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k-CSqu: Ensuring connected k-coverage using cusp squares of square tessellation

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A B S T R A C T

In planar wireless sensor networks (PWSNs), the most essential functionalities of the sensor nodes are both sensing and communication, which are evaluated using two fundamental concepts, namely coverage and connectivity, respectively. However, coverage alone is not sufficient for the correct operation of PWSNs. Additionally, it is important that network connectivity be ensured, where all the sensors are connected to one another, so that every pair of sensors can communicate with each other. To account for both coverage and connectivity, this paper aims at solving the problem of connected k-coverage in PWSNs, where every point in a field of interest is covered by at least k sensors ($k > 1$) at the same time, while all the sensors are mutually connected directly or indirectly. In order to solve this problem, we initially tessellate the entire field into adjacent and non-intersecting square tiles. Then, we construct a cusp-square inside each square tile of the tessellation for sensor placement. Based on this cusp-squared square tile, we compute the minimum planar sensor density for k-coverage in PWSNs. Also, we establish a relationship between the sensing and communication radii of the sensors to guarantee network connectivity in PWSNs. Finally, we validate our theoretical analysis using simulation results.

1. Introduction

Planar wireless sensor networks (PWSNs) are wirelessly connected infrastructure-less networks that are composed of tiny, low-powered sensors, which are planarly dispersed in a field of interest. These sensors are dedicated to monitor specific environmental conditions in the field and relay the gathered information to a central entity, called *sink*, for further analysis and processing. Specifically, thanks to their sensing capabilities, these sensors are capable of detecting and measuring various environmental parameters, including temperature, light, sound, humidity, vibrations, pollutants, pressure, and many others. Moreover, owing to their communication capabilities, these sensors are able to forward the collected information to the sink. These sensing and communication capabilities of the sensors are tightly related to the fundamental concepts of sensing coverage and network connectivity, respectively. Therefore, in order to have a successful data collection and delivery to the sink during their monitoring task, these PWSNs should ensure both coverage and connectivity during their operational lifetime.

It is clear that coverage and connectivity should be always guaranteed so all the deployed sensors can accomplish their mission successfully. To this end, PWSNs should be deployed in planar fields of interest in such a way that there are no coverage and connectivity holes. Furthermore, for some critical applications, such as intruder detection and tracking, it is essential that every point be covered (or sensed) by more than one sensor simultaneously. This type of redundant coverage is required so as to ensure fault-tolerant data collection during the network operation. Indeed, the sensors may fail to work properly according to one of the following two scenarios. First, these low-powered sensing devices may die when they deplete all their limited battery power (or energy). Second, they may become faulty due to a hardware problem, which may occur at any time. Thus, in this paper, we focus on a more general concept of coverage, called k-coverage. Precisely, we attempt to solve the connected k-coverage problem in PWSNs. Next, we state this problem (Section 1.1). Then, we summarize our major contributions in this paper (Section 1.2).

1.1. Problem statement

We want to investigate the problem of connected k-coverage in PWSNs, where each point in a planar field of interest is sensed by

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(or falls under the sensing range of) at least k sensors at the same time, while all the sensors are connected to each other, so that any pair of sensors can freely communicate with each other, where $k \geq 1$. This connected k-coverage problem can be further divided into four major inter-related sub-problems, and we aim to provide comprehensive answers to all of them. These four sub-problems can be stated as follows:

- **Sub-problem 1:** What is the optimal sensor deployment strategy, so that every point in a planar field of interest is covered (or sensed) by at least k sensors at the same time while using a minimum number of sensors, where k is a natural number with $k \geq 1$?
- **Sub-problem 2:** What is the corresponding minimum planar sensor density (*i.e.*, number of sensors per unit area) to achieve k-coverage of a planar field of interest?
- **Sub-problem 3:** What is the relation that should exist between the sensing radius and communication radius of the sensors in order to ensure network connectivity?
- **Sub-problem 4:** How the sensors would be selected and scheduled (or duty-cycled) to k-cover a planar field of interest using a deployed sensor density that is as close as possible to the theoretical one, which is computed in solving Sub-problem 2 above?

1.2. Contributions and organization

We consider the concept of square tessellation and deploy the sensors in a planar field of interest with the goal to ensure connected k-coverage of PWSNs using a minimum number of deployed sensors. The major contributions of this paper can be summarized as follows:

- We tessellate a planar field of interest using adjacent and non-intersecting square tiles of specific dimensions, which are proportional to sensing radius of the sensors.
- We provide an optimal characterization of k-coverage using PWSNs. To this end, we construct a cusp-square inside each square tile and deploy a minimum number of sensors inside that cusp-square area in order to ensure k-coverage of each square tile, thus, ensuring k-coverage of the entire planar field of interest, where $k > 1$.
- We compute the corresponding planar sensor density for the proposed sensor deployment in the square tiles to k-cover a planar field of interest, where $k > 1$.
- We establish the relationship that should exist between the sensing radius and the communication radius of the sensors for the above proposed sensor deployment so that the entire planar field of interest is k-covered while all the sensors involved in the k-coverage process are mutually connected, thus, achieving connected k-coverage in PWSNs, where $k > 1$.
- We propose a sensor selection protocol, where the selected sensors are scheduled (or duty-cycled) to ensure k-coverage of a planar field of interest.
- We validate our proposed theoretical analysis using simulation. We find a close-to-perfect match between our theoretical results and the ones obtained through simulation.

The remainder of this paper is structured as follows. In Section 2, we present some fundamental concepts and introduce our energy and network models used in our analysis of the connected k-coverage problem in PWSNs. In Section 3, we review a sample of existing solutions that were proposed to solve the problem of k-coverage. In Section 4, we construct the square tessellation and cusp-square for each square tile for sensor deployment so as to k-cover a planar field of interest. Also, we compute the corresponding planar sensor density. In addition, we determine the relationship that should exist between the sensing radius and the communication radius of the sensors, so the entire field of interest is k-covered, while the network formed by these sensors is connected. In Section 5, we discuss our proposed connected k-coverage protocol, called k-CSqu. In Section 6, we provide simulation results for assessing the performance of k-CSqu and compare the simulation results with the theoretical ones. Furthermore, we assess the performance of our protocol k-CSqu in comparison with existing tessellation based k-coverage protocols, DIRACC_k [8] and RCH_k [7]. In Section 7, we provide concluding remarks and summary of the work done in this paper and discuss possible extensions of the proposed approach in this paper as our future work.

2. Preliminaries and models

In this section, we introduce the specific terminology, which is used throughout this paper. Also, we describe models, such as energy model and network model, along with their assumptions, which are used to discuss our proposed solution to the connected k-coverage problem.

2.1. Terminology

Definition 1 *(Sensing range).* The *sensing range* of a sensor s is the area SA around it, where every occurring event in SA is detected by s.

Definition 2 *(Communication range).* The *communication range* of a sensor s is the area CA around it, where sensor s is able to communicate with any other sensor located in CA.

Definition 3 *(k-coverage).* A field of interest F is said to be k-covered if every point in F is sensed by at least k sensors at the same time. A PWSN monitoring a k-covered field of interest is said to provide k-coverage, where k is the degree of coverage guaranteed by the underlying network with $k > 1$.

Definition 4 *(Connected k-coverage).* A PWSN is said to provide *connected k-coverage* if the field of interest it monitors is k-covered and all the sensors involved in the k-coverage process are connected to each other such that there is at least one communication path between any pair of these sensors.

Definition 5 *(Planar sensor density).* The *planar sensor density* of a PWSN covering a field of interest is the number of sensors per unit area of that field.

2.2. Energy model

To compute the energy consumption due to data transmission and data reception by the sensors, we use the energy model proposed by Heizelman et al. [14]:

$$E_t(d) = b \times (\varepsilon d^\alpha + E_e)$$

$$E_r = b \times E_e$$

where $E_t(d)$ is the energy consumed by sensor s while transmitting a message of b bits over a distance d, E_r is the energy consumed by sensor s while receiving a message of b bits, E_e is the electronical energy, $\varepsilon \in \{\varepsilon_{fs},\varepsilon_{mp}\}$ is the transmitter amplifier in the free-space (ε_{fs}) or multi-path (ε_{mp}) model, and $\alpha \in [2, 4]$ is the path-loss exponent.

The Energy spent by the sensors due to phenomenon sensing is estimated using the energy model proposed by Ye et al. [25].

Ideally, a sensor consumes 0.012 J in idle mode, 0.0003 J in sleep mode, and the energy utilized for moving a sensor is selected randomly in [0.008, 0.012] J/m [23].

2.3. Network model

Assumption 1 *(Sensor deployment).* All the sensors are deployed randomly and uniformly in a planar field of interest.

Assumption 2 *(Location awareness).* All the sensors are aware of their own locations through a global positioning system (GPS) or some localization technique [10].

Assumption 3 *(Disk model).* The communication and sensing ranges of the sensors are modeled as disk-shaped of radii r_c and r_s, respectively, where the centers coincide with the location of that corresponding sensor.

Assumption 4 *(Sensor homogeneity).* All the sensors have same sensing range r_s, same communication range r_c, and same initial energy.

3. Related work

In this section, we provide an overview of existing approaches solving the coverage and k-coverage problem in PWSNs. Precisely, we briefly discuss these solutions and the limitations of existing research compared to our research. Also, we provide an explanation about the difference in current paper's solution to the earlier solutions of our research lab [4–8].

3.1. Literature review

Wang et al. [22,24] proposed coverage configuration protocol (CCP) that uses k-coverage eligibility algorithm for toggling the state of a sensor (to keep sensor active or inactive) based on the coverage of intersection points of sensing ranges of that sensor and its neighboring sensors. Ammari has studied the geometrical properties of the Reuleaux triangle and developed k-coverage theory using Reuleaux triangle-based tessellation, where k-coverage is attained by placing k sensors in intersection lens of two Reuleaux triangles. Leveraging this k-coverage theory, Ammari has proposed stochastic protocol SCP_k [4], deterministic randomized protocols CERACC_k and DIRACC_k [8], deterministic clustering-based protocols T-CRACC_k and D-CRACC_k [8], and heterogeneous protocols PR-Het-CCC_k and PR-Het-DCC_k [6] for PWSNs. It was observed that protocols CERACC_k, DIRACC_k, T-CRACC_k and D-CRACC_k [8] has better performance compared to CCP [22,24] in terms of energy consumption and operational network lifetime. Yu et al. [26] developed a theory of k-coverage that uses regular pentagons for modeling the sensing range of sensors and proposed stochastic k-coverage protocol ISCP_k. In this theory, a regular pentagon with central area, formed by the intersection of five sensors' sensing ranges placed at each vertex of that regular pentagon, is constructed and four of such regular pentagons with central area are used to model the sensing area of sensor, where k-coverage is ensured by placing k-1 sensors in those four central areas.

Qiu et al. [20] have used k-order Voronoi diagram construction for creating k-order local k-coverage Voronoi diagram (LVD), that assigns neighboring sensor to k-cover and precision check the critical points of any sensor, and proposed distributed Voronoi-based cooperation (DVOC) scheme, which uses these k-order LVDs and k-order Delaunay triangle for coverage hole mitigation. Leveraging Ammari's [4–6,8] Reuleaux triangle-based tessellation k-coverage theory, Yu et al. [27] built coverage contribution area (CCA) for sensor deployment. Based on this CCA-based Reuleaux triangle tessellation, k-coverage protocols SCRT-PCA_k, DCRT-PCA_k and DIRT-PCA_k were proposed. Sun et al. [21] has developed a k-coverage algorithm based on the optimization node deployment process. Abbasi et al. [2] suggested a method for coverage control in continuous and potentially long regions and passages, where a group of autonomous mobile sensors move within the boundaries of the regions/passages for ensuring optimal coverage. Qin and Chen [19] leveraged binary differential evolution (DE) to search for an improved subset of nodes, that ensures specific coverage ratio and proposed an area coverage algorithm which meets the coverage demand. Chenait et al. [11] has suggested SRA-Per and SRA-SP protocols based on sector redundancy determination algorithm that slices the sensing range of sensor based on predefined sector angle and determines the redundant sensors which are not required for k-coverage process. Krishnan et al. [16] exploited four optimization schemes, namely heuristic algorithm, ABC algorithm, ant colony optimization (ACO) algorithm and particle swarm optimization (PSO) algorithm, for determining the sensor placement positions and minimum dominating set-based heuristics for sensor scheduling, and proposed ten different approaches with multiple combinations of above mentioned sensor placement and sensor scheduling schemes.

Elhoseny et al. [12] suggested a genetic algorithm-based (GA) approach for k-coverage of selected target locations in the field of interest, with an objective of maximized network lifetime. Hoyingcharoen and Teerapabkajorndet [15] computed the expected sensing probability of any given location as well as the expected connectivity level of any sensor to sink, and demonstrated the capabilities of their suggested theory in forecasting the connectivity and coverage levels. Similar to Qin and Chen [19], Naik and Shetty [17] exploited the DE algorithm for determining the optimal candidate locations for sensor placement in the field of interest, such that k-coverage of specific target locations in the field of interest is achieved. Harizan and Kuila [13] have developed k-coverage solutions by leveraging heuristic and nature-inspired algorithms. Optimal positions for sensor placement are determined using GA, PSO, DE and gravitational search algorithms, such that k-coverage of target locations in the field of interest is achieved. Natarajan and Parthiban [18] have used shuffled frog leaping Nelder-Mead algorithm, for optimal node placement for achieving k-coverage of target locations in the field of interest. Unlike from previous research [4–6,8], Ammari [7] has exploited on regular hexagon-based tessellation for k-coverage where sliced hexagons are used for sensor placement, and proposed k-coverage algorithm RCH_k, which works for both deterministic and stochastic sensing model and applicable to both homogeneous and heterogeneous configurations of PWSNs. Alibeiki et al. [3] has also leveraged GA-based approach for addressing k-coverage problem in directional PWSNs of both over-provisioned and under-provisioned configurations.

3.2. Shortcomings of existing research

In comparison to our computational geometry-based k-coverage research, DVOC [20] uses k-order LVDs for attaining k-coverage whereas we use regular convex polygonal tessellation, here in this paper it is square tessellation, for k-coverage. Moreover, DVOC [20] needs k-order Delaunay triangle for mitigating existing or newly created coverage holes, that are formed due to the k-order LVDs, whereas in our case, k-coverage of each tile of the tessellation ensures zero coverage holes to deal with. Latest research leveraging metaheuristic and nature-inspired algorithms, use optimal number of sensors for k-coverage process achieving minimal sensor usage. But the limitation is, these metaheuristic and nature-inspired algorithms based solutions can be employed to k-cover only specific

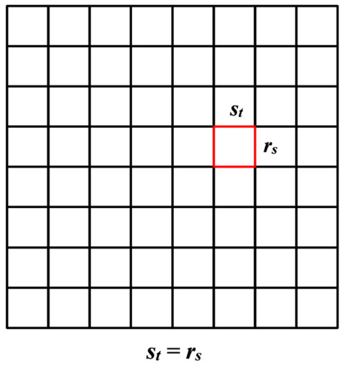

Fig. 1. Square tessellation of square tile side length s_t.

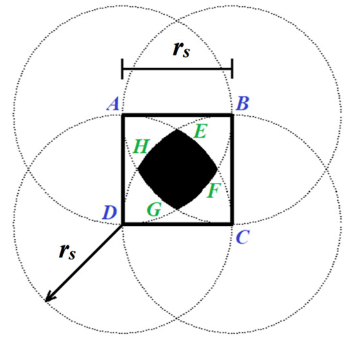

Fig. 2. Cusp-square *EFGH* inside square tile *ABCD*.

target locations/positions in the field of interest, whereas our tessellation based solution can be employed to k-cover the entire field of interest, k-covering each and every point/location. Moreover, except Yu et al. [26,27] and our tessellation based k-coverage research, none of the other approaches were able to provide quantitative estimate of the minimum sensor density required to k-cover an entire field of interest in PWSNs.

In comparison with our lab's previous k-coverage research [4–8], in this paper our proposed approach (discussed in Section 4 below) utilizes geometrical properties of squares for achieving k-coverage in PWSNs, while earlier approaches were based on the geometrical properties of Reuleaux triangles and regular hexagons. It is worth mentioning that our square tessellation approach outperforms the previous approaches [4–8] in terms of planar sensor density, number of active sensors for k-coverage and operational network lifetime.

4. Square tessellation-based k-coverage

In this section, we investigate the problem of k-covering a field of interest using square tiles. Next, we state our instance of the planar k-coverage problem as follows:

Instance of the k-coverage problem: Given a square tessellation and a set of sensors, what is the sensor placement strategy for attaining k-coverage of a field of interest, where every square tile of the tessellation can be k-covered by at least k sensors?

To solve this k-coverage problem as stated above, we consider the following two steps:

- Step 1: Planar field of interest square tessellation
- Step 2: Sensor placement area construction

Next, we discuss these two steps in detail.

4.1. Planar field of interest square tessellation

As an initial step towards solving the above instance of the planar k-coverage problem, we tessellate a planar field of interest into adjacent and non-intersecting square tiles of side length s_t whose value is equal to the sensing radius r_s of the sensors. Fig. 1 shows this tessellation.

4.2. Sensor placement area construction

After tessellating a planar field of interest, as shown in Fig. 1, we construct a cusp square area inside each square tile for sensor placement. Precisely, we place k sensors in each cusp square area in order to achieve k-coverage of each square tile.

Let us consider a square tile T of the tessellation. Now, we draw circles of radius r_s centered at each vertex of T, where an enclosed area is formed due to the intersection of these four circles. We call this enclosed area, *cusp square*. The distance between any adjacent pair of vertices in this cusp square is the same (as in a square), and the sides of this cusp square are the arcs of the four circles.

Lemma 1 gives an upper bound on the distance between any vertex of the square tile and any vertex of the cusp square.

Lemma 1 *(Largest distance). The maximum Euclidean distance between two points X and Y is r_s, where the domain of X is the set of vertices of a square tile and the domain of Y is the set of vertices of the corresponding cusp square. That is, $\delta(X, Y) \leq r_s$, $X \in$ {vertices of square tile} and $Y \in$ {vertices of cusp square}, where δ is the Euclidean distance function.*

Proof. Let us consider vertex A of square tile (Fig. 2) and the farthest vertices of cusp square from vertex A are the vertices F and G. However, the vertices F and G are two points located on the circle whose center is vertex A and radius is r_s. Also, the other vertices H and E are inside the circle, making their distance from vertex A lesser than r_s. Similarly, the other vertices B, C and D exhibit the same geometric properties towards the vertices of the cusp square. Therefore, we can say that the largest possible distance between any vertex of a square tile and any vertex of its corresponding cusp square is r_s.

Lemma 2 below, which exploits the results of Lemma 1, establishes the necessary condition for k-coverage of a square tile of a square tessellation.

Lemma 2 *(Square tile k-coverage). A Square tile of side length r_s is k-covered if there are k active sensors placed in its corresponding cusp square area, where r_s is the radius of the sensing range of the sensors.*

Proof. We can proceed by considering the lower and upper bound cases for the placement of sensors in the cusp square area of the tile. The lower bound case corresponds to the placement of a sensor at the center of the cusp square, while the upper bound case corresponds to the placement of a sensor at any vertex of the cusp square.

Case 1 *(Lower bound).* In this case, the distance d_1 between a sensor and the farthest point on the square tile (vertex of the square tile) is given by:

$$d_1 = \frac{\sqrt{2}}{2} r_s = 0.707 r_s$$

Case 2 *(Upper bound).* From Lemma 1, the distance d_2 between a sensor and the farther point on the square tile (vertex of the square tile) is computed as follows:

$$d_2 = r_s$$

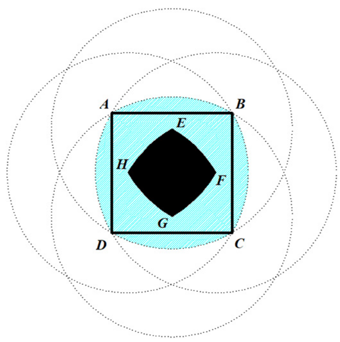

Fig. 3. k-Coverage area for a square tile.

Therefore, the distance between a sensor and the farthest point on a square tile falls in the range of $[0.707r_s, r_s]$. From this, it is clear that any sensor placed between these lower and upper position bounds will be able to cover the entire square tile. Consequently, if there are k sensors placed in between these lower and upper position bounds, all these k sensors will be able to k-cover the entire square tile. Therefore, placing k sensors in the cusp square area of the square tile ensures the k-coverage of that tile.

Theorem 1, which exploits the Lemma 2, states the sufficient condition for k-coverage of the entire field of interest.

Theorem 1 *(k-covered field). A field of interest is k-covered if each of the square tiles of the tessellation has at least k active sensors placed in its corresponding cusp square area.*

Proof. From the Lemma 2, a square tile is k-covered if it has k active sensors in its corresponding cusp square area. Therefore, if all the square tiles of the tessellation are k-covered then the entire field of interest is said to be k-covered.

Lemma 3 below computes the size of the k-covered area based on the cusp square area of its corresponding square tile.

Lemma 3 *(k-covered area). The k-covered area A_k formed by the intersection of the sensing disks of k sensors, which are placed in a cusp square area of its corresponding square tile, can be computed as follows:*

$$A_k = \left(\frac{2\pi + 3 - 3\sqrt{3}}{3}\right) r_s^2$$

where r_s is the radius of the sensing range of the sensors.

Proof. The k-covered area corresponds to the largest area of the intersection, which is formed by the sensing disks of the sensors that are placed at the vertices of a cusp square area of its corresponding square tile. This k-covered area A_k is given by:

$$A_k = A_{Square\ ABCD} + A_{arc\ AB\ \&\ line\ AB} + A_{arc\ BC\ \&\ line\ BC} + A_{arc\ CD\ \&\ line\ CD} + A_{arc\ DA\ \&\ line\ DA}$$

where $A_{Square\ ABCD}$ is the area of square ABCD and $A_{arc\ AB\ \&\ line\ AB}$ is the curved area formed between the arc AB and line segment AB, as shown in Fig. 3.

Notice that we have:

$$A_{arc\ AB\ \&\ line\ AB} = A_{arc\ BC\ \&\ line\ BC} = A_{arc\ CD\&line\ CD} = A_{arc\ DA\ \&\ line\ DA}$$

This implies that:

$$A_k = A_{Square\ ABCD} + 4 \times A_{arc\ AB\ \&\ line\ AB}$$

where both $A_{Square\ ABCD}$ and $A_{arc\ AB\ \&\ line\ AB}$ are computed as follows:

$$A_{Square\ ABCD} = r_s^2$$

$$A_{arc\ AB\ \&\ line\ AB} = \left(\frac{\pi}{6} - \frac{\sqrt{3}}{4}\right) r_s^2$$

Therefore, we obtain:

$$A_k = \left(\frac{2\pi + 3 - 3\sqrt{3}}{3}\right) r_s^2$$

Theorem 2 below, which exploits the result of Lemma 3, computes the planar sensor density that is necessary to ensure k-coverage of a field of interest. It is based on the sensor placement within a cusp square.

Theorem 2 *(Planar sensor density). The planar sensor density $\lambda(k, r_s)$, which is required to k-cover a field of interest, is computed as follows:*

$$\lambda(k, r_s) = \frac{0.734k}{r_s^2}$$

where r_s is the radius of the sensing disks of the sensors, and $k \geq 1$.

Proof. The planar sensor density of a square tile is the number of sensors deployed per unit area of the tile. Hence, given that k sensors are placed within a cusp square to k-cover A_k, this planar sensor density, denoted by $\lambda(k, r_s)$, is given by:

$$\lambda(k, r_s) = \frac{k}{A_k}$$

By substituting the value of A_k from Lemma 3, we get:

$$\lambda(k, r_s) = \frac{k}{\left(\frac{2\pi+3-3\sqrt{3}}{3}\right) r_s^2} = \frac{0.734k}{r_s^2}$$

Notice that the planar sensor density $\lambda(k, r_s)$ depends only on k and r_s.

Remark 1. Our result in Theorem 2 shows that we have a lesser planar sensor density compared to the one computed in Ammari's works [4–8]. That is, our approach requires fewer number of sensors to k-cover a planar field of interest, compared to the one proposed in Ammari's works [4–8].

Lemma 4 below states the relationship that should exist between the radii of the sensing and communication disks of the sensors for ensuring network connectivity of PWSNs. This type of relationship is essential for producing connected k-coverage configurations during the whole operational lifetime of PWSNs.

Lemma 4 *(Network connectivity). A square tessellation-based k-coverage configuration is said to be connected if the radii of sensing and communication disks of the sensors, r_s and r_c, respectively, satisfy the following inequality:*

$$r_c \geq 2r_s$$

Proof. The necessary condition for ensuring network connectivity is that two farthest sensors should be able to communicate with each other. Let us consider the cusp square configuration of adjacent square tiles, as shown in Fig. 4. Also, sensors are far from each other when they are placed at the vertices of cusp square areas that correspond to adjacent square tiles. For cusp square

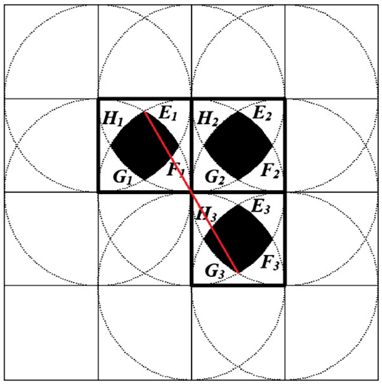

Fig. 4. Cusp-square configuration for adjacent square tiles.

$E_1F_1G_1H_1$, if a sensor s_i is placed at vertex E_1, the farthest sensor s_j from s_i should be placed at vertex G_3 of cusp square $E_3F_3G_3H_3$, which corresponds to a square tile that is adjacent to the one associated with cusp square $E_1F_1G_1H_1$. The distance between vertex E_1 and vertex G_3 is twice the radius of the circle passing through the vertices E_1, E_2, F_2, F_3, G_3 and H_1. The line segment E_1G_3 forms the diameter of that circle, *i.e.*, $E_1G_3 = 2r_s$. In other words, to ensure that the two sensors s_i and sj at vertex E_1 and vertex G_3, respectively, can communicate with each other, the radius of the communication disks of the sensors should be at least the value of line segment E_1G_3. Therefore, $r_c \geq 2r_s$.

Leveraging all the above-discussed and proved properties, we introduce our k-coverage protocol, called *k-CSqu*, which utilizes the cusp square areas of the square tiles of the square tessellation of a field of interest. Next, we discuss *k-CSqu* in detail.

5. Our k-coverage protocol using Cusp Squares

In this section, we discuss our k-coverage using *C*usp *Squ*ares (*k-CSqu*) protocol is a centralized protocol for deterministic sensing process, which is performed by the sink. Our protocol has two major steps:

- Step 1: Cusp Square generation for square tessellation
- Step 2: Sensor selection and scheduling

Next, we discuss both steps in detail.

5.1. Cusp Square generation for square tessellation

In this first step, before starting the rounds of k-coverage, the sink tessellates a planar field of interest using square tiles. Then, as discussed earlier, it constructs the cusp square areas for all square tiles of the tessellation in order to schedule the sensors for each k-coverage round. The generated cusp square areas remain static (unchanged) throughout all the k-coverage rounds for all square tiles, and act as restriction areas for the sensor selection process for k-covering the entire field of interest.

5.2. Sensor selection and scheduling

In this second step, the sink selects the sensors and schedules their participation in the k-coverage process. The main goal of this step is to select the sensors and schedule them in a way that their energy depletion rate is almost the same. This helps guarantee that all the sensors deplete their battery power (or energy) at almost the same time, *i.e.*, they have similar lifetimes. In addition, the second goal to be achieved is minimizing the battery

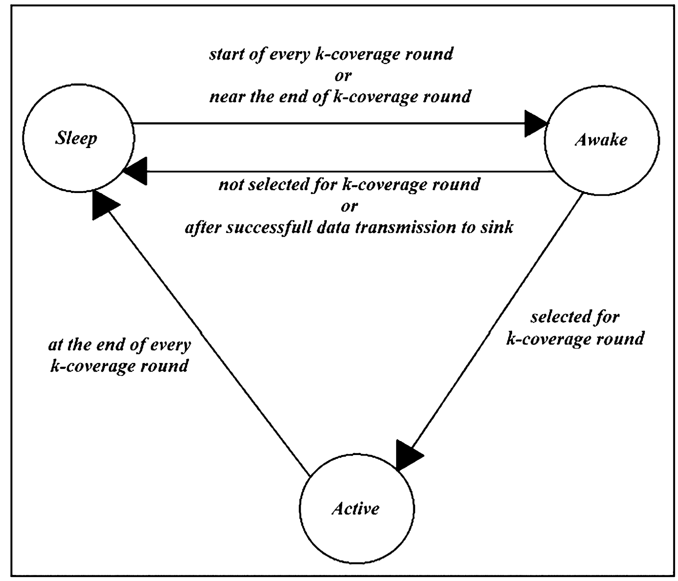

Fig. 5. Finite state machine.

power consumption per round in order to conserve the individual battery power of the sensors, which helps extend their lifetime. This will in turn help elongate the network operation lifetime. The sink identifies every sensor uniquely using its *id* and considers the sensors' locations and remaining battery power in the selection process for sensor scheduling (or duty-cycling) in every k-coverage round.

Initially, all sensors are in sleep mode and for each k-coverage round, the sensors that are in sleep mode wake up for the reception of scheduling instructions from the sink. Sometimes, the scheduled sensors might be around the cusp square areas but not inside. In such cases, the sensors will move inside cusp square area of their square tiles, thus, consuming battery power due to their mobility. The sink follows applies the results of Lemma 2 and Theorem 1 for selecting the sensors to k-cover a planar field of interest. At the end of this step, sink broadcasts the schedule to all sensors, which consists of the *id*s of selected sensors for the current k-coverage round. When a sensor receives the schedule, it checks whether its *id* is present in it. If so, the sensor deletes its *id* from the schedule, forwards the modified schedule to its one-hop neighbors, and stays active for participating in the coverage process. Otherwise, it simply forwards the schedule to its one-hop neighbors and switches to the sleep mode.

5.3. State transition diagram

According to the functioning of our proposed k-coverage protocol, k-CSqu, a sensor can be present in any of the three states, namely *Sleep*, *Awake*, and *Active*. The state transition diagram shown in Fig. 5 above summarizes the lifetime of a sensor. This diagram indicates all the three possible states and transitions between any pair of states. Next, we discuss these states and transitions.

- As discussed earlier, initially all the sensors are in the sleep mode. This means that they are in the Sleep state at the start of the operation of our k-coverage protocol, k-CSqu.
- In Sleep state, a sensor is not involved in any of the sensing and communication activities. Consequently, in this state, a sensor does not do anything, which enables it to dissipate only a minimal amount of battery power.
- At the start of every k-coverage round, all the sensors wake up and switch from the Sleep state to the Awake state.

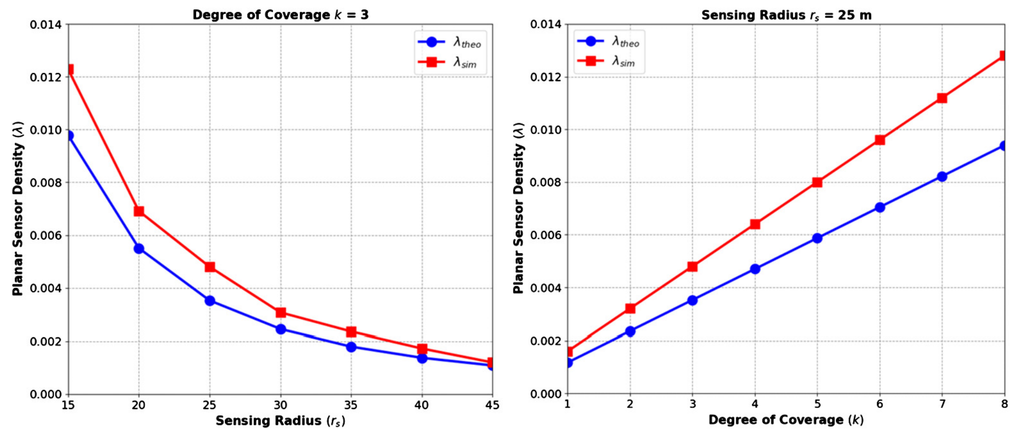

Fig. 6. Planar sensor density λ versus (a) sensing radius r_s and (b) degree of coverage k.

- In the Awake state, a sensor will be waiting and listening for the scheduling instructions that would be sent by the sink.
- When a sensor in the Awake state receives the scheduling instructions from the sink and finds out that it is selected to participate in the current k-coverage round, it transits from the Awake state to the Active state. Otherwise, this sensor is not selected to k-cover a field of interest, and switches immediately to the Sleep state.
- In the Active state, a sensor will be actively involved in the sensing and the communication activities. That is, it participates in the k-coverage process, where it covers an area of a field of interest and communicates with its neighbors to transmit and forward the sensed data toward the sink.
- Near the end of each k-coverage round, the sensors that are in the Sleep state switch to the Awake state. This will allow them to participate in the process of data forwarding to the sink, where the data is originated from the sensors that are in the Active state. This state transition will alleviate the burden that would be placed on the sensors in the Active state due to their sensing activities.
- Regardless of the state whether it is Active or Awake, every sensor sends its collected data to its neighboring sensors, and the sensed data is forwarded to the sink through a shortest path.
- Once the sensed data is successfully transmitted to the sink, all the non-scheduled sensors, which switched from the Sleep state to the Awake state, will switch back to the Sleep state from their current Awake state.
- At the end of every k-coverage round, each sensor in the Active state that has already successfully transmitted its collected sensed data to the sink will switch to the Sleep state and wait for the next k-coverage round instructions.

6. Performance evaluation

In this section, we present the simulation results of our proposed k-coverage protocol, k-CSqu, using an open source high-level simulator [1], which is built using *C* and *Python* languages. We have modified the simulator to simulate k-coverage scenarios where degree of coverage k and tiling shape are provided as inputs. Also, we have added functionalities for plotting multiple results of the simulations performed. Next, we specify our simulation setup. Then, we discuss the simulation results of our protocol for solving the connected k-coverage problem in PWSNs.

6.1. Simulation environment

Our k-coverage protocol k-CSqu can be employed on any planar area regardless of its geometrical shape, be an irregular or regular polygon, like triangle, rectangle, hexagon, or decagon, to name a few. In this paper, we have considered a square-shaped field of interest of side length 250 m. The initial battery power of sensor is assumed to be 70 J and as mentioned earlier in our energy model (Section 2.2), all forms of battery power consumption, namely data sensing, data transmission, data reception, sensor mobility, and control messages, are accounted for in order to guarantee a correct operation of our connected k-coverage protocol, k-CSqu. We assume that 1000 sensors are deployed in the monitoring field, which are randomly and uniformly deployed in the entire field of interest (Section 2.3). In fact, there are various sensing applications that deploy several sensors for their correct operation. For instance, the intruder detection and tracking application requires the deployment of a large number of sensors to accomplish the corresponding tasks appropriately. In order to complete their mission successfully, these sensors are indispensable for detecting any possible intrusions and also for tracking all the possible trajectories and movements of any intruder who attempt to access a critical environment or facility. Also, we assume that the radii of the sensing and communication disks of the sensors be 25 m and 50 m, respectively. All simulations are performed repeatedly for 100 times and all the results are averaged.

6.2. Simulation results

In this section, we present the simulation results of our k-CSqu protocol. In Section 6.3, we compare k-CSqu with DIRACC$_k$ [8] and RCH$_k$ [7].

Fig. 6 shows the variation of theoretical planar sensor density λ_{theo} (based on Theorem 2) and simulation planar sensor density λ_{sim} (for our k-CSqu protocol) with changing sensing radius r_s and degree of coverage k. Fig. 6(a) plots both λ_{theo} and λ_{sim} for various values of r_s, where $k = 3$. As expected, both λ_{theo} and λ_{sim} decrease with increasing r_s for a constant value of k. Fig. 6(b) plots λ_{theo} and λ_{sim} for various values of k, where $r_s = 25$ m. We observe that both λ_{theo} and λ_{sim} increase with increasing k for a constant value of r_s. Though the behavior is as expected, there is slight difference between the λ_{theo} and λ_{sim} that is clearly visible, and our protocol k-CSqu requires slightly higher sensor density compared to the one computed in Theorem 2. This is because, as calculated in Theorem 2, λ_{theo} considers all the common k-cover regions around the square tile, which includes the square area as well as the four curved areas on each side of each square tile.

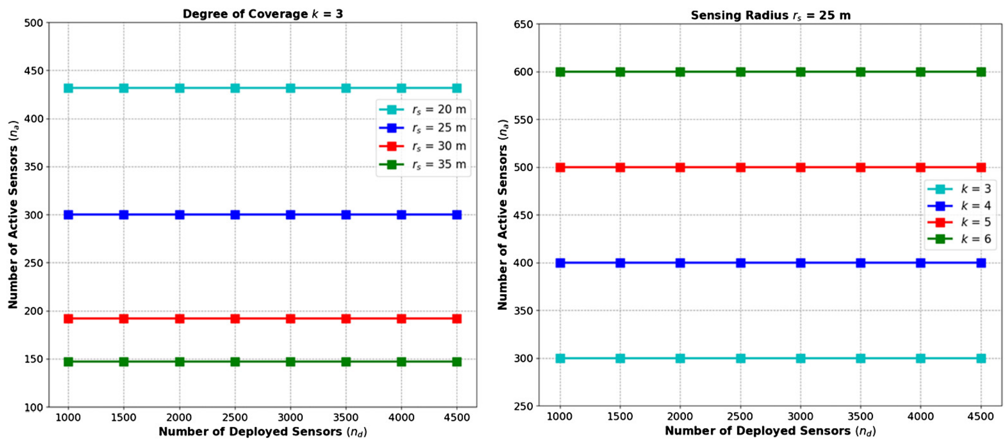

Fig. 7. Number of active sensors n_a versus Number of deployed sensors n_d for different (a) Sensing radius r_s and (b) Degree of coverage k.

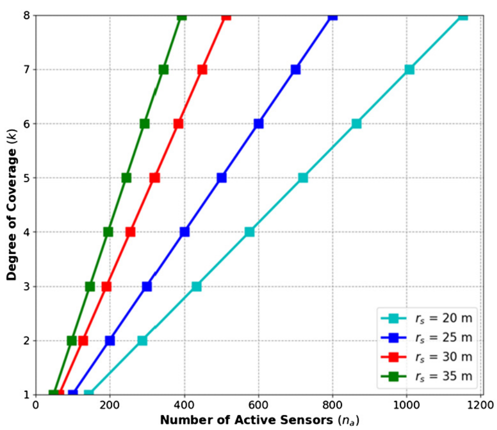

Fig. 8. Degree of coverage k versus number of active sensor n_a.

These curved areas form over k-covered regions in the field of interest. However, they are not considered in the calculation of λ_{sim}.

Fig. 7 shows the number of active sensors n_a, which are required to k-cover a field of interest, compared to the number of deployed sensors n_d for our k-CSqu protocol. In Fig. 7(a), we performed experiments by varying the radius of the sensors' sensing range r_s with $k = 3$, whereas in Fig. 7(b), we performed experiments by varying the degree of coverage k with $r_s = 25$. It is evident that for larger values of r_s, we require lesser number of sensors, whereas for larger values of k, we require higher number of sensors, for providing the desired coverage degree k. Moreover, in both experiments, it is clear that n_a depends only on the values of r_s and k, but not on the values of n_d.

Fig. 8 plots the variation of the degree of coverage k with regard to the number of active sensors n_a for our k-CSqu protocol. It is clear that k increases proportionally with n_a. Also, it is worth noting that for a constant number of active sensors, k increases as r_s increases. That is, larger values of the sensing range of the sensors r_s help augment the coverage degree k.

6.3. Comparison of k-CSqu with DIRACC$_\mathrm{k}$ and RCH$_\mathrm{k}$

In this section, we compare k-CSqu with DIRACC$_\mathrm{k}$ [8] and RCH$_\mathrm{k}$ [7]. As discussed earlier in Section 3, Ammari's works investigated the problem of k-coverage in PWSNs and proposed Reuleaux triangle-based k-coverage protocols [4–6,8] and regular hexagon-based k-coverage protocols [7], while considering a degree of coverage $k \geq 3$. Hence, we consider $k = 3$ for comparing our protocol k-CSqu with Ammari's protocols DIRACC$_\mathrm{k}$ [8] and RCH$_\mathrm{k}$ [7] which are proved to be better than CCP [22,24].

Table 1
Confidence levels and intervals.

Confidence Level	Confidence Interval	
	Upper Limit	Lower Limit
0.9	3.2258	3.2237
0.95	3.2258	3.2236
0.99	3.2259	3.2236

Fig. 9 plots the comparison of the simulation results obtained for the planar sensor density λ with regard to k-CSqu, DIRACC$_\mathrm{k}$ and RCH$_\mathrm{k}$ protocols with varying sensing radius r_s in Fig. 9(a), and varying degree of coverage k in Fig. 9(b). From both plots, it is clear that our protocol k-CSqu has lower sensor density λ compared to that of DIRACC$_\mathrm{k}$ and RCH$_\mathrm{k}$, for any values of r_s and k. Thus, for a desired degree of coverage k of a field of interest, k-CSqu requires lesser number sensors compared to DIRACC$_\mathrm{k}$ [8] and RCH$_\mathrm{k}$ [7]. Conversely, compared to DIRACC$_\mathrm{k}$ [8] and RCH$_\mathrm{k}$ [7], k-CSqu can offer a higher coverage degree k for a constant λ. Also, k-CSqu requires lower sensing radius of the sensors for a constant λ, which indicates that k-CSqu requires less powerful sensors in terms of their sensing range compared to DIRACC$_\mathrm{k}$ [8] and RCH$_\mathrm{k}$ [7].

Fig. 10(a) shows the differences between k-CSqu, DIRACC$_\mathrm{k}$ and RCH$_\mathrm{k}$ in terms of the required total number of active sensors n_a compared to the total number deployed sensors n_d. As inferred earlier from Fig. 9 results, Fig. 10(a) proves that lesser number of active sensors are required for our k-CSqu protocol for attaining the same degree of coverage k. Fig. 10(b) plots the degree of coverage k versus number of active sensors n_a for k-CSqu, DIRACC$_\mathrm{k}$ and RCH$_\mathrm{k}$ protocols. This plot is evident and proves our earlier inference that for the same number of active sensors, k-CSqu offers higher degree of coverage k compared to that of DIRACC$_\mathrm{k}$ and RCH$_\mathrm{k}$. Therefore, for any coverage degree k, our protocol k-CSqu yields significant amount of energy savings, which in turn helps extend the operational network lifetime.

We have computed the confidence interval for Energy Consumption (per round) of all sensors for the plot in Fig. 11. These Confidence Levels 90%, 95%, and 99% are shown in Table 1 above.

Fig. 11 plots the remaining energy versus time to reflect the energy consumption rate and operational network lifetime of k-CSqu, DIRACC$_\mathrm{k}$ and RCH$_\mathrm{k}$ protocols. The results of this plot prove our earlier inferences, which are derived from the results of Fig. 10(a) and 10(b), and it is evident that the operational network lifetime obtained for k-CSqu is higher than that of DIRACC$_\mathrm{k}$ and RCH$_\mathrm{k}$.

Fig. 12(a) below plots n_a versus r_s, whereas Fig. 12(b) plots n_a versus r_c with $r_s = 25$ m, for different values of k. In both cases, we have considered the values of k as 3 and 4. From these results, it is evident that k-CSqu offers higher coverage degree k with

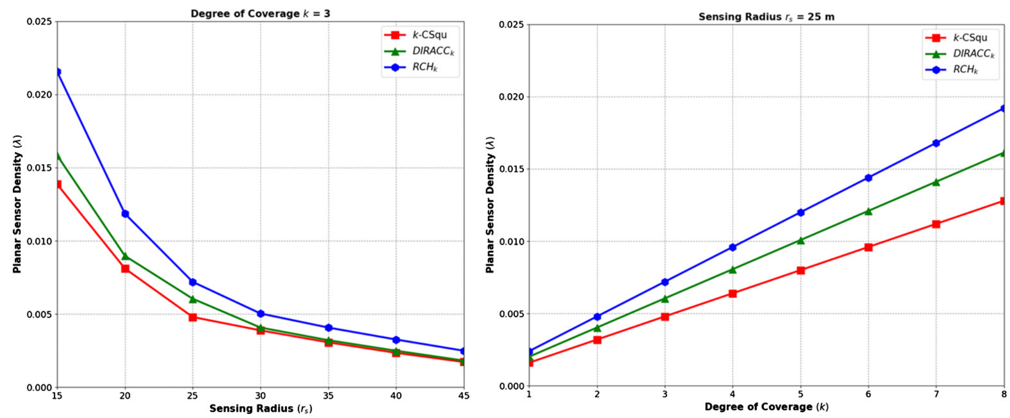

Fig. 9. Comparison of k-CSqu with DIRACC_k and RCH_k: Planar sensor density λ versus (a) sensing radius r_s and (b) degree of coverage k.

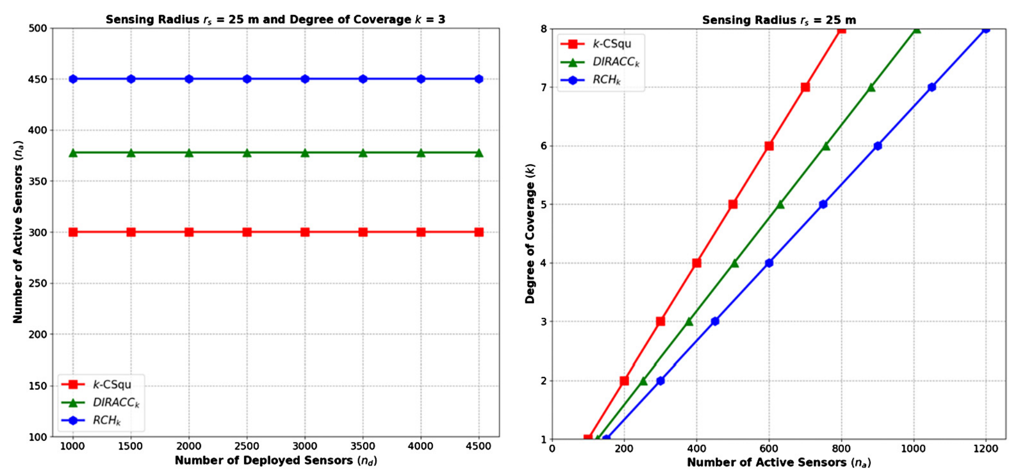

Fig. 10. (a) Number of active sensors n_a versus number of deployed sensors n_d. (b) Degree of coverage k versus number of active sensor n_a (comparing k-CSqu and DIRACC_k).

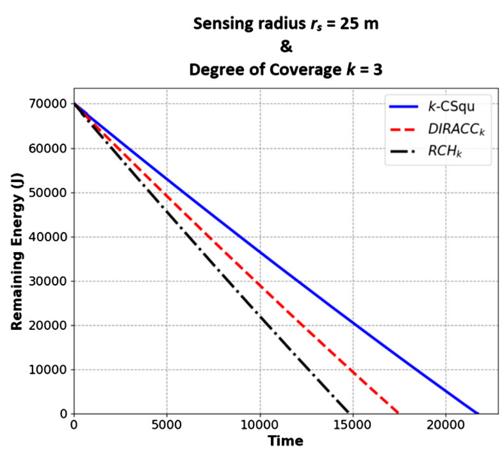

Fig. 11. Remaining energy versus time (indicating network lifetime).

fewer active sensors compared to DIRACC_k and RCH_k. It is worth noting that for k-CSqu, DIRACC_k and RCH_k protocols, the number of active sensors n_a depends only on r_s and k, and does not depend on r_c.

7. Conclusion

In this paper, we investigate the connected k-coverage problem in PWSNs using a square tessellation-based approach. Specifically, we address the sensor placement problem by constructing a cusp square area inside each square tile and compute the planar sensor density required to maintain k-coverage of the field. Then, we establish a relationship that should exist between the sensing range and communication range of the sensors to maintain network connectivity, thus, ensuring connected k-coverage configuration during the network operation. Furthermore, based on all the proved theoretical results and properties, we propose a centralized k-coverage protocol, k-CSqu. Based on the simulation results, it is proved that k-CSqu has better performance and is more energy-efficient compared to DIRACC_k [8] and RCH_k [7] in terms of number of active sensors required and operational network lifetime for the k-coverage process. It is worth mentioning that DIRACC_k [8] and RCH_k [7] was proved to perform better than CCP [22,24].

Our future work, which will focus on extending our proposed cusp square areas of square tessellation approach, is four-fold. First, we plan to consider in our study heterogeneous sensors, which have varied characteristics in terms of their initial energy, sensing range, and communication range [6,7]. Second, we will generalize our work to account for the irregularity of the sensing and communication ranges of the sensors using more general and realistic sensing and communication models, which are stochastic [4,7] rather than deterministic. Third, we want to extend our proposed approach to investigate the problem of connected k-coverage in three-dimensional WSNs, such as underwater WSNs. Finally, we will be placing our protocols into practice using a sensor-testbed [9] in order to determine whether they can be used in practical situations.

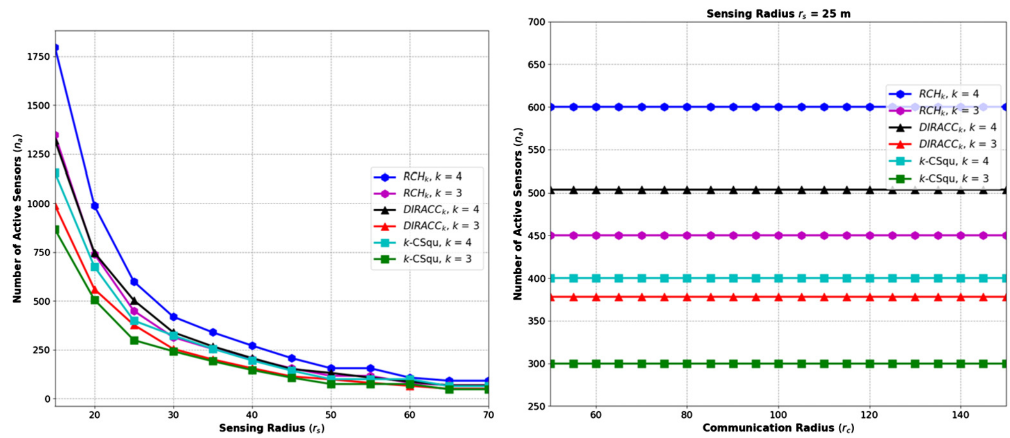

Fig. 12. Number of active sensors n_a versus (a) Sensing radius r_s and (b) Communication radius r_c.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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