Published in final edited form as:

IEEE Trans Cogn Commun Netw. 2017 September ; 3(3): 437–449. doi:10.1109/TCCN.2017.2748121.

3.5 GHz Environmental Sensing Capability Detection Thresholds and Deployment

Thao T. Nguyen, Michael R. Souryal [Member, IEEE], Anirudha Sahoo [Member, IEEE], and Timothy A. Hall [Member, IEEE]

Communications Technology Laboratory, National Institute of Standards and Technology,
Gaithersburg, MD 20899 USA

Abstract

Spectrum sharing in the 3.5 GHz band between commercial and government users along U.S. coastal areas depends on an environmental sensing capability (ESC)—that is, a network of radio frequency sensors and a decision system—to detect the presence of incumbent shipborne radar systems and trigger protective measures, as needed. It is well known that the sensitivity of these sensors depends on the aggregate interference generated by commercial systems to the incumbent radar receivers, but to date no comprehensive study has been made of the aggregate interference in realistic scenarios and its impact on the requirement for detection of the radar signal. This paper presents systematic methods for determining the placement of ESC sensors and their detection thresholds to adequately protect incumbent shipborne radar systems from harmful interference. Using terrain-based propagation models and a population-based deployment model, the analysis finds the offshore distances at which protection must be triggered and relates these to the detection levels of coastline sensors. We further show that sensor placement is a form of the well-known set cover problem, which has been shown to be NP-complete, and demonstrate practical solutions achieved with a greedy algorithm. Results show detection thresholds to be as much as 22 dB lower than required by current industry standards. The methodology and results presented in this paper can be used by ESC operators for planning and deployment of sensors and by regulators for testing sensor performance.

Index Terms

3.5 GHz; aggregate interference; radar; sensing; sensor placement; spectrum sharing

I. Introduction

THE NEW Citizens Broadband Radio Service (CBRS) in the U.S. will share spectrum with government and non-government incumbents in the 3.5 GHz band. While initial use of the 3550 MHz to 3650 MHz portion of this band by CBRS will be restricted to geographic areas outside of coastal and certain inland exclusion zones, the CBRS rules and architecture allow

(Corresponding author: Michael R. Souryal. souryal@nist.gov).

Parts of this work were presented at DySPAN 2017 [1]. The associate editor coordinating the review of this paper and approving it for publication was R. Bendlin.

for the eventual deployment of a sensing capability that will permit CBRS devices (CBSDs) to operate in these previously-excluded zones. Termed an Environmental Sensing Capability (ESC), its purpose is to detect federal incumbent radar signals and communicate their presence (frequency and geographic area) to a Spectrum Access System (SAS) which coordinates CBSD access to the band. Together, the SAS and ESC must ensure that CBSDs do not generate harmful interference to incumbent systems.

The Federal Communications Commission has adopted rules for CBRS [2], and the Wireless Innovation Forum (WINNF) Spectrum Sharing Committee (SSC) is developing requirements and specifications for the SAS, ESC, and CBSDs. However, an open issue is the detection threshold for ESC sensors, that is, the received signal level from an incumbent shipborne radar at which a sensor must flag incumbent activity to enable adequate interference protection. The detection threshold is a function of the aggregate CBSD interference at the incumbent receiver: the greater the interference, the more sensitive a sensor needs to be. Preliminary work by the National Telecommunications and Information Administration (NTIA) and the WINNF SSC, discussed below, references the required sensitivity to the aggregate interference, but little has been done to quantify the aggregate interference and, thus, the detection requirement.

This paper proposes a methodology for determining the ESC's required sensitivity as a function of CBSD deployment. Because realistic deployments of CBSDs will vary by population density and other factors, the proposed methodology takes these factors into account. Inputs include population data, terrain elevation, radio frequency transmitter and receiver characteristics, and incumbent interference protection criteria. We present formal algorithms both for determining the number and placement of ESC sensors from a set of candidate locations and for determining the necessary detection threshold of each sensor. We also present an algorithm for finding the *interference contour*, which defines the offshore boundary where the radar will begin to experience harmful interference when moving towards the coast and thus where protection must be triggered.

We formulate our sensor placement algorithm as the well-known *set cover* problem [3] and use a greedy algorithm [4, p. 975] to minimize the total number of ESC sensors required. Besides cost considerations, a key motivation for minimizing the number of sensors is to mitigate operational security concerns of the federal incumbent. However, there exists a tradeoff between minimizing the number of sensors for cost and security concerns on one hand and improving fault tolerance to sensor outage, on the other hand. To adjust this tradeoff, the algorithms proposed in this paper take as an additional input a *redundancy factor*, that is, the minimum number of ESC sensors that must simultaneously detect the incumbent. We apply these algorithms to the east and west coasts of the continental United States, which comprise a range of population density and terrain features.

The contributions of this paper are the following: (i) a methodology comprised of three algorithms that compute the interference contour along a coast, the required sensitivity of candidate ESC sensors, and the minimum number of sensors needed, along with their respective detection thresholds and locations along the coast, (ii) use of realistic scenarios of CBSD deployments based on population density and other factors, (iii) use of terrain-based

propagation models and elevation data along the east and west coasts of the United States, (iv) identification of the sensor placement problem as a set-cover problem, and (v) resulting detection thresholds as much as 22 dB lower than previous results.

The paper is organized as follows. Section II reviews related work on ESC sensor thresholds and placement, and compares them to the contributions of this paper. Section III describes the proposed methodology for determining sensor detection thresholds and placement, including formal algorithm descriptions. Section IV details the modeling framework and assumptions, including CBSD deployment, transmitter and receiver characteristics, and channel propagation models. Section V applies the methodology and modeling framework to the U.S. coasts and discusses the results. Finally, Section VI concludes with recommendations for future work.

II. Related Work

In a recently published technical report, NTIA proposed exploiting channel reciprocity to determine the received power level at which an ESC sensor must trigger detection [5]. The argument is based on the fact that the propagation loss from a shipborne radar transmitter to a sensor on the coastline is no more than the propagation loss from any land-based CBSD to the radar receiver. The analysis uses this principle to derive a trigger-detection threshold at the sensor of -64 dBm received radar peak power in a 1 MHz bandwidth. However, the derived threshold assumes a *single* co-channel Category B (high power) CBSD in the radar's beam. The authors recognized that, in practice, aggregate CBSD interference may exceed that of a single Category B CBSD, and that the trigger thresholds "will therefore be expected to vary along segments of coastline depending on the exact characteristics of actual CBSD deployments" [5, Sec. 2.6]. Our analysis in this paper seeks to address this very question, that is, to apply accepted models for CBSD deployment and channel propagation to predict the actual aggregate interference and thereby derive the trigger threshold of each sensor.

The NTIA report goes on to propose a uniform ESC sensor spacing along the coastline of approximately 50 km, based on a geometric argument and the radio-horizon distance. The algorithms proposed in this paper, on the other hand, result in non-uniform sensor spacing that depends on CBSD deployment density, terrain features, and the desired sensor redundancy.

WINNF SSC requirements specify an ESC detection threshold in terms of the maximum propagation loss over which a coastline sensor must be able to detect shipborne radar [6]. The maximum loss is derived to be 184 dB in similar fashion to the trigger threshold of [5]: it corresponds to the path loss between a single coastline Category B CBSD and the radar receiver such that the interference-to-noise ratio (I/N) at the radar receiver is -6 dB [6, Appendix A.2]. Similarly to the aforementioned NTIA report, the WINNF SSC requirements acknowledge that "ongoing investigations into the effects of aggregate interference from multiple CBSDs and their locations may need to be taken into account to better establish this figure."

A straightforward methodology for uniform placement of ESC sensors is presented in [7]. Using a linear coastline with a parallel line in the water to represent the required radar detection distance, it finds the maximum distance between sensors that provides complete coverage of the detection distance along the coast. It presents a distance calculation for non-redundant coverage (i.e., area covered by a single sensor) as well as one for redundant coverage (i.e., area covered by a minimum of 2 sensors). The differences in this approach and ours is that we use an actual map of the coastline and location-specific CBSD deployment densities that result in a non-uniform spacing of sensors.

Joshi *et al.* [8] present an approach for optimal non-uniform sensor node placement. They use a piecewise linear representation of the coastline and of the isolation boundary (analogous to our interference contour). Possible sensor locations comprise a grid in the coastal land area. For each of the knot points (segment endpoints) in the isolation boundary, the grid point nearest in distance to it is selected as a candidate sensor location. This initial set is then used in a constrained optimization problem to find the minimum number of sensors needed to provide complete coverage of the knot points. They use a sequential convex programming algorithm to solve it. They also consider redundant sensor coverage. While the approach in [8] does result in nonuniform sensor placement, they use an abstract representation of the coast and interference boundary instead of using actual maps and modeling aggregate CBSD interference. A further distinction is that we identify the problem of sensor placement as a set cover problem and use a greedy algorithm to solve it.

The models used in our analysis are based in large part on those used by NTIA to develop the revised 3.5 GHz exclusion zones [9]. That study calculated the contours delineating areas in which CBSDs are not permitted to operate in the absence of an ESC, in order to protect federal incumbent radar systems. The NTIA study relied on a CBSD deployment model, CBSD and radar transmitter and receiver parameters, propagation models, and an aggregate interference model. Our analysis attempts to follow the models and assumptions in the NTIA exclusion zone analysis as closely as possible.

Algorithm 1

Compute Interference Contour

Input: $l_1, l_2, \dots, l_N$: Initial ship locations along the coastline
 $I_{\text{threshold}}$: Interference threshold that defines harmful interference to the radar receiver
 stepSize : distance ship moves away from coast in every iteration
 p_{th} : defines the number of maximum aggregate interference values, out of 100 iterations, which should be less than interference threshold to declare the corresponding ship location as a point on the interference contour

Output: $L_1, L_2, \dots, L_N$: ship locations which define the piece-wise linear interference contour

```

1 for each initial ship location  $l_i \in \{l_1, l_2, \dots, l_N\}$  do
2    $l_{tmp} = l_i$ ;
3    $I_{agg}[1..360] = 0$ ;
4    $done1\_iter = NOT\_DONE$ ;
5   while ( $done1\_iter \neq DONE$ ) do
6     randomly deploy CBSDs within the area around  $l_i$ ;
7     for each azimuth of the main-beam of the radar antenna  $az_j \in \{1, \dots, 360\}$  do
8        $I_{agg}[j] = \text{Aggregate interference from CBSDs to the radar receiver at location } l_{tmp}$ ;
9      $I_{MaxAgg\_az} = \max_{1 \leq j \leq 360} (I_{agg}[j])$ ;
10    if  $I_{MaxAgg\_az} > I_{\text{threshold}}$  then
11       $l_{tmp} = \text{new ship location after it is moved by } \text{stepSize} \text{ away from the coastline}$ ;
12    else
13       $done1\_iter = DONE$ ;
14   $I_{agg}[1..360] = 0$ ;
15   $I_{MaxAgg}[1..100] = 0$ ;
16   $done100\_iter = NOT\_DONE$ ;
17  while ( $done100\_iter \neq DONE$ ) do
18    for  $k = 1$  to 100 do
19      randomly deploy CBSDs within the area around  $l_i$ ;
20      for each azimuth of the main-beam of the radar antenna  $az_j \in \{1, \dots, 360\}$  do
21         $I_{agg}[j] = \text{Aggregate interference from CBSDs to the radar receiver at location } l_{tmp}$ ;
22       $I_{MaxAgg}[k] = \max_{1 \leq j \leq 360} (I_{agg}[j])$ ;
23     $I\_count = \text{number of maximum aggregate interference values in } I_{MaxAgg}[] \leq I_{\text{threshold}}$ ;
24    if  $I\_count \leq p_{th}$  then
25       $l_{tmp} = \text{new ship location after it is moved by } \text{stepSize} \text{ away from the coastline}$ ;
26    else
27       $L_i = l_{tmp}$ ;
28       $done100\_iter = DONE$ ;
29 return  $\{L_1, L_2, \dots, L_N\}$ ;

```

III. Overview of Approach

A. Problem Formulation

To analyze ESC sensor detection requirements, we divide the problem into three parts. First, the *interference contour* of a shipborne radar is computed. The interference contour defines the offshore boundary where the radar will begin to experience harmful interference when moving towards the coast. Second, the sensors' required sensitivity is determined such that a radar can be detected at any point on the interference contour. Finally, the third part is to determine the minimum number of ESC sensors, their locations, and their detection thresholds such that a radar is detected with a desired level of redundancy. Minimizing the number of ESC sensors is desirable from an operational security standpoint in order to mitigate the risk of an adversary learning ship locations and frequencies, as well as to keep sensor deployment cost down.

To illustrate our approach, we apply our method to the east and west coasts of the continental U.S. Along these coastlines, there are variations in population density as well as terrain features. To keep the computation manageable, we compute the interference contour as a piece-wise linear curve by connecting the discrete points at which maximum aggregate interference to the radar is just below the harmful interference threshold. Likewise, equally spaced discrete locations along the coast are chosen as *candidate* ESC sensor locations.

Now, we can formally state our problem as follows. Using the aggregate interference model, determine the piece-wise linear interference contour as N discrete locations $L_1, L_2, \dots, L_N$.

Let $E_1, E_2, \dots, E_M$ be M discrete candidate locations for ESC sensor deployment. Let RD be the *redundancy factor* required for detection of the radar, i.e., at least RD number of ESC sensors should be able to simultaneously detect the radar when it is on the interference contour. Assuming that each ESC sensor will have the same sensitivity, compute the required sensitivity. The next task is to determine the minimum number of ESC sensors, their locations (among the M candidate locations), and their detection thresholds such that a radar at any of the N locations on the interference contour is detected with a redundancy factor of RD .

B. Computation of Interference Contour

The computation of the interference contour, presented in Algorithm 1, starts with initial ship locations along the coastline. Each initial ship location gives rise to one point on the interference contour. CBSDs are randomly deployed in proportion to the population density, and the maximum aggregate interference to the radar receiver (over all azimuth angles of the radar antenna) is computed at a given ship location. If the aggregate interference exceeds the harmful interference threshold (I_T) (as derived in (2)), then the ship location is moved along its latitude by a discrete step size away from the coast. The step-size iterations stop at the location where the aggregate interference falls below I_T . At this point, the algorithm checks if this location is indeed on (or near) the interference contour within a level of statistical confidence by repeating the last computation for 100 random, independent deployments of CBSDs (Lines 18 to 28).

Algorithm 2

Compute Sensitivity of ESC Sensor

```

Input:  $L_1, L_2, \dots, L_N$ : radar locations on the interference contour
         $E_1, E_2, \dots, E_M$ : candidate ESC sensor locations
         $RD$ : Redundancy Factor /* minimum number of ESC sensors required to simultaneously detect any given radar location */
Output:  $S$ : required minimum sensitivity of each ESC sensor
1 for each radar location  $L_j \in \{L_1, L_2, \dots, L_N\}$  do
2   for each candidate ESC location  $E_i \in \{E_1, E_2, \dots, E_M\}$  do
3      $P_r[i]$  = Received peak power at  $E_i$  when radar is at location  $L_j$ ;
4   Sort the elements of  $P_r[i]$  in a non-increasing order;
5    $S[j] = P_r[RD]$  /* 'RD' number of ESC sensors can detect radar at location  $L_j$ , when sensitivity of the ESC sensors is set at  $S[j]$  */
6  $S = \min_{1 \leq j \leq N} (S[j])$  /* Pick the minimum of the sensitivities */
7 return  $S$ ;

```

C. Computation of Sensitivity of ESC Sensors

To compute the required sensitivity of the ESC sensors, Algorithm 2 first calculates the received peak power at each candidate ESC sensor location from a given radar location on the interference contour. It then picks the RD^{th} highest received power as the sensitivity that would ensure redundancy factor RD when detecting radar at that given location (Line 5). This process is repeated for every radar location, and the minimum among those sensitivity values is chosen as the required sensitivity for all ESC sensors.

D. Placement of ESC Sensors

The algorithm for placement of ESC sensors, Algorithm 3, starts with a *detection matrix*, whose rows represent candidate ESC sensor locations on the coast and whose columns

represent radar locations on the interference contour. An entry is 1 if the ESC sensor at that row can detect, or *cover*, the radar located at that column; otherwise it is 0. Then, the problem reduces to choosing the minimum number of rows from the detection matrix which together can cover all the radar locations. This is the *set cover* problem, which is known to be NP-complete [3]. Hence, Algorithm 3 uses an iterative *greedy* method [4, p. 975] to find the set cover. In each iteration, the greedy method chooses, from the unselected rows, the row which has the maximum number of 1's at radar locations which are still not covered (Line 16). The greedy method also ensures that the redundancy factor is taken into account while computing the coverage of each radar location (Line 25). When the greedy method selects an ESC sensor location, it also records the radar locations which are detected by that ESC sensor (Line 22). Next, (in the *for loop* in Line 29) the algorithm tries to increase the detection threshold of each ESC sensor while making sure that the ESC sensor still detects the same set of radar locations on the interference contour in order to minimize areas of detection of radar beyond the interference contour.

The greedy algorithm may choose a candidate sensor location that is not necessary to satisfy the coverage requirement. In those cases, a final pruning step (not shown in Algorithm 3) should be applied to remove such locations.

Antenna directionality may also affect sensor placement, due to the need to provide sufficient overlapping coverage of directional antenna patterns. However, the impact of directionality on placement was neglected in this analysis.

IV. Analysis Model

This section describes the models and assumptions used in this analysis. They include propagation models, terrain and other databases, the aggregate interference model, the CBSD deployment model, and the technical parameters of the incumbent radar, CBSD, and ESC sensor. Wherever possible, the same models and assumptions used in [9] are used in this analysis.

A. Shipborne Radar Technical Parameters

The federal incumbent radar system is the one referred to as Shipborne Radar 1 in [9]. The technical parameters for the radar transmitter and receiver are obtained from [5] and [9] and are summarized in Table I.

Algorithm 3

Placement of ESC Sensors

```

Input:  $L_1, L_2, \dots, L_N$ : radar locations on the interference contour
        $E_1, E_2, \dots, E_M$ : candidate ESC sensor locations
        $S$ : sensitivity of each ESC sensor
        $RD$ : Redundancy Factor /* minimum number of ESC sensors required to simultaneously detect any given radar
       location
Output:  $ESC\_and\_det\_threshold$ : set of tuples, each containing location of ESC sensor and its detection threshold
1 Initialize Detection Matrix  $D[1..M][1..N] = 0$ ;
2 for each radar location  $L_j \in \{L_1, L_2, \dots, L_N\}$  do
3   for each candidate ESC location  $E_i \in \{E_1, E_2, \dots, E_M\}$  do
4      $P_r$  = Received peak power at  $E_i$  when radar is at location  $L_j$ ;
5     if ( $P_r \geq S$ ) then
6        $D[i][j] = 1$  /* ESC sensor at location  $E_i$  can detect radar at location  $L_j$  */
/*  $D[i][j]$  is the detection matrix */
7 placement = NOT_DONE;  $ESC\_set = \emptyset$ ;  $ESC\_and\_det\_threshold = \emptyset$ ;
8 covered[1..N] = 0;
9 Sensor_loc[1..M] = NOT_SELECTED;
/* keeps track of ESC locations which are still available */
10 Holes[1..N] = 0;
/* keeps track of radar locations which are covered */
11 COVERAGE_MATRIX[1..M][1..N] = 0;
12 for each candidate ESC location  $E_i \in \{E_1, E_2, \dots, E_M\}$  do
13    $DRL_i = \emptyset$  /* Initialize the Detected Radar Location (DRL) for each ESC sensor location */
/* start the greedy method */
14 while (placement != DONE) do
15   Let  $AVAIL\_LOC$  be the set of indices in  $Sensor\_loc[]$  whose values equal NOT_SELECTED;
16   Let  $i \in AVAIL\_LOC$  be the index of the row in  $D[i][j]$  which has maximum number of 1's at the positions corresponding to 0's in  $Holes[]$ ;
17   In case of a tie, pick the row with maximum number of 1's in the entire row;
18    $COVERAGE\_MATRIX[i][j] = D[i][j]$ ;
/* copy the  $i^{th}$  row of  $D$  matrix; Sensor location at row  $i$  covers maximum radar locations not covered
yet */
19    $Holes[1..N] \&= COVERAGE\_MATRIX[i][1..N]$  /* bit-wise AND the two vectors to mark the corresponding radar
locations as covered */
20    $Sensor\_loc[i] = SELECTED$ ;  $ESC\_set = ESC\_set \cup \{E_i\}$ ;
21   covered[1..N] = covered[1..N] +  $COVERAGE\_MATRIX[i][1..N]$  /* vector addition */
22    $DRL_i = DRL_i \cup \{L_j | COVERAGE\_MATRIX[i][j] = 1\}$  /* Get all the radar locations which are detected by ESC  $E_i$  */
23   if all elements in  $Holes[] = 1$  then
24     for each element  $i$  in covered[1..N] do
25       if covered[i] < RD then
26          $Holes[i] = 0$  /* this radar location still needs coverage with required redundancy */
27       if all elements in  $Holes[] == 1$  then
28         placement = DONE;
/* try to increase detection threshold of each selected ESC sensor while making sure it can still detect
radar at the same set of interference contour points */
29 for each ESC location  $E_i \in ESC\_set$  do
30    $P = \emptyset$ ;
31   for each radar location  $L_j \in DRL_i$  do
32      $P_r$  = Received peak power at  $E_i$  when radar is at location  $L_j$ ;
33      $P = P \cup P_r$ ;
34    $P_{min} = \min(P)$  /* find the minimum in the set  $P$  */
/*  $P_{min}$  is the minimum among the received peak power of all the radar locations that  $E_i$  can detect */
35    $ESC\_and\_det\_threshold = ESC\_and\_det\_threshold \cup (E_i, P_{min})$ ;
36 return  $ESC\_and\_det\_threshold$ ;

```

The generalized mathematical model of the radar system antenna is described in Recommendation ITU-R M.1851 [10]. It is used to obtain the radar receive and transmit antenna gain in the azimuth and elevation orientations in the direction of the CBSDs.

Given the radar receiver bandwidth and the noise figure, the receiver noise power can be computed as follows:

$$N = 10 \log_{10} \left(k \times T \times BW_{rx} \times 10^6 \right) + NF \quad (1)$$

where N is the receiver noise power (dBm), $k = 1.38 \times 10^{-23}$ is Boltzmann's constant (J/K), T is the receiver temperature (K), BW_{rx} is the receiver bandwidth (MHz), and NF is the receiver noise figure (dB). If the receiver has a bandwidth of 1 MHz, 3 dB noise figure, and a temperature of 290 K, the receiver noise power is -111 dBm.

The interference threshold, I_T , at the radar receiver can be determined as:

$$I_T = N + I/N \quad (2)$$

where I_T is the interference threshold (dBm), and I/N is the maximum permissible interference-to-noise ratio at the radar receiver (dB). If I/N is set to -6 dB as in [9], the interference threshold is -117 dBm.

B. ESC Sensor Technical Parameters

The ESC sensor technical parameters are provided in Table II. The power levels are referenced to the antenna input, therefore the antenna gain and antenna patterns of the ESC sensor are neglected. In the analysis, the antenna height is varied from 6 m to 100 m.

C. Initial Ship and ESC Sensor Locations

Geographic Information System (GIS) 2011 National Land Cover Database (NLCD) data [11] is used to place the initial ship locations and the candidate ESC sensors along the coast in this analysis. The NLCD 2011 data is divided into 30 m by 30 m pixels and assigns a land cover classification code to each pixel (e.g., dense urban, urban, suburban, rural).

The initial ship locations are placed along the edge of the NLCD data, which is close to the shoreline. The separation between 2 ship locations is 667 pixels (i.e., approximately 20 km) in latitude. The locations of the candidate ESC sensors can be found by projecting the initial ship locations on the shoreline, which is formed along the open water regions with classification code of 11.

Fig. 1 illustrates the placement of initial ship and candidate sensor locations near Virginia Beach on the east coast of the U.S. The area of interest extends around 250 km along the coast. There are 12 initial ship locations $\{I_{46}, \dots, I_{57}\}$ and 12 candidate sensor locations $\{E_{46}, \dots, E_{57}\}$ placed along this stretch of coast.

While the candidate sensor locations are equally spaced in this example, our methods apply just as well to any arbitrary set of candidate locations. Thus, one can exclude areas that are unavailable for sensor deployment, such as certain private properties, wildlife refuges, and locations near ground-based radar operating at 3.5 GHz that would otherwise desensitize the sensor.

D. CBSD Technical and Deployment Parameters

The CBSD technical and deployment parameters are listed in Table III. Only low-power Category A CBSDs are considered in line with the assumptions of [9], but the analysis can easily accommodate high-power Category B CBSDs, as well.

Four data sources are used to deploy the CBSDs within an area of interest, i.e., the NLCD 2011 data [11], the 2010 U.S. Census population data [12], the census tract polygons [13], and the daytime commuter factors [14], as well as other assumptions described in [9].

The pixels of the NLCD data are grouped into 90 m by 90 m bins. The classification of a bin (dense urban, urban, suburban, or rural) is determined by the majority of classification codes of its component pixels. As mentioned in [9], the number of CBSDs per classification is computed from the population density, the daytime traveling factor, a market penetration factor of 20 %, a channel scaling factor of 10 %, and a ratio of users to CBSD for each classification.

Fig. 2 illustrates an example of CBSD deployment extending 150 km west, north, and south, and 120 km east of the initial ship location I_{53} . Table IV shows the calculation of the number of CBSDs in detail; the “daytime population” includes the daytime commuter adjustment, MP is the market penetration factor, and CS is the channel scaling factor. In this example, the total number of CBSDs deployed in the area of interest is 5146. The CBSDs are deployed randomly by varying different parameters including location, indoor antenna height, building attenuation, and clutter loss.

E. Propagation Models

Two propagation models, the ITS Irregular Terrain Model (ITM) and the extended Hata (eHATA) model, are used to compute the median basic transmission loss from the CBSD to the radar receiver. The point-to-point mode is used in both models, and the great circle terrain elevation profile between the CBSD and radar location is extracted and used as input to these models. For CBSDs in dense urban, urban, and suburban environments with a height above ground of less than 18 m, the maximum of the ITM and eHATA basic transmission losses is used in order to account for clutter loss not included in the ITM model. For CBSDs in rural areas—as well as in dense urban, urban, and suburban areas above 18 m—only the ITM model is used. For rural CBSDs, where antenna height is assumed less than 18 m, an additional, random clutter loss, uniformly distributed in the range (0 to 15) dB, is applied.

For the path loss from the radar transmitter to the ESC sensor, only the ITM model is used based on the assumption that coastline ESC sensors are located in rural areas. In addition, no additional clutter loss is added to this median basic transmission loss.

F. Aggregate Interference Calculation

For each ship location, the azimuth angle of the radar antenna is swept 360° in 1° increments. The aggregate interference from all CBSDs in the area is computed for each azimuth angle of the main beam of the radar antenna. The maximum aggregate interference over all azimuth angles is compared with the radar receiver’s interference threshold.

1) Interference Calculation for a Single Path—The interference power received at the radar from each CBSD is computed as follows:

$$I = EIRP_{CBSD} - L_{i_CBSD} - L_{building} - L_{prop} - L_{clutter} + G_{radar} - L_{i_radar} - B_{radar/CBSD} \quad (3)$$

where I is the received interference power at the output of the radar antenna (dBm), $EIRP_{CBSD}$ is the equivalent isotropically radiated power (EIRP) from the CBSD (dBm), L_{i_CBSD} is the CBSD transmitter insertion loss (dB), $L_{building}$ is the building attenuation loss

(dB), L_{prop} is the median propagation loss from the CBSD transmitter to the radar receiver, $L_{clutter}$ is the clutter loss (dB), G_{radar} is the radar receiver antenna gain toward the CBSD (dBi), L_{i_radar} is the radar receiver insertion loss (dB), and $B_{radar/CBSD}$ is the frequency dependent rejection (dB).

The frequency dependent rejection is defined as $B_{radar/CBSD} = 10 \log_{10}(B_{radar_rx}/B_{CBSD_tx})$, if $B_{radar_rx} < B_{CBSD_tx}$; and $B_{radar/CBSD} = 0$, otherwise. Note that B_{radar_rx} and B_{CBSD_tx} are the bandwidths of the radar receiver and the CBSD transmitter, respectively.

2) Aggregate Interference—Given the interference power computed for each individual path from the CBSD transmitter to the radar receiver, the aggregate interference power to the radar receiver is:

$$I_{agg} = 10 \log \left(\sum_{k=1}^N 10^{I_k/10} \right) \quad (4)$$

where I_{agg} is the aggregate interference level at the radar receiver from all CBSD transmitters (dBm), N is the number of CBSD transmitters, and I_k is the interference power at the radar receiver from each individual CBSD transmitter (dBm).¹

G. Model Validation

We validated our implementation and use of the aforementioned CBSD deployment, propagation, and aggregate interference models by repeating the NTIA exclusion zone analysis [9] in selected coastal areas. In this analysis, CBSDs are randomly deployed as described in Section IV-D, and the aggregate interference is computed at a fixed ship location 10 km offshore. Specifically, the azimuth angle of the radar antenna is swept in one-degree increments, and at each angle the radial distance is determined at which the aggregate I/N at the radar receiver from CBSDs beyond that distance drops just below -6 dB. This process is repeated for 10 000 independent CBSD deployments. The exclusion zone boundary at a given azimuth angle is based on the 95th percentile of the radial distances obtained from the Monte Carlo iterations.

In one departure from [9], we used the United States Geological Survey (USGS) Digital Elevation Model terrain database [15] rather than the resampled Spatial Data Transfer Standard terrain data used by NTIA [16] due to incompatibility of the latter with our geodata software. However, both databases have the same resolution of 90 m (3-arc-second).

Fig. 3 shows our computed 95th percentile distances (the dark-green dashed line) overlaid on top of the results from [9] for an area near San Diego, California. The 95th percentile distances match very well with those of [9] for most azimuth angles, except between 305° and 350°. The discrepancy at these angles could be due to the usage of different terrain databases.

¹As in [9], we approximate the interference from user equipment (UEs) as being included in (4) since the access scheme is expected to be time division duplex, in which CBSDs and UEs are not transmitting simultaneously.

V. Analysis Results

We apply the methodology for determining the required ESC sensor detection thresholds and sensor placement to the east and west coasts of the U.S. The two coasts differ considerably in terrain features, and these differences are reflected in the results for sensor placement and detection thresholds.

The National Oceanic and Atmospheric Administration (NOAA) Global Land 1-km Base Elevation (GLOBE) terrain database [17] is used to extract the elevation profiles between the CBSD and radar and between the radar and ESC sensor. The GLOBE database has a coarser resolution, i.e., 1 km (30-arc-second), than other databases. It was used in this study to increase the speed of extracting the elevation profile.

A. Interference Contour

We applied Algorithm 1 developed in Section III to find the piece-wise linear curve along which the aggregate interference caused by CBSDs to the radar receiver is just below a permissible I/N of -6 dB. The initial ship locations were placed near the shoreline of each coast as described in Section IV and were moved along their latitudes with a step size of 10 km away from shore. The algorithm stopped when at least 95 of the 100 random CBSD deployments resulted in aggregate interference below the interference threshold (2). Fig. 4(a) shows the resulting interference contour off the U.S. west coast; likewise, Fig. 4(b) shows the resulting interference contour off the east coast.² The distribution of the aggregate interference at one particular point on the east coast interference contour is illustrated in the histogram of Fig. 5 as an example. Over both interference contours, the standard deviation of I/N ranged from 3 dB to 13 dB.

A key difference between the two interference contours is their distance offshore. Fig. 6 plots the minimum distance from shore to each interference contour point for both coasts. While the east coast interference contour varies from 30 km to 80 km offshore, the west coast contour is generally further out to sea, varying from 65 km to as much as 170 km offshore. We believe these differences are attributable to the markedly different terrain characteristics between the east and west coasts. On the west coast, the terrain rises more precipitously inland from the coast, whereas on the east coast the increase in elevation is more gradual. Hence, CBSDs generally have a higher effective height on the west coast and, therefore, have lower propagation loss to the incumbent receiver at sea. Lower propagation losses translate to greater offshore distances of the interference contour.

B. Sensor Placement

We select the locations of ESC sensors along each coast by applying Algorithms 2 and 3 as described in Section III.

²In determining one of the interference contour points south of Los Angeles, we found that the propagation loss was not monotonically increasing with distance due to shadowing by Santa Cruz Island. Hence, for this point, Algorithm 1 was started with an initial location west of the shadowed region.

For each potential ship location on the interference contour, we compute the received peak power from the radar at all candidate ESC sensor locations along the coast using an equation similar to (3). The received peak power is measured when the main beam of the radar transmitter is pointed directly toward the sensor location. Using the received power levels at each candidate sensor location, Algorithm 2 determines the required sensitivity. Algorithm 3 then selects the sensor locations from the list of candidate locations that provide the needed coverage of the interference contour.

Fig. 4 depicts the selected sensor locations along the east and west coasts assuming a 25 m sensor antenna height and a redundancy factor (RD) equal to one. In this case, the east coast is covered by 27 sensors, whereas the west coast requires only 10 sensors. The difference owes to the fewer population centers, more sensitive sensors, and shorter coastline of the west coast.

To illustrate the coverage of the selected sensors, Fig. 7 shows a coverage matrix for each interference contour, with the rows representing the selected sensors, ordered north to south, and the columns representing points on the interference contour. A cell in the matrix is filled if that row's sensor covers that column's point on the interference contour. Most sensors cover a contiguous section of the interference contour, usually with some overlap with neighboring sensors. However, the two southernmost sensors on the west coast have non-contiguous coverage of the interference contour due to shadowing by San Nicolas Island.

Fig. 8 plots histograms of the spacing between the selected sensors along both coasts, calculated as the distance along the great circle path between consecutive pairs of sensors. Reflecting the different densities of sensors, east coast sensors are spaced 25 km to 200 km apart, whereas west coast sensors are spaced 64 km to 330 km apart. For reference, the analysis in [5] gave a uniform spacing between sensors of 50 km, resulting in 56 sensors on the east coast and 42 sensors on the west coast; and the analysis in [7] gave a spacing of 132 km for an interference contour 70 km from shore, resulting in 25 sensors on the east coast and 16 sensors on the west coast (assuming dual-sensor redundancy in this case).

C. Detection Thresholds vs. Sensor Antenna Height

Once the sensor locations are determined, Algorithm 3 finds the detection threshold of each sensor. The detection threshold of a sensor is simply the minimum signal strength received by that sensor from the interference contour points it covers. Fig. 9 plots the detection thresholds of the 27 east coast sensors selected assuming an antenna height of 25 m. They range from -76 dBm/MHz for sensor E_{19} on Cape Cod, Massachusetts, to -53 dBm/MHz for sensor E_{28} near New York. We refer to the minimum detection threshold of these sensors (-76 dBm/MHz) as the required sensitivity of the sensors on the east coast.

To explore the impact of sensor antenna height on the detection thresholds, we repeated the analysis above for antenna heights of (6, 10, 25, 50, 75, 100) m. Fig. 10 shows box plots of the distributions of the thresholds for each antenna height. Because higher antennas generally result in lower propagation loss, we expect detection thresholds to increase with antenna height; but a striking difference is seen between the results for the east and west coasts. On the east coast, increasing the antenna height raises the median detection threshold

by over 30 dB. However, on the west coast, the same increase in antenna height raises detection thresholds by only 4 dB.

The difference in sensitivity to antenna structure height between the two coasts is due to the respective difference in offshore distance of the interference contour and the radio horizon distance of the ESC sensor. Fig. 11 plots the total line-of-sight (LOS) distance from the radar transmitter, which is 50 m above sea level, to the ESC sensor antenna, which we vary from 6 m to 100 m above ground level.³ Note that the highest sensor antenna height of 100 m has a LOS-distance to the radar transmitter of 70 km. Since most of the east coast interference contour points are within 70 km of shore (see Fig. 6), increasing the sensor antenna height to 100 m reaches most of the contour with low propagation. On the west coast, however, most of the interference contour points are beyond 70 km; hence, increasing the antenna height to 100 m does not affect the propagation loss nearly as much.

Another key difference is that the west coast requires considerably more sensitive sensors than the east coast. The median detection threshold on the west coast is 15 dB lower than that on the east coast at an antenna height of 25 m. The lower detection thresholds on the west coast are consistent with the higher offshore distances of the interference contour observed in Fig. 6.

Figs. 12 and 13 summarize the required sensitivity (minimum detection threshold) and number of selected sensors on both coasts as a function of sensor antenna height. Also shown are results for a redundancy factor (RD) equal to two. Recall that setting $RD = 2$ in the algorithms requires that each point on the interference contour be covered by at least two sensors. Two-fold redundancy increases the number of required sensors by 40 % to 50 % on the east coast and by 55 % to 90 % on the west coast.

Interestingly, the number of required sensors does not change significantly with antenna height. The increase in required sensitivity level effectively maintains the coverage of each sensor such that approximately the same number of sensors are needed. In addition, we observe that the sharp increase in sensitivity with antenna height on the east coast is mitigated to a great extent when a redundancy factor of two is used due to the difficulty of finding a second sensor location to cover certain interference contour points.

VI. Conclusion

In summary, we have presented a methodology for determining the required detection thresholds and placement of ESC sensors to adequately protect 3.5 GHz incumbent shipborne radars from harmful interference. Given a maximum allowable interference-to-noise ratio (I/N threshold) at the radar receiver, we described a systematic algorithm for determining the boundary at sea at which a shipborne radar would experience interference at this threshold. Termed the *interference contour*, this boundary depends on the aggregate interference at the radar receiver from CBSDs deployed on land, computed from propagation models using terrain elevation data as well as clutter and building attenuation losses. We

³Because we assume sensors are deployed near the shoreline, ground level is near sea level in most cases.

applied this methodology to the east and west coasts of the U.S. and found that the interference contour ranged from 30 km to 170 km offshore, depending on the number of CBSDs deployed in the surrounding area and their effective height.

We also described systematic algorithms that, given the interference contour at sea, determine the locations of coastline sensors and their detection thresholds so that a radar crossing any point of the interference contour can be detected. We showed that the sensor selection algorithm is a form of the well-known set cover problem and applied a greedy approach to obtain solutions. The algorithm finds the minimum number of sensors to cover the interference contour with the desired level of sensor redundancy for fault tolerance. In the analysis of the U.S. coasts, and with a baseline sensor antenna height of 25 m, we found that the east coast requires 27 sensors with a required sensitivity (minimum detection threshold) of -76 dBm/MHz, and that the west coast requires 10 sensors with a sensitivity of -86 dBm/MHz. We note that these received signal levels are 12 dB to 22 dB lower, respectively, than the detection thresholds proposed in [5] and [6]. The detection level rises dramatically with sensor antenna height on the east coast, but not so on the west coast where the interference contour is beyond the radio horizon of even the highest sensor antenna. To achieve dual-sensor redundancy, approximately 40 % to 90 % more sensors are needed, depending on geography and antenna height.

In this work, the number of sensors and their locations computed by the proposed algorithm assume specific propagation models and Category A CBSD deployment densities. Future work should consider a more advanced approach that can determine the sensor detection thresholds dynamically based on changes in the environment and actual CBSD deployment for both Categories A and B. Also, the approach should take into account the placement of additional sensors, given that the positions of previously deployed sensors are fixed. This final step aims to cover additional areas that require protection due to changes in propagation and CBSD deployment.

This paper only analyzed the received signal level at the sensor from the incumbent radar transmitter. However, in practice, sensors will also experience co-channel interference from CBSDs. While this interference can be mitigated to some extent with the use of directional antennas pointed to sea, irregular coastlines and nearby CBSD transmitters will nonetheless generate unwanted interference at the sensor. Hence, an important figure of merit for sensor detection performance is the signal-to-interference ratio (SIR). The analysis in this paper can be extended to predict the SIR at each sensor and to factor this metric into the sensor placement algorithm.

Biographies

Thao T. Nguyen received the B.S., M.S., and Ph.D. degrees all in electrical engineering from George Mason University, Fairfax, VA, USA, in 2004, 2006, and 2013, respectively.

She was with Shared Spectrum Company, Vienna, VA, USA, as a Senior Communications Systems Engineer for eight years. She is currently an Electronics Engineer with the National Institute of Standards and Technology. Her main topics of interest are wireless communications and signal processing. Her focus is on research and development

Michael R. Souryal (M'89) received the B.S. degree in electrical engineering from Cornell University, Ithaca, NY, USA, in 1990, the M.S. degree in information networking from Carnegie Mellon University, Pittsburgh, PA, USA, in 1991, and the D.Sc. degree in electrical engineering from George Washington University, Washington, DC, USA, in 2003.

He is with the Communications Technology Laboratory, National Institute of Standards and Technology (NIST) conducting research in wireless communication systems. He was with Telcordia Technologies, where he was engaged in new service development for public network providers. He has also held an adjunct appointment as a Professorial Lecturer with the George Washington University. His research interests are in communication theory, spectrum sharing, and public safety communications. He was a recipient of the NRC Post-Doctoral Fellowship in 2004 from NIST.

Anirudha Sahoo (M'95) received the B.Sc. (Engg.) degree in electrical engineering from the National Institute of Technology, Rourkela, India, the M.S. degree in computer science from the University of Louisiana, Lafayette, LA, USA, and the Ph.D. degree in computer science from Texas A&M University, College Station, TX, USA. He worked as a Software Engineer with Intergraph Corporation, Huntsville, AL, USA, and then as a Senior Software Engineer with Cisco Systems, San Jose, CA, USA. He was an Associate Professor with IIT Bombay, India. He is currently a Computer Scientist with the National Institute of Standards and Technology. He is also an Adjunct Professor with the Department of Computer Science, University of Maryland, College Park, MD, USA.

Timothy A. Hall (M'88) received the B.E.E. and M.E.E. degrees and the Ph.D. degree in electrical engineering in 1994 from the University of Delaware. After working for a small company developing software for scientific and engineering applications, he joined the National Institute of Standards and Technology in 1999, where he has worked on network modeling and simulation, voice quality in Internet telephony, wireless networks, and conformance testing of cryptographic algorithms. He is currently researching on aspects of spectrum sharing, including dynamic spectrum access, operational security, and interference protection.

References

1. Nguyen, TT., Sahoo, A., Souryal, MR., Hall, TA. 3.5 GHz environmental sensing capability sensitivity requirements and deployment. Proc IEEE Dyn Spectr Access Netw (DySPAN); Piscataway, NJ, USA. Mar. 2017; p. 1-10.
2. Citizens broadband radio service. 2 CFR. 2016:96.
3. Garey, MR., Johnson, DS. Computers and Intractability: A Guide to the Theory of NP-Completeness. New York, NY, USA: W H Freeman; 1979.
4. Cormen, TH., Leiserson, CE., Rivest, RL. Introduction to Algorithms. New York, NY, USA: McGraw-Hill; 1990.
5. Sanders, FH., Drocella, EF., Sole, RL. Nat Telecommun Inf Admin. Washington, DC, USA: Mar. 2016 Using on-shore detected radar signal power for interference protection of offshore radar receivers. Tech Rep TR 16-521[Online]. Available: <http://www.its.bldrdoc.gov/publications/2828.aspx>
6. Requirements for Commercial Operation in the US 3550–3700 MHz Citizens Broadband Radio Service Band. Wireless Innov. Forum; Reston, Virginia: May. 2016 document WINNF-15-S-0112 Version V1.0.0[Online]. Available: https://workspace.winnforum.org/kws/public/document?document_id=2413
7. Application of Google Inc. for certification to provide spectrum access system and environmental sensing capability services. Appendix B: Environmental Sensing Capability (ESC) Siting Considerations. 2016. GN Docket 15-319[Online]. Available: <https://ecfsapi.fcc.gov/file/60001851224.pdf>

8. Joshi S, et al. ESC sensor nodes placement and location from moving incumbent protection in CBRS. Proc WInnComm, Mar. 2016:119–125.
9. Drocella, EF., et al. Nat Telecommun Inf Admin. Washington, DC, USA: Mar. 2016 3.5 GHz exclusion zone analyses and methodology. Tech Rep TR 15-517[Online]. Available: <http://www.its.bldrdoc.gov/publications/2805.aspx>
10. Recommendation ITU-R M.1851. Int. Telecommun. Union; Geneva, Switzerland: Jun. 2009 Mathematical models for radiodetermination radar systems antenna patterns for use in interference analyses. [Online]. Available: <https://www.itu.int/rec/R-REC-M.1851-0-200906-I/en>
11. 2011 National Land Cover Database. Accessed: Aug. 5, 2016. [Online]. Available: <http://viewer.nationalmap.gov/basic/>
12. 2010 National Census Tracts Gazetteer. Accessed: Oct. 1, 2015. [Online]. Available: <http://www.census.gov/geo/maps-data/data/gazetteer2010.html>
13. 2010 TIGER/Line Shapefiles: Census Tracts. Accessed: Mar. 15, 2017. [Online]. Available: <http://www.census.gov/cgi-bin/geo/shapefiles/index.php?year=2010&layergroup=Census+Tracts>
14. Commuter Adjusted Daytime Population: 2006–2010. Accessed: Jun. 5, 2016. [Online]. Available: <http://www.census.gov/hhes/commuting/data/daytimepop.html>
15. USGS 1-Degree Native Format—United States. Accessed: Jun. 28, 2016. [Online]. Available: http://www.webgis.com/terr_us1deg.html
16. Re-Sampled Terrain Data. Accessed: Apr. 19, 2016. [Online]. Available: <http://www.its.bldrdoc.gov/resources/radio-propagation-software/resampled-terrain-data/re-sampled-terrain-data.aspx>
17. Global Land 1-km Base Elevation (GLOBE) Terrain Data. Accessed: Feb. 25, 2016. [Online]. Available: <http://www.ngdc.noaa.gov/mgg/topo/globeget.html>

Fig. 1.
Initial ship and candidate sensor locations near Virginia Beach.

Fig. 2.
Sample CBSD deployment near Virginia Beach.

Fig. 3. Overlaid exclusion zone results. The red, green, yellow, and blue curves are the maximum, 95th percentile, mean, and minimum exclusion zone distances on each of the individual azimuths of the radar antenna, respectively.

Fig. 4. Interference contour off the U.S. west and east coasts and selected sensors ($RD = 1$, $h_{\text{ESC}} = 25$ m).

Fig. 5.
Histogram of aggregate interference at point L_{53} on the east coast interference contour.

Fig. 6.
Off-coast distances of interference contour points.

(a) West Coast

(b) East Coast

Fig. 7.
Coverage matrices of west and east coast sensors, ordered north to south ($RD = 1$, $h_{ESC} = 25$ m).

Fig. 8.
Histograms of sensor spacing ($RD = 1$, $h_{\text{ESC}} = 25$ m).

Fig. 9.
Detection thresholds of east coast sensors ($RD = 1$, $h_{\text{ESC}} = 25$ m).

Fig. 10. Detection threshold box plots by antenna height ($RD=1$). The central mark of each box is the median, the edges of the box are the 25th and 75th percentiles, the “whiskers” are 1.5 times the interquartile range above and below the edges, and outliers are denoted by plus symbols.

Fig. 11.
Total line-of-sight (LOS) distance from radar transmitter vs. ESC sensor antenna height.

(a) West Coast

(b) East Coast

Fig. 12.
Sensor sensitivity vs. antenna height and redundancy.

(a) West Coast

(b) East Coast

Fig. 13.
Number of sensors vs. antenna height and redundancy.

TABLE I

Shipborne Radar-1 Technical Parameters

Radai-1 Parameter	Value
Transmitted Power to Antenna (dBm)	90
Mainbeam Antenna Gain (dBi)	32
Antenna Directivity/Patterns	Recommendation ITU-R M.1851
Half-power beamwidth (degree)	0.81
Transmit/Receive Bandwidth (MHz)	1
Center Frequency (MHz)	3600
Antenna Height (m)	50
Insertion/Cable Losses (dB)	2
Noise Figure (NF) (dB)	3
Interference-to-Noise Ratio (I/N) (dB)	−6

TABLE II

ESC Sensor Technical Parameters

ESC Sensor Parameter	Value
Receive Bandwidth (MHz)	1
Center Frequency (MHz)	3600
Antenna Height (m)	6 to 100
Insertion/Cable Losses (dB)	2

TABLE III

CBSD Technical Parameters

CBSB Parameter		Value
EIRP (dBm)		30 (Outdoor), 26 (Indoor)
Channel Bandwidth (MHz)		10
Signal Bandwidth (MHz)		9
Center Frequency (MHz)		3600
Region	Channel Usage (%)	Percent Indoor
Dense Urban/Urban	60	80
Suburban	40	99
Rural	20	99
Antenna Height (m)		
Outdoor		6
Indoor - Dense Urban	50%:(3–15); 25%:(18–30); 25%:(33–60)	
Indoor - Urban	50%: 3; 50%: (6–18)	
Indoor - Suburban	70%: 3; 30%: (6–12)	
Indoor - Rural	80%: 3; 20%: 6	
Building Atten. Loss (dB)		20%:20; 60%:15; 20%:10 (Indoor)
Insertion/Cable Losses (dB)		2 (Outdoor)

TABLE IV

Calculation of Number of Cbsds Near Virginia Beach

Region	Population	Daytime Popul.	MP	CS	CBSD/User	No. of CBSDs
Urban	348 861	367188	0.2	0.1	0.02	147
Suburban	663 032	684561	0.2	0.1	0.05	685
Rural	652 374	647042	0.2	0.1	0.33	4314