get protected points on and within DPA polygon */
    cand_sensor_locs ← GetCandSensorLoc(dpa, tower_locs); /* get tower locations along the inner edge of DPA */
    max_det_radius ← EstMaxDetRadius(cand_sensor_locs, min_det_threshold, radar_pars); /* estimate maximum sensor
        detection radius */
    foreach C ∈ cand_sensor_locs do
        points_of_interest ← GetPointInsideCircle(C, max_det_radius, grid_points, dpa); /* get grid points (including
            those on DPA polygon) inside the circle centered at C and radius of max_det_radius */
        azimuths ← CalcAzimuths(C, dpa, az_step); /* compute antenna azimuths, with az_step step size, between 2
            inner edge corners of DPA polygon */
        foreach pattern ∈ ant_patterns do
            foreach az ∈ azimuths do
                detected_points = ∅;
                foreach point ∈ points_of_interest do
                    RSS ← CalcRSS(points_of_interest, radar_pars, itm_p2p_pars, C, pattern, az); /* calculate received
                        signal strength from radar location point to sensor location C */
                    if RSS ≥ min_det_threshold then
                        detected_points += point;
                detected_dpa_points ← {∀p : p ∈ detected_points ∧ p ∈ dpa_points};
                detected_excess_sea ← {∀p : p ∈ detected_points ∧ p ∈ excess_sea_points};
                detected_excess_land ← {∀p : p ∈ detected_points ∧ p ∈ excess_land_points};
                detected_excess_nbrDPA ← {∀p : p ∈ detected_points ∧ p ∈ all_protected_points ∧ p ∉ dpa_points};
                A_detection[C][pattern][az] ← ComputeArea(detected_points);
                A_coverage[C][pattern][az] ← ComputeArea(detected_dpa_points);
                A_excess_sea[C][pattern][az] ← ComputeArea(detected_excess_sea);
                A_excess_land[C][pattern][az] ← ComputeArea(detected_excess_land);
                A_excess_nbrDPA[C][pattern][az] ← ComputeArea(detected_excess_nbrDPA);
                A_weighted_excess[C][pattern][az] ← A_excess_sea[C][pattern][az] × w_excess_sea +
                                                    A_excess_nbrDPA[C][pattern][az] × w_excess_nbrDPA +
                                                    A_excess_land[C][pattern][az] × w_excess_land;
    max_A_coverage ← max_{∀(C,pattern,az)}(A_coverage[C][pattern][az]);
    max_coverage_indices ← {(C, pattern, az) : A_weighted_excess[C][pattern][az] = max_A_coverage};
    (C_out, pattern_out, az_out) = min_{∀(C,pattern,az)∈{max_coverage_indices}}(A_weighted_excess[C][pattern][az]);
    P_coverage ← max_A_coverage/A_dpa;
    P_fa_nbrDPA ← A_excess_nbrDPA[C_out][pattern_out][az_out]/A_detection;
    P_fa_sea ← A_excess_sea[C_out][pattern_out][az_out]/A_detection;
```

coverages for all coastal DPAs on the West coast as well as on the East and Gulf coasts. Fig. 3 shows the DPA polygons in red contours, the resulting sensor locations in red squares and their detection coverages in white shaded areas.

Upon examination of the results, we found that only a single sensor equipped with a single antenna is needed to fully cover each DPA. The West coast requires 14 sensors, whereas the East and Gulf coasts require 26 sensors located near the shoreline. Most of these sensors employ a maximum antenna height of 100 m; only a few sensors have antenna height ranging from 50 m to 95 m. Selecting higher antenna height provides a larger detection coverage of the DPA. Antenna patterns with small beamwidths and high peak gains are preferred

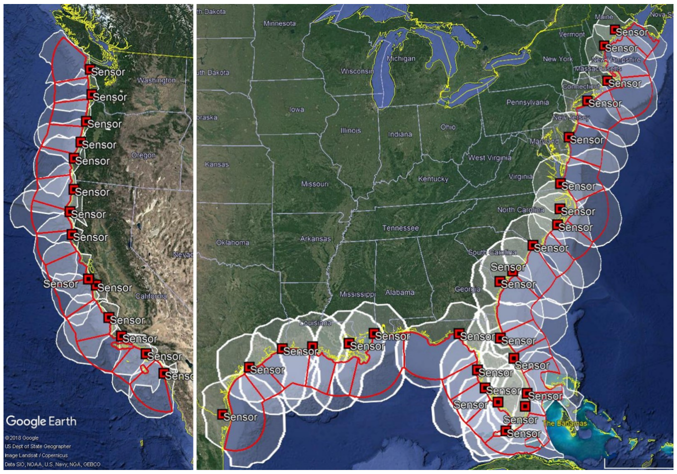

Fig. 3. Sensor locations and detection coverages for all coastal DPAs. DPA polygons are in red contours, resulting sensor locations in red squares and their detection coverages in white shaded areas.

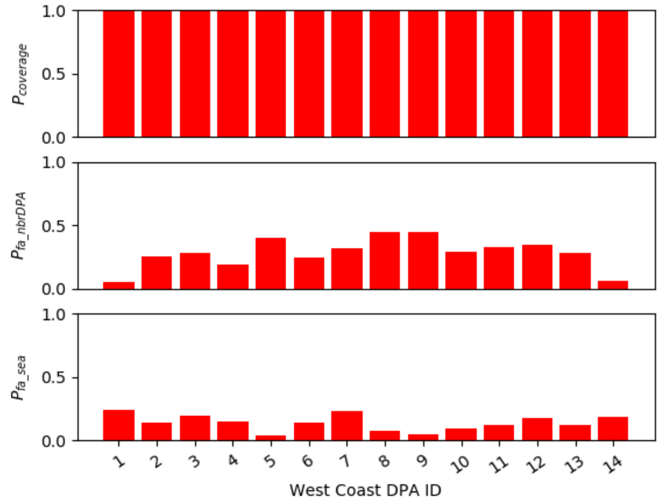

Fig. 4. Performance results of West coast.

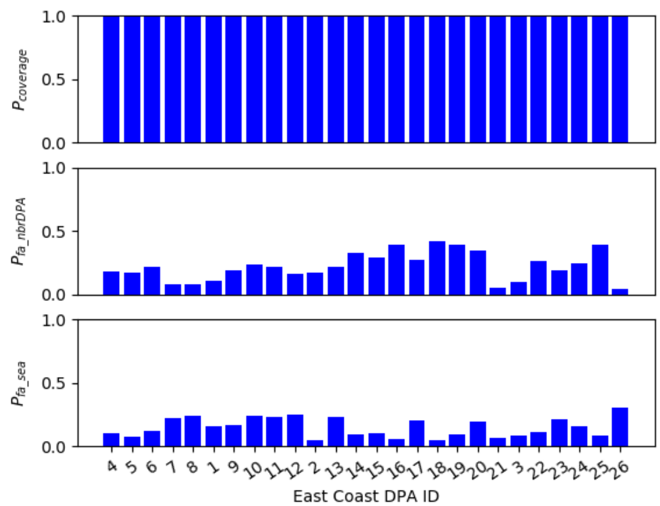

Fig. 5. Performance results of East and Gulf coasts.

to minimize the excess area outside the DPA. Our results show that only 9 locations used antenna patterns of $(90°, 15$ dBi) and $(60°, 16$ dBi) to cover large DPAs, whereas the remaining locations used antenna patterns $(30°, 18$ dBi) and $(45°, 17$ dBi).

Comparing with the results presented in [17], it is observed that our scheme uses fewer sensors and antenna patterns. However, it is worth noting that the DPA dataset used in [17] is an older version and slightly different. Besides, the sensor sensitivity in [17] was varied while it is fixed at the minimum detection threshold at -89 dBm/MHz in this study. We found no meaningful benefit in the form of lower excess coverage from raising the detection coverage above this minimum threshold at any location.

B. Performance Results

We analyze our detection coverage results for each DPA in terms of two performance metrics, i.e., *probability of coverage* and *probability of false alarm*. Figs. 4 and 5 show performance results of our algorithm when applied to the DPAs along the West coast and the combined East and Gulf coasts, respectively.

1) Probability of Detection Coverage: We define probability of DPA detection coverage as $P_{coverage} = A_{coverage}/A_{DPA}$, conditioned on the median pathloss value, to represent the probability of a shipborne radar being detected when it is inside the DPA. To ensure the DPA is fully monitored by the ESC sensor(s), $P_{coverage}$ needs to be close to one. The top subplots in Figs. 4 and 5 present $P_{coverage}$ computed for each DPA. In all cases, $P_{coverage} = 1$, which meets the objective of detecting the shipborne radar anywhere within DPA contours.

2) Probability of False Alarm: We consider two types of false alarms as follows.

a) False Alarm from Neighboring DPAs: This false alarm is raised when a DPA is activated because its associated ESC sensor(s) detects signal from a shipborne radar present in its neighboring DPA. This is clearly an undesired event since the radar in the neighboring DPA should only be detected by the ESC sensor(s) in that neighboring DPA. The probability of this false alarm is defined as $P_{fa\_nbrDPA} = A_{excess\_nbrDPA}/A_{detection}$.

The middle subplots in Figs. 4 and 5 show P_{fa_nbrDPA} for each DPA, and it is within the range of (0.05 to 0.45). DPAs that are small narrow polygons are prone to have larger values of P_{fa_nbrDPA}.

b) False Alarm Out at Sea: This is the false alarm due to the excess coverage area further out at sea and is defined as $P_{fa\_sea} = A_{excess\_sea}/A_{detection}$. This metric captures the likelihood that an ESC sensor activates its associated DPA even though the radar is further out at sea and outside of the DPA. P_{fa_sea} should be as low as possible to avoid unnecessary shutdown of CBSDs.

The bottom subplots in Figs. 4 and 5 depict P_{fa_sea} for each DPA. For both coasts, DPAs have P_{fa_sea} values in the range of (0.04 to 0.3). Because of the geometric shapes of the DPAs, sensor deployment, and antenna patterns, there is always a trade-off between P_{fa_nbrDPA} and P_{fa_sea}.

Comparing with the results presented in [17] for comparable DPAs, we found that this algorithm along with the selected parameters provide better performance for all $P_{coverage}$, P_{fa_nbrDPA}, and P_{fa_sea}.

To further decrease excess area to land and neighboring DPAs, we applied weighting factors $w_{excess\_land} = 10$, $w_{excess\_nbrDPA} = 5$, $w_{excess\_sea} = 1$ to the total excess area. However, we found that the improvement is insignificant, indicating the selection of sensor locations and operation parameters provide a near-optimal solution.

VI. Conclusion and Future Work

This paper presents an approach to determine locations and operational parameters of ESC sensors to detect the presence of federal incumbent shipborne radar operating in the 3.5 GHz band. We formulate the problem as a coverage problem where one or more ESC sensors fully covers the DPA while minimizing the excess areas both out at sea and in its neighboring DPAs. We design and implement an algorithm that achieves this objective. We apply our algorithm to DPAs along the coasts of the contiguous United States as defined by NTIA at the time of this submission [5] and present the performance results for each DPA.

We used the ITM point-to-point mode [18] to compute the path loss between the radar and the sensor. In addition, we used existing tower locations along the coast as candidate sites for the sensors. Future work should consider a higher reliability value for the ITM model to compute the path loss and deploy more than one sensor for each DPA if there is an outage area within the DPA. Other propagation models applicable to the CBRS band, e.g., ITU-R P.2001 [28] and extended Hata [23], should also be examined.

References

[1] J. Mitola, J. Guerci, J. Reed, Y. D. Yao, Y. Chen, T. C. Clancy, J. Dwyer, H. Li, H. Man, R. McGwier, and Y. Guo, "Accelerating 5G QoE via public-private spectrum sharing," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 77–85, May 2014.

[2] Nokia, "Bridging the spectrum gap with 5G," http://networks.nokia.com/news-events/insight-newsletter/articles/bridging-the-spectrum-gap-with-5g, 2013, [Online; accessed 07-July-2016].

[3] National Telecommunications and Information Administration (NTIA), "An assessment of the near-term viability of accommodating wireless broadband systems in the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, and 4200-4220 MHz, 4380-4400 MHz band," National Telecommunications and Information Administration (NTIA), Fast Track Report, Oct. 2010.

[4] "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

[5] "DPA kml file (e-dpas.kml)," [Accessed 17-Sep-2018]. [Online]. Available: https://www.ntia.doc.gov/fcc-filing/2015/ntia-letter-fcc-commercial-operations-3550-3650-mhz-band

[6] M. Cardei and J. Wu, "Energy-efficient coverage problems in wireless ad-hoc sensor networks," *Computer communications*, vol. 29, no. 4, pp. 413–420, 2006.

[7] J. Carle and D. Simplot-Ryl, "Energy-efficient area monitoring for sensor networks," *Computer*, vol. 37, no. 2, pp. 40–46, 2004.

[8] S. Slijepcevic and M. Potkonjak, "Power efficient organization of wireless sensor networks," in *Communications, 2001. ICC 2001. IEEE International Conference on*, vol. 2. IEEE, 2001, pp. 472–476.

[9] D. Tian and N. D. Georganas, "A coverage-preserving node scheduling scheme for large wireless sensor networks," in *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*. ACM, 2002, pp. 32–41.

[10] M. Cardei and D.-Z. Du, "Improving wireless sensor network lifetime through power aware organization," *Wireless Networks*, vol. 11, no. 3, pp. 333–340, 2005.

[11] K. Kar and S. Banerjee, "Node placement for connected coverage in sensor networks," in *WiOpt'03: Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, 2003, pp. 2–pages.

[12] M. A. Guvensan and A. G. Yavuz, "On coverage issues in directional sensor networks: A survey," *Ad Hoc Networks*, vol. 9, no. 7, pp. 1238 – 1255, 2011. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1570870511000461

[13] S. Joshi and K. B. S. Manosha and M. Jokinen and T. Hänninen and Pekka Pirinen and H. Posti and M. Latva-aho, "ESC sensor nodes placement and location from moving incumbent protection in CBRS," *Proceedings of WInnComm 2016*, Mar. 2016.

[14] "Application of Google Inc. for Certification to Provide Spectrum Access System and Environmental Sensing Capability Services," GN Docket No. 15-319, Appendix B: Environmental Sensing Capability (ESC) Siting Considerations, 2016. [Online]. Available: https://ecfsapi.fcc.gov/file/60001851224.pdf

[15] T. T. Nguyen, A. Sahoo, M. Souryal and T. A. Hall, "3.5 GHz Environmental Sensing Capability Sensitivity Requirements and Deployment," in *IEEE DySPAN '17*, March 2017, pp. 1–10.

[16] T. T. Nguyen and M. R. Souryal and A. Sahoo and T. A. Hall, "3.5 GHz Environmental Sensing Capability Detection Thresholds and Deployment," *IEEE Transactions on Cognitive Communications and Networking*, vol. 3, no. 3, pp. 437–449, Sept 2017.

[17] A. Sahoo, M. Ranganathan, T. T. Nguyen and T. A. Hall, "Sensor Placement and Detection Coverage for Spectrum Sharing in the 3.5 GHz Band," in *to appear in IEEE PIMRC '18*, Sep 2018.

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

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

[20] M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness*. W. H. Freeman, 1979.

[21] "American Tower." [Online]. Available: http://www.americantower.com/corporateus/articles/find-sites.htm

[22] F. H. Sanders, E. F. Drocella, and R. L. Sole, "Using On-Shore Detected Radar Signal Power for Interference Protection of Off-Shore Radar Receivers," National Telecommunications and Information Administration, Technical Report TR 16-521, Mar. 2016. [Online]. Available: http://www.its.bldrdoc.gov/publications/2828.aspx

[23] 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

[24] "3.5 GHz Radar Waveform Capture at Point Loma," National Institute of Standards and Technology (NIST), Technical Note NIST.TN.1954, May 2017. [Online]. Available: http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1954.pdf

[25] "Technical Specification Group Radio Access Network; Feasibility study for enhanced uplink for UTRA FDD," Technical Report 3GPP-TR25.896, Mar. 2004. [Online]. Available: http://www.qtc.jp/3GPP/Specs/25896-600.pdf

[26] G. Hufford, A. Longley, W. Kissick, U. S. N. Telecommunications, and I. Administration, *A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode*, ser. NTIA report. U.S. Department of Commerce, National Telecommunications and Information Administration, 1982. [Online]. Available: https://www.ntia.doc.gov/files/ntia/publications/ntia_82-100_20121129145031_555510.pdf

[27] "SAS data repository." [Online]. Available: https://github.com/Wireless-Innovation-Forum/SAS-Data

[28] "ITU-R P.2001 : A general purpose wide-range terrestrial propagation model in the frequency range 30 MHz to 50 GHz." [Online]. Available: https://www.itu.int/rec/R-REC-P.2001-2-201507-I/en