3.5 GHz Environmental Sensing Capability Sensitivity Requirements and Deployment

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***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), 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 required sensitivity and placement of ESC sensors 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 a minimum required signal detection level at 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 required sensitivities to be 4 dB to 16 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.**

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 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 [1], 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 sensitivity requirement for ESC sensors, that is, the received signal level from an incumbent shipborne radar that a sensor must be able to detect to enable adequate interference protection. The sensitivity requirement 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 to our knowledge no study has quantified the aggregate interference and, thus, the sensitivity 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 a global sensitivity requirement and for determining the number and placement of ESC sensors from a set of candidate locations.

We formulate our sensor placement algorithm as the well-known *set cover* problem [2] and use a greedy algorithm 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. To illustrate their use and to provide representative results, the algorithms are applied to two specific coastal areas, with different population and terrain characteristics.

The paper is organized as follows. Section II reviews related work on ESC sensor sensitivity and placement, and compares them to the contributions of this paper. Section III describes the proposed methodology for determining sensor sensitivity and placement, including formal algorithm descriptions. Section IV details the modeling framework and assumptions,

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including CBSD deployment, transmitter and receiver characteristics, and channel propagation models. Section V applies the methodology and modeling framework to two different coastal areas and presents 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 [3]. 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" [3, Section 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 along a segment of coastline.

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 [4]. The maximum loss is derived to be 184 dB in similar fashion to the trigger threshold of [3]: 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. 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" [4, Appendix A.2].

A straightforward methodology for uniform placement of ESC sensors is presented in [5]. 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 as well as one for redundant coverage. 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.

The authors in [6] present an approach for optimal non-uniform sensor node placement. They use a piecewise linear representation of the coastline and of the interference contour. Possible sensor locations comprise a grid in the coastal land area. For each of the knot points (segment endpoints) in the interference contour, 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 [6] does result in non-uniform 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 [7]. 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.

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 and their locations 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 costs down.

To illustrate our approach, we apply our method to geographical areas around the two U.S. coastal cities of Virginia Beach and San Francisco. These regions differ both in population density and in terrain characteristics. 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

$L_1, L_2, \ldots, L_N$. Let $E_1, E_2, \ldots, E_M$ 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 and their locations (among the M candidate locations) 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), then the ship location is moved 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).

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 [2]. Hence, Algorithm 3 uses an iterative *greedy* method 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 14). The greedy method also ensures that the redundancy factor is taken into account while computing the coverage of each radar location (Line 22).

TABLE I
SHIPBORNE RADAR-1 TECHNICAL PARAMETERS.

Radar-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

For finite lengths of coastline, the greedy algorithm may choose a candidate sensor location that is not necessary to satisfy the coverage requirement. For this reason, a final pruning step 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 [7] 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 [7]. The technical parameters for the radar transmitter and receiver are obtained from [3], [7] and are summarized in Table I.

The generalized mathematical model of the radar system antenna is described in Recommendation ITU-R M.1851 [8]. 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:

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

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:

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

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Algorithm 1: Compute Interference Contour

Input: $l_1, l_2, \ \dots \ , l_N$: Initial ship locations along the coastline
$I\_threshold$: 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: $L_1, L_2, ..., L_N$: ship locations which define the piece-wise linear interference contour

for *each initial ship location* $l_i \in \{l_1, l_2, \dots, l_N\}$ **do**
  $l_{tmp} = l_i$;
  $I_{agg}[1..360] = 0$;
  $done1\_iter = NOT\_DONE$;
  while *(done1_iter != DONE)* **do**
    randomly deploy CBSDs within the area around l_i ;
    for *each azimuth of the main-beam of the radar antenna* $az_j \in \{1, .., 360\}$ **do**
      $I_{agg}[j]$ =Aggregate interference from CBSDs to the radar receiver at location l_{tmp} ;
    $I\_MaxAgg\_az = \max_{1 \leq j \leq 360}(I_{agg}[j])$;
    if $I\_MaxAgg\_az > I\_threshold$ **then**
      l_{tmp} = new ship location after it is moved by $stepSize$ away from the coastline ;
    else
      $done1\_iter = DONE$;
  $I_{agg}[1..360] = 0$;
  $I\_MaxAgg[1..100] = 0$;
  $done100\_iter = NOT\_DONE$;
  while *(done100_iter != DONE)* **do**
    for *k = 1 to 100* **do**
      randomly deploy CBSDs within the area around l_i ;
      for *each azimuth of the main-beam of the radar antenna* $az_j \in \{1, .., 360\}$ **do**
        $I_{agg}[j] =$ Aggregate interference from CBSDs to the radar receiver at location l_{tmp} ;
      $I\_MaxAgg[k] = \max_{1 \leq j \leq 360}(I_{agg}[j])$;
    I_count = number of maximum aggregate interference values in $I\_MaxAgg[] \leq I\_threshold$;
    if $I\_count \leq p_{th}$ **then**
      l_{tmp} = new ship location after it is moved by $stepSize$ away from the coastline ;
    else
      $L_i = l_{tmp}$;
      $done100\_iter = DONE$;
return $\{L_1, L_2, .., L_N\}$;

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: $\mathcal{S}$: required minimum sensitivity of each ESC sensor

for *each radar location* $L_j \in \{L_1, L_2, \dots, L_N\}$ **do**
  for *each candidate ESC location* $E_i \in \{E_1, E_2, \dots, E_M\}$ **do**
    $P_r[i]$ = Received peak power at E_i when radar is at location L_j ;
  Sort the elements of $P_r[\,]$ in a non-increasing order ;
  $S[j] = P_r[RD]$ `/* 'RD' number of ESC sensors can detect radar at location` L_j`, when sensitivity of the ESC sensors is set at` $S[j]$ `*/`
$\mathcal{S} = \min_{1 \leq j \leq N}(S[j])$ `/* Pick the minimum of the sensitivities */`
return $\mathcal{S}$;

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 [7], 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.

TABLE II
ESC Sensor Technical Parameters.

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

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Algorithm 3: Placement of ESC Sensors

Input: $L_1, L_2, \ldots, L_N$: radar locations on the interference contour
$E_1, E_2, \ldots, E_M$: candidate ESC sensor locations
$\mathcal{S}$: sensitivity of each ESC sensor
RD: Redundancy Factor /* minimum number of ESC sensors required to simultaneously detect any given radar location */
Output: ESC_set : set of deployment locations of ESC sensors
Initialize Detection Matrix $D[1..M][1..N] = 0$;
for *each radar location* $L_j \in \{L_1, L_2, \ldots, L_N\}$ **do**
    for *each candidate ESC location* $E_i \in \{E_1, E_2, \ldots, E_M\}$ **do**
        P_r = Received peak power at E_i when radar is at location L_j ;
        if $(P_r \geq \mathcal{S})$ **then**
            $D[i][j] = 1$ /* ESC sensor at location E_i can detect radar at location L_j */
/* $D[\ ][\ ]$ is the detection matrix */
$placement = NOT\_DONE$; $ESC\_set = \emptyset$;
$covered[1..N] = 0$;
$Sensor\_loc[1..M] = NOT\_SELECTED$;
/* keeps track of ESC locations which are still available */
$Holes[1..N] = 0$;
/* keeps track of radar locations which are covered */
$COVERAGE\_MATRIX[1..M][1..N] = 0$;
/* start the greedy method */
while *(placement != DONE)* **do**
    Let $AVAIL\_LOC$ be the set of indices in $Sensor\_loc[\ ]$ whose values equal $NOT\_SELECTED$;
    Let $i \in AVAIL\_LOC$ be the index of the row in $D[\ ][\ ]$ which has maximum number of 1's at the positions corresponding to 0's in $Hole[\ ]$;
    In case of a tie, pick the row with maximum number of 1's in the entire row;
    $COVERAGE\_MATRIX[i] = D[i][1..N]$;
    /* copy the i^{th} row of D matrix; Sensor location at row i covers maximum radar locations not covered yet */
    $Holes[1..N]\ \ \&= COVERAGE\_MATRIX[i][1..N]$ /* bit-wise AND the two vectors to mark the corresponding radar locations as covered */
    $Sensor\_loc[i] = SELECTED$; $ESC\_set = ESC\_set \cup \{E_i\}$;
    $covered[1..N] = covered[1..N] + COVERAGE\_MATRIX[i][1..N]$ /* vector addition */
    if *all elements in* $Holes[] == 1$ **then**
        for *each element* i *in* $covered[1..N]$ **do**
            if $covered[i] < RD$ **then**
                $Holes[i] = 0$ /* this radar location still needs coverage with required redundancy */
        if *all elements in* $Holes[] == 1$ **then**
            $placement = DONE$;
return ESC_set ;

C. Initial Ship and ESC Sensor Locations

Geographic Information System (GIS) 2011 National Land Cover Database (NLCD) data [9] 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 333 pixels (i.e., approximately 10 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. The area of interest extends around 200 km along the coast. There are 19 initial ship locations $\{L_1, \ldots, L_{19}\}$ and 19 candidate sensor locations $\{E_1, \ldots, E_{19}\}$ placed along the coast.

While the candidate sensor locations are equally spaced in

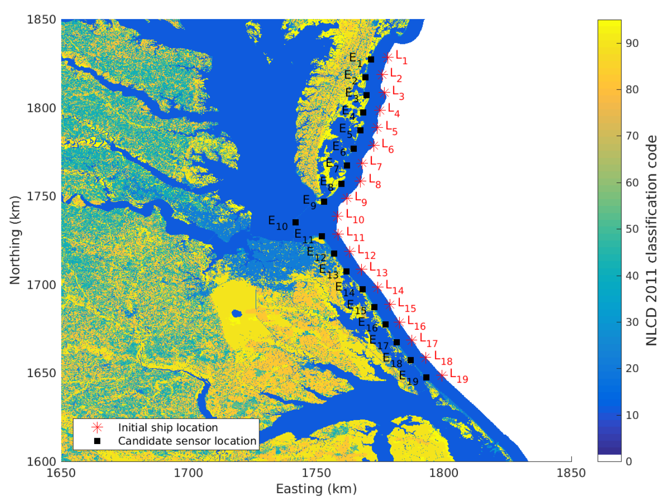

Fig. 1. Initial ship and candidate sensor locations.

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

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TABLE III
CBSD TECHNICAL PARAMETERS.

CBSD 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)	

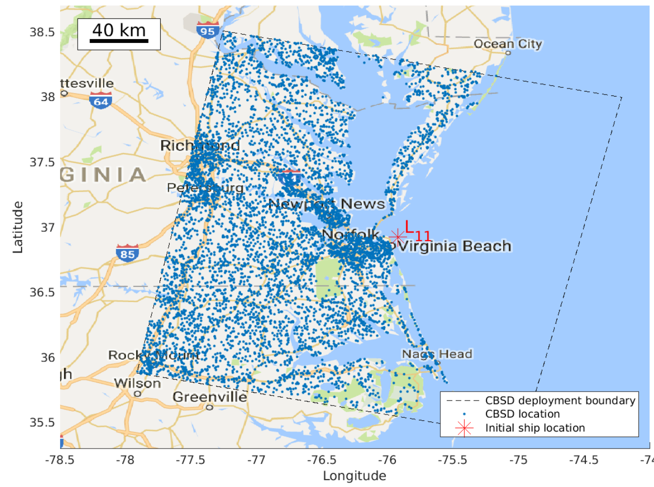

Fig. 2. Sample CBSD deployment.

TABLE IV
CALCULATION OF NUMBER OF CBSDS.

Region	**Population**	**Daytime Popul.**	**MP**	**CS**	**CBSD/ User**	**No. of CBSDs**
Urban	448 760	489 077	0.2	0.1	0.02	196
Suburban	775 051	809 581	0.2	0.1	0.05	810
Rural	867 118	864 844	0.2	0.1	0.33	5 766

properties, wildlife refuges, etc.

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 [7], 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 [9], the 2010 U.S. Census population data [10], the census tract polygons [11], and the daytime commuter factors [12], as well as other assumptions described in [7].

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 [7], 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 L_{11}. 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 6 772. 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. 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, 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 degrees in 1 degree 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.

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

$$\begin{aligned} I = EIRP_{CBSD} - L_{i\_CBSD} - L_{building} - L_{prop} \\ - L_{clutter} + G_{radar} - L_{i\_radar} - B_{radar/CBSD} \end{aligned} \quad (3)$$

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}

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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.

b) 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:

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

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).

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 [7] 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 [7], we used the United States Geological Survey (USGS) Digital Elevation Model terrain database [13] rather than the resampled Spatial Data Transfer Standard terrain data used by NTIA [14] 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 [7] for an area near San Diego, California. The 95th percentile distances match very well with those of [7] for most azimuth angles, except between 305° and 350°. The discrepancy at these angles could be due to the usage of different terrain databases.

V. Analysis Results

We apply the methodology for determining the required ESC sensor sensitivity and placement to two U.S. coastal

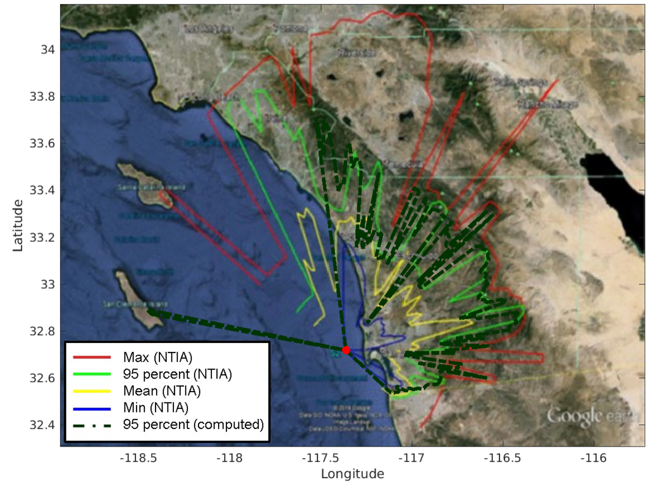

Fig. 3. Overlaid exclusion zone results.

areas, San Francisco on the west coast and Virginia Beach on the east coast. The former has a higher population as well as a higher terrain elevation relative to sea, factors which are expected to lead to greater interference to shipborne radar.

The National Oceanic and Atmospheric Administration (NOAA) Global Land 1-km Base Elevation (GLOBE) terrain database [15] 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. Virginia Beach

Results for the interference contour as well as the sensitivity requirements and deployment of ESC sensors for Virginia Beach are described below.

1) 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 as described in Section IV and were moved 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 shows the histogram of the aggregate interference at one of the locations on the interference contour. Across the 19 ship locations on the interference contour, the standard deviation of the interference ranged from 3 dB to 9 dB.

Fig. 5 shows the interference contour result for the Virginia Beach area. The distance from each point on the interference contour to the shoreline ranges from 36 km to 67 km. As expected, the distance depends on the number of CBSDs deployed in the surrounding area, i.e., the more CBSDs are deployed, the larger the interference distance needed to protect the incumbent.

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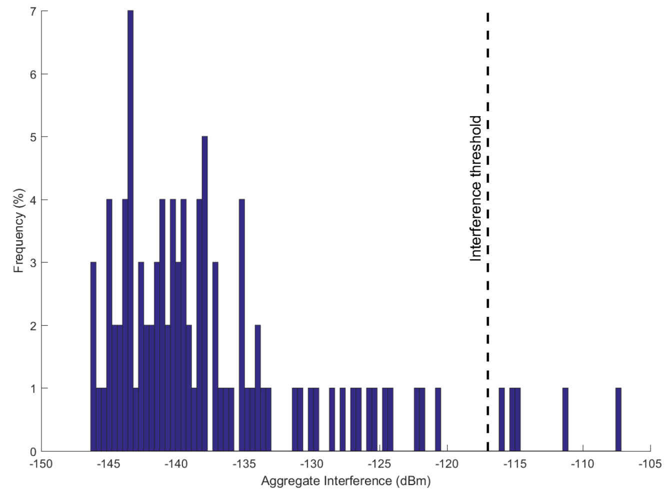

Fig. 4. Histogram of aggregate interference at point L_{11} on the Virginia Beach interference contour showing 95 % of realizations below the -117 dBm threshold.

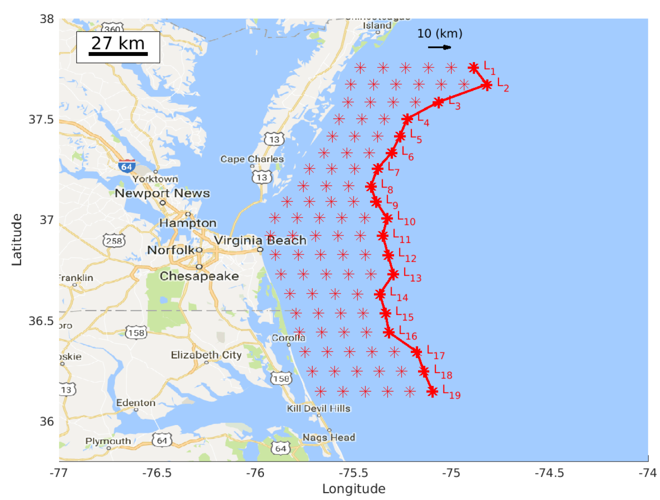

Fig. 5. Interference contour near Virginia Beach.

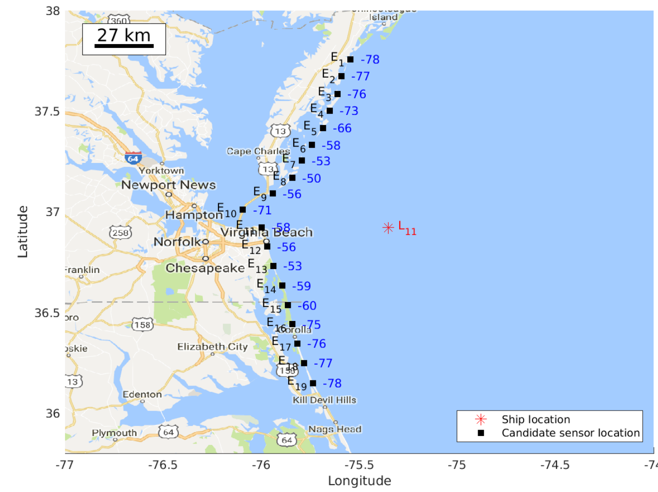

Fig. 6. Received peak power in dBm at ESC sensor locations.

Virginia Beach: RF = 1, Sensitivity = -68 dBm/MHz																				
		Ship location																		
		L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_10	L_11	L_12	L_13	L_14	L_15	L_16	L_17	L_18	L_19
Candidate sensor location	E_1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	E_2	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
	E_3	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	E_4	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
	E_5	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	E_6	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	E_7	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
	E_8	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
	E_9	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0
	E_10	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
	E_11	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0
	E_12	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0
	E_13	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
	E_14	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0
	E_15	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0
	E_16	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
	E_17	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0
	E_18	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	E_19	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
No. det. sensors		1	1	2	2	2	2	2	1	1	1	2	1	1	2	2	2	2	1	1

Fig. 7. Detection matrix with redundancy factor of 1, Virginia Beach.

2) ESC Sensor Sensitivity Requirements and Deployment: We derive the sensitivity requirements and location of ESC sensors along the coast near Virginia Beach by applying Algorithms 2 and 3 as described in Section III, respectively.

For each ship location on the interference contour, we compute the received peak power from the radar at all 19 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. Fig. 6 shows the received peak power from ship location L_{11} to all candidate sensor locations $\{E_1, \ldots, E_{19}\}$.

a) Redundancy Factor = 1: If each ship location on the interference contour is required to be detected by only one ESC sensor, using Algorithm 2, the sensitivity requirement for the ESC sensor is computed to be -68 dBm/MHz. The corresponding detection matrix is computed and shown in Fig. 7.

Applying Algorithm 3 to this detection matrix, a set of candidate sensor locations $\{E_1, E_5, E_{15}, E_{18}\}$ is selected. The sensor location E_5 is selected first since it can detect the most ship locations (9) on the interference contour. (Sensor locations E_7 and E_{13} also detect 9 interference locations, but E_5 is selected as it precedes them in the ordered list). The sensor location E_{15} is selected next because it can detect the most uncovered ship locations by E_5, i.e., $\{L_{12}, \ldots, L_{17}\}$, followed by E_1 covering $\{L_1, L_2\}$, and E_{18} covering $\{L_{18}, L_{19}\}$. The last row in the figure shows the number of selected sensor locations that can detect each ship location on the interference contour (the sum along each column of the highlighted rows).

Fig. 8 depicts the selected candidate sensor locations $\{E_1, E_5, E_{15}, E_{18}\}$ and their associated coverage of the interference contour. Each ship location can be detected by at least one selected sensor location. Ignoring the edge sensors, whose placement is affected by the finite length of coastline, we observe that the spacing between sensors E_5 and E_{15} is approximately 100 km.

For reference, the analysis in [3] found the required sensitivity to be -64 dBm/MHz and gave a uniform spacing between sensors of 50 km, while the analysis in [5] found the required

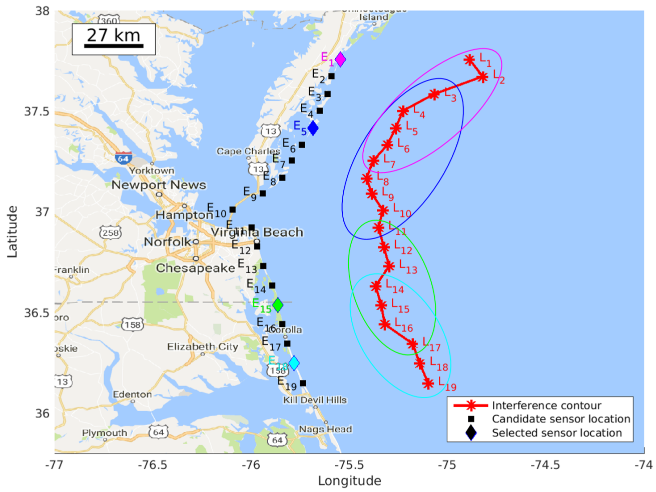

Fig. 8. Coverage of the interference contour (redundancy factor = 1), Virginia Beach.

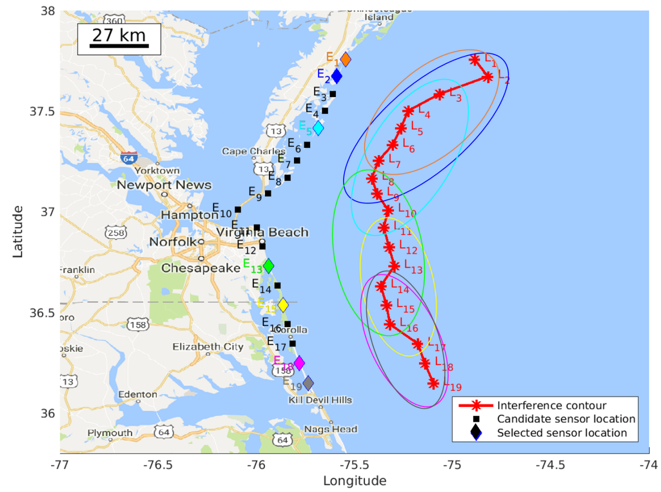

Fig. 9. Coverage of the interference contour (redundancy factor = 2), Virginia Beach.

sensitivity to be -100 dBm/MHz with a spacing of 264 km when the interference contour is 70 km from shore.

b) Redundancy Factor = 2: If each ship location on the interference contour is required to be detected by at least two ESC sensors, i.e., the redundancy factor is equal to 2, the sensitivity requirement for the ESC sensor lowers (becomes more sensitive) by 2 dB.

Applying Algorithm 3, the set of candidate sensor locations in the order of selection is $\{E_2, E_{13}, E_{18}, E_5, E_{15}, E_1, E_{19}\}$. With this selection, at least 2 selected sensor locations can detect any ship location on the interference contour.

Fig. 9 depicts the selected candidate sensor locations $\{E_2, E_{13}, E_{18}, E_5, E_{15}, E_1, E_{19}\}$ and their associated coverage of the interference contour. Compared to the previous case with redundancy factor of 1, nearly twice the number of sensors are needed. To reduce the number of sensors while still meeting the redundancy requirement, one could improve the sensitivity of the ESC sensor such that its coverage area increases. The tradeoff between sensor sensitivity and number of deployed sensors could be a subject of future work.

B. San Francisco

We repeat the same analysis for the San Francisco area, which is more densely populated and, in general, has higher terrain elevation than the Virginia Beach area. Of interest is to what extent a different environment affects the interference contour, sensitivity requirement, and sensor placement.

1) Interference Contour: There are 20 initial ship locations $\{L_1, \ldots, L_{20}\}$ and 20 candidate sensor locations $\{E_1, \ldots, E_{20}\}$ used in this area. The resulting interference contour from these initial ship locations is shown in Fig. 10. In this case, the offshore distance of the interference contour ranges from 106 km to 146 km, roughly two to three times that observed in the Virginia Beach area. This is due to the significantly larger number of CBSDs deployed at higher elevation in San Francisco as compared to Virginia Beach.

2) ESC Sensor Sensitivity Requirements and Deployment: Given the interference contour, the sensitivity requirement and

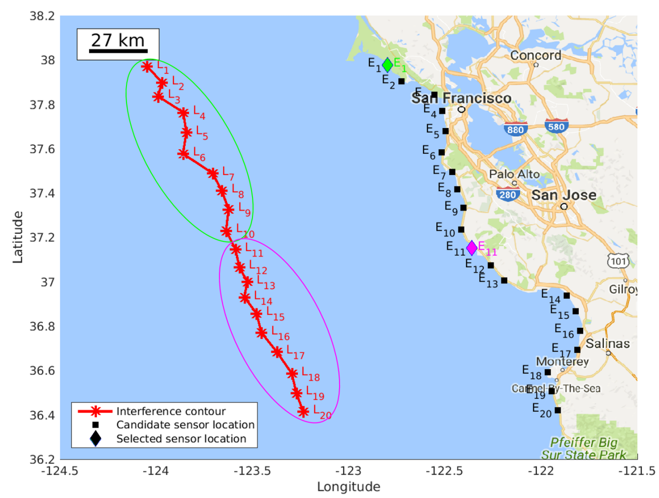

Fig. 10. Coverage of the interference contour (redundancy factor = 1), San Francisco.

set of sensor locations are determined for redundancy factors of 1 and 2, as follows.

a) Redundancy Factor = 1: For a redundancy factor of 1, the sensitivity requirement for the ESC sensor is found to be -80 dBm/MHz, 12 dB more sensitive than in Virginia Beach, and the set of sensor locations after pruning is found to be $\{E_1, E_{11}\}$. Fig. 10 depicts the selected sensor locations and their coverage of the interference contour.

b) Redundancy Factor = 2: For a redundancy factor of 2, the sensitivity requirement for the ESC sensor lowers (becomes more sensitive) by only 0.3 dB. The set of sensor locations in order of selection is $\{E_9, E_1, E_{11}, E_2\}$. Fig. 11 depicts the selected candidate sensor locations and their coverage of the interference contour. In this case, the greedy algorithm achieves the desired redundancy with twice the number of sensors.

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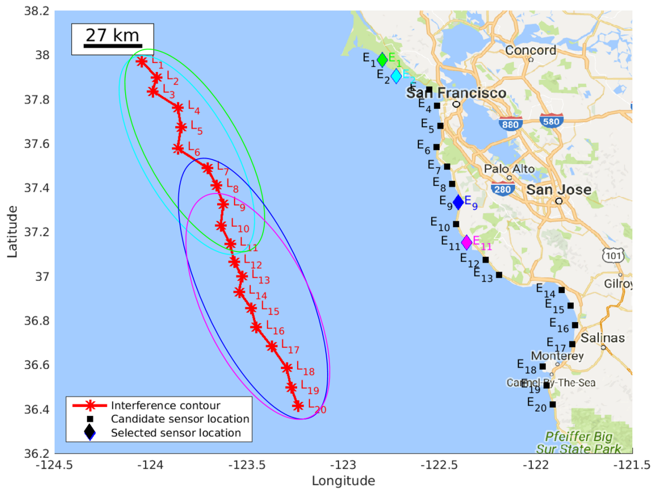

Fig. 11. Coverage of the interference contour (redundancy factor = 2), San Francisco.

VI. Conclusion

In summary, we have presented a methodology for determining the required sensitivity 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. In illustrative examples near Virginia Beach and San Francisco, on the eastern and western coasts of the U.S., respectively, we found that the interference contour ranged from 36 km to 146 km offshore, depending on the number of CBSDs deployed in the surrounding area.

We also described systematic algorithms that, given the interference contour at sea, determine the locations of coastline sensors and their required sensitivity 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 two examples provided, we found that a 200 km segment of coastline can be addressed by 2 to 4 sensors with a required sensitivity of -68 dBm/MHz to -80 dBm/MHz, in coastal areas with a lower and higher CBSD density, respectively. We note that these received signal levels are 4 dB to 16 dB lower than the detection thresholds proposed in [3], [4]. To achieve dual-sensor redundancy, roughly twice the number of sensors are needed.

In this work, we solved for sensor sensitivity and sensor placement as a two-step process. First, we found a global sensitivity requirement for all sensors along a segment of coastline, and then used that sensitivity in the placement algorithm. Future work should consider the *joint* selection of sensor sensitivity and placement, with the potential that some sensors are more sensitive than others. Naturally, this analysis can be applied to the U.S. coastlines in their entirety as follow-on work, as well.

Another consideration for future work is the signal-to-interference ratio at the ESC sensor. 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.

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