# Sensor Placement and Detection Coverage for Spectrum Sharing in the 3.5 GHz Band 

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#### Abstract

The Federal Communications Commission rules for operation in the 3.5 GHz band require that an Environmental Sensing Capability (ESC) system detect the presence of a federal incumbent shipborne radar in order to protect it from harmful interference. Thus, ESC operators have to deploy ESC sensors along the coasts to comply with the rules. We formulate the ESC sensor deployment problem as a coverage problem where ESC sensors need to cover a predefined geometric area inside which radar may experience harmful interference. Using propagation models and radar parameters, we compute antenna lobe patterns for different beamwidths and detection thresholds of the ESC sensors. These patterns are then used to cover the geometric area such that both outage and excess coverage areas are minimized. We present a greedy algorithm and apply it to Dynamic Protection Areas currently being defined for the coasts of the contiguous United States. We evaluate its performance in terms of some key metrics important to the federal incumbent as well as commercial operators.


## I. Introduction

The Federal Communications Commission (FCC) has published rules [1] to allow the use of frequencies from 3550 MHz to 3700 MHz by commercial operators. However, this band, referred to as the Citizens Broadband Radio Service (CBRS) band, has to be shared by commercial operators with the incumbents. The incumbents have the highest priority, i.e., when an incumbent uses the band, CBRS devices (CBSDs) that cause harmful interference to the incumbent must vacate the spectrum. The CBSDs will be managed by a Spectrum Access System (SAS). Part of the CBRS band from 3550 MHz to 3650 MHz is currently being used by U.S. Navy radars. CBSDs deployed near the coast should not cause harmful interference to these incumbent shipborne radars, i.e., the interference to noise ratio ( $\mathrm{I} / \mathrm{N}$ ) at the radar receiver should be below -6 dB [2]. The presence of this incumbent will be detected by an Environmental Sensing Capability (ESC) consisting of a number of strategically placed sensors along the coast, which will then inform the SAS about the presence of the incumbent.

The National Telecommunications and Information Administration (NTIA) is in the process of specifying Dynamic Protection Areas (DPAs). A DPA is a predefined protection area that may be activated to protect a federal incumbent radar or deactivated when the radar is outside the DPA [3]. The entire area of an activated DPA must be protected from aggregate interference from CBSDs. Hence, ESC sensors associated with each DPA are responsible for detecting the radar signals anywhere within the DPA. As per the draft version from the NTIA,
there are 15 non-overlapping coastal DPAs covering the West Coast and 26 non-overlapping coastal DPAs covering the East Coast and Gulf Coast. DPAs around major Navy ports are closer to the coastline (depicted in red in Fig. 3) while the rest start approximately 10 km from the coastline (depicted in light blue in Fig. 3).

For each DPA, an ESC operator must decide the sites and operational parameters of sensors so that the incumbent shipborne radar is detected anywhere inside the DPA. In other words, for a given DPA, the set of one or more ESC sensors should provide coverage (in terms of detecting the radar) for that DPA. In this paper, we present a generalized approach and corresponding algorithm that determines ESC sensor locations, antenna orientations and detection thresholds, such that coverage to a geometric shape is achieved while the excess coverage area is minimized. Considering DPAs as a use case, we formulate performance metrics for our algorithm and present the results when applied to the entire coast of the contiguous United States (CONUS). To the best of our knowledge, most analyses in the literature have focused on covering the protection area of the incumbent, but there is no analogous study to minimize excess area of coverage outside the protection area, which is important to the commercial operators. Thus, our study addresses both incumbent protection and spectral utilization (by commercial operators) aspects of the CBRS band related to ESC sensor deployment.

## II. Related Work

There is a rich literature on coverage of sensor networks. Sensor coverage requires that each location in the monitoring area of interest be covered or sensed by at least one sensor node. The sensor coverage problem can be classified as area coverage or point coverage. In area coverage, the goal is to cover a particular area of interest [4]-[6]. In point coverage, a set of points needs to be covered [7], [8]. A comprehensive survey of various coverage schemes is presented in [9]. However, our problem is quite different from the traditional sensor coverage problem studied in the aforementioned research. In the traditional sensor network coverage problem, typically each sensor is assumed to have fixed detection sensitivity, with an omnidirectional antenna. Hence, in most of those previous works, researchers assume the coverage area of each sensor is a circle of constant radius. In addition, the solutions typically require a multi-hop sensor network with suitable density in order to achieve certain optimization objectives (e.g., energy efficiency,
redundancy). Although in this paper we are also looking at an area coverage problem, the requirements and configuration issues are not the same. The ESC sensors, which will be deployed along the coasts, are required to cover an area out in the sea while limiting their coverage over land. Therefore, employing directional antennae pointing at a carefully computed azimuth angle towards sea is desirable to solve our problem. Furthermore, due to the security concerns of localization of the incumbent, a multi-hop sensor network is not applicable to our problem.

Simplifying assumptions were made in the first efforts to specify ESC sensor placement and detection criteria. An NTIA report used channel reciprocity to determine an ESC detection threshold [10] of $(-64) \mathrm{dBm}$ received radar peak power in a 1 MHz bandwidth. It proposed uniform ESC sensor spacing of about 50 km based on a geometric argument and the radio-horizon distance. The Wireless Innovation Forum (WINNF) Spectrum Sharing Committee (SSC) requirements [3] reference an ESC detection threshold of $(-89) \mathrm{dBm} / \mathrm{MHz}$ from the NTIA Technical Memorandum 17-527 at which a coastline sensor must be able to detect shipborne radar. A technique for uniform placement of ESC sensors is presented in [11], using a linear coastline with a parallel line in the water to represent the required radar detection distance. It presents a distance calculation for redundant coverage, where every point between the two lines is covered by at least two sensors, as well as one for non-redundant coverage. In this paper, we derive a method for nonuniform placement and dynamic detection thresholds of ESC sensors.

The authors in [12] present an approach for optimal non-uniform sensor node placement. They use an abstract, piecewise linear representation of the coastline and of the isolation boundary. They use a sequential convex programming algorithm to solve for the minimum number of sensors needed for redundant as well as non-redundant coverage. The differences between this approach and ours are that we use an actual map of the coastline and DPA database, and then apply a greedy algorithm to solve it. Maps of the US coastlines and realistic CBSD deployments are used in [13] and [14] to compute aggregate interference, which are then used to determine non-uniform sensor locations and their detection thresholds. Sensor placement is formulated as a set cover problem and solved using a greedy approach for both redundant and non-redundant coverage. However, the above approach assumes omni-directional antennae and focuses on covering discrete points along the contour where radar starts to experience harmful interference while moving towards the coast. In this paper, we take into account directional antennae and attempt to cover the entire area within any given DPA.

We would like to point out that the solutions provided in [11]-[14] predate the concept of DPAs. They are either applicable to covering one large coastal area (e.g., entire east or west coast of the USA) [11], [12], or covering certain points along the boundary of one large protection area [13], [14], rather than a relatively smaller area like a DPA. Since those approaches deal with only one large area, they do not have to deal with any neighboring area.

Hence, unlike our scheme, they do not need to consider false alarms due to coverage spilling into a neighboring DPA and, therefore, comparing their performance with that of our scheme is not appropriate.

## III. Overview of Approach

## A. Problem Formulation

In a CBRS system, ESC sensors will be deployed along the coast to detect the presence of shipborne radars anywhere inside a given DPA. We formulate this detection problem as a coverage problem in which the ESC sensors need to cover a Required Coverage Area (RCA), which can be any geometrical shape such as a DPA.

If we assume that the ESC sensors have omnidirectional antennae and that the propagation loss from the radar to the ESC sensor is the same for a given distance regardless of the sensor location, then the sensor coverage geometry would be a circle. The circle radius depends on the detection threshold of the ESC sensor. A higher detection threshold leads to a smaller coverage radius and vice-versa.

Given a set of candidate ESC sensor site locations along the coast and an RCA, we can find the set of circles centered at any of the sensor sites such that the union of circles covers the entire RCA. However, there are two constraints to be satisfied: (1) the excess coverage area of the union of circles outside of the RCA is minimized and (2) the distance between centers of two consecutive circles has to be more than a specified distance. The first constraint is needed to minimize the occurrence of false alarms, i.e., ESC sensors detecting a radar outside of their associated RCA. The second constraint is needed to address the Operational Security (OPSEC) requirements of the federal incumbent [15].
However, since ESC sensors only need to detect radar out at sea, an omni-directional antenna is not necessary. Furthermore, an omni-directional antenna would incur more interference from CBSDs deployed on land to the ESC sensor. Therefore, in practice, ESC sensors will use sectorized antennae facing towards the sea. Using the Irregular Terrain Model (ITM) propagation model in area mode [16] and radar parameters, we can find a family of antenna coverage patterns at different detection thresholds for a given beamwidth of an ESC sensor antenna (see Fig. 2). Each antenna lobe corresponds to a given detection threshold. A point on a given lobe at a given angle (with respect to its boresight) represents the maximum distance at which the sensor can detect a radar at that detection threshold and angle.
The problem can now be defined as follows: given an RCA, a set of candidate ESC sensor sites, and a family of antenna lobe coverage patterns, find the subset of sites where ESC sensors should be placed, subject to a minimum distance constraint between adjacent ESC sensor sites. For each placement site, find the angles at which one or more member lobes should be used. When the deployment is complete, the entire RCA should be covered in such a way that the excess area, i.e., the difference between union of total area covered by all the lobes and the area of the RCA, is minimized.

Subroutine 1: find_max_min_circle: Find the tightest circle that covers each point $p \in$ points_to_cover, and return the circle with largest radius among these circles.

```
Input: candidate_sites: Set of possible centers (candidate
            sites of ESC sensors).
            points_to_cover: A set of points for which max_min
            circle is to be found.
    Output: Circle \((c, r)\) : the largest circle (center \(c\), radius \(r\) )
                among all the tight circles covering each point \(p \in\)
            points_to_cover.
    for each point \(p \in\) points_to_cover do
        for each \(c \in\) candidate_sites do
            \(\mathrm{d}[\mathrm{c}]:=\) euclidean distance between \(p\) and \(c\);
        (center, radius) \(:=\)
        \((c, d[c]) \mid \min _{\forall c \in \text { candidate_sites }}(d[c])\)
        min_circle \([p]:=\) (center, radius)
\(5(c, r):=(\) min_circle \([p] . c e n t e r\), min_circle \([p]\). radius \() \mid\)
    \(\max \forall p \in\) points_to_cover (min_circle \([\bar{p}]\). radius \()\);
6 return \(\operatorname{Circle}(\bar{c}, r)\);
```


## B. Approach

To simplify the problem, we discretize the RCA to a set of grid points, transforming the problem from covering an area to covering a set of points. Minimizing the cost of covering a set of points using a circle of radius $r$ with a cost function $f(r)=r^{\alpha}, \alpha>1$ (i.e., our circlecover problem above) is shown to be NP-hard in [17]. Covering a set of points with lobe coverage patterns such that the excess area is minimized can also be shown to be NP-hard.

We use a two-step greedy approach to solve the problem. In the first step, we use a greedy method to cover the set of points with circles centered on a subset of candidate sensor site locations such that the excess area is minimized. In the second step, for each circle, we choose a lobe coverage pattern whose length along its major axis is larger than the radius of the circle by a factor greater than one. This ensures that a finite number of the same lobe coverage pattern can cover the entire circle with no outages. We then find the minimum number of the chosen lobes and corresponding orientation angles that tightly cover the points inside the circle.

## C. Greedy Algorithm

For a given set of potential candidate ESC sensor sites and set of points to be covered, Subroutine 1 considers one point at a time and finds the tightest circle (centered at one of the candidate sensor sites) that covers that point (Line 4). It then returns the circle of maximum size (Line 5) out of all circles.

Subroutine 2 finds the set of circles that provides the minimum area cover to a set of points, such that the distance between the centers of any two consecutive circles is more than a predefined distance constraint. The algorithm finds the max_min circle for the given set of points using Subroutine 1 (Line 3). The centers that are within the distance constraint of the max_min circle are taken off of the possible center list (Line 14), and the points covered by the max_min circle are taken off the list of points to be covered (Line 15). This process is repeated until all the points are covered.

Our approach uses the minimum area circle cover as an intermediate step to provide minimum area coverage

```
Subroutine 2: min_area_circle_cover_greedy:
Greedy algorithm to find minimum area circle cover to a
given set of protection points.
    Input: protection_points: Set of protection points to be
            covered.
            candidate_sites: Set of possible centers (candidate sites
            of ESC sensors)
            min_distance: Minimum distance permissible between
            two adjacent circle centers.
    Output: circle_cover : A set of circles that completely covers
            the points in protection_points.
    circle_cover = \emptyset;
    while protection_points != \emptyset do
        Circle(center,radius) := find_max_min_circle
        (candidate_sites, protection_points);
        covered_points := {p:p\in protection_points and p is
        inside Circle(center,radius) };
        found := False ;
        for each Circle(c,r) \in circle_cover do
            if c== center then
                circle_cover := (circle_cover - {Circle (c,r)})
                \cup {C\overline{rrcle}(c,max(rad\overline{ius},r))};
                found := True ;
        if found == False then
            circle_cover := circle_cover U
            Circle(center,radius);
        for each center c (candidate_sites - center) do
            if euclidean_distance(c, center) \leqmin_distance
            then
                candidate_sites := candidate_sites - c;
        protection_points := protection_points -
        covered_points ;
    16 return circle_cover
```

with antenna lobe patterns. Subroutine 3 takes a set of points to cover within a circle and an antenna lobe pattern to be used for coverage. The algorithm first finds the angle subtended by the two intersection points between the circle and the lobe at the center of the circle. Based on the subtended angle it then computes the incremental rotation angle to get a different orientation (angle with respect to horizontal direction) of the lobe. It first picks the lobe orientation (angle) that covers the maximum number of points (Line 16). This process is repeated for the rest of the points using the remaining lobe orientations (while loop in Line 10).

Algorithm 1 calls Subroutine 2 to get the greedy minimum area circle cover for the points (Line 1). For each circle, from the set of concentric lobes, it chooses the smallest lobe with radius larger than the radius of the circle by an overlap_factor. It then calls Subroutine 3 to find the angles (orientation) of the lobes, such that all the points are covered. This process is repeated for all the circles.

We illustrate our solution in Fig. 1. In the figure, an RCA is shown as the polygon ABCD (with some piecewise linear sides in between). The points marked as " X " are potential ESC sensor locations. Subroutine 2 finds that two circles can cover the RCA (actually a discrete set of grid points in the RCA). For each circle, a lobe overlap factor times the radius is chosen and the orientation of the lobes are computed using Subroutine 3. The larger circle is chosen first by Algorithm 1 and the common points within this circle and the RCA are

Subroutine 3: find_antenna_overlay_for_sector : Given a circle covering all points in points_to_cover, find the orientations of the lobe which tightly covers the points.

```
Input: points_to_cover : A set of grid points to be covered by
            lobe(s), which are within the circle
            Circle(center, radius).
            detection_coverage_lobe : Antenna lobe to be used for
            coverage of points_to_cover (of size
            overlap_factor \(*\) radius oriented in the horizontal
            direction).
    Output: angles : A vector of angles giving the orientations of
            the lobe that covers the sector.
subtended_angle \(:=\) find_subtended_angle
    (radius, detection_coverage_lobe) ;
npatterns := (int) ( \(2 * \pi /\) subtendeded_angle) ;
delta_angle \(:=2 * \pi /\) npatterns ;
rotated_lobes := \(\emptyset\);
for \(i=1\) to npatterns do
    angle := i* delta_angles ;
    lobe \(:=\) rotate_and_translate(detection_coverage_lobe,
    center, angle) ;
    rotated_lobes \(:=\) rotated_lobes \(\cup\) (angle, lobe) ;
angles := \(\emptyset\);
    while points_to_cover \(!=\emptyset\) do
        max_points \(:=0\);
        for each (angle, lobe) \(\in\) rotated_lobes do
            points_covered = find_cover(angle, lobe) ;
            if lenḡth (points_covēred) > max_points then
                max_points \(:=\) length \((\) points_covered \()\);
                \((\) max_angle, max_lobe) \(:=(\) angle, lobe \()\);
                max_points_covered \(:=\) points_covered ;
        angles \(:=\) angles \(\cup\) max_angle ;
        rotated_lobes \(:=\) rotated_lobes -
        (max_angle, max_lobe);
        points_to_cover := points_to_cover -
        max_points_covered ;
    return angles
```

```
Algorithm 1: min_antenna_cover_greedy : Find the
antenna cover for all the points in protection_points.
    Input: protection_points: Set of protection points to be
        covered.
        candidate_sites: Set of candidate sites as centers.
        min_distance: Minimum distance permissible between
        two adjacent circle centers.
        detection_coverage: An array of non-intersecting
        concentric detection coverage lobes for the antenna. Each
        lobe has the same aperture angle (or beamwidth) and is
        oriented in the horizontal direction.
    Output: \(\{(\) center, lobe, \(\{\) angles \(\})\}\) : A set containing
        (center, lobe, \(\{\) angles \(\}\) ) for lobe \(\in\)
        detection_coverage identifying the location, antenna
        lobe and azimuth angles of the lobes placed at the
        center such that all the points in protection_points
        are covered.
    cover :=
    min_area_circle_cover_greedy(protection_points,
    candidate_sites,min_distance) ;
    antenna_cover \(:=\emptyset\);
    for each circle \(C \in\) cover do
        lobe \(:=\) the smallest lobe \(\in\) detection_coverage such that
        lobe.radius \(\geq\) overlap_factor \(*\) (C.radius) ;
        points_to_cover \(:=\{p \mid p \in\) protection_points and \(p\)
        is inside circle \(C\}\);
        angles :=
        find_antenna_overlay_for_sector(points_to_cover,
        C.center, C.radius, lobe) ;
        antenna_cover \(:=\) antenna_cover \(\cup\)
        \(\{(\) C.center, lobe, angles \()\}\);
    8 return antenna_cover
```

covered by four lobes (pink in color). Then the smaller circle is chosen which is covered by two lobes (blue in


Fig. 1. Example of coverage of an RCA using our approach.
color).
The time complexity of our algorithm is $O(n * m)$, where $n$ is the number of discrete points to be covered in a RCA and $m$ is the number of candidate sensor sites. It can be improved by using spatial data structures for a nearest neighbor search.

Our algorithm terminates when all the protected points are covered by antenna lobes. In the intermediate step, coverage is provided by circles. For every protection point, the Subroutine 1 will always find a circle that covers it. Hence, circle coverage provided by Subroutine 2 terminates. In Subroutine 3, lobe size is chosen to be larger than circle radius (by overlap_factor) and the angle of rotation of lobes is chosen such that the rotated lobes overlap with each other. Thus, it is guaranteed that all the protection points inside a circle will be covered by one or more lobes in rotated_lobes. Hence, Subroutine 3 also terminates.
In the final stage, we apply simulated annealing to our cover (not shown in the algorithm). To keep the search space reasonable, we apply random perturbations only to the orientation of the antenna lobes. The centers and the lobe sizes are obtained from the previous step. Simulated annealing attempts to drive a defined energy function to a minimum by randomly perturbing a given starting solution. A valid solution is one in which the antenna lobes cover the RCA. Area of the cover is used as the energy function, and the minimum energy solution in 1000 trials is picked. Finally, redundant lobes are removed, followed by the removal of sensors that have no lobe.

## IV. Analysis Model

In this section, we describe the models and assumptions used in our analysis. Table I lists technical parameters used in this analysis.
The technical parameters for a federal incumbent radar transmitter, referred to as Shipborne Radar 1 in [2], are found in [2], [10]. The ESC sensor technical parameters are found in [14], [18]. The generalized mathematical model for the ESC sensor antenna gain pattern is calculated using the methodology in [19] as follows:

$$
\begin{equation*}
G_{E S C}(\theta)=G_{E S C \_p e a k}-\min \left[12\left(\frac{\theta}{\theta_{3 d B}}\right)^{2}, A_{H}\right] \tag{1}
\end{equation*}
$$

where $G_{E S C}(\theta)$ is the sensor antenna gain $(\mathrm{dBi})$ at the off-axis angle $\theta,-180^{\circ} \leq \theta \leq 180^{\circ}, G_{\text {ESC_peak }}$ is

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) | 3600 |
| Antenna Height (m) | 50 |
| Insertion/Cable Losses (dB) | 2 |
| ESC Sensor Parameter | Value |
| Antenna Directivity/Patterns | 3 GPP |
| Peak Antenna Gain (dBi) | 6.9 |
| 3-dB Beamwidth Ant. Gain (deg.) | $60,90,120$ |
| Receive Bandwidth (MHz) | 1 |
| Center Frequency (MHz) | 3600 |
| Antenna Height (m) | 25 |
| Insertion/Cable Losses (dB) | 2 |
| ITM Input 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) |
| Time/Location/Confidence Var. (\%) | $50 / 50 / 50$ |

the ESC peak antenna gain $(\mathrm{dBi}), \theta_{3 d B}$ is the $3-\mathrm{dB}$ beamwidth of the antenna (degree), and $A_{H}=20 \mathrm{~dB}$ is the maximum attenuation.

The path loss from the radar transmitter to the ESC sensor is computed using ITM propagation model [16]. The area prediction model is used to estimate the loss from empirical medians without details of the terrain profile between the radar and ESC sensor.

We define the detection coverage of an ESC sensor as a region within which the radar's peak signal level can be detected by the sensor. The area of the sensor detection coverage depends on the ESC detection threshold. For a given ESC detection threshold $D_{\text {th_esc }}$ and a given angle $\theta$ that the radar subtends relative to the boresight of the ESC sensor antenna, the propagation loss from the radar transmitter to the ESC sensor is estimated as:

$$
\begin{array}{r}
L(\theta)=P_{\text {radar }}+G_{\text {peak_radar }}-L_{i_{-} \text {radar }}+G_{E S C}(\theta) \\
\quad-L_{i_{-} E S C}-B_{E S C / \text { radar }}-D_{\text {th_esc }} \tag{2}
\end{array}
$$

where $L(\theta)$ is the estimated propagation loss at a given angle $\theta(\mathrm{dB}), P_{\text {radar }}$ is the transmit power of the radar $(\mathrm{dBm}), G_{\text {peak_radar }}$ is the peak antenna gain of the radar $(\mathrm{dBi}), L_{i_{-} \text {radar }}$ is the radar transmitter insertion loss ( dB ), $G_{E S C}(\theta)$ is the ESC antenna gain in the direction of the radar ( dBi ), $L_{i_{-} E S C}$ is the ESC receiver insertion loss $(\mathrm{dB})$, and $B_{E S C / \text { radar }}$ is the frequency dependent rejection $(\mathrm{dB})$. The frequency dependent rejection is defined as $B_{E S C / \text { radar }}=10 \log _{10}\left(B_{E S C_{-} r x} / B_{\text {radar_tx }}\right)$, if $B_{E S C \_r x}<B_{\text {radar_tx }}$; and $B_{E S C / \text { radar }}=0$, otherwise. Note that $B_{E S C_{-} r x}$ and $B_{\text {radar_tx }}$ are the bandwidths of the ESC receiver and the radar transmitter, respectively.

Once the propagation loss $L(\theta)$ at each angle $\theta$ is computed, the distance $d$ corresponding to the propaga-


Fig. 2. Antenna coverage lobe patterns for $\theta_{3 d B}$ of $60^{0}$.
tion loss $L(\theta)$ is determined from a Propagation Loss vs. Distance graph (similar to Fig. B-1 in [11]) using the ITM area mode with appropriate parameter values. The point is then plotted as a polar point $(d, \theta)$. This procedure is repeated for different azimuth angles $\theta$ of the antenna, which results in a lobe coverage pattern for the detection threshold $D_{t h \_e s c}$. A family of such antenna lobe coverage patterns is obtained by varying the detection threshold in the range of $[-89,-50] \mathrm{dBm} / \mathrm{MHz}$. Fig. 2 shows a family of lobe coverage patterns for antenna beamwidth of $60^{\circ}$.
The draft DPA data from NTIA is expressed in latitude/longitude in World Geodetic System (WGS) 84 reference coordinate system. To convert them to northing/easting projected coordinates, we use the Hammer map projection technique to preserve areas. This conversion is required to carry out various geometric operations during DPA coverage analysis. The reference geographic center of the U.S. is chosen as (latitude, longitude $)=(37.1669,-95.9669)$.

## V. Results

## A. ESC Detection Coverage

We applied our proposed approach to find the detection coverage for all DPAs along the CONUS. Fig. 3 shows the final sensor locations (yellow pushpins) and their detection coverages (orange contours) computed using our method with overlap_factor set to 1.2.

For the West Coast, 15 sensors with sensitivities in the range of $(-83$ to -71$) \mathrm{dBm} / \mathrm{MHz}$ and 18 antenna lobes were needed to cover 15 DPAs. Whereas, for the East and Gulf Coasts, 32 sensors with sensitivities in the range of $(-89$ to -75$) \mathrm{dBm} / \mathrm{MHz}$ and 40 antenna lobes were required to cover 26 DPAs. These antenna lobes have beamwidths of $60^{\circ}$ and $90^{\circ}$. For most DPAs, only a single sensor equipped with a single antenna lobe is needed to provide coverage. However, there are some exceptions for cases with large and/or irregular shape DPAs. As an artifact of the algorithm, which tries to minimize the excess area, some DPAs have multiple small lobes (with substantial overlapping areas among themselves) instead of having one large lobe.


Fig. 3. Detection coverage of all coastal DPAs


Fig. 4. Illustration of outage and excess areas.

## B. Performance Metrics

To formulate our performance metrics, let us define $A_{D P A}$ as the total area of a DPA and $A_{E S C}$ as the detection coverage area of ESC sensor(s) associated with the DPA. Furthermore, let the area that is inside a DPA as well as in its detection coverage area be defined as $A_{\text {cov }}=A_{D P A} \cap A_{E S C}$. The area, which is inside a DPA but is outside of its detection coverage area, is defined as $A_{\text {outage }}=A_{D P A} \cap \overline{A_{E S C}}$. Finally, the area that is outside of a DPA but is inside its detection coverage area is defined as $A_{\text {excess }}=\overline{A_{D P A}} \cap A_{E S C}$.

We further note that the excess area $A_{\text {excess }}$ of a DPA has three components: a) excess area overlapping with its neighboring DPAs $\left(A_{\text {excess_nbr } D P A}\right)$, b) excess area extending out to the sea ( $\bar{A}_{\text {excess_sea }}$ ), and c) excess area covering sea and land region along the shoreline $\left(A_{\text {excess_shore }}\right)$. Thus, we have $A_{\text {excess }}=$ $A_{\text {excess_nbrDPA }}+A_{\text {excess_sea }}+A_{\text {excess_shore }}$.

The areas defined above are illustrated in Fig. 4. We now define the performance metrics used in our study.

1) Probability of Outage: For a given DPA, we define probability of outage as $P_{\text {outage }}=A_{\text {outage }} / A_{D P A}$. The probability of outage represents the probability of a shipborne radar not being detected when it is inside the DPA, assuming that its position inside the DPA


Fig. 5. Performance results of West Coast.
is uniformly distributed. This value should be zero or significantly small to ensure that the DPA is fully monitored by the ESC sensor(s).
2) Probability of False Alarm: For a DPA we define two types of false alarms as follows.
a) False Alarm Out at Sea: This is the false alarm due to the excess coverage area further out at sea and is defined as $P_{\text {fa_sea }}=A_{\text {excess_sea }} /\left(A_{E S C}-\right.$ $\left.A_{\text {excess_shore }}\right)$.
This metric captures the odds that an ESC sensor activates its associated DPA even though the radar is further out in the sea and outside of the DPA. $P_{f a_{-} s e a}$ should be as low as possible to avoid unnecessary shutdown of CBSDs. We subtract the $A_{\text {excess_shore }}$ from $A_{E S C}$ in the denominator with the assumption that the shipborne radar is unlikely to operate in the $A_{\text {excess_shore }}$.
b) 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 $P_{f a \_n b r D P A}=A_{\text {excess_nbrDPA }} /\left(A_{E S C}-\right.$ $\left.A_{\text {excess_shore }}\right)$.

## C. Performance Results

Figs. 5 and 6 show performance results of our algorithm when applied to the DPAs along the West Coast and the combined East/Gulf Coasts, respectively.

The top subplot in each figure presents $P_{\text {outage }}$ computed for each DPA. In most cases, $P_{\text {outage }}$ is either zero or close to zero, except for the brem DPA (Bremerton, WA) in the West Coast which has a higher value. These small outages are artifacts of discretization of area of DPAs. They can be minimized further by having finer grid size. Nevertheless, the results indicate that the shipborne radar can be detected in any DPA with a very high probability.

The middle subplot in each figure depicts $P_{f a \_s e a}$ for each DPA. On the West Coast, except for the brem DPA,


Fig. 6. Performance results of East and Gulf Coasts.
other DPAs have values in the range of ( 0.07 to 0.27 ). The brem DPA has an extremely narrow shape, for which an antenna lobe of even $60^{\circ}$ beamwidth is too wide. This leads to an extremely large excess area into the sea, resulting in $P_{\text {fa_sea }}=0.95$. On the East and Gulf Coasts, $P_{f a-s e a}$ values vary in the range of ( 0.09 to 0.43 ). The large values of $0.34,0.43$, and 0.33 belong to DPAs 12 , 13 , and 14 , respectively. These DPAs are close to Florida and have large sharp concave areas due to the islands in the Bahamas. This causes the lobes to cover substantial amount of areas outside of the concave parts of the DPAs. Using antennas with narrower beamwidths, e.g., $30^{\circ}$, will not considerably improve $P_{\text {fa_sea }}$ performance, but it might cause OPSEC concern of geolocating incumbent activity [15].

The bottom subplot in each figure shows $P_{f a \_n b r D P A}$ for each DPA. $P_{f a \_n b r D P A}$ values for all DPAs are in the range of (0 to 0.5). Because of the geometric shapes of the DPAs and antenna lobes, improving $P_{f a \_n b r D P A}$ will worsen $P_{f a_{-} s e a}$ for a given DPA. Weighting factors could be applied to these false alarms to achieve desired operational performance.

## VI. Conclusion and Future Work

This paper presents an approach for an ESC operator to determine location and operational parameters of ESC sensors to detect the presence of federal incumbent shipborne radar. We formulate the problem as a generalized coverage problem where an ESC sensor covers a geometric shape (RCA) such that the excess area is minimized. We apply our algorithm to DPAs along the coasts of CONUS as a use case and present the performance results for each DPA.

We used the ITM area mode, without details of terrain information, to compute the antenna coverage patterns. Based on the final ESC sensor parameters, future work should consider using the ITM point-to-point mode [16] to evaluate the detection coverage areas and corresponding performance metrics. In addition, we used locations along the coast as candidate sites. However, ESC operators may prefer to use existing tower locations as candidate ESC sensor sites to minimize the cost of deployment. Hence, it would be worthwhile to study the performance of our algorithm for that scenario.

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