ESC SENSOR NODES PLACEMENT AND LOCATION FOR MOVING INCUMBENT PROTECTION IN CBRS

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ABSTRACT

We consider environmental sensing capability sensor node placement and location problem in coastal areas for the moving incumbent protection in citizens broadband radio service. The problem is a combinatorial optimization problem. We propose a suboptimal but fast-converging algorithm based on sequential convex programming. We have considered two criteria for sensor nodes placement to protect the moving incumbents from the harmful interference that might occur due to the citizens broadband radio service devices. First, we consider the protection of the incumbents by deploying a minimum number of sensors in the coastal area. Then, we consider the robustness against the sensor failures.

1. INTRODUCTION

The number of data users are increasing rapidly in each year along with new applications requiring very high data rates. The vision of the industry is to increase the capacity by thousand folds to serve this requirement [1], [2]. The idea is to gain the expected capacity by focusing on three main aspects: increasing the amount of usable spectrum, deploying more access points, and improving the spectral efficiency. To achieve aforementioned goals, the academia, industry, and regulatory bodies are closely collaborating, which sheds the light towards the development of innovative technologies and services. As a methodology to increase the usable spectrum for mobile broadband services, novel spectrum sharing concepts, in the Europe the Licensed Shared Access [3], [4] and in the United States the Citizen Broadband Radio Services (CBRS) concepts [5], were introduced.

In CBRS, it was recommended by the *the National Broadband Plan* in March 2010, that the Federal Communications Commission make 500 MHz available for broadband use by 2020, with 300 MHz suitable for mobile use by 2015 [5]. However, currently the regulatory bodies and the industry are active in the rule making process to make 150 MHz to become available for the commercial use. In fact, in the CBRS the primary idea is to allow to share the spectrum between federal and commercial users. Hence, it is important to provide interference protection to the federal (incumbent) users.

The protection of incumbent users from the harmful interference, generated by the citizens broadband radio service devices (CBSDs) transmission, is the key to the success of the spectrum access system (SAS) deployment. In [5] two approaches have been proposed for the protection of the incumbent users: 1) protection via exclusion zone and 2) protection via a use of environmental sensing capability (ESC) network.

The ESC consists of a network of sensors that will detect incumbents' operations in and around the 3.5 GHz band, and provide the information regarding the incumbent detection to the SAS in order to protect the incumbents from CBSDs transmissions [5]. Thus, the ESC network converts the exclusion zone into a protection zone [5]. The main challenge in the deployment of the ESC network is to find the optimum number of sensors and their locations (see *Example 1* in Section 1.1.).

In [6] the greedy algorithm based sensor node placement method is proposed to protect the incumbent in coastal area. The algorithm in [6] assumes that the target position of the incumbent user is known (i.e., a fixed location incumbent user is considered). However, the incumbent users in the coastal area are usually moving incumbents. Moreover, detecting the location of the federal naval incumbent is forbidden [5].

In this work, we consider ESC sensors placement problem in coastal areas for the moving incumbent protection in CBRS. We provide the protection for the moving incumbents in the coastal area by deploying a minimum number of sensors. The problem of finding the minimum number of ESC sensors, and their placement locations is a combinatorial optimization problem. We propose a suboptimal but fast-converging algorithm based on sequential convex programming (SCP) [7] for ESC sensor node placement and location problem in coastal areas for the moving incumbent protection in CBRS.

Due to the shadowing and multi path fading effects, and the sensor failures, the redundancy in ESC sensor measurements of incumbent user is desirable. The probability of incumbent detection improves with the number of ESC sensors [8]. Therefore, we extend the proposed algorithm to find the minimum number of ESC sensors, and their placement locations, such that the moving incumbent user is detected with N (number of) ESC

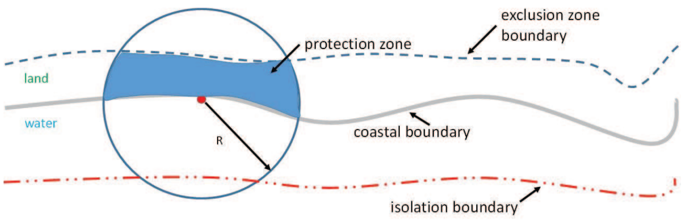


Figure 1: Illustration of a sensor node placement in the coastal region. Once the sensor node detects an incumbent, the protection zone associated with the sensor is activated.

sensors in any location of the coastal area.

The remainder of the paper is organized as follows. In Section 2, we introduce the system model and formulate the ESC sensor node placement and location problem. In section 3, we derive the proposed algorithm. Next, in Section 4, we modify the algorithm proposed in Section 3 to address the sensor failure issues, and propose a robust sensor node location and placement algorithm. Numerical results are presented in Section 5, and Section 6 concludes our paper.

1.1. Example 1: Sensor node deployment scenario

Figure 1 shows a sensor node deployment scenario in the coastal area to protect the moving incumbent. We assume that the moving incumbent can be protected from harmful interference from the CBSDs, if it can be detected before crossing the isolation boundary. By using the sensing node with an effective sensing radius R, a protection zone can be defined as shown in the figure. In this example, the problem is to find the optimum number of sensor nodes and their placement locations, such that the moving incumbent can be detected before it moves inside the isolation boundary

2. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we describe the ESC network model used throughout the paper, and then formulate a problem to find the minimum number of ESC sensors and their placement positions for the moving incumbent protection.

2.1. System Model

A coastal area as shown in Figure 2 is considered. The coastal area is divided into grid, and we assume that at each grid point an ESC sensor can be deployed. We denote the set of grid points where ESC sensors can be placed by $\mathcal{S}$, and we label them with the integer values $s = 1, \ldots, S$. Let $x_s \in \mathbb{R}^2$ for $s \in \mathcal{S}$ represent the positions of grid points. We consider an isolation boundary as a piecewise-linear curve with knot points $d_i, \ldots, d_D$ (see Figure 2), where $d_i \in \mathbb{R}^2$ for $i = 1, \ldots, D$. We denote the set of isolation boundary knot points by $\mathcal{D}$. We model

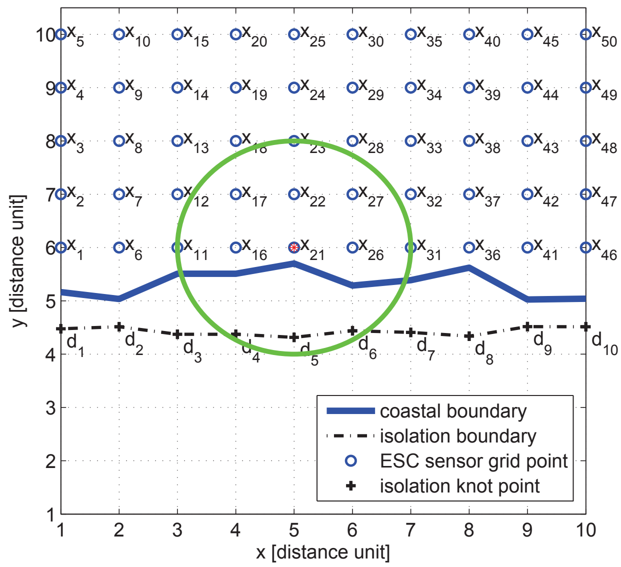


Figure 2: ESC sensor placement problem. Coastal area is divided into grid, there are $S = 50$ possible ESC sensor placement positions, and $D = 10$ isolation knot points. An ESC sensor with sensing radius R placed at grid point x_{21} provides protection for the incumbent moving through isolation boundary section $d_4 - d_5 - d_6$.

the *sensing region* of each ESC sensor as a disc with radius R. For each isolation knot point d_i, furthermore, we denote a set of possible ESC sensor node positions by $\mathcal{S}_i$, that are within a distance of R, i.e., $\mathcal{S}_i \subseteq \mathcal{S}$.

The Euclidean distance of a grid point x_s from an isolation knot point d_i can be expressed as

$$\mathbf{dist}(d_i, x_s) = \|d_i - x_s\|_2. \tag{1}$$

Therefore, for the ith isolation knot point, a distance to the nearest grid point where an ESC sensor can be placed is

$$r_i^{\min} = \inf_{s \in \mathcal{S}} \mathbf{dist}(d_i, x_s) = \inf_{s \in \mathcal{S}_i} \mathbf{dist}(d_i, x_s). \tag{2}$$

Let b_{is} be a binary variable associated with an isolation knot point d_i and a grid point x_s. We set a binary variable b_{is} to one if an isolation knot point d_i is within a coverage area of an ESC sensor that is placed in grid x_s. Hence, an ESC sensor position that can detect incumbent at d_i isolation knot point is a solution of the following expressions

$$r_i^{\min} \leq \sum_{s \in \mathcal{S}_i} b_{is} \|d_i - x_s\|_2 \leq R \tag{3}$$

$$\sum_{s \in \mathcal{S}_i} b_{is} = 1 \tag{4}$$

$$b_{is} = \{0, 1\}, \quad s \in \mathcal{S}_i. \tag{5}$$

Expression (3) ensures that an ESC sensor is placed at a grid point that is within the nearest distance $r_i^{\min}$ and the ESC sensor sensing radius R. Expression (4) ensures that only one grid point is used to place a sensor node to detect an incumbent at d_i isolation knot point.

We deploy an ESC sensor node at grid point x_s, if a value of binary variable b_{is} is one for any $i \in \mathcal{D}$. Hence, associated with each grid point $s \in \mathcal{S}$, let us introduce a binary variable a_s as

$$a_s = \begin{cases} 1 & \text{if } b_{is} = 1 \text{ for any } i \in \mathcal{D} \\ 0 & \text{otherwise} \end{cases}, \tag{6}$$

which is equivalent to $a_s = \max\{b_{1s}, \ldots, b_{Ds}\}$. Hence, if the value of variable a_s is one, an ESC sensor is placed in grid position x_s.

2.2. Problem Formulation

Let us define a vector $\mathbf{a} = [a_1, \ldots, a_S]^{\mathrm{T}}$. Hence, a number of ESC sensor nodes to be deployed in the system is given by cardinality $\mathbf{card}(\mathbf{a})$ of the vector $\mathbf{a}$, i.e., the number of nonzero elements of vector $\mathbf{a}$. Therefore, the problem of finding a minimum number of sensor nodes, such that the moving incumbent can be detected before crossing the isolation boundary can be expressed as

$$\begin{array}{ll} \text{minimize} & \mathbf{card}(\mathbf{a}) \\ \text{subject to} & r_i^{\min} \leq \sum_{s\in\mathcal{S}_i} b_{is}\|d_i - x_s\|_2 \leq R, \quad i \in \mathcal{D} \\ & \sum_{s\in\mathcal{S}_i} b_{is} = 1, \quad i \in \mathcal{D} \\ & b_{is} = \{0,1\}, \quad i \in \mathcal{D}, s \in \mathcal{S} \\ & \max\{b_{1s}, \ldots, b_{Ds}\} = a_s, \quad s \in \mathcal{S}, \end{array} \tag{7}$$

with variables $\{a_s\}_{s\in\mathcal{S}}$ and $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$. Note that problem (7) is a combinatorial optimization problem, and it requires an exponential complexity to find a global solution.

3. ALGORITHM DERIVATION

In this section we derive a fast but possibly suboptimal algorithm for problem (7). The proposed algorithm is based on the sequential convex programming (SCP) [7].

We start by approximating the objective function of problem (7). The commonly used approximation of cardinality function is an ℓ_1-norm function [9]. By using the ℓ_1-norm approximation of the objective function, and relaxing the fourth set of constraints of problem (7), it can be expressed as

$$\begin{array}{lll} \text{minimize} & \|\mathbf{a}\|_1 & \\ \text{subject to} & r_i^{\min} \leq \sum_{s\in\mathcal{S}_i} b_{is}\|d_i - x_s\|_2 \leq R, \quad i \in \mathcal{D} & \text{(8a)} \\ & \sum_{s\in\mathcal{S}_i} b_{is} = 1, \quad i \in \mathcal{D} & \text{(8b)} \\ & b_{is} = \{0,1\}, \quad i \in \mathcal{D}, s \in \mathcal{S} & \text{(8c)} \\ & b_{is} \leq a_s, \quad i \in \mathcal{D}, s \in \mathcal{S}, & \text{(8d)} \end{array}$$

with variable $\{a_s\}_{s\in\mathcal{S}}$ and $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$. As the variable $a_s \geq 0$ for all $s \in \mathcal{S}$ in problem (8), the ℓ_1-norm $\|\mathbf{a}\|_1 = \sum_{s\in\mathcal{S}} a_s$. Now, instead of hard binary constraint (8c), we employ a penalty function to promote a binary value for variables $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$, leading to

$$\begin{array}{ll} \text{minimize} & \sum_{s\in\mathcal{S}} a_s - \delta \sum_{i\in\mathcal{D}} \sum_{s\in\mathcal{S}} b_{is}\log(b_{is}) \\ \text{subject to} & r_i^{\min} \leq \sum_{s\in\mathcal{S}_i} b_{is}\|d_i - x_s\|_2 \leq R, \quad i \in \mathcal{D} \\ & \sum_{s\in\mathcal{S}_i} b_{is} = 1, \quad i \in \mathcal{D} \\ & 0 \leq b_{is} \leq 1, \quad i \in \mathcal{D}, s \in \mathcal{S} \\ & b_{is} \leq a_s, \quad i \in \mathcal{D}, s \in \mathcal{S}, \end{array} \tag{9}$$

with variable $\{a_s\}_{s\in\mathcal{S}}$ and $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$; where $\delta > 0$ is a problem parameter. Note that a penalty function $-b_{is}\log(b_{is})$ is an entropy function, and it has a minimum value at b_{is} equal to zero or one. Thus, the parameter δ can be tuned to achieve a binary value for variable b_{is} for all $i \in \mathcal{D}$ and $s \in \mathcal{S}$. It is worth noting that problem (9) is a non-combinatorial optimization problem, however, it is a nonconvex problem due to the entropy function $-b_{is}\log(b_{is})$. In fact, the objective function of problem (9) is a difference of convex functions $\sum_{s\in\mathcal{S}} a_s$ and $\delta\sum_{i\in\mathcal{D}}\sum_{s\in\mathcal{S}} b_{is}\log(b_{is})$. In the sequel, we approximate the objective function of problem (9) with a convex function, and then present an iterative algorithm that solves a sequence of approximate convex problem to solve problem (9).

Let $\{\hat{b}_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$ be an arbitrary positive point. Then the best convex upper bound approximation of the entropy function $-b_{is}\log(b_{is})$ near an arbitrary point $\hat{b}_{is}$ can be expressed as

$$-b_{is}\log(b_{is}) \leq -\hat{b}_{is}\log(\hat{b}_{is}) - (1+\log(\hat{b}_{is}))(b_{is} - \hat{b}_{is}), \tag{10}$$

for all $i \in \mathcal{D}$ and $s \in \mathcal{S}$. Then, by using expression (10), we approximate problem (9) near an arbitrary positive point $\{\hat{b}_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$ as the following convex optimization problem:

$$\begin{array}{ll} \text{minimize} & \sum_{s\in\mathcal{S}} a_s - \delta \sum_{i\in\mathcal{D}} \sum_{s\in\mathcal{S}} (1+\log(\hat{b}_{is}))(b_{is} - \hat{b}_{is}) \\ \text{subject to} & r_i^{\min} \leq \sum_{s\in\mathcal{S}_i} b_{is}\|d_i - x_s\|_2 \leq R, \quad i \in \mathcal{D} \\ & \sum_{s\in\mathcal{S}_i} b_{is} = 1, \quad i \in \mathcal{D} \\ & 0 \leq b_{is} \leq 1, \quad i \in \mathcal{D}, s \in \mathcal{S} \\ & b_{is} \leq a_s, \quad i \in \mathcal{D}, s \in \mathcal{S}, \end{array} \tag{11}$$

with variables $\{a_s\}_{s\in\mathcal{S}}$ and $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$. Note that in the objective function of problem (11), we have dropped a constant term $-\sum_{i\in\mathcal{D}}\sum_{s\in\mathcal{S}}\hat{b}_{is}\log(\hat{b}_{is})$ since it does not effect the solution of the problem.

Finally, we summarize the proposed suboptimal algorithm based on SCP for problem (7) in *Algorithm* 1.

Algorithm 1 *Algorithm based on SCP for problem (7)*

1. Initialization: given initial feasible starting point $\{b^0_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$ and parameters $\delta > 0$ and $R > 0$. Set iteration index $k = 0$.
2. By setting $\hat{b}_{is} = b^k_{is}$ for all $i \in \mathcal{D}$ and $s \in \mathcal{S}$, solve problem (11). Denote the solution by $\{a^\star_s\}_{s\in\mathcal{S}}$ and $\{b^\star_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$.
3. Stopping criterion: if the stopping criterion is satisfied STOP by returning the suboptimal solution $\{a^\star_s\}_{s\in\mathcal{S}}$ and $\{b^\star_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$. Otherwise go to step 4.
4. Update $b^{k+1}_{is} = b^\star_{is}$ for all $i \in \mathcal{D}$ and $s \in \mathcal{S}$. Set $k = k + 1$ and go to step 2.

The first step initializes the algorithm. Step 2 solves the approximated problem (11). Step 3 checks the stopping criteria; here, the algorithm is stopped when a difference between the successive iterations is less than a given threshold. Finally, step 4 update variables $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$, then repeat the iteration from step 2.

4. ROBUSTNESS AGAINST SENSOR FAILURES

In practice, detecting the incumbent users by using multiple sensor nodes is desirable to deal with the multipath fading and shadowing, and against the sensor failure. In this section, we extend *Algorithm* 1 such that an incumbent users can be detected with multiple ESC sensor nodes before crossing the isolation boundary.

Let N be the redundancy in measurements required to provide the robustness against the ESC sensor failures. In other words, we assume that N sensor measurements are required to overcome the multipath fading and shadowing effects. We can obtain the required N measurements at the isolation boundary by extending problem (7). The problem of finding the minimum number of ESC sensor nodes such that incumbents in each isolation knot points are detected by N (number of) ESC sensors can be written as

$$\begin{array}{ll}\text{minimize} & \mathbf{card}(\mathbf{a})\\ \text{subject to} & r^{\min}_i \le \sum_{s\in\mathcal{S}_i} b_{is}\|d_i - x_s\|_2 \le NR, \quad i\in\mathcal{D}\\ & \sum_{s\in\mathcal{S}_i} b_{is} = N, \quad i\in\mathcal{D}\\ & b_{is} = \{0,1\}, \quad i\in\mathcal{D}, s\in\mathcal{S}\\ & \max\{b_{1s},\ldots,b_{Ds}\} = a_s, \quad s\in\mathcal{S},\end{array} \tag{12}$$

with variables $\{a_s\}_{s\in\mathcal{S}}$ and $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$. Note that we have scaled the first and second set of constraints of problem (7) by a factor of N in problem (12). Thus, we can protect each knot point $\{d_i\}_{i\in\mathcal{D}}$ by N number of sensor nodes. For example, when $N = 3$ any knot point $\{d_i\}_{i\in\mathcal{D}}$ is protected by three sensors.

Now, by following the discussion of Section 3, the approximation of problem (12) near an arbitrary positive point $\{\hat{b}_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$ can be expressed as

$$\begin{array}{ll}\text{minimize} & \sum_{s\in\mathcal{S}} a_s - \delta\sum_{i\in\mathcal{D}}\sum_{s\in\mathcal{S}}(1+\log(\hat{b}_{is}))(b_{is}-\hat{b}_{is})\\ \text{subject to} & r^{\min}_i \le \sum_{s\in\mathcal{S}_i} b_{is}\|d_i - x_s\|_2 \le NR, \quad i\in\mathcal{D}\\ & \sum_{s\in\mathcal{S}_i} b_{is} = N, \quad i\in\mathcal{D}\\ & 0\le b_{is}\le 1, \quad i\in\mathcal{D}, s\in\mathcal{S}\\ & b_{is}\le a_s, \quad i\in\mathcal{D}, s\in\mathcal{S},\end{array} \tag{13}$$

with variables $\{a_s\}_{s\in\mathcal{S}}$ and $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$; where $\delta > 0$ is a problem parameter. Problem (7) and (12) are identical, thus we adopt *Algorithm* 1 to solve problem (12). Specifically, we solve problem (13) at step 2 of *Algorithm* 1, instead of problem (11).

5. NUMERICAL RESULTS

We illustrate the performance of the proposed *Algorithm* 1 by the setup with a rectangular coastal area of size 20×15 [distance unit] $\times$ [distance unit] as shown in Figure 3. There are $S = 140$ possible ESC sensor positions, and $D = 20$ knot points in the isolation boundary. The minimum distance between the coastal boundary and the isolation boundary is denoted by $d^{\min}$. In the simulation, we set $d^{\min} = 1$ [distance unit], and $D = 20$ knot points are arbitrarily chosen in y-axis as shown in Figure 3.

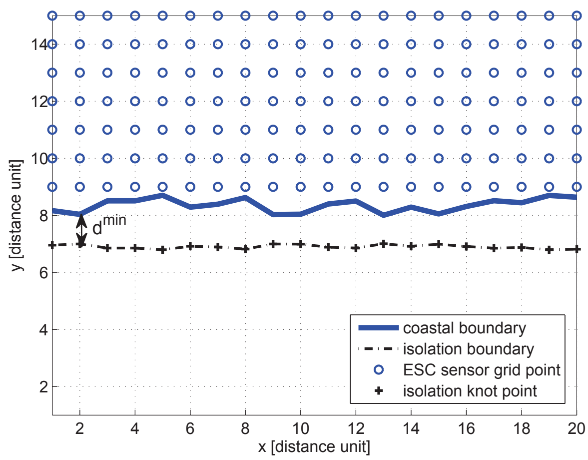


Figure 3: Coastal area is divided into grid points, there are $S = 140$ possible ESC sensor placement positions, and $D = 20$ isolation knot points.

Figure 4 shows the convergence behavior of *Algorithm* 1 for ESC sensing radius $R = 2.5$ and $R = 5$ [distance unit]. The objective values of approximated problem (9) are evaluated after step 2 of *Algorithm* 1. Results show that the proposed algorithm converges within a few iterations.

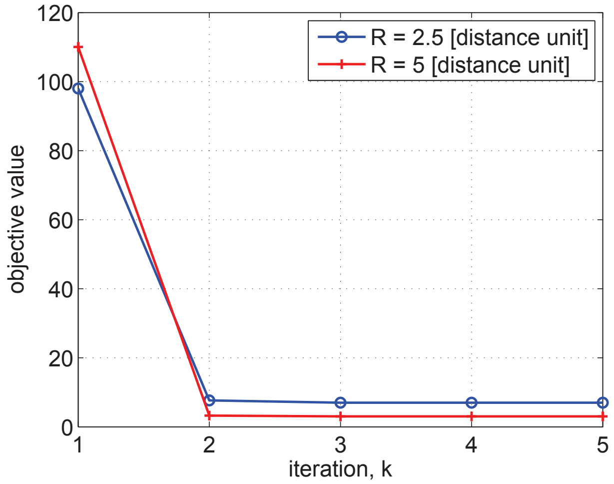


Figure 4: Objective value of problem (9) versus iteration for $R = 2.5$ and 5 [distance unit].

Figure 5 shows the distributions of variables $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$ for ESC sensing radius $R = 2.5$ and 5 [distance unit]. Results show that the values of $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$ are either near to zero or one. Hence, by solving approximated problem (11) in *Algorithm* 1, the third binary constraints of the original problem (7) can be achieved.

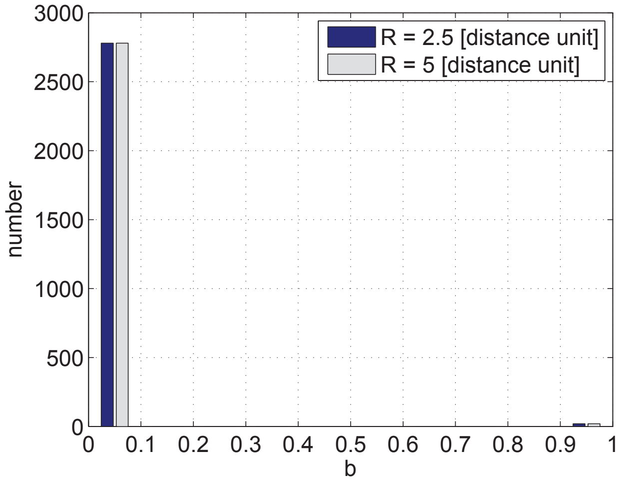


Figure 5: Distribution of variables $\{b_{is}\}_{i\in\mathcal{D},s\in\mathcal{S}}$ for $R = 2.5$ and 5 [distance unit].

Figure 6 shows an evolution of $f(\mathbf{a}) = \sum_{s\in\mathcal{S}} a_s$ (i.e., the total number of required ESC sensors obtained by solving approximated problem (9)) for ESC sensing radius $R = 2.5$ and 5 [distance unit]. The value of $f(\mathbf{a})$ is evaluated after step 2 of *Algorithm* 1. Results show that for ESC sensors with sensing radius $R = 2.5$ [distance unit], an amount of 7 ESC sensors are required to protect the moving incumbent for the coastal area as shown in Figure 3; and with sensing radius $R = 5$ [distance unit], we need 3 ESC sensors to protect the moving incumbent for the coastal area as shown in Figure 3. The grid points to locate the ESC sensors are given by variables $\{a_s\}_{s\in\mathcal{S}}$, and the ESC sensor placement is shown in Figure 7. Results show that the moving incumbent can be detected before it moves inside the isolation boundary by using seven and three ESC sensors for ESC sensing radius $R = 2.5$ and $R = 5$ [distance unit], respectively.

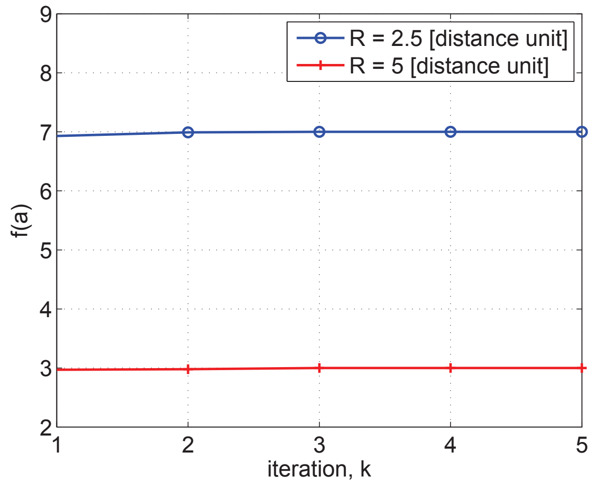
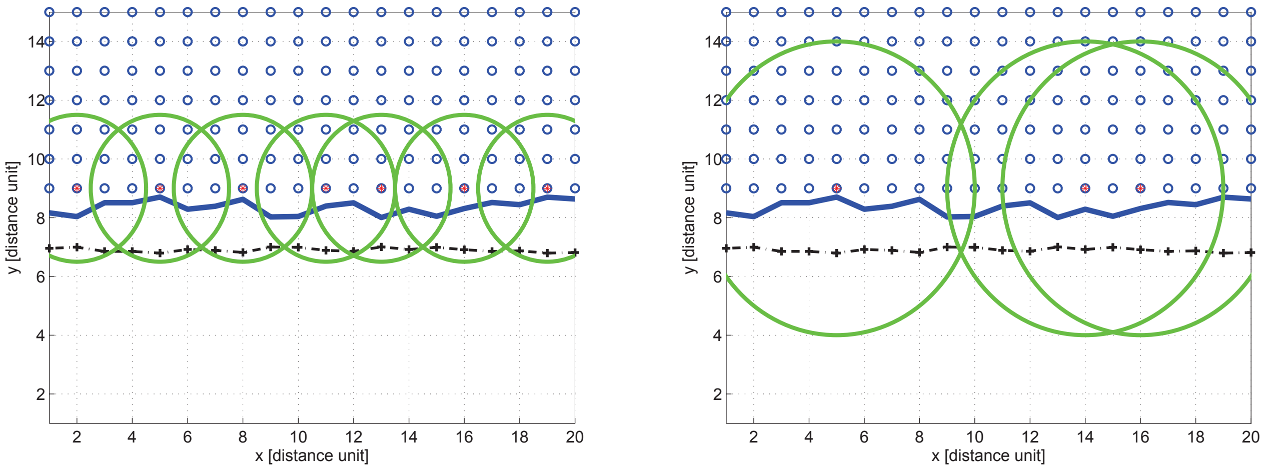


Figure 6: ESC sensor number $f(\mathbf{a})$ obtained by solving approximated problem (9) versus iteration for $R = 2.5$ and 5 [distance unit].

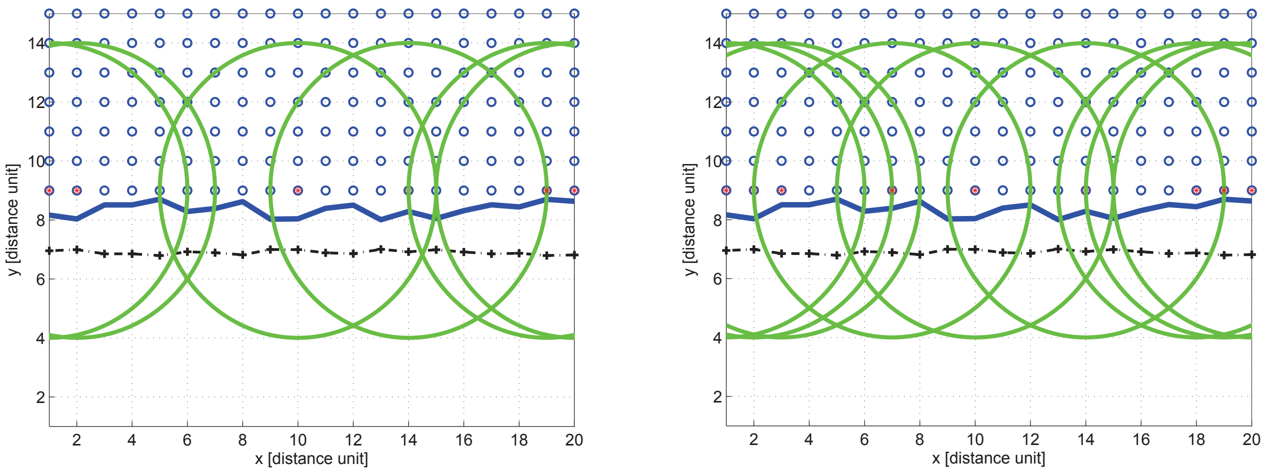
Next we evaluate the performance of the proposed *Algorithm* 1, when the ESC sensor placement is performed to overcome the ESC sensor failures due to shadowing and multipath fading. In the simulation, we set ESC sensor's sensing radius $R = 5$ [distance unit], and the redundancy in ESC sensor measurements required for any isolation knot points by $N = 2$ in problem (12).

Figure 8 shows the minimum number of ESC sensors and their locations obtained by running *Algorithm* 1 for algorithm parameter $\delta = 1$ and $\delta = 5$. For parameter $\delta = 1$ (see Figure 8(a)), each isolation knot points except $d7, d8$, and $d9$ are within the sensing region of at least 2 ESC sensors. For parameter $\delta = 5$ (see Figure 8(b)) all the isolation knot points are within the sensing region of at least 2 ESC sensors. As problem (12) is solved suboptimally, there exists a value of δ that can be set to find the minimum number of ESC sensors and their locations, to achieve the required redundancy in ESC sensor measurements.



(a) (b)

Figure 7: ESC sensor placement. The marker $*$ shows the location of the deployed sensor node: (a) ESC sensing radius $R = 2.5$ [distance unit]; (b) ESC sensing radius $R = 5$ [distance unit].



(a) (b)

Figure 8: ESC sensor placement for sensing radius $R = 5$ [distance unit] and required redundancy in measurements $N = 2$. The marker $*$ shows the location of the deployed sensor node: (a) parameter $\delta = 1$; (b) parameter $\delta = 5$.

6. CONCLUSION

We have considered the problem of environmental sensing capability (ESC) sensor node placement in the coastal areas for the moving incumbent protection in citizens broadband radio service. The problem of finding the minimum number of ESC sensors and their locations is a combinatorial optimization problem. We have proposed a suboptimal but fast-converging algorithm based on sequential convex programming. Then, we extend the proposed algorithm to overcome the sensor failures due to shadowing and multipath fading.

7. ACKNOWLEDGEMENT

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