

Protecting Ports using Range-Free Triangulated Sensor Networks: A Case Study

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Abstract: - Range-free wireless sensor networks rely on sensors that detect only the bearing of an incoming signal, so that localizing a transmitter requires simultaneous detection by at least three sensors, a condition known as triangulated coverage. This paper extends a previously developed geospatial computational framework with a formal treatment of sensor activation and applies it to the protection of the port of Thessaloniki, Greece. Eleven sensors, in the presence of seven known transmitters that induce angular blind zones, monitor four areas of interest that form successive protection layers: the dock, the gulf, the maritime passage, and the adjacent airport zone. We formulate the protection of several areas as a constrained combinatorial optimization problem over sensor activations and orientations, and present a group-based activation strategy, stated as an explicit algorithm, which restricts the problem to a feasible subset, determined by the geography of the deployment. Each group of sensors is oriented towards its nearest area, and neighboring sensors reinforce it only when coverage is insufficient. We further prove that the blind zones induced by the transmitters are invariant under rotation of a sensor's field of view, so that the reachable set of the sensors yields a computable upper bound on the coverage that is attainable by any configuration of the network. We also show that the triangulated coverage ratio of an area is exactly the probability of detecting and localizing a new transmitter that is equally likely to appear anywhere in it. All four areas of interest achieve high triangulated coverage. The proposed group-based activation strategy is a practical, transparent, and computationally cost-effective approach to the protection of critical infrastructures.

Key-Words: - wireless sensor networks, triangulated coverage, range-free localization, port protection, critical infrastructure, sensor activation, combinatorial optimization, coverage bounds, geospatial visualization.

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1 Introduction

Wireless sensor networks (WSNs) are widely used in modern monitoring systems for environmental observation, infrastructure protection, spectrum surveillance, and remote sensing [1], [2], [3], [4], [5]. A fundamental performance metric in such

networks is coverage, i.e., the ability of the deployed sensors (SRs) to reliably monitor a geographical region [6], [7].

A specific type of sensing system uses directional SRs that detect the bearing of an incoming signal but not its range. In these range-

free systems, locating a transmitter (TR) requires triangulation from multiple SRs which detect the same source simultaneously. Usually, at least three SRs are needed, which leads to the concept of triangulated coverage, meaning the area that can be observed simultaneously by three or more SRs [6]. The performance of such networks is further affected by the presence of known TRs within the sensing range of the SRs. Each such TR creates an angular blind zone in the field of view of the nearby SRs [6].

Ports are among the most critical infrastructures, and their protection is subject to international regulatory standards [8] and forms part of the wider maritime domain awareness problem [9], [10], [11]. The operational goal is the timely detection and localization of any new TR entering such a protected zone. Range-free sensing systems are particularly suitable for this task, as localization is achieved exclusively through the geometric intersection of directional bearings, without any distance information [6], [7].

In previous work, we developed a geospatial computational framework for the quantification and visualization of triangulated coverage areas [6], and we addressed the optimization of the SR network configuration by means of a genetic algorithm [12]. More specifically, in [12] the joint selection of active SRs and of their angular orientation was formulated as a constrained combinatorial optimization problem and solved by a constraint-aware genetic algorithm. Related formulations of joint sensor selection and orientation have been studied for directional networks by means of integer programming and greedy heuristics [13], [14] and by genetic algorithms with target priorities [15]. In all of these studies, a single area of interest (AoI) was considered.

The protection of a port, however, is intrinsically a multi-area problem. A vessel approaching the port crosses a sequence of successive zones, and the assets to be protected are of different nature and of different operational priority. Since each SR carries a single angular orientation at any given time, it generally cannot serve two spatially separated AoIs simultaneously, and the allocation of the SRs among the AoIs becomes part of the problem. The present study formulates this multi-area protection problem and proposes a group-based activation strategy for it. The strategy is not an alternative to optimization but an explicit restriction of the optimization problem in [12] to a feasible subset, determined by the deployment geography. The SRs are assigned to their nearest AoI, and are reinforced by SRs of the neighboring groups only where the achieved

triangulated coverage is insufficient. Since only the orientations of the SRs need to be adjusted, no search procedure is implemented. The method is fully transparent to a human operator and allows practically near-instantaneous reconfiguration of the network. Such rapid reconfiguration is particularly important for port protection applications, where operational conditions may change rapidly and a fast, responsive adaptation of the network is required.

The main contributions of the present paper are the following: First, we formulate the simultaneous protection of several AoIs by a single range-free network as a constrained combinatorial optimization problem, and we express the group-based rule as a restriction of that problem. Second, we state the group-based activation strategy as an explicit algorithm. Third, we prove that the blind zones induced by known TRs are invariant under rotation of the field of view of an SR, and we derive from this an orientation-independent upper bound on the triangulated coverage that is attainable by any configuration of the network. Fourth, we show that the triangulated coverage ratio of an AoI coincides with the probability of detecting and localizing a new TR arriving in it, so that the geometric results admit a direct probabilistic reading. Fifth, we demonstrate the above on a realistic scenario and report the achieved coverage. The scenario used throughout the paper covers the port of Thessaloniki, the second largest city of Greece, together with its approach gulf, its maritime passage, and the adjacent airport area.

The remainder of the paper is organized as follows. Section 2 presents the network model, the definition of triangulated coverage and its probabilistic interpretation, the port protection scenario, the proposed group-based activation concept, and the upper bound on the attainable coverage. Section 3 presents the resulting coverage maps and the coverage percentages for each of the four AoIs. Section 4 discusses the results, and finally, Section 5 concludes the paper.

2 Problem Formulation

2.1 Network Model

We consider a set of predefined AoIs, monitored by N range-free SRs, which are placed at fixed and known locations outside them, see also [6], [7], [12], [16], [17]. Each SR, denoted as SR_i ($i = 1, \dots, N$), is located at point x_i , and has a maximum sensing range R_i and an angular field of view Φ_i . The only free parameter of each SR is its angular orientation

θ_i , i.e., the direction towards which its field of view is turned. The effective detection region of SR_i at orientation θ_i , denoted as $D_i(\theta_i)$, is the part of its angular sector that remains after the removal of the blind zones caused by M known TRs, intersected with the AoI. As in [6] and [12], each TR_j ($j = 1, \dots, M$) that lies within the sensing range of SR_i creates a blind zone that extends δ_{before} degrees before and δ_{after} degrees after the exact bearing of TR_j , in a clockwise direction.

In the present work, all SRs share a common fixed angular field of view $\Phi_i = \Phi = 70^\circ$ and common blind-zone parameters $\delta_{\text{before}} = 2^\circ$ and $\delta_{\text{after}} = 7^\circ$. These values remain constant throughout the study. The maximum sensing ranges R_i differ and range from 11 Km to 36 Km. The individual values are listed in Table 1.

For a given set of orientations $\theta = (\theta_1, \dots, \theta_N)$ and for every point p of an AoI A , we define the coverage count function:

$$n(p) = \sum_{i=1}^N \mathbb{1}[p \in D_i(\theta_i)] \quad (1)$$

where $\mathbb{1}[\cdot]$ denotes the indicator function. The coverage level sets of A are defined as:

$$\begin{aligned} A_{=k} &= \{p \in A : n(p) = k\}, \\ A_{\geq k} &= \{p \in A : n(p) \geq k\} \end{aligned} \quad (2)$$

2.2 Triangulated Coverage and Probability of Detection

Following [6], [7], [12], [18], a point of an AoI is considered covered if it belongs simultaneously to the detection regions of at least three SRs. The triangulated region of an AoI is therefore the level set $A_{\geq 3}$, i.e., the union of all points of this AoI that lie in the intersection of three or more detection regions. The corresponding triangulated coverage ratio is defined as the ratio of the area of the triangulated region to the total area of the AoI:

$$C_{\geq 3} = \mu(A_{\geq 3}) / \mu(A) \times 100\% \quad (3)$$

where $\mu(\cdot)$ denotes area. A triangulated coverage ratio close to 100% guarantees that a new TR entering the AoI at any point can be detected by at least three SRs simultaneously and can therefore be localized by triangulation [6], [7], [12]. The quality of that localization depends on the relative positions of the SRs and the TRs, particularly on how well the SRs are positioned to accurately estimate the TRs location [19], [20]. The present study treats a point as covered on the purely combinatorial criterion $n(p) \geq 3$.

The coverage ratio of Eq. (3) admits a direct probabilistic interpretation, which we state explicitly

because it is the quantity of operational interest in a protection scenario.

Proposition 1: Suppose a new TR appears at a random position P in the area of interest A , and that it is detected and localized if and only if at least three SRs observe it simultaneously. If P has probability density f on A , then the probability of detection and localization is:

$$P_{\text{det}} = \int_A [n(p) \geq 3] f(p) dp. \quad (4)$$

In particular, for a transmitter appearing at a uniformly random position, i. e., $f(p) = 1/\mu(A)$, there is:

$$P_{\text{det}} = \mu(A_{\geq 3}) / \mu(A) = C_{\geq 3} / 100 \quad (5)$$

so that the triangulated coverage ratio of the area is exactly the probability of detection.

Proof: By assumption, the TR is detected precisely when it lands in the triangulated region $A_{\geq 3}$. The probability of this is the integral of f over $A_{\geq 3}$, and since the indicator equals 1 on $A_{\geq 3}$ and 0 elsewhere, that integral is Eq. (4). Setting $f(p) = 1/\mu(A)$ makes it $\mu(A_{\geq 3})/\mu(A)$, which by Eq. (3) is $C_{\geq 3} / 100$. ■

Every triangulated coverage percentage is at the same time a geometric ratio and a probability of detection. Proposition 1 also shows how the analysis could be made more realistic without any change to the computational framework. At sea, a vessel is not equally likely to appear anywhere in a gulf, since traffic follows the navigation channel [10], [11]. If f is chosen so that it is concentrated along that channel instead of spread evenly, Eq. (4) can be evaluated on exactly the same coverage count $n(p)$ as Eq. (1), and the result is a traffic-weighted probability of detection that reflects the operational risk more closely. Throughout the present study, we report the uniform case, and we identify this weighting as a direct extension.

2.3 The Port Protection Scenario

The scenario studied in this paper concerns the protection of the port of Thessaloniki, Greece. The port is located at the head of the Thermaic Gulf. Any vessel approaching must successively cross the outer maritime passage, enter the gulf, and finally reach the docks inside the port. In addition, the city's international airport is located near the coastline, close to the port but outside it.

The sensing network of the scenario presented here consists of $N = 11$ SRs placed at fixed and known positions on the coastline and the surrounding terrain [9]. The union of the AoIs is surrounded by SRs from all accessible directions. In addition, $M = 7$ known TRs are located at fixed

positions outside the AoIs. The presence of these TRs may degrade the fields of view of the nearby SRs through the blind-zone mechanism described in Section 2.1. Figure 1 shows the complete setup on a satellite map of the area.

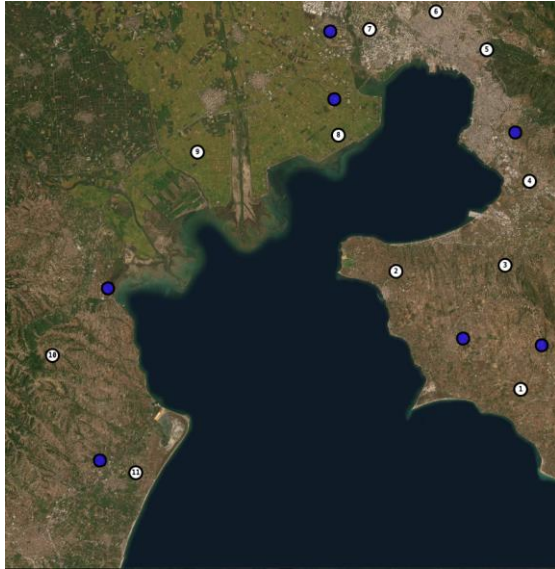


Fig. 1: The complete setup on a satellite map of the area. The blue circles denote the known TRs, and the white numbered circles denote the SRs (SR₁ to SR₁₁)

Source: created by the authors

This geography naturally defines four AoIs, which act as successive protection layers [21], [22], [23]:

- AoI₁ (the passage): the outer maritime passage through which any vessel must sail in order to enter the gulf
- AoI₂ (the gulf): the body of water that leads to the port
- AoI₃ (the dock): the pier area inside the port, which constitutes the final asset to be protected
- AoI₄ (the airport zone): the area that includes the airport, adjacent to the port but outside it.

Any TR approaching the dock by sea must first cross AoI₁ and then AoI₂, so that detection in the outer layers provides early warning well before the TR reaches the port itself. This layered structure is the two-dimensional analogue of barrier coverage, where the guarantee concerns any crossing path rather than any point of a region [21], [22]. AoI₃ and AoI₄ protect the critical assets directly.

2.4 The Concept of Group-based Activation

Let L denote the number of AoIs, and let $\mathbf{a} \in \{0, 1\}^L$ be the activation vector of the network, with $a_i = 1$ if SR _{i} is active [12]. Following [12], the orientation of

each active SR is selected from a discrete set B_i of P_i candidate angular sectors, obtained by rotating its field of view in steps of a common angular turning step θ_{step} . The protection of the L areas is then the constrained problem:

$$\begin{aligned} & \text{maximize } \sum_{\ell} w_{\ell} \cdot C_{(\geq 3), \ell} \\ & \text{subject to } \sum_i a_i \leq K, \quad \theta_i \in B_i \end{aligned} \quad (6)$$

where $C_{(\geq 3), \ell}$ is the triangulated coverage ratio of AoI _{ℓ} , K is the number of active SRs (see also [12]), and $w_{\ell} \geq 0$ are operational priority weights (for this study we chose $w_{\ell} = 1$ for the area under consideration, and $w_{\ell} = 0$ otherwise). Problem (6) carries a structural constraint that does not arise in the single-area formulation of [12]: since SR _{i} possesses one orientation at a time, it can contribute to two areas simultaneously only if the total angular span of those two areas, as seen from x_i , does not exceed Φ . Otherwise, the SR must be allocated to one area or the other. The feasible set of (6) therefore has the size reported in [12], namely $Z = \sum_j \prod_{\{i \in Q_j\}} P_i$ summed over the admissible activation sets Q_j , and exhaustive enumeration is impractical for the deployment considered here. Coverage maximization problems of this type have been reported to be NP-hard, and no polynomial-time algorithm can approximate maximum coverage better than $1 - 1/e$, unless $P = NP$ [25], [26].

The group-based activation concept restricts problem (6) to a small feasible subset that is determined by the geography of the deployment rather than by search. It rests on two rules:

1. Primary assignment: The N SRs are partitioned into geographic groups $G_1, \dots, G_L$, according to their proximity to the AoIs. Each group is assigned to its nearest AoI, and every SR of the group is oriented so that its field of view Φ points towards that AoI.

2. Reinforcement: If the triangulated coverage ratio achieved by the primary group of an AoI is not sufficient for the operational requirements, the nearest SRs of the neighboring groups are additionally re-oriented towards that AoI, one at a time, until sufficient coverage is achieved.

Table 1 presents the primary assignment of each of the SRs, together with their maximum sensing range.

Table 1. The maximum sensing range of the SRs and their primary assignment

SR	Max. sensing range (Km)	AoI group
SR ₁	36	AoI ₁ (passage)
SR ₂	23	AoI ₁ (passage)
SR ₃	15	AoI ₂ (gulf)
SR ₄	21	AoI ₂ (gulf)
SR ₅	20	AoI ₃ (dock)
SR ₆	12	AoI ₃ (dock)
SR ₇	11	AoI ₃ (dock)
SR ₈	13	AoI ₃ (dock)
SR ₉	27	AoI ₂ (gulf)
SR ₁₀	33	AoI ₁ (passage)
SR ₁₁	27	AoI ₁ (passage)

Source: created by the authors

Algorithm 1 was constructed to make the resulting configuration reproducible:

Algorithm 1: Group-based activation
Input: the SR positions and ranges $\{x_i, R_i\}$, the field of view Φ , the known TR positions, the areas of interest $\{AoI_\ell\}$, and a coverage target τ .

1. Partition $\square$ into groups $G_1, \dots, G_L$ by assigning each SR to its nearest AoI.
2. For every ℓ , orient each SR of G_ℓ towards the centroid of AoI_ℓ .
3. For every ℓ , compute the coverage count $n_\ell(p)$ of Eq. (1) and the coverage $C_{(\geq 3),\ell}$ of Eq. (3).
4. While $C_{(\geq 3),\ell} < \tau$ and some unassigned SR strictly increases $C_{(\geq 3),\ell}$:
 - a) among the SRs not yet assigned to AoI_ℓ , select the SR_j nearest to AoI_ℓ
 - b) re-orient SR_j towards AoI_ℓ and set $G_\ell \leftarrow G_\ell \cup \{j\}$
 - c) recompute $n_\ell(p)$ and $C_{(\geq 3),\ell}$.
5. For every ℓ , report $C_{(\geq 3),\ell}$

The number of coverage evaluations performed by Algorithm 1 is $L + \sum_\ell r_\ell$, where r_ℓ is the number of reinforcement steps executed for AoI_ℓ , and it is bounded above by $L + \sum_\ell (N - |G_\ell|)$. Step 4 of Algorithm 1 is a greedy marginal-gain selection, a standard approach to coverage maximization [25], [27]. For the deployment of Section 2.3, the algorithm performs seven coverage evaluations in total, against Z evaluations for exhaustive enumeration and population size times number of generations for the genetic algorithm of [12]. Regarding the value of the coverage target, it is operator-defined. For the present study, it was set equal to $\tau=97.5\%$.

2.5 An Upper Bound on the Attainable Coverage

Algorithm 1 makes no attempt to maximize coverage over the feasible set of problem (6). It is therefore natural to ask how far the output can be from the optimum. In this section, we show that a non-trivial answer is available at the cost of a single coverage computation, without solving (6) and without any optimization. The argument is based on a simple property of the blind-zone model of Section 2.1.

Lemma 1: The blind zone induced in SR_i by a known TR_j is invariant under rotation of the field of view of SR_i .

Proof: As described in Section 2.1, the blind zone of SR_i that is caused by TR_j extends δ_{before} degrees before and δ_{after} degrees after the bearing of TR_j . That bearing is determined by the positions x_i and x_j alone, both of which are fixed. The blind interval is therefore fixed in absolute bearing, and does not depend on θ_i . ■

In other words, as an SR rotates, its angular sector sweeps across a set of blind zones that remain stationary. Therefore, the largest region an SR can ever observe is its whole range disc, with those blind zones removed. Writing Z_i as the union of the blind zones of SR_i caused by all TRs within its sensing range, we can define:

$$U_i = \{p \in A : \|p - x_i\| \leq R_i\} \setminus Z_i \quad (7)$$

as the reachable set of SR_i in the AoI A . If SR_i can only turn within a limited range of bearings, as is often the case for installations facing the sea, U_i is intersected with the bearings it can reach, which only makes U_i smaller and the bound tighter.

Proposition 2: Let $\tilde{n}(p) = \sum_{i=1}^N \square[p \in U_i]$ and let $C^{\max} = \mu(\{p \in A : \tilde{n}(p) \geq 3\}) / \mu(A) \times 100\%$.

(8)

Then $C_{(\geq 3)} \leq C^{\max}$ for every set S of active SRs and every admissible set of orientations θ . In particular, denoting by C^* the coverage of the globally optimal solution of problem (6) on A , there is $C^* \leq C^{\max}$.

Proof: By Lemma 1, the set Z_i does not depend on θ_i , and the angular sector of SR_i at any orientation is always contained in its range disc. Hence $D_i(\theta_i) \subseteq U_i$ for every θ_i . Therefore, for every point p of A there is $\square[p \in D_i(\theta_i)] \leq \square[p \in U_i]$. Summing over $i \in S$ and using $a_i \leq 1$ gives $n(p; S, \theta) \leq \tilde{n}(p)$ pointwise. It follows that $A_{(\geq 3)}(S, \theta) \subseteq \{p : \tilde{n}(p) \geq 3\}$. Since μ is monotone, there is $\mu(A_{(\geq 3)}(S, \theta)) \leq \mu(\{p : \tilde{n}(p) \geq 3\})$. Dividing by $\mu(A)$ gives the result. The globally optimal solution of (6) is a

particular admissible pair (S, θ) , so it obeys the same bound. ■

Three properties of the bound (8) are worth emphasizing. First, $C^{\max}$ does not depend on the orientations, so it bounds every configuration equally: the one produced by Algorithm 1, the one found by the genetic algorithm of [12], and the one that exhaustive enumeration would find. Second, it costs a single evaluation of the coverage count, requiring N discs with the blind zones removed, and involves no search. Third, it is purely geometric [27].

3 Problem Solution

This section presents the application of the group-based activation concept to each of the four AoIs of the port protection scenario. For each AoI, we report the SRs of the primary group and their orientations, the resulting map of the triangulated region, the achieved triangulated coverage ratio, and the reinforcement step and the improved coverage.

All computations and visualizations of the present study were performed with the geospatial computational framework introduced in [6]. The framework is implemented in Python. The geometric operations (angular sectors, blind-zone subtraction, multi-SR intersections, and area computations) are performed with the Shapely library. The interactive satellite maps are generated with the Folium library. The framework dynamically recomputes and redraws the triangulated regions whenever the orientations of the SRs change. This makes it directly suitable for the operational activation study presented here.

3.1 AoI₁: The Passage

The maritime passage constitutes the outermost protection layer. Any vessel approaching the port by sea must cross it. Its primary group consists of $\{SR_1, SR_2, SR_{10}, SR_{11}\}$. Figure 2 shows the resulting triangulated region.

The effect of the two TRs within the sensing range of SR_{10} can be easily observed in Figure 2. The achieved triangulated coverage ratio of AoI₁ with the primary group is 95.2%.

In case reinforcement is needed, SR_9 can be oriented towards AoI₁, raising the coverage to 98.7% (Figure 3). By Proposition 1, a new TR entering the passage at a uniformly distributed position is therefore detected and localized with probability 0.987. The upper bound of Eq. (8) for this AoI is $C_1^{\max} = 99.8\%$.

It is worth noting that high coverage of the passage guarantees the earliest possible warning, since a TR is detected and localized before it enters the gulf.

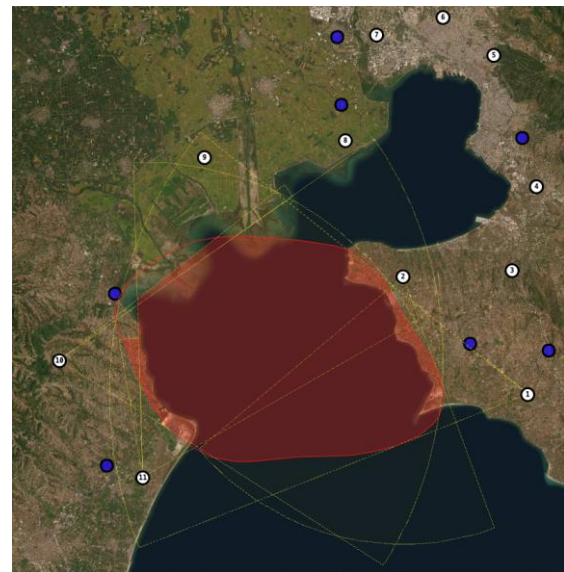


Fig. 2: AoI₁ (red closed curve) and the triangulation area (in red) of its primary SR group (triangulated coverage ratio 95.2%)

Source: created by the authors

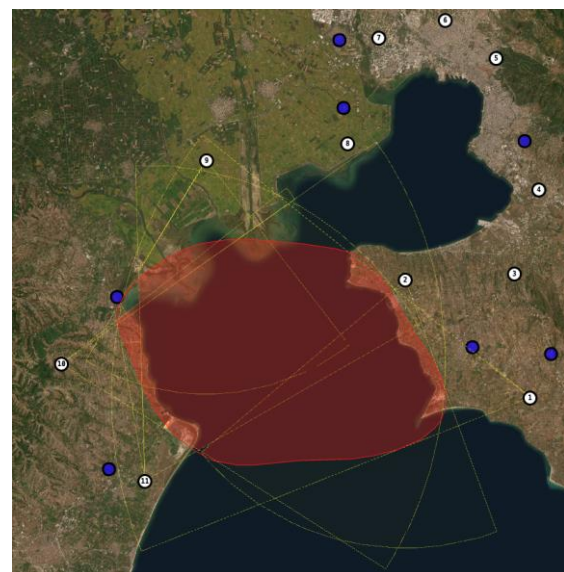


Fig. 3: AoI₁ (red closed curve) and the triangulation area (in red) of its primary SR group plus SR_9 (triangulated coverage ratio 98.7%)

Source: created by the authors

3.2 AoI₂: The Gulf

Due to the geometry of the gulf leading to the port, only three SRs $\{SR_3, SR_4, SR_9\}$ are selected as the active primary group for this region. Figure 4 shows the resulting triangulated region (in red). The opening in SR_3 's field of view, caused by the presence of the TR, can also be easily observed.

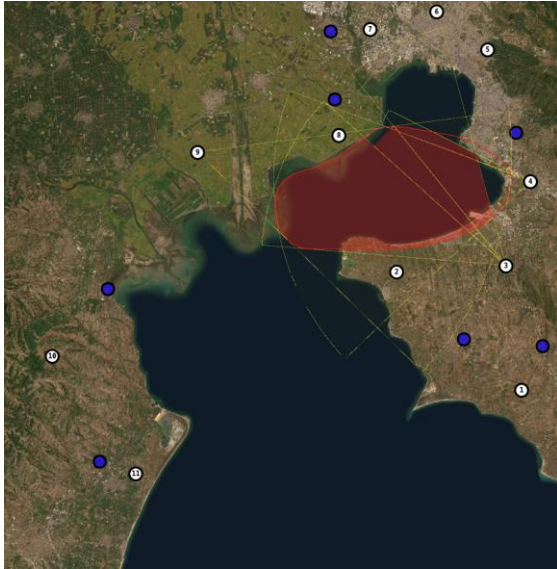


Fig. 4: AoI₂ (red closed curve) and the triangulation area (in red) of its primary SR group (triangulated coverage ratio 91.3%)

Source: created by the authors

The achieved triangulated coverage ratio of AoI₂ with the primary group is 91.3%. In case reinforcement is needed, SR₂ can be re-oriented towards AoI₂, raising the coverage to 97.9%.

The upper bound of Eq. (8) for this AoI was calculated to be $C_2^{\max} = 100.0\%$.

3.3 AoI₃: The Dock

The dock area inside the port constitutes the smallest of the four AoIs and the final asset to be protected. Its primary group consists of {SR₅, SR₆, SR₇, SR₈}, which are the SRs closest to the port. Each SR of the group is oriented towards the center of AoI₃. Figure 5 shows the resulting configuration and the triangulated region that covers AoI₃.

The achieved triangulated coverage ratio of AoI₃ with the primary group is 97.4%. If reinforcement is needed, SR₄ of the neighboring group can be additionally oriented towards AoI₃, raising the triangulated coverage to 100%. Since the coverage of an AoI cannot exceed 100%, the bound of Proposition 2 is attained, and the reinforced configuration of AoI₃ is globally optimal: no activation of the eleven SRs and no assignment of their orientations can improve the triangulated coverage of the dock.

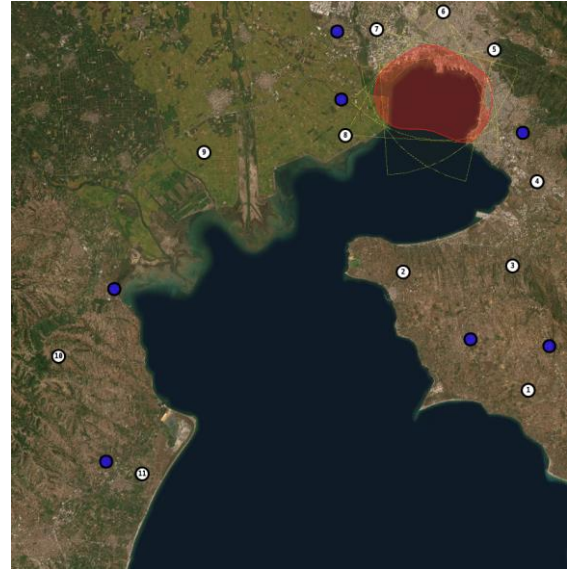


Fig. 5: AoI₃ (red closed curve) and the triangulation area (in red) of its primary SR group (triangulated coverage ratio 97.4%)

Source: created by the authors

3.4 AoI₄: The Airport Zone

The airport zone is located near the port but outside it and is the only AoI that extends primarily over land. If full coverage of this AoI is needed, SR₂, SR₃, and SR₄ can change the orientation of their fields of view. The triangulated coverage ratio of AoI₄ that can be achieved with this group of SRs is 100% (Figure 6).

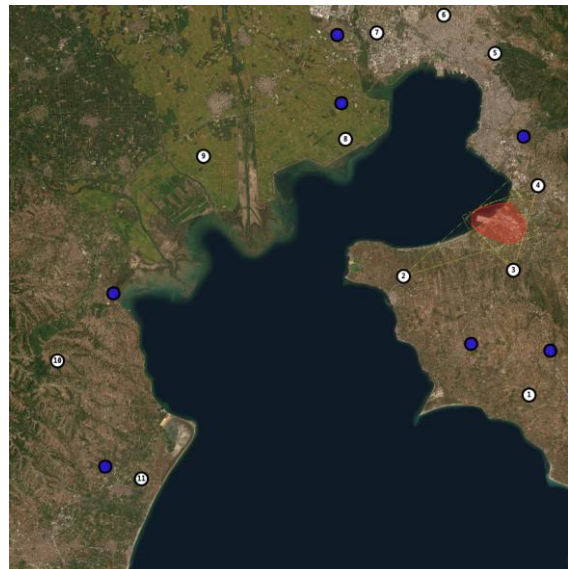


Fig. 6: AoI₄ (red closed curve) and the triangulation area (in red) of the group of {SR₂, SR₃, SR₄} (triangulated coverage ratio 100%)

Source: created by the authors

As was the case for the dock, the bound of Proposition 2 is attained, and the configuration is globally optimal.

It should be noted that SR_2 , SR_3 and SR_4 belong to the primary groups of AoI_1 and AoI_2 , so that the protection of the airport zone at this level competes with the protection of the maritime layers. This is precisely the structural constraint identified in Section 2.4: the angular separation of the airport zone and of the maritime areas, as seen from these SRs, exceeds Φ , and no single orientation serves both. The configuration reported here is therefore to be understood as the response to a threat picture in which the airport zone has become the priority, rather than as a configuration held simultaneously with those of Sections 3.1 and 3.2.

3.5 Summary of Results

Table 2 summarizes the results for all four AoI s.

Table 2. Summary of the group-based activation results

AoI	$C(\geq 3)$ primary (%)	Reinforcing SR	$C(\geq 3)$ final (%)	C_{max} (%)
AoI_1	95.2	SR_9	98.7	99.8
AoI_2	91.3	SR_2	97.9	100.0
AoI_3	97.4	SR_4	100.0	100.0
AoI_4	—	—	100.0	100.0

Source: created by the authors

For each AoI , Table 2 reports the primary group, the triangulated coverage achieved by the primary group, the SRs added during the reinforcement step, the final triangulated coverage, and the upper bound of Eq. (8).

4 Discussion

The results of Section 3 demonstrate that the port of Thessaloniki, its maritime approaches, and the adjacent airport zone can be protected by a network of eleven fixed, range-free SRs, which are activated according to a simple group-based rule. Since all four AoI s achieve high triangulated coverage, a new TR entering the passage, the gulf, the port, or the airport zone falls, with the probability quantified in section 3.5, inside a triangulated region. It can therefore be detected and localized simultaneously by at least three SRs. Moreover, the layered structure of the AoI s ensures that a TR approaching the dock by sea is detected first in AoI_1 and then in

AoI_2 , providing early warning well before the TR reaches the protected asset.

Several factors make the group-based rule attractive in operational practice. First, no optimization is required [14]: the primary assignment follows directly from the geography of the deployment, and the reinforcement rule is applied only when needed, so that the coverage evaluations reported in section 2.4 replace the enumeration of a search space of size Z . Second, the strategy is fully transparent to a human operator, who can immediately understand and verify which SRs protect which area. Third, reconfiguration is practically instantaneous, since the sensing range R and the field of view Φ are fixed hardware parameters and only the orientations of the SRs change. Finally, the groups map naturally onto the layered geography of the port approach, so that the reinforcement rule corresponds to the intuitive operational action of "turning the neighboring SRs towards the threatened area". In this sense, the group-based activation strategy can be regarded as a different concept of optimization. Instead of maximizing coverage algorithmically, the operator selects the appropriate group of SRs and their appropriate orientations.

The approach presented here has the limitation that the group-based rule depends on the AoI s being geographically separable. Within this limitation, however, the strategy is well suited to routine operation and to rapid manual reconfiguration, and dynamic re-grouping of the SRs. Another limitation is that no claim of optimality is made for the group-based configurations. Their value lies in their operational simplicity. A third limitation is that triangulated coverage is a binary geometric criterion: a point counted as covered by three nearly collinear bearings is treated identically to one covered by a well-conditioned geometry, although the resulting localization accuracy differs substantially [20], [28], [29].

5 Conclusion

This paper presented a case study of critical infrastructure protection using a range-free triangulated coverage network: the protection of the port of Thessaloniki, Greece, of its approach gulf and maritime passage, and of the adjacent airport zone. Four AoI s were defined as successive protection layers and were monitored by eleven fixed SRs, in the presence of seven known TRs.

The protection of several AoI s by a single network was formulated as a constrained combinatorial optimization problem over activations

and orientations, subject to the structural constraint that an SR carrying a single orientation cannot serve two widely separated areas at once. A group-based activation strategy was then presented as an explicit restriction of that problem. Each geographic group of SRs is oriented towards its nearest AoI, and SRs of the neighboring groups are re-oriented as reinforcement only where the coverage is insufficient. The strategy was stated as an algorithm, and its cost was quantified as seven coverage evaluations for the deployment considered.

Two analytical results accompany the case study. The triangulated coverage ratio of an AoI is exactly the probability that a new TR arriving in it is detected and localized, under a uniform arrival prior, so that the reported percentages admit a direct probabilistic reading and can be refined to a traffic-weighted detection probability without any change to the computational framework. We further proved that the blind zones induced by known TRs are invariant under rotation of a sensor's field of view. This yields an orientation-independent upper bound on the triangulated coverage attainable by any network configuration, computable from a single coverage evaluation.

The results showed that all four AoIs achieve high triangulated coverage, so that any new TR entering the protected areas can be detected and localized by triangulation.

The study demonstrates that, for deployments whose geography naturally suggests a partition of the SRs into groups, a transparent operational rule can replace algorithmic optimization at negligible computational cost, making the approach directly applicable to the protection of ports and similar critical infrastructures.

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