Thesis for the Degree of Doctor of Philosophy

Maximizing Coverage Quality Using Minimum Number of Nodes in Clustered Directional Sensor Networks

Registration No: 180/2016 - 2017

Department of Computer Science and Engineering
University of Dhaka
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by

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Registration No: 180/2016 - 2017

Supervised by

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Submitted to the Department of Computer Science and Engineering
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As the candidate's supervisor, I have approved this dissertation for submission.

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Declaration of Authorship

We declare that this thesis titled "Maximizing Coverage Quality Using Minimum Number of Nodes in Clustered Directional Sensor Networks" and the works presented in it are our own. We confirm that:

- The full part of the work is done during PhD research study in University of Dhaka, Bangladesh.
- Any part of this thesis has not previously been submitted for a degree or any other qualification in this University or any other institution.
- We have consulted the published works of others with appropriate references.
- This thesis work is done entirely by us and our contributions and enhancements from other works are clearly stated.

Signed: ______________________

Candidate

Countersigned: ______________________

Supervisor: Dr. Md. Abdur Razzaque

Co-supervisor: Dr. Md. Mustafizur Rahaman

Abstract

The invention of directional sensor nodes has given birth of a special kind of network namely Directional Sensor Network (DSN), which provides better network lifetime and sensing coverage compared to its omni-directional counterpart. These two cutting-edge features help DSNs attracting interests of research and industrial communities, particularly for the areas of high quality sensing in Smart City applications including healthcare, infrastructure security, traffic and access monitoring, etc. In this thesis, we focus on two fundamental reasearch topics of DSNs - area coverage and target coverage.

The area coverage problem in Directional Sensor Networks (DSNs) presents great research challenges including minimization of number of active sensors and overlapping sensing coverage area among those, determination of their active sensing directions in an energy-efficient way, etc. Existing solutions permit to execute coverage enhancement algorithms at each individual sensor nodes, leading to high communication and computation overheads, loss of energy and reduced sensing coverage. In this thesis, we first formulate the problem of maximizing area coverage with minimum number of active nodes as a mixed-integer linear programming (MILP) optimization problem for a clustered DSN. Due to its NP-completeness, we then develop a greedy alternate solution, namely α-overlapping area coverage (α-OAC). In α-OAC, each cluster head (CH) takes the responsibility of determining the active member nodes and their sensing directions; where, each sensing node is allowed to have at most $\alpha\%$ coverage overlapping with its neighbors. The α-OAC CHs activate a sensor node if and only if the later has sufficient residual energy and send other member nodes to the *sleep* state. The proposed α-OAC system is distributed and scalable since it requires single-hop neighborhood information only. Results from extensive simulations, done in Network Simulator version 3 (ns-3), reveal that the α-OAC system outperforms state-of-the-art works in terms of area coverage, network lifetime and operation overhead.

Conventional researches on target coverage in Directional Sensor Networks (DSNs) mainly focus to increase the network lifetime, overlooking the coverage quality of targets; especially, they don't consider the targets that have heterogeneous coverage requirements. Increasing sensing quality is of utmost importance to ensure comfort living in Smart Cities. In this dissertation, we have designed a generalized framework, namely MQMS-DSN (Maximizing coverage Quality with Minimum number of Sensors in DSN), that has the ability to maximize the target coverage quality or the network lifetime or to make an efficient tradeoff between the two following an application demand. Using a probabilistic model for measuring the sensing coverage quality, we have developed optimal, suboptimal and greedy solutions for MQMS problem. Empirical evaluations of the proposed MQMS systems have been carried out in ns-3. The results show the effectiveness of the proposed systems compared to state-of-the-art-works in terms of sensing quality and network lifetime.

Acknowledgment

At last the journey comes to its end point and I have got the opportunity to express my sincere honors and thanks to those who helped me throughout this research.

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Chapter 1

Introduction

1.1 Introduction

Now-a-days, it seems that we are living in a vast sea surrounded by sensors just like air encloses us. In todays world, it is quite impossible to pass a day without enjoying sensor based services. In general, a sensor node is a small-tiny battery-powered device [1, 2, 3], mainly consisting of sensing, processing and communication units. It is difficult to answer the question what cannot be done with the sensors. Starting from the human's five basic senses - hearing, sight, touch, smell and taste, the latest sensors are capable to measure heart rate, electrical voltage, gas, light, sound, temperature, distance and many more [2, 4, 5, 6]. A wireless sensor network (WSN) consists of spatially distributed autonomous sensor devices that can monitor physical or environmental conditions collaborating with each other [1, 2, 7]. Current progresses in micro-electro-mechanical systems (MEMS) technology, digital electronics and wireless communications have added the ability to apply the sensors to any field, and in any environment [1, 2, 7, 8].

A Directional Sensor Network (DSN) is an special kind of WSN, mainly consists of large number of small battery powered directional sensor devices that can sense and report event data to a sink [9, 10, 11, 12]. A directional sensor device can, at a certain time, sense in only one direction or in a particular angle as it has limited range of sensing capabilities contrasting to omni-directional sensors. Directional camera, ultrasonic or infrared sensors [13, 14, 15, 16, 17, 18] are some commonly used directional sensors. The DSNs offer increased network performance and sensing coverage compared to their omni-directional counterpart and these two cutting-edge features help DSNs attracting interests of research and industrial communities, particularly for the areas of high quality sensing in Smart applications including health-care, infrastructure security, traffic and access monitoring, military surveillance and many more [4, 9, 19, 20, 21].

One of the very fundamental and prominent research problems in WSNs is the sensing coverage problem [10, 22]. Usually, coverage indicates how much quality of service (surveillance) can be maintained by a particular network [2, 22, 23]. The settlement of coverage problem is the premise and base of implementing any surveillance tasks. Under the demand of various monitoring applications the coverage problem can be explored from different perspectives. Two variations of coverage problems are *area coverage* and *target coverage*. The problem of *area coverage* refers to maximizing the sensing area coverage percentage of perception area with minimum number of sensors, termed as MCMS, which is a well known classic problem [10, 24]. It is of great importance for many real-life applications including security monitoring of historical or vital places, wildlife monitoring in the forests, battlefield surveillance, etc [9, 15]. In the literature, this *area coverage* problem has been proved as an NP-hard one [10, 25] and a greedy alternative or heuristic approach is used to achieve near-optimal solution. The complexity of the problem is further complicated for directional nodes since we need to fix the active sensing nodes as well as their sensing sectors [9, 10, 26] so that the area coverage is maximized by using as minimum number of nodes as possible. Furthermore, finding the solution of the area coverage problem is more sophisticated as overlapping happens among the sensing regions of the sensor node that forces to activate a large portion of sensor nodes, resulting high energy depletion. Also, it is desirable that the solution strategy has the ability to maintain the scalability of the network.

Besides achieving full or partial coverage, some applications may need to monitor only specific points or targets in the terrain known as *target coverage* [11, 12, 27, 28]. For DSNs, a large number of sensors are dropped to monitor dispersed targets of interests within a given terrain. Conventional researches on *target coverage* mainly focus to enhance the network lifetime ensuring continuous monitoring of as maximum number of targets as possible [10, 23, 29] i.e., they try to maximize the number of covered targets assuming each target has equal importance. However, in reality, distinct targets may have different significance and their required coverage qualities might greatly differ from each other [30, 31]. Moreover, the conventional researches based on binary disk model fail to focus the actual sensing behaviors of the sensor nodes [22, 32, 33].

From the above discussion, it is apparent that for *area coverage* problem providing maximum coverage through activating minimum number of sensors is as important as minimizing the overlapping regions. Note that, this problem can be translated into minimizing coverage area overlapping among the sensor nodes while all points in the target area are covered. We also observe that, focusing on only coverage quality or network lifetime without considering the both, failed to reflect the actual requirements of diverse applications. Moreover, if the residual energy and the coverage quality are not considered jointly, it is difficult to achieve enhanced network lifetime since the energy depletion rates of different sensor nodes vary greatly from each other.

In this dissertation, we explore the coverage problem in terms of overlapping areas, coverage quality, node's energy and network lifetime. To accomplish the aforementioned challenges, at first, we have developed a network lifetime aware area coverage system, that enhances the coverage area as well as limits the percentage of overlapping area coverage among nodes by a threshold for a clustered DSNs. Next, to address the sensing coverage quality of specific points or targets in the terrain, we develop a general framework, that is applicable to maximize the target coverage quality or the network lifetime or to make an efficient tradeoff between the two following application demands.

In the rest of this chapter, we give an overview of DSNs, pros and cons of DSNs, their applications. Next, we formulate the thesis problem, scope of the work, design methodology and finally give focus on our thesis contributions.

1.2 An Overview of DSNs

Most of the conventional researches on wireless sensor networks adopt omni-directional sensors [1, 24, 34]. However, various directional sensors, e.g. ultrasonic sensors, infrared

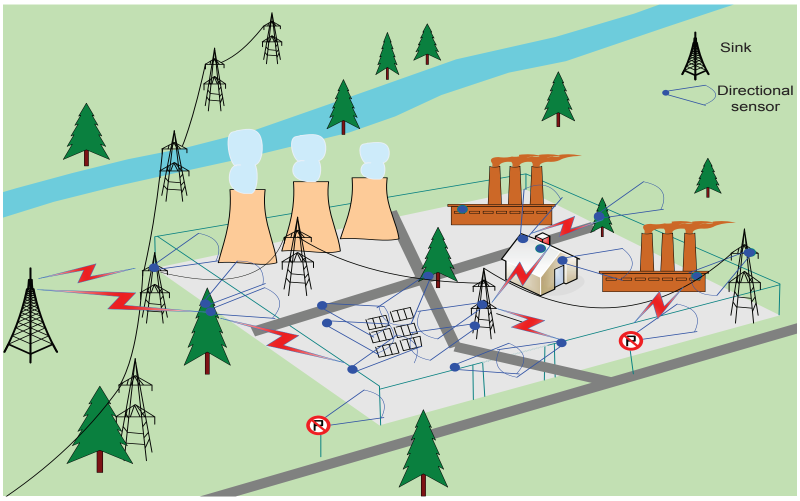


Figure 1.1: Architecture of a Directional Sensor Networks

sensors, video sensors and audio sensors are frequently used in numerous practical applications [9, 15, 16, 17]. A directional sensor network (DSN) normally consists of directional sensors that can sense only in a particular direction (Fig. 1.1). In general, wireless sensors come into two sensing shapes: omni-directional (disk-shaped) and directional (fan-shaped) [9, 10, 35]. While the omni-directional sensors follow circular sensing model, sector-like sensing behavior is adopted in directional sensors. Unlike omni-directional sensors, both the location (position) and orientation (direction) are required to identify a directional sensor. Day by day, the demand of using directional sensors in the networks is upsurging for their low cost and energy conservation, as a result diverse smart applications, e.g. infrastructure security, environmental monitoring, military surveillance, agricultural assistance, traffic and access monitoring, health-care, person location service are developed using DSNs [9, 12, 35, 36]. Some of the benefits of DSNs are highlighted as follows:

- Increased network lifetime: Energy is one of the key concerns in any WSNs as sensors are small battery powered device and it is not always easy to change or recharge the sensors. Therefore, prolonging the network-life is a fundamental objective of WSNs that can be solved using the benefits of DSNs. Compared to omni-directional sensor, directional sensors consume less energy for their directional properties. If a sensor has a unified lifetime E for serving omnni-directionally i.e., in all directions simultaneously, then a directional sensor can serve in a particular sector providing lifetime by multiple of the total direction with E. As a result, DSNs can boost up the lifetime of the network a lot [9, 10, 37].

- Increased sensing quality: It is observed that, due to their directionality, directional sensors can enhance the sensing quality as a result, DSNs can increase the coverage efficiency [26, 38].
- Enhanced network performances: In DSNs, the network performance is enhanced as directional communication can scale down the interference and fading in the network [26, 35, 38].

1.2.1 Directional Sensor Device

The fundamental difference between an isotropic sensor and directional sensor is that, a directional sensor has a finite angle of view and hence, cannot sense the whole circular region like directional sensors. At a given time, directional sensors work in a specified direction and may adjust their working direction based on the necessity of the application. A directional sensor node has typically four basic components: a processing unit, a sensing unit, a communication unit and a power unit [5, 39] shown in Fig. 1.2 . Normally a micro-controller or microprocessor with memory resides in the processing unit and its job is to perform tasks and processes and control the functionality of other components. The sensing unit contains one or more sensors with analog to digital converters (ADCs). Sensors measure physical data and based on the observed phenomenon generate analog signals that are converted to digital signal and fed to processing unit. The communication unit consists of a device called transceiver that is capable of doing the function transmitter and receiver. Typically, transceivers can be put into different operational states: transmit, receive, idle and sleep. Battery is used in the power unit to supply power to all other components. Besides, a sensor node may also consists of some other

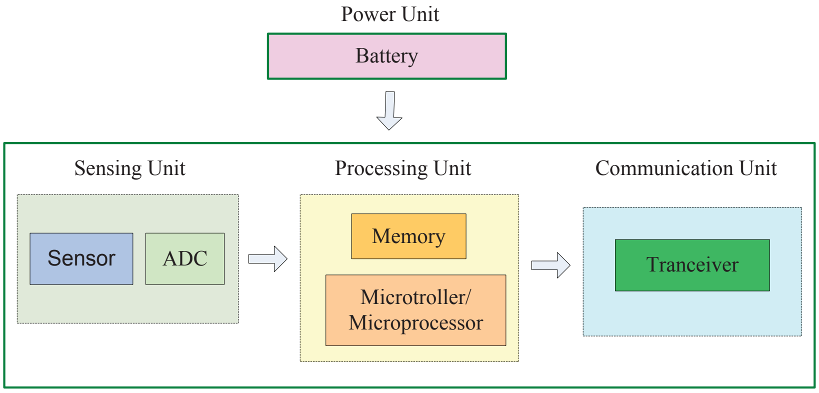


Figure 1.2: Internal architecture of a sensor node

units for some specific application (e.g., GPS).

Sensors can be categorized using two characteristics - energy and direction. Based on energy related issue, sensors may be active (Radar) or passive (light, thermometer, microphones, hygrometer) [2, 39] sensor and based on direction omni-directional (temperature, light sensor) [2] and directional sensors. Some of the frequently used directional sensors are ultrasound sensors, infrared sensors and video sensors (listed in table 1.2.1) [9, 26, 35].

Figure 1.3: Example of some infrared sensors

- Infrared sensors: An infrared sensor (IR) is an electronic instrument which is used to sense certain characteristics of its surroundings either by emitting and/or detecting infrared radiation (Fig. 1.3). Using the infrared waves, that are not visible to the human eye, infrared sensors are capable of measuring the heat being emitted by an object and detecting motion. The key advantages of infrared sensors include their simple circuitry, low power requirements and their portable features [9, 16, 35, 38].

Figure 1.4: Example of some ultrasound sensors

- Ultrasound sensor: An Ultrasound or ultrasonic sensor is able to measure the distance of an object by using sound waves [18](Fig. 1.4). The distance is calculated by sending out a sound wave at a specific frequency and listening for that sound wave to bounce back. As ultrasonic sensors utilize sound rather than light for detection, they are frequently used in applications where photoelectric sensors may not [9, 18, 35, 38].

Figure 1.5: Example of some video sensors

- Video sensor: Video sensors are used to evaluate scenes recorded by a video camera [17](Fig. 1.5). Objects and their characteristics (size and speed for example) are compared and verified with some pre-set examples or templates and if there is a match between object and model, the frame and the objects are marked digitally which can be used for further processing. Video surveillance (CCTV) systems are mostly deployed with video sensors and the commercial use of video sensors is upsurging day by day [9, 17, 35, 38].

Besides the above sensors, at present there are also some directional sensors available in the market like audio sensors, passenger sensors, people sensor that function using the infrared or ultrasound technology.

Table 1.1: List of some practical sensors

Sensors	**Manufacturer**
ADCM-1700 (video sensor)	Angilent
OV7620 (video sensor)	Omnivision
Ultra-U family (ultrasound sensor)	Senix
RU18-D90 family (ultrasound sensor)	Riko
Parallax PIR sensor (Infrared sensor)	Senix
MP Motion sensor (Infrared sensor)	Senix

1.2.2 Sensing Models for Directional Sensors

In order to facilitate the requirements of the monitoring application, various types of sensor nodes (e.g. temperature, smoke, humidity, infrared, audio/video etc) are utilized. Several attributes exist for categorizing available sensors and sensing model, an indication of the sensitivity or the capability of the sensor is one of them [9, 22, 33]. The sensing model can further be classified according to the sensing space, ability as illustrated in Fig. 1.6.

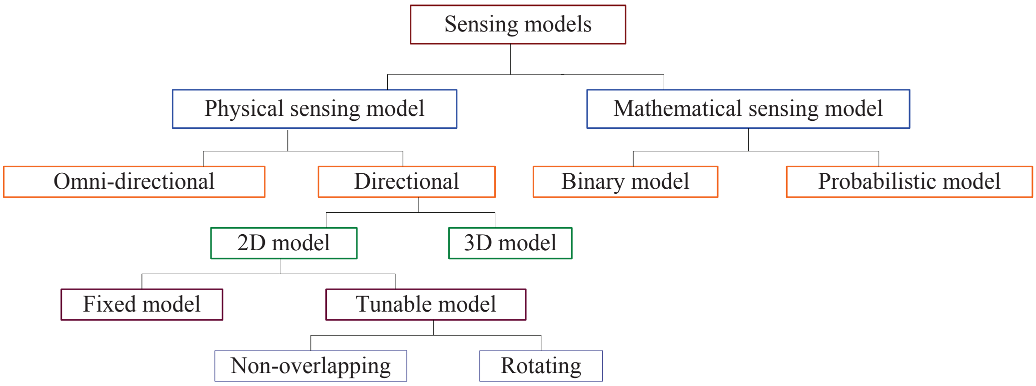


Figure 1.6: Classification of sensing models

Unlike conventional omni-directional sensor model, a directional sensor has a finite angle of view and cannot sense the whole circular zone. The simplified 2D fixed directional sensor model was first introduced in Ma et al. [29] that has a sector-based sensing area. A directional sensor is represented by 4-tuple $< (x, y), R_s, \vec{V}, \theta_s >$ where (x, y) is the location coordinate; R_s is the maximum sensing radius; $\vec{V}$ is the center line of sight of the sensor termed as sensing orientation or field of view and θ_s is the offset angle of the field of view (Fig. 1.7). The directional sensing model can be turned to a conventional sensing model using $\theta_s = 360°$. A directional sensor network can be described more precisely by 3D model [40]; however, due to the high complexity in design and analysis, most of the existing works focus on the 2D model [9, 35].

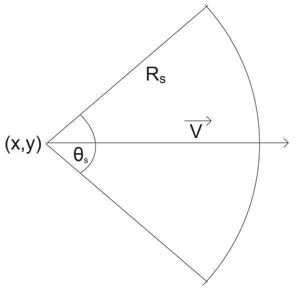


Figure 1.7: The 2D directional sensing model

The Boolean or binary disk model [9, 22, 32, 33, 35] states that a point is said to be covered if it is inside the sensing sector of the node, otherwise not. A majority of the existing researches have been conducted based on the binary model. However, due to the variation of the RF signal, in reality a sensor would be more accurately observed an event that is physically nearer to the sensor than one that is close to the edge of its sensing range [9, 22, 32, 35]. Therefore, a probabilistic model that consider the distance and physical property combinedly is a more suitable sensing one.

Besides the fixed model the tunable directional sensing model can be further categorized into two types: non-overlapping model and rotating model. In non-overlapping model or the sector-based model, a directional sensor can work only in between a finite set of mutually disjoint sensing sectors. A continually Rotating Directional Sensor (RDS) model is explored in [41] where a sensor can rotate at a certain speed and the sensing angle θ_s can be varied from 0°to 360°.

1.2.3 Sensing Properties and Behaviors

A directional sensor node has some distinct sensing features, that put out some new challenges for designing applications using DSNs [9, 26, 35]. A directional sensor hold all the basic properties of isotropic sensing model such as fixed radius, location co-ordinate. Besides, it holds some some unique features like sensing orientation, sensing angle, field-of-view (FoV) and so on [9, 35]. The working direction or the sensing orientation of a directional sensor is one of the crucial parameters for network coverage. Note that, due to this feature, the coverage performance can be varied significantly even if two directional sensor nodes are located at close proximity. In DSNs, nodes are usually deployed with random distribution and sensors need to adjust their working direction to provide high coverage ratio.

Unlike a traditional omni-directional sensor node, a directional sensor has limited angle of sensing coverage that brings extra challenges. Theoretically,the angle of view or the sensing angle may vary from 1° to 360° and to achieve better coverage excessive number of nodes is required when the sensing angle is small. The field-of-view (FoV) denotes the maximum volume of a directional sensor that can be decided by sensing orientation, location coordinate and sensing radius.

The sensing behaviors of a directional sensor can be represented by its motility and mobility. The ability of adjusting the working direction based on the application demand, is the motility of a sensor node [9, 35]. A significant advancements on coverage can be achieved by judicious actuation, e.g., combining two or more actuations together. For video sensor nodes three defined motions are defined: pan, tilt and zoom [9, 35]. Motility can be easily be implemented into sensors for the low cost of hardware and low energy overhead.

Although, sensor nodes are deployed randomly and densely, it is not always possible to achieve higher coverage ratio after the initial deployment. Therefore, some sensor nodes have the ability to relocate those to new positions i.e., mobility in order to potentially fill the coverage holes and contribute to provide better coverage.

1.2.4 Communication Models for Directional Sensors

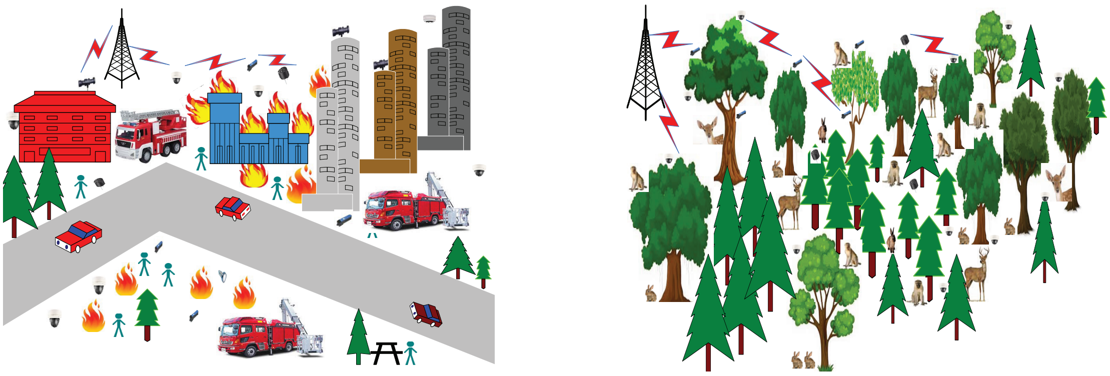
Multi-hop communication is highly used in WSNs since the destination sink is typically located far away from most of the sensor nodes deployed in a field [9, 42, 43]. Furthermore, long-distance single-hop communication is costlier than low-range multi-hop communication. In DSNs, the communication among the antenna can be happened using four ways: (1) omni-directional transmission and reception, (2) directional transmission - omni-directional reception,(3) omni-directional transmission - directional reception, and (4) directional transmission - directional reception. In the first case, the communication happens using the same procedure as omni-directional sensor networks. For the later case, when communication is directional, there also arise two situations: (a) sensing and communication directions are the and (b) sensing and communication directions are different. For these choices, the connectivity issue becomes more complicated in DSNs than its counter-part omni sensor networks; therefore for simplicity most of the existing works assume omni-directional communication model [9, 42, 44, 45].

1.2.5 Clustering in Directional Sensor Networks

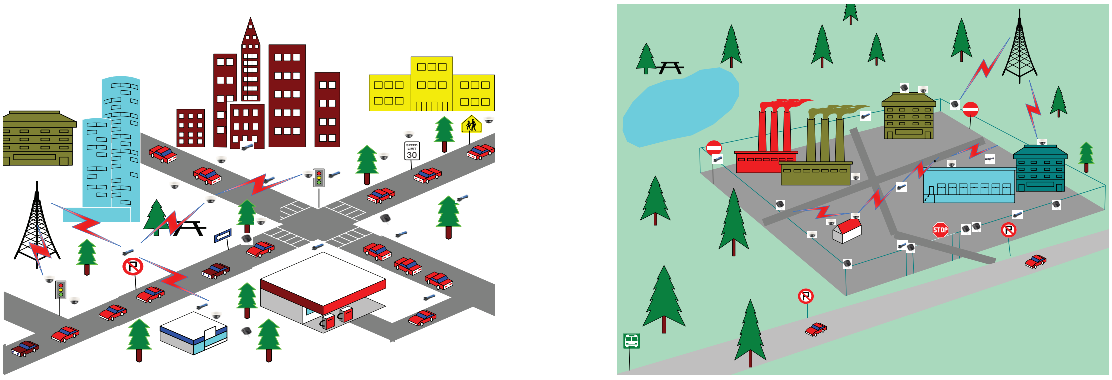
In sensor networks, usually nodes are distributed without any fixed infrastructure that demands them to be able to self-configured. To share the information across the network and among the sensors, direct communication to the sink is sometimes not possible, rather to enhance the scalability and energy conservation multi-hop communication is more suitable. Therefore, nodes are grouped into clusters [38, 46, 47] to maintain the scalability and energy conservation in the network. In this dissertation, we have developed our proposed solution exploiting the advantages of clustering in the network.

1.2.6 Applications of Directional Wireless Sensor Networks

A lot of promising applications are being developed using DSNs, some of them are discussed here.



(a) Emergency response (b) Forest monitoring



(a) Traffic monitoring (b) Security monitoring

Figure 1.8: Some applications of DSNs

- *Environmental applications:* Because of growing concerns about the impacts of humans in the environment, various applications are developed in the environmental sector. Habitat monitoring, ecosystem or bio-diversity mapping, forest fire detection are example of some applications where DSNs are widely used [48, 49, 50, 51]. For example, DSNs can be a very useful technology to monitor intruder attack and tracking of animals in the forest as shown in Fig. 1.8(b).

- *Health-care applications:* The health-care field is always searching for more powerful and efficient ways to aid the patients with the best care and comfortable services. Now-a-days, the prosperity of a nation can be measured by the health-care facilities provided to the citizens. Using DSNs various health-care applications are now easily accomplished, e.g., monitoring the patient and updating their conditions, hospital monitoring, observing the elderly-people in home, tele-medicine and many more [4, 15, 48, 52].

- *Military surveillance:* The settlement of coverage problems is the foundation and pre-dominant for implementing military surveillance tasks that can be conveniently employed using the benefits of DSNs. Miscellaneous military applications are evolved using DSNs like intruder detection, battlefield Surveillance, target (enemy) tracking, equipments safeguarding, forces monitoring, etc [4, 27, 28, 53].
- *Emergency responses:* Emergency situations may arise at any moment due to the random environmental events or may be occurred by man e.g. terrorist or criminal activities. Since DSNs are combined with different types of IR, ultrasound or audio, video sensors, they can be employed for disaster response, surveillance, intruder warning and due to their advantages they can provide accurate results to the administrator [4, 48, 54]. For example, emergency situation can be handled more quickly by simply establishing a DSN as shown in Fig. 1.8(a).
- *Transportation systems:* DSNs can be easy and effective solutions to the diverse traffic related applications. Traffic monitoring, car parking, vehicle monitoring systems are now developed using DSNs to facilitate the administrative and user community [4, 55, 56, 57]. For example, DSNs can be used to provide more quality to the crucial points to monitor the traffic more accurately and precisely as shown in Fig. 1.8(c).
- *Security surveillance applications:* Security monitoring is now the burning issue to all and everyone is concern about it. Applying a proper security system became a necessity for enterprise buildings, shopping malls, grocery store, historical places etc [53, 58, 59, 60]. In surveillance networks, visual sensors combined with video summarization technology are used for detection of abnormal events and intrusions and day by day use of DSNs in security monitoring system is high rising.

Architecture of such a network is shown in Fig. 1.8(d).

- *Smart city and IoT*: The smart city, smart homes, smart grid, smart water networks, intelligent transportation, are infrastructure systems that have changed our ways of living more than we ever thought possible. Such systems are possible using the concept of the Internet of things (IoT), where the entire physical infrastructure is closely coupled with information and communication technologies through sensors so as to enable intelligent monitoring and management services via the utilization of networked embedded devices [19]. The DSNs can be used to develop such IoT based smart applications like smart homes, intelligent transportation, surveillance IoT, healthcare-IoT, etc [6, 61, 62, 63, 64].

1.3 Problem Description and Solution Methods

One of the most fundamental and classic problems in WSNs is sensing coverage [9, 22, 65]. Finding an appropriate solution of coverage problem is the key of any surveillance task. The notion of coverage can be considered as a measure of quality of service (QoS) for sensor networks [22]. Once nodes are deployed in the terrain, the basic function of any WSN application is to collect data from the environment and hence providing coverage to the important points is necessary. In the literature, coverage problem in WSNs has been widely explored and researched and most of the sensor applications aim to provide maximum coverage with minimum sensors. The coverage problems can be classified in three types:

- Area coverage: In area coverage, each point in the terrain is under the surveillance of at least one sensor [1, 9, 22]. As, each point needs monitoring, for this type of coverage the sensing nodes are densely deployed that results highly overlapped coverage. “Art gallery problem, forest protection against fire” are examples of area coverage problem [66].

- Target coverage: In target coverage, it is required to select sensors in a given area that can monitor only a limited of discrete objects/targets or a set of interesting points [12, 26, 28, 38] .
- Barrier coverage: Barrier coverage ensures the detection of events happened crossing a barrier of sensors [27, 35, 36, 38].

In addition to this, some sensor applications require high level of sensing reliability and need to monitor the target point with multiple sensors, say k sensors. This type of coverage problem is known as k-coverage problem [35, 67].

1.3.1 Coverage Enhancement Approaches in DSNs and Challenges

In DSNs, several approaches can be adopted to enhance the coverage ratio in the environment. The nodes nodes can be deployed in the terrain using two approaches: (a) *pre-determined deployment* and (b) *random-deployment*. The *pre-determined deployment* strategy considers the required number of nodes is known before the deployment of nodes that can be calculated using some mathematical formulation [68, 69]. This deployment approach is normally used for indoor applications like security of a museum. However, this approach is not always suitable due to the cost and computation complexity as well as for the unknown environment. For this reason, *random deployment* is more preferable and popular.

Using *random deployment* strategy, i.e., deploying more directional sensor nodes compare to theoretical assumption, can give coverage to more regions [9, 10, 25, 38]. However, it is not possible to ensure 100% coverage guarantee for random deployment of nodes. Besides, it requires a high budget as the prediction of required number of nodes is difficult.

In order to achieve high coverage ratio, another approach is to adjust *working direction*, *sensing radius,* and *angle of view* [10, 38]. Compared to an omni-directional sensor node, the probability of overlapping among the sensing regions of directional sensor nodes is quite notable, therefore, most of the related studies give importance on adjusting the working directions of the sensor nodes. Compared to the former method, changing the angle of view and sensing radius incurs huge energy depletion and cost.

Mobility can sometimes be used to increase the coverage percentage of the terrain. In the network, some nodes may not function properly and it is not always easy to replace the nodes, therefore coverage holes may be created. The *mobility* feature of sensor nodes can be used to recover this problem [70]. However, a directional sensor node with mobility feature is more prone to different kinds of failures as well as costly. It is examined that, to move a sensor node only 1 m from one location to another, it takes almost 30 times more energy than transmitting 1 KBytes of data [9].

Re-deployment may be another approach to enhance the coverage where initial random deployment fails to provide sufficient coverage. Nevertheless, the available redeployment policies, incur a huge cost in the network [71]. Sometimes, both the static and mobile nodes are used to provide coverage, i.e., *hybrid* solutions are used to enhance the coverage ratio [9, 72, 73]. Using hybrid solutions, balance can be achieved by using a combination of static and mobile nodes, while ensuring sufficient coverage.

1.3.2 Enhancement of Coverage Quality in DSNs

Most of the conventional researches in sensor networks assume each target has equal importance. However, in practical applications, the importance of each target may be dissimilar and the required coverage quality of each target is related to its importance. For example, in a video monitoring system, some vital sites (such as nuclear power reactors, entrances, and exits) require to be monitored by multiple sensors so as to ensure the fault tolerance of the system. Moreover, if the monitoring data of targets have a certain precise requirements, the targets also need to be observed under the surveillance by more sensors so as to upgrade the sampling frequency.

1.3.3 Dissertation Problem and Solution Methodology

In this section, we briefly discuss about the problem addressed in the dissertation and the solution methodologies.

1.3.3.1 Scope of the Work

Providing an efficient coverage solution plays an integral part in determining the quality of service in any surveillance type application. Determining the appropriate number of sensor nodes to give sufficient coverage in the terrain is difficult to calculate so a large number of sensor nodes are deployed that devise overlapping among the nodes. On the other hand, scheduling of sensor nodes is necessary to prolong the network life by giving coverage responsibility to a set of nodes turn by turn. This problem has attacked before in [10, 74, 75]. However, some issues are not addressed yet. The coverage area enhancement requires an energy-efficient scalable solution that can minimize the overlapping among the nodes so as to activate as less number of sensors as possible. Moreover, the solution methods should incorporate the shortcomings of distributed and centralized solution strategies. In addition to this, in the terrain, we need to give more importance to some specific points or target [30, 31]. More specifically, sometimes quality of target is more critical than lifetime and sometimes increasing lifetime maintaining sufficient quality is vital. Applications may require to give emphasis on enhancing coverage quality or network lifetime or both based on the significance of the application. For example, an emergency rescue operation may need high coverage quality; on the other hand, remote monitoring of elderly people at home using multimedia sensor networks may demand longer network lifetime maintaining a certain coverage quality [15].

1.3.3.2 Design Objectives

The design objectives of the proposed coverage mechanism are as follows:

- **Energy-efficient solution:** Energy is the main concern in any sensor network. In coverage problem, the goal is to maximize the coverage with minimum number of sensors as well as at the same time increase the network lifetime. To address the aforementioned specification, we have proposed network lifetime aware coverage solution mechanism.

- **Reduced overlapping:** To enhance the lifetime of the network, the number of active nodes should be kept as minimum as possible. On the contrary, as the sensing area of a sensor node is disk-shaped and nodes are randomly deployed in the terrain, overlapping occurs that is impossible to avoid. In other words, the least amount of sensing area overlapping activates the minimum number of nodes, resulting in higher network lifetime and vice-versa. Our proposed coverage mechanism on area coverage try to keep the overlapping within percentage value.

- **Distributed control and low computational overhead:** Providing coverage solution driven by a centralized controller in DSN, where the number of sensor nodes is quite large, would increase the computation delay, a single point of failure might lead to wrong decisions. On the contrary, fully distributed solution incurs huge communication cost and instead of minimizing the overlapping zones, it may further increase due to distributed decision. Therefore, we have proposed our solution for a clustered DSNs, which is neither fully centralized nor distributed, rather each cluster head (CH) acts as a central controller to its member nodes.

- **Scalable:** For any sensor networks, scalability is one of the key concerns. In general, the deployed number of sensors in the terrain is application specific; they can range anywhere from a handful of nodes to on the order of approximately 10^7 devices [76]. Therefore, the solution strategy should have the ability to accommodate with variations of the applications.

- **Enhanced quality:** Works related to sensing quality [30, 31] solution methods are adopted by maximizing the network lifetime maintaining the required sensing quality for each target. However, it is observed that there is an inverse relationship between the quality and the lifetime i.e., to extend network lifetime keeping the number of active nodes as less as possible is important; on the other hand, to increase quality it needs to engage more sensor nodes in activation process, resisting extended network lifetime. Therefore, an efficient solution is needed to address both the quality and lifetime that can reflect the actual application demand. Besides, in

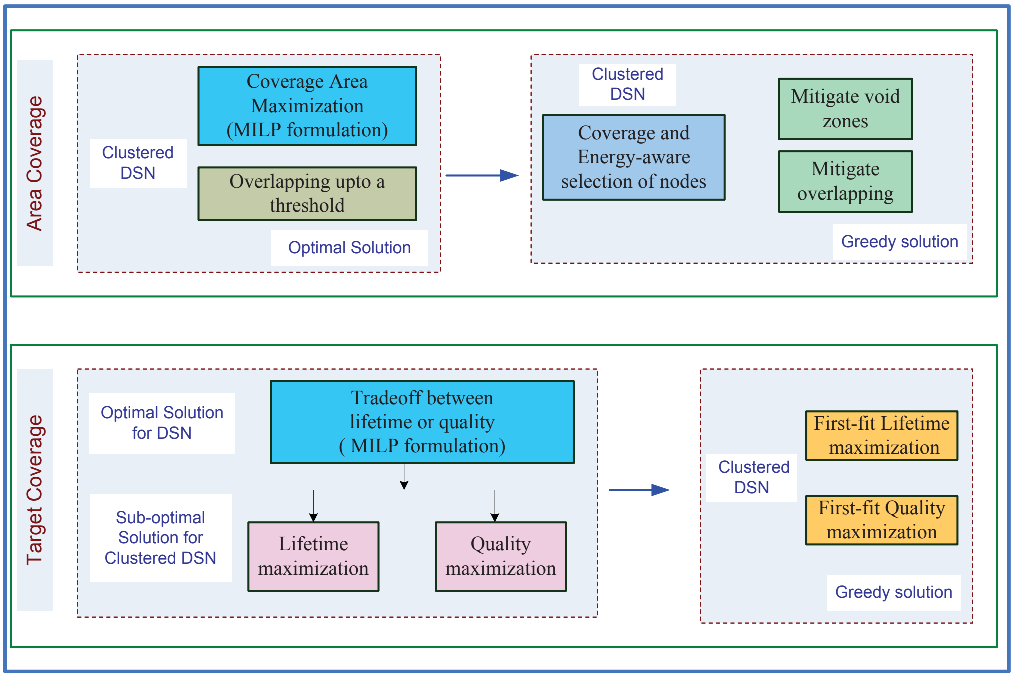


Figure 1.9: Framework of the proposed mechanism

existing literature studies, the coverage quality that sensors can provide to targets are measured using the distance between sensors and targets. However, in reality, sensing quality is imprecise and inhomogeneous and mostly follows probabilistic model [22, 32] and thus a more realistic measurement might boost up the system performance.

1.3.3.3 Solution Methodology

In this dissertation, we develop a mechanism to enhance the coverage in an energy-efficient way for a clustered DSNs. The developed framework (Fig. 1.9) employs coverage solution exploiting nodes energy, overlapping among the nodes as shown in Fig. 1.9. At first, we develop solution mechanisms for maximizing the coverage area. The optimal solution activates minimum number of nodes to cover the sensing area for a clustered

DSN. Later, greedy solution is adopted to find the results in polynomial-time. The detail discussions of this study are in Chapter 3. To further address the quality of some targets or points in the terrain, we develop solutions considering both quality and lifetime. For a directional sensor network, optimal solution is developed and sub-optimal solution is promoted for clustered directional sensor networks. However, the greedy solution can enhance either the sensing quality or network lifetime for a clustered DSN. The detail discussions of this mechanism are in Chapter 4.

1.4 Contributions of the Thesis

The first contribution of this dissertation is to develop a network lifetime aware area coverage system, called α-OAC, that limits the percentage of overlapping area coverage among nodes. We assume that the deployment area is divided into small grids, where sensor nodes are placed and assembled into clusters. Each cluster head (CH) runs the α-OAC algorithm to determine the active sensing member nodes with their sensing directions following the number of grids they cover in a sector, coverage area overlapping caused by the activation and their residual energy values. There is a trade-off among these parameters and nodes that fulfill certain conditions will be active while the others will remain in sleep state. In α-OAC, each CH acts as a centralized controller for its member nodes and the CHs are distributed over the network. The simulation results, carried out in ns-3 [77, 78], demonstrate that the proposed α-OAC significantly outperforms the state-of-the-art works in terms of coverage ratio, network lifetime, percentage of active nodes and standard deviation of residual energy.

Next, we develop a general framework, namely MQMS-DSN (Maximizing Coverage Quality with Minimum Number of Sensors in DSN), that is applicable to maximize the target coverage quality or the network lifetime or to make an efficient trade-off between the two following application demands. However, to accommodate with large networks, sub-optimal and greedy solutions are developed for clustered DSN. Each cluster head (CH) takes coverage decisions independently following current situations of its vicinity.

Measuring the coverage quality using a probabilistic sensing model (i.e., Elfes probabilistic model [22, 32, 79]), the residual energy-aware selection of active nodes helps our MQMS-DSN formulation to achieve enhanced network lifetime. Finally, the performance results of the proposed solutions, carried out in ns-3 [77, 78], show that the proposed MQMS-DSN outperforms state-of-the-art-works in terms of network lifetime, coverage quality, percentage of active sensor nodes and standard deviation of residual energy.

1.5 Organization of the Thesis

The rest of the chapters of this thesis are organized as follows. In chapter 2, we discuss on the motivation of this work by elaborately discussing the state-of-the-art works. In Chapter 3, we develop a solution exploiting α overlapping to maximize the coverage area using an energy-efficient way. Chapter 4, gives emphasis to develop methods to maximize the coverage quality to targets. Finally, we conclude the thesis in Chapter 5 by summarizing the findings in the thesis and observing the future extensions of this work.

Chapter 2

Background and Research Motivation

2.1 Introduction

In recent years, sensing coverage is a major research problem in DSNs and it has received immense interests both from the industrial and academic communities. The appropriate solution of coverage problems is the heart and foundation for performing any surveillance tasks. Besides, quality of service (QoS) is closely related to the coverage issues. Studies related to the sensing coverage field fall into three categories: (1) *sensing area coverage*, (2) *sensing target coverage* and (3) *sensing barrier coverage*. In *area coverage*, we need to activate sensors so that a certain or full region falls under the sensing coverage [80, 81, 82]. In the *target coverage* field, researchers determine a subset of sensors to cover some specific targets or positions [11, 12, 23, 26, 83, 84]. The *barrier coverage* guarantees the detection of events crossing a barrier of sensors [85, 86]. Besides, some sensor applications demands high level of sensing reliability. As a result, monitored points require to be covered by multiple sensors, say k sensors so as to enhance the sensing reliability. This type of coverage problem is known as k-coverage problem.

A considerable amount of research has been performed on coverage related issues for networks using omni-directional sensors, i.e., for WSNs. Nevertheless, now-a-days research community is also focusing their attention on coverage issues in DSNs. The unique characteristics of directional sensors, drive the researchers to generate distinct solutions compared to that of WSNs. In the literature, solutions mainly progress considering two approaches: adjusting the working directions of the sensor nodes and scheduling the working durations of sensors. Theoretically, a directional sensor node may work at different directions [10, 12]. The basic intention of adjusting the working direction is to pick out the best direction, where occlusion effect and overlapping zones are minimized. As a result, a directional sensor node can work with high efficiency. Yet, to enhance the network lifetime, selection of appropriate direction is not sufficient, cause there may be excessive nodes that can cover the same area or targets. In order to prolong the network lifetime and to conserve energy, scheduling algorithms are proved to be quite useful [23, 31, 38].

In DSNs, sensors can be deployed by using random methods or deterministic methods [9]. In friendly accessible environment, it is suitable to deploy the nodes deterministically; on the contrary, in harsh, inaccessible or hostile environment random deployment is convenient. In the literature, we found a good number of works based on random deployments [31, 38, 74, 87, 88]. However, enhancing coverage using planned deployment [69, 89, 90, 91] is also the main focus of some studies. According to the application requirement, some studies focus to maximize the sensing coverage area [82, 92], where as providing coverage to some specific targets or points are addressed in [12, 30, 31]. In many applications, importance or priorities paid to targets are not equal, and thereby their coverage quality requirements differ from each other [30, 31].

In this chapter, the state-of-the-art works on sensing coverage issues in DSNs have been categorized on the basis of different types of coverage strategies such as centralized or distributed, grid-based, computational geometry based and is listed in Table 2.1 and Table 2.2.

The rest of the chapter is organized as follows. In section 2.2, we focus on the state-of-the-art-works that provide solution for sensing area coverage and scrutinize the different solving strategies. The section 2.3 examines state-of-the-art-works on sensing target coverage area and the characteristic comparison report among the different works are condensed in section 2.3.7. And finally, we summarize this chapter in Section 2.4.

2.2 Methods for Sensing Area Coverage Problem

Among the different coverage problems, a good number of research contributions has been carried out on sensing area coverage issues. Studies related to sensing area coverage exploit various approaches to enhance the coverage area that are discussed in the next sections.

2.2.1 Centralized Approach

Once sensor nodes are deployed in the terrain, an algorithm or solution is run to determine if sufficient coverage exists [74, 80, 82, 92, 93]. The execution process of the algorithm can be either centralized or distributed. A centralized algorithm is run on one or more nodes in a centralized location usually near the data sink.

The authors Dan et al. address the coverage enhancement problem for DSN in [93], which is one of the pioneer works in this area. In order to enhance the coverage area, they propose centralized solution based on rotatable sensing model for a randomly deployed DSN. At first, methods are developed to deterministically estimate the amount of directional nodes for a given scenario. The key idea of this work, is to find the Sensing Connected Sub-graph (SCSG) that divide the directional sensor network into several parts in a distributed manner. And later, model each SCSG as a mulit-layer convex hull set to optimize the process of increasing area coverage and decreasing the time complexity. Nevertheless dividing the whole network into subgraphs in SCGS method incurs additional computational cost.

In [82], the authors present the area-coverage enhancement problem as Maximum Directional Area Coverage (MDAC) problem and prove the NP-completeness of the MDAC. The MDAC problem tries to find a subset of directions of sensor nodes from all nodes with the aim to maximize the sensing coverage area under the constraint that at a time only one sensing direction per sensor can be activated. To solve the MDAC, a central controller is required which is sometime not practical for large scale networks. Besides, connectivity issue is not considered here.

A centralized group based strategy, namely grouping scheduling protocol (GSP) is developed in [75] for satisfying given coverage probability requirement by analyzing the deployment strategies in a DSN. Besides, methods are also developed for checking and repairing the connectivity of the network. The authors in [80], name the coverage problem as optimal coverage problem in directional sensor networks (OCDSN). Similar to other studies, they focus to cover maximal area while activating as few number of sensors as possible and propose centralized algorithm (VCA) to solve OCDSN.

2.2.2 Distributed Approach

For sensor network, distributed approaches are more suitable due to the very large size of sensor networks. A distributed or localized algorithm is run on nodes throughout the network. Distributed algorithms involve multiple nodes working together to solve a computing problem. It spread the workload out more evenly than the centralized algorithm. In the literature, a good number of studies [82, 94, 74, 88] have been performed on enhancing the sensing coverage area to fulfill specific tasks and provide solutions using distributed manner.

Along with the centralized MDAC solution an alternate distributed greedy solution (DGreedy) is presented in [82] focusing to maximize the coverage area of a randomly deployed DSN. Two new concepts, virtual sensor and virtual field is defined here, whereas a virtual sensor represents one working direction of a directional sensor and a virtual field is a minimal region that is formed by the intersection of sensing regions of a number of virtual sensors. The key philosophy of DGreedy algorithm is to choose the least overlapped direction as the working direction for every directional sensor nodes. To put the sensing neighbors into an order each sensor is assigned a unique priority where higher priority sensing neighbors are allowed to make their decision earlier than lower priority neighbors.

In [87, 92, 94] the authors propose distributed solutions to enhance the coverage area (details are described in section 2.2.4). The key philosophy here is to divide the sensing area of each node into grids and each sensor takes the decision individually to select its working directions considering the centroid location, so as to enhance the coverage area and minimize the overlapping along with their neighbor sensors. However, determining grids for each individual nodes and along with their neighbors make the computation more complex.

Using the concept of Voronoi-diagram in computational geometry, distributed solutions are developed in [74, 80, 88] (details are described in section 2.2.3) to maximize the coverage ratio. However, with the increasing number of nodes, calculating the Voronoi-diagram for large scale network upsurges the time complexity of the coverage algorithms.

Although, distributed solutions are more scalable than their centralized counterparts as they are being run on many more nodes throughout the network, the distributed algorithms are more complex and require huge communication overhead than the centralized algorithms. Also, individual decision making may increase the coverage overlapping rather than lessen it.

2.2.3 Voronoi-diagram Based Strategy

To solve coverage problems for DSNs, Voronoi-diagram based method has drawn much attention of the researchers. The Voronoi diagram is an important data structure in computational geometry, which is a fundamental construct defined by a discrete set of points [95]. The Voronoi diagram for a sensor network is a diagram of boundaries around each sensors such that every point within a sensor's boundary is closer to that sensor than any other sensor in the network.

Addressing the coverage problem as optimal coverage problem in directional sensor networks (OCDSN) the authors in [25] focus to cover maximal area while activating as few sensors as possible. A greedy approximation algorithm is advanced introducing an assistant sensor to collect global information by traveling the edges of Voronoi diagram and while moving, the assistant sensor senses whether an edge is being covered by active sensors per unit time. If not, it checks whether there is an inactive directional sensor within its sensing circle in time. This helps to change the state of an inactive sensor to active state that has the least Euclidian distance from the edge, so as to minimize the overlapping. However, the concept of assistance sensor incurs burden in the network and therefore the authors extends their idea in [80] and introduce Voronoi based distributed approximation (VDA) algorithm that makes sensors cover the Voronoi edges as much as possible. Without the help of assistance sensor, centralized algorithm VCA and distributed algorithm VDA are also presented here. The key idea of VDA is that, each sensor calculates a weight collecting information from the neighbors. If the calculated weight is maximal, it chooses the orientation for the purpoase of covering the maximal edges and sends messages to inform its neighbors. However, this work is based on the idea that if most Voronoi edges are covered, then the most area will be covered; this is not definite and has the chance to increase the coverage overlapping.

Observing the limitations of [25, 80], the authors Tien et al. study the characteristics of Voronoi diagram and direction-adjustable directional sensors and propose a distributed greedy algorithm in [74], which can improve the effective field coverage of DSNs. The sensor field is divided into Voronoi cells by the calculation of sensors, and the sensor working direction is evaluated based on Voronoi vertices. Considering the coverage contribution of convex polygonal cell of sensors and the coverage overlap of direction selection among neighbor sensors, the working direction is adjusted and controlled, so as to improve the overall sensing field coverage ratio in the sensor network environment without global information. For this, two algorithms: Intra-cell working direction (IDS) and Inter-cell working direction adjustment (IDA) are developed exploiting Voronoi vertices. In IDS, the coverage regions inside the cell are enhanced and IDA tries to minimize the overlapping regions that are formed for IDS. Furthermore, they propose out-of-field coverage avoidance (OFCA) algorithm to control the direction of sensors outside boundary that also reduces the number of active sensors significantly.

In order to maximize the sensing coverage area, sometimes it is efficient to use mobile sensor nodes along with static nodes although employing mobile nodes is not always possible in network. Utilizing mobile and direction-rotatable sensor nodes to enhance the overall field coverage, a distributed algorithm is proposed in [88], that makes sensors self-redeploy to the new location and new direction without a global information by utilizing the features of geometrical Voronoi cells. In paper, [96] Guanglin et al. study the area coverage of directional sensor networks (DSNs) with random node distribution. They transform the network area coverage problem into cell coverage problem by exploiting the Voronoi diagram, which only needs to optimize local coverage for each cell in a decentralized way. Addressing the cell coverage problem, three local coverage optimization algorithms are developed to improve the cell coverage, namely Move Inside Cell Algorithm (MIC), Rotate Working Direction Algorithm (RWD) and Rotation based on boundary (RB), respectively.

Although, Voronoi-diagram based strategies can enlarge the covered area, yet for large scale network it is not suitable. In a large network, where sensor nodes are densly deployed, the size of Voronoi cells happen to be too small, as a result computation of overlapping incurs huge time complexity rather than to narrow it. Moreover, it also leads to the energy-efficiency problem in the network respectively.

2.2.4 Grid-based Strategy

Other than previous approaches, another strategy for sensing coverage is based on dividing the sensing sector into grids [87, 92, 94]. This strategy is based on the location determination of sensing nodes, dividing the sensing sector of nodes into pieces that aids to compute the overlapping area due to the irregularity of overlapping zones. Along with grids, the theory of virtual potential field has been employed in [92, 94].

Based on the idea of potential field, the authors in [94] present an electrostatic field-based coverage-enhancing algorithm (EFCEA) to enhance the coverage area of WMSNs by turning sensors to the correct orientation and decreasing the coverage overlap of active sensors. To maximize the network lifetime they also come up with the idea to shut off as much redundant sensors as possible based on the theory of grid approach. The performance of EFCEA algorithm varying with the number of the deployed sensors where the coverage ratio can be improved much if the number is small and the coverage ratio does not increase significantly when there is already a large number of sensors. Nevertheless, in the later case, many redundant sensing nodes go into sleeping and the lifetime of WMSNs is prolonged along with the higher coverage ratio.

Concerning [94], the authors advance their ideas considering the effect of whole neighboring sensors on the current node in virtual centripetal force-based coverage-enhancing algorithm (VCFCEA) [92]. Based on a novel centripetal force model, VCFCEA adjusts the nodes direction and quantizes the overlapping region of each node. Each node rotates an amount of corresponding angle according to the value of centripetal force where rotating direction is also decided by the direction of centripetal force. However, VCFCEA requires nodes to sequentially calculate virtual force coming from each neighboring sensors so that the computational complexity is increased due to vector calculus. Besides, VCFCEA shuts off redundant nodes simultaneously to prolong the network lifetime that creates potential problem on the occurrence of sensing blanks for this strategy.

Another grid-based strategy, coverage-enhancing algorithm (OSRCEA) is exploited in [87], based on overlap-sense ratio (OSR). Introducing the parameter of OSR to describe the effect of the whole neighboring sensors, the scalar operation of OSR reduces the computational complexity compared to centripetal force. Besides, the network coverage achieves a further enhancement by employing the reasonable mapping relationship between OSR and rotation angle compared with VCFCEA. Moreover, to extend the network lifetime a modified strategy of shutting off redundant sensors is proposed here. However, they paid less attention to the exact quantification of the overlapping areas and the energy-aware selection of active nodes.

2.2.5 Discussion

The key characteristics of some of the sensing area coverage methods are summarized in Table 2.1. Note that, all the studied mechanisms are based on the binary disk model to measure the coverage where a point is said to be covered if it is inside the sensing range and sensing sector of a sensor node, otherwise not [22, 32]. The works in [75, 80, 82, 93] aims to enhance the sensing coverage area; yet, due to the employment of central controller, they are unable to address temporal network dynamics and are not scalable. Though distributed approach has been adopted in [74, 82, 88, 94] to enlarge

Table 2.1: A comparison among the different methods of area coverage problem

Sensing Coverage Method	Centralized	Distributed	Voronoi-based	Grid-based	Binary sensing Model	Probabilistic sensing model	Static sensor nodes	Mobile sensor nodes
SCSG [93]	✓	✗	✗	✗	✓	✗	✓	✗
MDAC [82]	✓	✗	✗	✗	✓	✗	✓	✗
VCA [80]	✓	✗	✓	✗	✓	✗	✓	✗
EFCEA [94]	✓	✗	✓	✗	✓	✗	✓	✗
IDA, OFCA [74]	✓	✗	✓	✗	✓	✗	✓	✗
VDA [80]	✗	✓	✓	✗	✓	✗	✓	✗
OSRCEA [87]	✗	✓	✓	✗	✓	✗	✓	✗

the area, they suffer from huge message passing and communication overheads. Voronoi-diagram of computational geometry leverages in [25, 74, 80, 88], but they exhibit low performance for large scale networks. Grid-based strategies [92, 94] aid to measure the overlapping region more definitely along with upsurging the sensing area, yet they achieve poor outcome for the absence of exact quantification of overlapping zones and selecting the nodes in an energy-efficient way. In this thesis, we propose solutions to increase the sensing area coverage in DSN, assuming the network is clustered. Proposed area coverage solution strategy minimizes the overlapping ratio as well as number of sleep nodes. The lifetime is increased through selecting the active nodes in an energy efficient way. Besides, quantification of overlapping area is also discussed here.

2.3 Methods for Target Coverage Problem

Recently, a good number of works has been done exploiting sensing target-coverage problem to maximize the number of covered targets with minimum number of sensor nodes which is proved to be NP-Complete [10, 12, 29]. Target-coverage problem arises when some applications are only interested in stationary or mobile target points such as buildings, flags, doors etc. Targets may reside in any point in the interested area and the solution strategies mainly focus to cover maximum number of targets along with enhancing the network lifetime. However, to enhance the reliability or maintaining the sensing quality of the application, some targets demand to cover them with more than one sensors. Unlike omni-directional sensors that have the full sensing angle, the directional sensors have limited sensing angle, that make the task to maximize the lifetime for target coverage more challenging. Moreover, energy-aware selection of nodes are desired to enhance the lifetime which is the primary objective of all applications.

2.3.1 Optimal Coverage of Targets

In target coverage problem optimization strategy [97, 98] is sometimes adopted to find the optimal value i.e., to maximize the number of covered targets using minimum number of active nodes. The problem Maximum Coverage with Minimum Sensors (MCMS) problem is introduced in [10], a pioneer work regarding to target-coverage in DSN. An exact Integer Linear Programming (ILP) is formulated for the MCMS that takes the number of directional sensors, the number of targets and the number of orientations available for each directional sensor as input. The objective function of this formulation maximizes the number of targets to be covered and imposes a penalty by multiplying the number of sensors to be activated by a positive penalty coefficient whose value must be small enough to guarantee a unique solution.

Unlike the MCMS problem [10] the Multiple Directional Cover Set problem (MDCS) [11, 12] organizes the directions of sensors into a group of non-disjoint cover sets to extend the network lifetime. Modeling the MDCS as Linear Mixed Integer Programming

(LMIP) the objective function maximizes the total work time of all the cover sets so as to enhance overall network lifetime.

Considering individual target has differentiated priority, the priority-based target coverage in DSNs [30], develops a function to minimize the subset of directional sensors covering all targets. Ensuring the required priority of each target, they come up with the idea that, if the number of active nodes is small, the network lifetime enhances automatically.

In order to achieve network's satisfied coverage reliability level that satisfies the application demand, the directional cover sets with coverage reliability (DCCR) [99], focus to maximize the network lifetime presenting a coverage reliability model for target coverage. Again, in [31, 100], the authors attempt to maximize the lifetime of the network maintaining the coverage quality for all targets.

To solve the directional sensor coverage problem, in [101] the authors present a mixed integer nonlinear programming formulation, where a given set of targets on a plane are to be covered by a set of sensors whose locations are known. Introducing a Lagrangian relaxation model a dual ascent procedure based on acting on a single multiplier at a time is also exploited to find a feasible solution at each ascent iteration.

Although the LP formulation delivers us the optimal solutions, it suffers from scalability and computation time complexity problems for large scale networks. Therefore, alternate methods like greedy and heuristic algorithms are developed to find the result in polynomial execution time.

2.3.2 Centralized Approach

An alternate solution for the MCMS (Maximum Coverage with Minimum Sensors) problem [10], Centralized Greedy Algorithm (CGA) changes the state of an inactive sensor to active state in each iteration, that can cover higher number of targets in a direction. However, due to the lack of proper choice of directions, Chen et al. [102] add weight to target and direction, and present Wighted Centralized Greedy Algorithm (WCGA) by modifying the CGA algorithm of [10]. Exploring both the connectivity and target coverage issues in DSN, the Minimum-Energy Connected Coverage (MeCoCo) aims to minimize the total energy cost of sensing and connectivity using the directional and omni-directional features of sensor nodes. Addressing the same problem to maximize the number of targets, an approximation algorithm is developed in [103] using the directional sensor model with tunable directions. To further maximize the number of covered target points, also Maximum K Directional Sensor Coverage (MKDSC) algorithm is proposed by selecting and assigning directions for a subset of K sensors.

Cai et al [11, 12] address the Multiple Directional Cover Set Problem (MDCS) by organizing the directions of sensors into non-disjoint cover sets, so as to maximize the network lifetime. To solve MDCS in polynomial-time, MDCS-Greedy algorithm is designed that iteratively exploits the minimum directions of sensor nodes that can cover the targets and have longer residual lifetime.

The authors in [37, 104, 105] assume the network has not sufficient sensor nodes to cover all the targets at a time and periodic scheduling is required to cover them. The Service Delay Minimization Problem (SDMP) consists a centralized protocol to minimize the maximum service delay where the targets may not be covered continuously. However, it does not take into account the network lifetime. In target Q-coverage (TQC) [37], coverage sets of directional sensor nodes, that satisfies the coverage quality requirement, are developed to employ each of those independently so that the network lifetime is extended. However, the coverage sets don't guarantee continuous monitoring of targets; rather, they can be served with tolerant service delay. Lu at. el. further advance the solution to Q-coverage problem by scheduling multiple sensors to cover a certain target at sporadic times but ensuring coverage by at least one sector in a given time period [105].

In order to give priority or importance to individual targets centralized strategies are adopted in [30, 31, 99, 100, 106]. The key idea is to enhance the lifetime as much as possible maintaining the required quality for each targets.

Similar to optimal solution, centralized approach is not well suited when the network is large and it has to work with a huge number of sensor nodes. As a result, distributed approaches are developed to find substitute solutions.

2.3.3 Distributed Approach

Along with centralized algorithm (CGA) in [10], a distributed solution (DGA) is also exploited for the MCMS problem by taking only the local information into account. Nevertheless, DGA algorithm cannot perform as good as the centralized method, but it is computationally more scalable. The key philosophy of DGA algorithm is to assign each node a unique variable, called priority and based on the priority level of their neighbors, sensor nodes make their decisions. Besides, they also provide SNCS (Sensing Neighborhood Cooperative Sleeping Protocol) that helps in the scheduling process of the sensor nodes for energy-efficiency. Here, residual energy is used as a priority for scheduling, and all the sensor nodes run the same DGA algorithm again. Hence, this scheduling mechanism incurs much overhead in the network and decreases the network lifetime as well as performance.

To extend the network lifetime, alternate distributed solution (MDCS-Dist) is evolved in [12], by assigning the direction selection policy to individual nodes rather than to a centralized controller. The pivot policy of MDCS-Dist is to assign priority to targets and finds a direction to cover the targets that can be covered by minimal number of directions.

Considering, rotatable directional sensors, the MCRS (Maximum Coverage with Rotatable Sensors) problem come up with the idea to minimize the rotation of angles of sensors so as to maximize the number of covered targets can be maximized.

Despite of achieving faster solution compare to centralized approach, due to the lack of any coordinator, the number of messages and information transmission is increased and high computational overhead of the sensor nodes has been observed in the network for distributed methods.

2.3.4 Cluster-based Strategy

Observing the pros and cons of centralized and distributed algorithms, the authors of [38] first exploit the cluster heads (by forming a clustered network) to greedily activate the minimum number of member sensor nodes that can cover all targets in the network in a distributed way. The TCDC (target coverage through distributed clustering) [38] develops a clustering mechanism for DSNs that selects the cluster heads considering sensor nodes energy, number of covered targets and distance from the sink. Each cluster head picks the active sensor nodes along with their sensing directions, where the key idea is to give higher chance to a sector by calculating priority value for each sector based on their covered targets and remaining energy.

2.3.5 Coverage-quality Based Approach

In the network, sometime it is necessary to give different importance to individual targets rather than giving equal priority to each targets [30, 31]. Considering varied priorities associated with each target, the authors in [30], propose the priority-based target coverage problem aiming to select a minimum subset of directional sensors that can monitor all targets, satisfying their desired priorities. To find the minimum subset of directional sensors genetic algorithm is used where the algorithm suffers from the limitations of genetic algorithm itself like huge time to spend for convergence, no guarantee of finding global maxima, etc.

The maximal network lifetime scheduling (MNLS) problem is addressed in the work conducted in [31]. The authors investigate a special target coverage problem where each target has a required coverage quality considering a sector based directional sensor model. They consider that the distance between the sensor and the target influences the coverage quality of the target and offers two greedy heuristic algorithms (MNLS-H and MNLS-H-T). The key idea of the solution strategy is to organize the directions into non-disjoint cover sets and one cover set is activated at a time that can maintain the coverage requirements of all targets.

The priority-based target coverage [106], propose a learning-automata-based algorithm to organize the directional sensors into several cover sets assuming that each target may have different coverage quality requirements in a randomly deployed DSN. The cover sets are formed in such a way that can satisfy coverage quality requirements of all the targets as well as to maximize the network lifetime.

Using a rotatable directional sensor model, the authors in [100] studied the similar problem discussed in [31] and propose solutions to solve the maximum cover set problem (MCS). Studying the intrinsic relationship between the work directions of sensors and the targets deployed within sensing region of sensors, at first a sensing direction partition (SDP) algorithm is offered to find all non-redundant directions for each sensor. Later a heuristic algorithm is designed for the maximum cover sets (HMCS) problem to divide the directions of sensors into non-disjoint cover sets so as to provide coverage to all targets satisfying their coverage quality requirements using the cover sets and then allocate work time for each cover set.

Even if the works address quality in their study [30, 31, 100, 106], the centralized solution approaches is not adaptable for real life practical wide networks. The key target of [30, 31, 100, 106] is to maximize the network lifetime maintaining the required coverage quality of each targets, where as for some applications sometimes it is also critical to enhance the coverage quality along with the network lifetime.

2.3.6 Sensing Model Based Approach

In binary disk model [22, 32], a sensor node covers a target with probability 1 if the target resides within the sensing range, 0 otherwise. Studies related to target coverage [10, 11, 12, 38, 42] exploits their strategies adopting the binary disk model. However, this is sometimes impractical because sensing quality mostly follows probabilistic nature [22, 32]. Unlike binary disk model, the sensing coverage quality is defined as a function of received signal strength in [99] and distance in [30, 31, 100, 106]. Nevertheless, a probabilistic sensing model [22, 32] is more appropriate as the phenomenon being sensed, sensor design and environmental conditions are all stochastic in nature.

Table 2.2: Characteristic comparison among the different target coverage strategies

Target Coverage Methods	Centralized	Distributed	Optimal Solution	Coverage-quality based	Binary sensing Model	Probabilistic sensing model	Static sensor nodes	Cluster-based
MCMS, CGA, DGA [10]	✓	✓	✓	✗	✓	✗	✓	✗
MDCS [12]	✓	✓	✓	✗	✓	✗	✓	✗
DCCR [99]	✓	✗	✓	✓	✓	✗	✓	✗
MNLS [31]	✓	✗	✓	✓	✓	✗	✓	✗
TCDC [38]	✗	✗	✗	✗	✓	✗	✓	✓

2.3.7 Discussion

The key working principles of different target coverage strategies are compiled in Table 2.2. Centralized approaches like [10, 11, 31, 99] leads to an unstable system due to the lack of scalability in the network. On the other hand, distributed methods [10, 12] solve the adaptability problem, yet they offer excess communication and computation overhead. The use of binary disk model and other distance based sensing model fail to address the stochastic nature of the system, rather probabilistic model is more reasonable. Assigning differentiated importance to individual targets, [30, 31] try to maximize the network lifetime, but due the employment of central controller they come up with low achievement. Moreover, they fail to address the situation, where enhancing quality is also as vital as lifetime. In this work, introducing the probabilistic sensing model to quantify the coverage quality of targets for a clustered DSN, we develop solution that can address the maximization of quality and network lifetime together and activates the sensor nodes in an energy-efficient way.

2.4 Summary

In this chapter, we present a comprehensive analysis of existing area coverage and target coverage solutions for DSNs. In Chapter 1, we discuss on the basic issues of DSNs to enhance the sensing coverage. Based on that, we discuss on the various design methodologies on area coverage and target coverage. In the next chapter, we design solutions that can mitigate the challenges of the state-of-the-art-works.

Chapter 3

Maximizing Sensing Coverage Area

3.1 Introduction

A Directional Sensor Network (DSN) consists of large number of small battery powered directional sensor devices that can sense and report event data to a sink. A directional sensor device can, at a certain time, sense and communicate in only one direction or in a particular angle as it has limited range of communication and sensing capabilities contrasting to omni-directional sensors. However, more spatial reuse of underlying communication channel, less radio interference, higher coverage range can be achieved using directional sensors which subsequently increase the overall network capacity. Thus, the DSNs offer increased network performance and many smart applications using directional camera [13, 15], ultrasonic or infrared sensors [14] are gaining much popularity in recent days.

The problem of area coverage refers to maximizing the sensing area coverage percentage of perception area with minimum number of sensors, termed as MCMS, which is a well known classic problem [24]. It is of great importance for many real-life applications including security monitoring of historical or vital places, wildlife monitoring in the forests, battlefield surveillance, etc. In the literature, this area coverage problem has been proved as an NP-hard one [80, 82] and a greedy alternative or heuristic approach is used to achieve near-optimal solution. The complexity of the problem is further complicated for directional nodes since we need to fix the active sensing nodes as well as their sensing sectors [9, 75], so that the area coverage is maximized by using as minimum number of nodes as possible. Note that, this problem is translated into minimizing coverage area overlapping among the sensor nodes while every point in the target area is covered. In other words, the least amount of sensing area overlapping activates the minimum number of nodes, resulting in higher network lifetime and vice-versa. This translated problem helps us to develop a distributed solution for the MCMS.

The existing solutions in the literature for the area coverage problem exploit diverse approaches. The authors in [80, 81] introduce Voronoi cells to determine active nodes and their sensing directions so as to increase the area coverage. The authors in [87] divide the sensing sectors of each node into small grids and thus the amount of active sensing nodes is minimized by lessening the overlapping area. Tien et al. [74] selects the nodes that can cover larger area in Voronoi cell to increase coverage ratio. *Moreover, in some cases, it becomes more costly to compute Voronoi diagram.* In the above works, an individual node takes its decision of sensing responsibility exploiting neighborhood information. These fully distributed approaches generate huge communication and computational overheads. In addition to that, to the best of our knowledge, none of the previous works considered residual energy levels of the nodes in support of enhancing the network lifetime.

In this work, we have developed a network lifetime aware area coverage system, called α-OAC (α Overlapping Area Coverage), that limits the percentage of overlapping area coverage among nodes by α. We assume that the deployment area is divided into small grids, where sensor nodes are placed and assembled into clusters. Each cluster head (CH) runs the α-OAC algorithm to determine the active sensing member nodes with their sensing directions following the number of grids they cover in a sector, coverage area overlapping caused by the activation and their residual energy values. There is a trade-off among these parameters and nodes that fulfill certain conditions will be active while the others will remain in sleep state. In α-OAC, each CH acts as a centralized controller for its member nodes and the CHs are distributed over the network. The key contributions of this work are summarized as follows:

- We formulate the area coverage problem as a mixed integer linear programming (MILP) problem considering the area is divided into smaller grids, which is proved to be an NP-hard problem.

- A greedy alternate solution, α-OAC, for the area coverage problem has been developed that allows as maximum as $\alpha\%$ overlapping and considers residual energy to activate nodes, helping to increase the network lifetime.
- The α-OAC runs at each CH and exploits single-hop neighborhood information only; thus, it is lightweight, distributed and scalable.
- We have also presented schemes to diminish void regions as well as coverage redundancy among inter-cluster sensing nodes.
- The results of performance evaluation studies, experimented on ns-3, show that the proposed α-OAC system accomplish better coverage ratio and network lifetime compared to those of a number of works in the literature.

The rest of this work is organized as follows. We define the system model and formulate the problem in Section 3.2. The details of our proposed α-OAC system is presented in Section 3.3 and the simulation results are presented in Section 3.4. Finally, we summarize the work in Section 3.5.

3.2 System Model and Problem Formulation

We assume a Directional Sensor Network (DSN) composed of a large set of directional sensor nodes $\mathcal{N}$ in a two dimensional plane. The sensors are deployed within an area of $\mathcal{A}$, which is divided into small square grids. The length of a grid is d, a predetermined constant and there are a total of $p \times q$ grids. The (x, y) co-ordinate of each grid is denoted as cell and each sensor i has a fixed and known cell-location $(x_i,\ y_i)$ in the grid. The co-ordinate information of the grid-area is embedded into every static sensor. The DSN has a sink node, to which all sensor devices send their sensed data packets in multi-hop fashion. Each sensor device is uniquely identified by its ID, which we assume to be an integer number. We assume that all the directional sensor nodes are homogeneous in terms of number of sensing sectors, sensing and communication radius and the initial energy E_0.

We also assume that a suitable clustering algorithm [38, 107], is running in the network that selects cluster heads (CHs) and gateways (GWs) to develop a communication backbone for the network. In the literature, a very good number of clustering algorithms exist that consider the coverage problem for omni-directional sensor networks [46, 47]. Nevertheless, those are not applicable for directional sensor networks since there are some basic differences between operational procedures of omni and directional sensor nodes. In the state-of-the-art works, we have found two leading clustering techniques that work with directional sensor networks - TCDC [38] and ACDA [107]. In autonomous clustering algorithm (ACDA) [107], individual nodes exchange messages for a random waiting time period to select cluster heads and gateway nodes. At the beginning, ACDA does not consider residual energy levels of nodes; however, later it renews the cluster heads and gateways studying the residual energy levels. On the other hand, the TCDC [38] selects a node as cluster head (or gateway) considering its residual energy level, number of neighbor nodes and its distance from the sink. The renew process is performed by existing CHs and gateways when their energy levels fall below a certain threshold. Both the ACDA and TCDC systems use gateways to route data packets from CHs toward the sink using the shortest hop single path strategy. We have studied the performances of our α-OAC system using the two existing clustering techniques ACDA and TCDC, as depicted in Section 3.4.

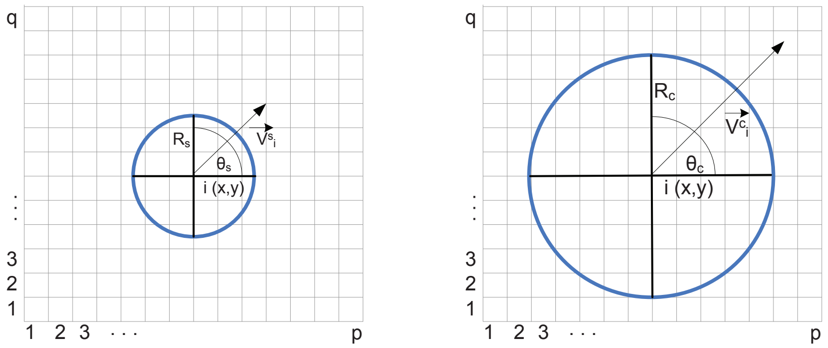
A sensor node can be in either *active* or in *sleep* state. When in *sleep* state, a sensor periodically wakes up and communicates with its CH to check if it has any new responsibility. In the network, no data packet aggregation is employed by the CHs. What follows next are the sensing and communication models of a sensor node.

3.2.1 Sensing Model of a Sensor Node

We have adopted the binary disk sensing model [9, 12] for a DSN with $\mathcal{N}$ directional sensor devices $\{i | i = 1, 2, \ldots, \mathcal{N}\}$. Each sensor has the following characteristics:

- Each sensor has a set of sensing sector Ψ_s. A sector $s \in \Psi_s$ is centered at the sensor node with a sensing radius R_s and the sensing angle θ_s. A sensor can work only at one sensing sector at a given time.

- R_s is the maximum sensing radius and a sensor device cannot sense anything beyond this radius.
- θ_s $(0 < \theta_s < 2\pi)$: the maximum sensing angle which is called field of view (FoV), as shown in Fig. 3.1(a).
- $\vec{V}_i^s$ is a directional vector that divides a sensing sector into two equal parts.



(a) Sensing model (b) Communication model

Figure 3.1: Directional sensor node model

3.2.2 Communication Model of a Sensor Node

Like sensing orientations, each sensor device has a set of communication sectors [43], characterized by the following attributes:

- $\theta_c (0 \leq \theta_c \leq 2\pi)$: the maximum communication angle, as shown in Fig. 3.1(b).
- $\vec{V}_i^c$: the directional vector which is the center line of a communication sector, as shown in Fig. 3.1(b).
- R_c: the maximum communication radius; typically, R_c is twice larger than the R_s [108] and a sensor node cannot communicate with other nodes beyond this radius.

Table 3.1: Notations used in α-OAC

α	Maximum overlapping threshold
$\mathcal{N}$	Set of all sensor nodes
$\mathcal{N}_k$	Set of cluster member nodes of CH k
Ψ_c	Communication sectors set for a node $i \in \mathcal{N}$
Ψ_s	Sensing sectors set for a node $i \in \mathcal{N}$
$<i, s>$	Sector s of node i
$n_{i,s}$	The set of i's neighbor nodes in sector $s \in \Psi_s$
Γ_k	List of neighbor CHs of CH k
$E_0(i)$	Node i's initial energy
$E_r(i)$	Node i's residual energy
$\mathbb{A}_k$	The set of grids that are inside total communication sector of CH k
$\mathbb{A}_{k,C}$	The set of grids that are inside active communication sector $C \in \Psi_c$ of CH k
$\mathbb{A}^T_{i,s}$	The set of grids that can be fully covered by a sector s of a node $i \in \mathcal{N}_k$
$\mathbb{A}_{<i,s>}$	The set of grids that are covered by a sector s of a node $i \in \mathcal{N}_k$
$O(i, j, s)$	The set of common grids between nodes i and j for a sector s
η_k	The set of active member nodes of CH k with active sector
Υ	Set of all CHs
$\chi^s_{i,j}$	The percentage of overlapping grids between node i and j for a sector s
ϖ	A descending ordered sorted list of $< i, s >$ based on the metric $\varepsilon_{i,s}$
λ_k	Set of sensor nodes i, initialized to $\mathcal{N}_k$

We also assume that each sensor node knows the location of itself and its neighbors by GPS or any other localization method [109]. The tasks of sensing and transmission are directional and the reception is omni-directional. Throughout the paper, we follow notations described in Table 3.1.

3.2.3 Problem Formulation

In this section, we provide a mixed integer linear program (MILP) formulation for the problem of maximizing area coverage with minimum number of sensors in DSNs. Each CH k takes decision whether to keep a member node in *active* or in *sleep* state. A CH k has a list of its member sensor nodes, denoted by $\mathcal{N}_k$, and it maintains a two dimensional matrix Π_k for the entire area $\mathcal{A}$. Thus, the entries of the matrix correspond to the state of a grid, whether it is already covered by a sensor node or not. The value of each grid

(x, y) is initialized by a CH $k \in \Upsilon$ as follows by,

$$\Pi_k(x,y) = \begin{cases} 0 & \text{if (x,y)} \in \mathbb{A}_k \text{ and is not covered yet,} \\ 1 & \text{if (x,y)} \in \mathbb{A}_k \text{ and is already covered.} \end{cases} \tag{3.1}$$

Here, the value $\Pi_k(x, y) = 1$ indicates the grid (x, y) is covered by a sector of a node, *i.e.*, the grid is under the sensing coverage of a member node. We also define a boolean variable $b_{i,s,k}$ that represents whether a sector s of a sensor $i \in \mathcal{N}_k$ is activated or not,

$$b_{i,s,k} = \begin{cases} 1 & \text{if } < i, s > \in \eta_k, \\ 0 & \text{otherwise.} \end{cases} \tag{3.2}$$

The MILP formulation for maximizing coverage area with minimum number of sensors is as follows:

Maximize:

$$\mathbf{Z} = \left(\sum_{x=1}^{p} \sum_{y=1}^{q} \sum_{\forall k \in \Upsilon} \Pi_k(x,y) - \sum_{\forall i \in \mathcal{N}_k, \forall s \in \Psi_s, \forall k \in \Upsilon} b_{i,s,k} \right), \tag{3.3}$$

subject to:

$$\sum_{\forall s \in \Psi_s} b_{i,s,K} \leq 1, \quad \forall i \in \mathcal{N}_k, \forall k \in \Upsilon \tag{3.4}$$

$$\Pi_k(x,y) = 1, \quad \forall (x,y) \in \mathbb{A}_{k,C},\ \forall k \in \Upsilon \tag{3.5}$$

$$\chi_{i,j}^{s} \leq \alpha, \tag{3.6}$$

$$E_r(i) \geq E_{th}, \quad \forall < i, s > \in \eta_k, \forall k \in \Upsilon \tag{3.7}$$

The constraint (3.4) ensures that a node can be activated only in a certain sector at a given time. Constraint (3.5) ensures that all the grids in the working communication sector of a CH are fully covered. Constraint (3.6) indicates that the amount of overlapping area among nodes can't be larger than a threshold α. A selected node must have residual energy greater than a minimum threshold value (E_{th}) which is ensured by constraint (3.7). The first part of the objective function in Eq. (3.3) corresponds to maximizing the number of grids covered by the activated sensors, while the second part is to minimize the number of active sensor nodes. The solution of this kind of MILP formulation requires a central controller which has all the network information in the vicinity. Moreover, if the number of sensor nodes increases to a large number, the space and time complexities of the MILP will increase as well. The same is true if the area $\mathcal{A}$ upsurges. In other words, the MILP becomes an NP-hard problem for $\mathcal{N} \to \infty$ and is not scalable. Therefore, we provide an alternative greedy solution, namely α-OAC, for the MCMS problem.

3.3 Design of α-OAC System

Given a DSN, where randomly deployed sensor devices are grouped into multiple clusters, our aim is to maximize the field area coverage by activating the number of sensor nodes as minimum as possible so as to enhance the network lifetime. The difficulty of the problem lies in minimizing the *uncovered* and *overlapped* regions. In α-OAC, each CH works as a central controller for its members to determine nodes for activation along with their direction of sensing. The CHs select the number of active sensing nodes so that the *coverage overlapping* as well as *uncovered regions* are minimized within and outside the clusters. The CHs also collect, process and transmit data packets toward the sink for all of its members. Therefore, our proposed α-OAC system is distributed and scalable, and it exploits single hop information only centered at each CH. What follows next is the details of the constituent components of the α-OAC system.

3.3.1 Active Node Selection in a CH

Each CH k maintains a temporary list λ_k, initialized to $\mathcal{N}_k$. When a node i and its sector s is selected by the CH k as active, it is moved from λ_k to the active list η_k *i.e.* $\eta_k \leftarrow < i, s >$. In the process of active node selection, the first step is to add the CH itself to active list η_k and its sensing direction will be the same as communication direction, *i.e.* $\eta_k \leftarrow < k, s >$, where $s \in \Psi_s$. When the CH k selects the sector $< k, s >$ as active, the grid points covered by the sector $< k, s >$ will be marked as covered in the matrix Π_k and accordingly the list Π_k is updated using Eq. (3.8).

$$\Pi_k(x, y) \leftarrow 1, \qquad \forall (x, y) \in \mathbb{A}_{<k,s>} \tag{3.8}$$

Since the communication radius is twice larger than the sensing radius of a node, a large portion of the communication sector region of the CH k will be covered by this selection. This potentially serves our purpose of activating minimum number of sensors. What follows next, we describe the selection process of cluster member nodes and their sectors for activation.

3.3.1.1 Selection of sectors of nodes having non-overlapping grids

After selecting its own active sector, the CH k runs the process of selecting its member sensor nodes and their active sensing directions. A CH $k \in \Upsilon$ first selects the sectors of sensors that can sense a particular non-overlapping communication grids of it, i.e., no other sensing direction of the member nodes can cover the same grids. There might be the possibility that these selected sensors can cover larger set of grids if they sense in other sectors. However, selecting these sectors based on maximum covered grids may leave some grids uncovered. The CH k finds the non-overlapping grids and moves the nodes that cover these grids from λ_k to η_k using Eq. (3.9) as follows,

$$\begin{aligned} &\eta_k \leftarrow \{\eta_k \cup < i, s > |(x,y) \neq null, \\ &(x,y) \in \{\mathbb{A}_{<i,s>} \backslash \{\mathbb{A}_{<i,s>} \cap \{ \bigcap_{\forall j \in n_{i,s}} \mathbb{A}_{<j,s>}\}, \forall s \in \Psi_s. \end{aligned} \tag{3.9}$$

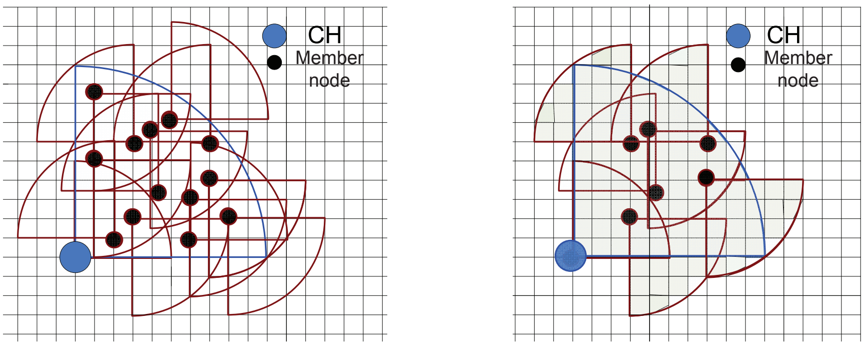
Whenever a node and its sector is selected as an active node, the matrix Π_k is updated using Eq. (3.8) for $\forall (x,y) \in \mathbb{A}_{<i,s>}$. How to decide whether a grid (x,y) is covered by a sector of a node or not is described in section 3.3.1.4.

3.3.1.2 Selection of sectors of nodes having overlapping grids

Now, the list λ_k contains only those nodes that have full grid coverage overlapping with the neighborhood nodes. At this stage, the proposed α-OAC selection process gives higher priority to the nodes having higher residual energy $(E_r(i))$ and to the sectors covering smaller amount of overlapping grid points $(O(i,j,s))$. Therefore, an integrated metric is defined for each sector $s \in \Psi_s$ of each node $i \in \lambda_k$, as follows,

$$\varepsilon_{i,s} = g_1 \times (1 - \chi_{i,j}^s) + g_2 \times \frac{E_r(i)}{E_o(i)}, \qquad \forall i \in \lambda_k, E_r(i) \geq E_{th}, \forall s \in \Psi_s \tag{3.10}$$

where, the value $\chi_{i,j}^s$ is the ratio of number of overlapping grids to total grids and the details of this calculation is found in Section 3.3.1.4; g_1 and g_2 are the weight factors, E_o is the initial energy and $E_r(i)$ is the residual energy of the node i which is larger than a threshold value E_{th}. Note that the Eq. (3.10) measures the value of the metric $\varepsilon_{i,s}$ as a weighted linear combination of two sub metrics, $\chi_{i,j}^s$ and $\frac{E_r(i)}{E_o(i)}$, corresponding to the portion of overlapping grids covered by a sector $s \in \Psi_s$ of any sensor $< i, s > \in \lambda_k$ and the portion of residual energy of a node $< i, s > \in \lambda_k$ has, respectively. Therefore, the metric $\varepsilon_{i,s}$ helps us to select the sensor that has higher residual energy and the sector having higher non-overlapping grid coverage, which in turn helps to increase the network lifetime as well as to decrease the coverage redundancy by judiciously choosing the active sensor nodes in the region.



(a) Initial situation (b) After selecting active nodes

Figure 3.2: Active node selection inside the communication sector of CH k

The CH k now produces a list $\varpi =< i, s >$, which is a descending order sorted list of nodes and their sectors following their $\varepsilon_{i,s}$ values. The CH k then checks whether the first entry of ϖ passes the inequality test in Eq. (3.11); if yes, the node entry $< i, s >$ is moved to the active list η_k; and simultaneously, the other entries for that node are removed from the list ϖ. In the case the Eq. (3.11) returns false, the CH k goes to the next entry. The checking will continue again and resume for two conditions: if all the entries of ϖ are checked, or the communication region of CH is fully covered.

$$\chi^s_{i,j} \leq \alpha, \qquad \forall < j, s > \in \eta_k,\ j \in n_{i,s}. \tag{3.11}$$

Note that the Eq. (3.11) helps the CH k to reduce the sensing overhead by activating a sensor node i and its sector s if it has grid overlapping less than the overlapping threshold, α. Finally the nodes that are in the active list η_k will be activated. The details of intra-CH node activation process has been summarized in Algorithm 1 and using it, a CH keeps some nodes in active states to cover its communication grids (Fig. 3.2). In the Algorithm 1, we start with a small value of α' (line 9) instead of α ($\alpha' = \alpha \times \frac{1}{w}$ where w is a multiplication factor). The introduction of α' helps the proposed system to further minimize the sensing overlapping among the activated nodes in the network.

Algorithm 1 Active Node Selection Algorithm for a CH

```
INPUT: $\mathcal{N}_k, \alpha$
OUTPUT: $\eta_k$
 1. $\eta_k \leftarrow \eta_k \cup < k, s >$
 2. update $\eta_k$, using Eq. 3.9
 3. update $\lambda_k$
 4. for all $i \in \lambda_k$ do
 5.   for all $s \in \Psi_s$ do
 6.     Find the value of $\varepsilon_{i,s}$ using Eq. 3.10
 7.   end for
 8. end for
 9. $\alpha' = \alpha \times \frac{1}{w}$
10. $\varpi \leftarrow$ Descending order sorted list of $< i, s >$ using $\varepsilon_{i,s}$
11. while $(\lambda_k \neq \phi)$ do
12.   for all $< i, s > \in \varpi$ do
13.     if Eq. 3.11 returns TRUE then
14.       $\eta_k \leftarrow \eta_k \cup < i, s >$
15.       remove all entries of node $i$ from $\varpi$
16.       $\lambda_k \leftarrow \lambda_k \setminus i$
17.     end if
18.     if Eq. (3.12) returns true OR $\alpha' > \alpha$ then
19.       Exit
20.     end if
21.   end for
22.   $\alpha' = \alpha' \times w$
23. end while
```

3.3.1.3 Determination of CH region is fully covered or not

Before, selecting a new active node, a CH k needs to check whether its communication region is fully covered or not, as stated in line number 18 of Algorithm 1. For this, the CH k checks the following equality test

$$\Pi_k(x, y) = 1, \quad \forall (x, y) \in (\mathbb{A}_k \cap \mathbb{A}_{k,C}). \tag{3.12}$$

Note that, the true return value of Eq. (3.12) specifies that all the grids that are inside the current communication sector of CH k are covered by some nodes. Note that, each time a sensor node i and its sector s has been selected to add in the active sensor list η_k, its corresponding grid points are marked as covered, *i.e.* the entry for the covered grid (x,y) is set to 1 in the matrix Π_k using Eq. (3.8).

The complexity of Algorithm 1 is quite straightforward to follow. The statements 4 $\sim$ 8 are enclosed in a loop that iterates $|\mathcal{N}_k| \times |\Psi_s|$ times, where $|\mathcal{N}_k|$ is the total number of member nodes of a CH k. In line 10, the worst-case computing cost of Bubble sort algorithm is $O\big((|\mathcal{N}_k| \times |\Psi_s|)^2\big)$. The maximum number of total entity in λ_k can be $|\mathcal{N}_k|$; therefore, the while loop may iterate at most $|\mathcal{N}_k|$ times in line 11 and inside it the for loop can run as maximum as $(|\mathcal{N}_k| \times |\Psi_s)$ times. So, lines 11 $\sim$ 23 has time complexity $O\big(|\mathcal{N}_k| \times (|\mathcal{N}_k| \times |\Psi_s|)\big) \approx O\big(|\mathcal{N}_k|^2 \times |\Psi_s|\big)$. The rest of the statements have constant unit time complexities. Therefore, the worst-case computational complexity of the algorithm is $O\big((|\mathcal{N}_k| \times |\Psi_s|)^2\big) + O\big(|\mathcal{N}_k|^2 \times |\Psi_s|\big) \approx O\big((|\mathcal{N}_k| \times |\Psi_s|)^2\big)$.

3.3.1.4 Determination of grid coverage

As stated previously, when a member node is decided to be activated by a CH k, it requires to decide whether a particular grid is covered by an active sensing sector or not. A sensing sector may have two types of grids: grids that are fully covered by the sector and grids that are partially covered, i.e., the border grids.

As each CH knows the length of a square grid (d), the radius of the sensing sector (R_s), the sensing angle (θ_s) and the grid location of member sensor nodes using some simple geometric equations, it can easily determine the grids that are fully covered by a sensing sector. For border grids, we consider a grid is covered if at least δ portion of the total grid area falls within the coverage area of a sector.

Let the four Cartesian co-ordinate points for a square grid G(x,y) are $P_1(d(x-1), d(y-1)), P_2(dx, d(y-1)), P_3(dx, dy), P_4(d(x-1), dy)$ (considering the positive side only) and $Q(g,h)$ is a point on the line of the directional vector $\vec{V}_i^s$ of the node i in sector s (Sec 3.2). For a grid to be fully covered, the distance of the farthest corner of the grid from sector center C must be less than or equal to sector radius and the corner point falls within the sector area. A true value of a binary variable $z_{(x,y)}$ in Eq. (3.13) indicates a grid G(x,y) is fully covered by the sensing sector of a node,

$$z_{(x,y)} = \begin{cases} 1 & \text{if } dist(C, P') \leq R_s,\ \angle P''CQ \leq \frac{\theta_s}{2}, \\ 0 & \text{otherwise,} \end{cases} \tag{3.13}$$

where, P' is the farthest corner of a grid from the center C and P'' is the nearest corner point of the grid, for example in Fig. 3.3(b) $P' = P_3$ and $P'' = P_1$. The function $dist(C, P')$ returns the Euclidian distance from C to P'. Similarly, to decide a gird G(x,y) is a border grid, the binary variable $u_{(x,y)}$ in Eq. (3.14) must be true.

$$u_{(x,y)} = \begin{cases} 1 & \text{if } dist(C, P'') \leq R_s,\ \angle P''CQ \leq \frac{\theta_s}{2},\ dist(C, P') \geq R_s \\ 0 & \text{otherwise.} \end{cases} \tag{3.14}$$

In Eq. (3.14), the point P'' is any corner point of the grid from center C and P' is any other point of the grid except P''. A border grid G(x,y) is considered to be covered

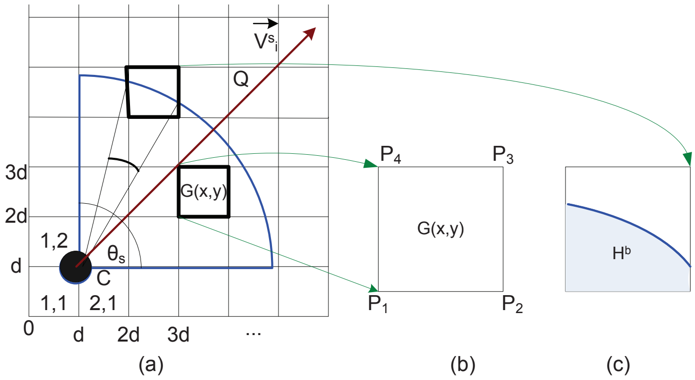


Figure 3.3: Grid coverage determination (a) Covered grids by a sector (b) A grid is inside the sector and (c) A border grid

if δ portion of the total grid area is covered by the arc of the sector, i.e, when the binary variable $t_{(x,y)}$ is true,

$$t_{(x,y)} = \begin{cases} 1 & H^b_{x,y} \geq \delta d^2 \\ 0 & \text{otherwise,} \end{cases} \tag{3.15}$$

where, $H^b_{x,y}$ is the covered area by a border grid, as shown in Fig. 3.3(c) and it can easily be measured using some lightweight geometric equations [26].

3.3.1.5 Determination of overlapping grids

In the active node selection process, overlapping grids may reside among the sectors of the member nodes of the CHs. As each CH knows the location of its member nodes β_k, the overlapping grids between the sectors of two nodes can be found by taking the common grids covered by them. These common grids can be found using Eq. (3.16).

$$O(i,j,s) \leftarrow \{(x,y) \mid (x,y) \in (\mathbb{A}_{<i,s>} \cap \mathbb{A}_{<j,s>}), \forall s \in \Psi_s, j \in n_{i,s}\} \tag{3.16}$$

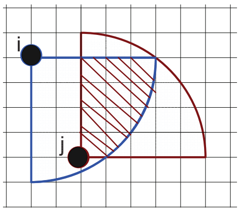


Figure 3.4: Coverage area overlapping by two nodes

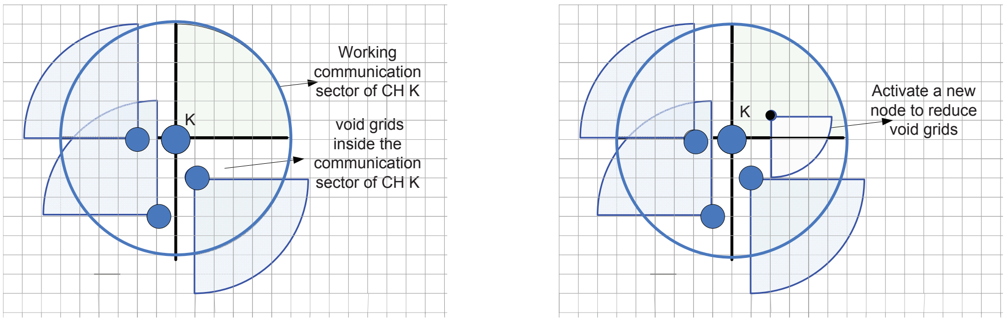
The percentage of overlapped grid coverage of a node i with any of its neighbor node j for a sector s can be calculated as,

$$\chi^s_{i,j} = \frac{|O(i,j,s)|}{|\mathbb{A}^T_{i,s}|} \times 100\%, \quad \forall j \in n_{i,s}, \forall s \in \Psi_s. \tag{3.17}$$

where, $A^{\mathbb{A}}_{i,s}$ is the set of all covered grid points of node i in sector s and $O(i,j,s)$ is the set of overlapping grids between nodes i and j.

3.3.2 Mitigating Inter-cluster Void Regions

When each CH selects its active member nodes to cover its working communication sector, this distributed decision of CHs may keep some grids void or uncovered inside the total communication region of a CH (Fig 3.5(a)). These types of void grids are formed as each CH works individually to keep its active communication sector under sensing coverage without considering the total communication sector and without communicating with neighbor CHs. To mitigate this problem, we allow neighbor CHs to share a tuple of information consisting of their working communication sector, the active sensor node list η_k, the grid point of their locations, and the matrix Π_k i.e., $< \Psi_c, \eta_k, (x, y), \Pi_k >$ with each other in all directions, so as to inform all the neighbors around the CH. Thus each CH can distributedly determine the void grids and take actions to mitigate them.



(a) Void grids among the CHs (b) Process of mitigating void grids

Figure 3.5: Mitigating void grids among the CHs

Upon receiving the neighborhood information a CH k updates its own matrix Π_k as follows:

$$\Pi_k(x, y) \leftarrow 1, \quad \forall (x, y) \in \mathbb{A}_{<i,s>} \ \& \ \ \forall < i, s > \in (\eta_k \cup \eta_l), \forall l \in \Gamma_k. \tag{3.18}$$

Updating the matrix Π_k, the CH k determines whether its total communication region (across all sectors) is fully covered or not by invoking the equality test in Eq. (3.19).

$$\Pi_k(x,y) = 1, \quad \forall (x,y) \in \mathbb{A}_k \tag{3.19}$$

Note that, Eq. (3.19) returns true if all the grids in $\mathbb{A}_k$ are covered by any of the sensor nodes; otherwise, the CH k attempts to switch on some of its sleep nodes to active state so as to cover the void grids using Eq. (3.20).

$$\begin{aligned} \Pi_k(x,y) \leftarrow 1,\ \eta_k \leftarrow < i,s > \ \mid \Pi_k(x,y) \neq 1, (x,y) \in \mathbb{A}_k, \\ \forall (x,y) \in \mathbb{A}_{<i,s>}, \forall < i,s > \in \lambda_k,\ E_r(i) \geq E_{th}. \end{aligned} \tag{3.20}$$

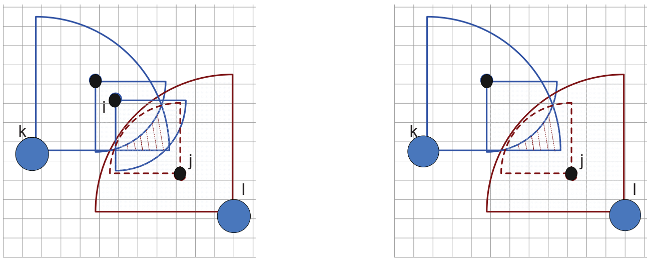
Note that, it won't be possible for a CH to cover some of the grids by activating its member nodes. However, while mitigating the void regions, there may be a chance to produce more overlapping grids among the members of the neighborhood CHs. What follows next, is the steps to mitigate the inter-cluster overlapping grids.

3.3.3 Mitigating Inter-cluster Overlapping Grids

In the active node selection process, distributed decision of each CH may form overlapping regions among the members of the neighborhood CHs. If the number of overlapping grids can be minimized by turning some *active* nodes off to *sleep* state, it can decrease the number of *active* nodes as well as enhance the lifetime of the network. In this section, we discuss how to minimize the number of overlapping grids among the members of neighborhood CHs.

A CH k first updates its matrix Π_k using Eq. (3.18) getting informations from all neighbor node $l \in \Gamma_k$. Getting information from the neighbors, a CH k, makes a list ϑ_k of its member sensor nodes using Eq. (3.21).

$$\vartheta_k \leftarrow < i,s > \mid \sum_{\forall <i,s> \in \eta_k} \ \sum_{\forall <j,s> \in \eta_l} \chi^s_{i,j} \geq \alpha, \quad \forall l \in \Gamma_k, \forall s \in \Psi_s \tag{3.21}$$



(a) Coverage overlapping (b) Minimizing coverage overlapping

Figure 3.6: Coverage overlapping among members of neigborhood CHs

Note that, the Eq. (3.21) ensures that the CH k considers only those active sensor nodes that have overlapping with neighbor CH $l \in \Gamma_k$ larger than the overlapping threshold α and keeps them in a list ϑ_k. The list ϑ_k is again sorted in decreasing order based on the amount of overlapping grid points with the CHs $l \in \Gamma_k$ [1]. The CH l now picks a sector $< i, s >$ serially from ϑ_k and checks whether there remains any uncovered grid if node $< i, s >$ is sent to *sleep* state, *i.e.*, the CH k needs to determine, whether its communication region is fully covered by the other active members of itself and neighbor CH $l \in \Gamma_k$. Hence, we boil down our problem only to check whether the entries of the matrix Π_k are still marked as covered by the nodes of $\eta_l(\forall l \in \Gamma_k)$ and $\eta_k \setminus < i, s >$, which can be determined by Eq. (3.22).

$$\Pi_k(x,y) = 1, \quad \forall (x,y) \in (\mathbb{A}_{<i,s>} \cup \mathbb{A}_{<j,s>}),$$
$$\forall < j, s > \in (\eta_l \cup (\eta_k \backslash < i, s >)),\ \forall l \in \Gamma_k,\ \forall < i, s > \in \vartheta_k, s \in \Psi_s \tag{3.22}$$

Note that, a true return value of Eq. (3.22) indicates that, dropping of $< i, s >$ from active sensor list does not affect any grids in the coverage list of Π_k. Hence, CH k may send its node $< i, s >$ to *sleep* state. However, before doing so, k gives a message to all

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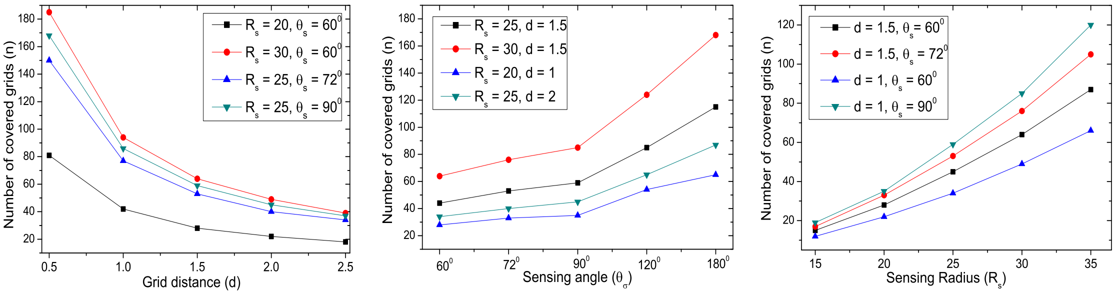
[1] Since k has the grid location information of active sensors of all its neighbors $l \in \Gamma_k$, it can easily calculate the list ϑ_k



(a) grid distance (d) (b) sensing angle (θ_s) (c) sensing radius (R_s)

Figure 3.7: Analysis of covered grids with varying grid distance, sensing angle and radius

$l \in \Gamma_k$ that, it wants to keep the node $< i, s >$ in *sleep* state. Upon receiving a reply OK message from $l \in \Gamma_k$, k removes the node $< i, s >$ from active list $i.e$, $\eta_k = \eta_k \backslash < i, s >$. The new updated list is broadcasted to all other neighbor nodes Γ_k. The whole process continues for each item of ϑ_k and stops as soon as an uncovered grid is found. In the Fig. 3.6(a) we find node j of CH l covers some grids of CH k. After calculation, CH k sends its node $< i, s >$ to *sleep* state as the grids covered by node $< i, s >$ are still covered by other node of k and l as shown in Fig. 3.6(b).

Lemma 1: The number of grid n, covered by a sensing sector, is a function of grid length (d), sensing radius (R_s), sensing angle (θ_s), and value of δ; and the maximum value of n for a node $< i, s >$ located at (x_i, y_i) is bounded by

$$\frac{\theta_s}{180}\Big(\sum_{x=x_i-w_1}^{x_i+w_1}\sum_{y=y_i}^{y_i+w_1} z_{(x,y)} + \sum_{x=x_i-w_2}^{x_i+w_2}\sum_{y=y_i}^{y_i+w_2} t_{(x,y)}u_{(x,y)}\Big),$$
$$w_1 = \left\lfloor \frac{R_s}{d} \right\rfloor,\ w_2 = \left\lceil \frac{R_s}{d} \right\rceil \tag{3.23}$$

Proof: Given that

$$n = f(R_s, \theta_s, d, \delta) \tag{3.24}$$

for a directional sensor node, the maximum value of sensing angle, $\theta_s = 180^0$. First, we calculate the maximum number of grids that can be covered when $\theta_s = 180^0$. Let n_1

represents the number of grids that are totally covered by the sensing sector and n_2 is corresponding to the grids that are partially (at least $\delta\%$) covered. Using Eq. (3.13), the value of n_1 is given by

$$n_1 \leq \sum_{x=x_i-w_1}^{x_i+w_1} \sum_{y=y_i}^{y_i+w_1} z_{(x,y)}, \quad w_1 = \left\lfloor \frac{R_s}{d} \right\rfloor. \tag{3.25}$$

Similarly, the value of n_2 can be found using Eq. (3.14) and Eq. (3.15) as follows,

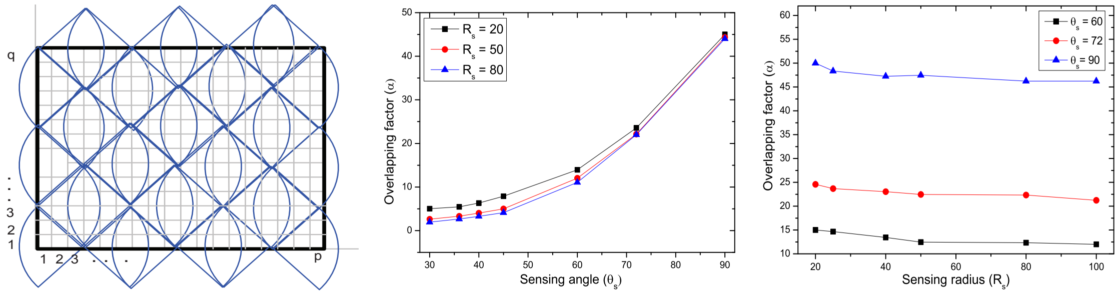
$$n_2 \leq \sum_{x=x_i-w_2}^{x_i+w_2} \sum_{y=y_i}^{y_i+w_2} t_{(x,y)} u_{(x,y)}, \quad w_2 = \left\lceil \frac{R_s}{d} \right\rceil. \tag{3.26}$$

Adding Eq. (3.26) and Eq. (3.25) and multiplying it by a value ϵ, we finally find the number of grids that are covered by a sensing sector of a node considering δ value for any sensing angle θ_s. The value ϵ is $\frac{\theta_s}{180^0}$ which represents the portion of θ_s with respect to 180^0, for example, when $\theta_s = 120^0$, $\epsilon = \frac{2}{3}$.

In α-OAC, a grid is covered when it is under the coverage of sensing sector of a node or at least δ portion of the grid area is covered (for the border grids) as defined in section 3.3.1.4. From Eq. (3.23), it is clear that if the value of δ is fixed, the maximum number of covered grids n depends on d, R_s and θ_s. Our results of simulation experiments, carried out in Matlab [110, 111], validate the theoretical expectations, as depicted in Fig. 3.7. The number of covered grids decreases exponentially with an increase in grid distance (d) (Fig. 3.7(a)). It is also observed that, for a fixed sensing radius (R_s), the number of covered grids are relatively larger for increasing value of sensing angle θ_s (blue and black lines in Fig. 3.7(a)). On the other hand, for fixed sensing angle θ_s, the number of covered grids is higher for large value of sensing radius (R_s). Similarly, the other graphs Fig. 3.7(b), (c) produce results as expected theoretically.

Lemma 2: The value of overlapping factor α is a function of sensing radius (R_s) and the sensing sector (θ_s), *i.e.,* $\alpha = f(R_s, \theta_s)$, and its minimum value α_{min} is bounded by

$$\alpha_{min} \approx \frac{1}{\kappa} \times \frac{(\theta_s - sin\theta_s)}{\theta_s R_s} \tag{3.27}$$



(a) Planned deployment (b) Overlapping vs. sensing angle (c) Overlapping vs. radius

Figure 3.8: Relation of coverage overlapping with sensing angle and radius

where, κ is a factor for error correction.

Proof: Note that, the minimum area coverage overlapping occurs when the nodes are deployed well planned in the terrain. In such a scenario, the number of grids in the overlapping region of two nodes depends on the sensing radius R_s and sensing sector size θ_s. The number of grids covered by a sensing sector is $\lceil\frac{\theta_s R_s^2}{2d^2}\rceil$, where d is the grid length [112]. The number of required sensor nodes to cover all grids $\lceil\frac{\mathcal{A}}{d^2}\rceil$ in the network can be determined as,

$$\left\lceil\frac{2\mathcal{A}}{\theta_s R_s^2}\right\rceil. \tag{3.28}$$

The overlapping region between two sensing nodes is $\lceil\frac{1}{2d^2}R_s^2(\theta_s - sin\theta_s)\rceil$ (Fig. 3.8(a)) [112]. Therefore, the minimum overlapping ratio in the terrain can be calculated as,

$$\left\lceil\frac{\frac{2\mathcal{A}}{\theta_s R_s^2} \times \frac{1}{2d^2}R_s^2(\theta_s - sin\theta_s)}{\frac{\mathcal{A}}{d^2}}\right\rceil. \tag{3.29}$$

Rewriting the Eq. (3.29), the minimum value of the overlapping factor can be measured as,

$$\left\lceil\frac{(\theta_s - sin\theta_s)}{2\theta_s R_s}\right\rceil. \tag{3.30}$$

However, Eq. (3.30) is not fully appropriate for a disk like sensing sector and it has some inaccuracy in calculation. Therefore, we have introduced an error correction factor to determine the minimum value of α as follows,

$$\alpha_{min} \approx \frac{1}{\kappa}\frac{(\theta_s - sin\theta_s)}{\theta_s R_s}, \tag{3.31}$$

where, κ is an error correction factor, the value is set from $0.002 \leq \frac{1}{\kappa} \leq 0.0025$, depicted from numerous simulation experiments in Matlab [110] for all practical values of θ_s and R_s. In fact, the number of overlapping grids rapidly increases with the sensing angle as the later increases the overlapping area among the nodes, as shown in Fig. 3.8(b). However, the number of overlapping grids decreases slightly with the increasing values of sensing radius since it increases the arc length and thereby reduces the ratio of overlapping, as shown in Fig. 3.8(c). Note also that the maximum threshold of α actually has no limit; it's a design choice and higher values may be chosen to cover a single point of interest by multiple sensing nodes for the sake of reliability.

3.3.4 Determination of Weighting Parameters

In α-OAC, an integrated metric $\varepsilon_{i,s}$, which is a weighted linear combination of two sub metrics (residual energy and covered grids), has been used to select the active nodes. The CH selects the active nodes and communicates with its neighbor CHs. Only single-hop neighborhood information has been exploited by α-OAC CHs. The CHs take the responsibility for computation and communication overheads. Therefore, the α-OAC gives a distributed solution in the network, where each CH works as a central controller for its member nodes.

Nevertheless, the main constraint of this work is the absence of mathematical expressions of weighing parameters g_1, g_2 used in Eq. (3.10) and δ in Eq. (3.15). The network density, initial energy of nodes, network shape and dimension influence the optimal selection of these weight factors. Inappropriate selection of weight factors may decrease the performance of α-OAC. We determine the weight factor values using extensive simulations; however, it does not ensure the ideal choice. In future, we are looking forward to develop an analytical model for dynamically selecting their optimal values.

3.4 Performance Evaluation

In this section, we present comparative performances of the proposed α-OAC system with two state-of-the-art solutions OSRCEA [87] and IDA-OFCA [74]. The proposed α-OAC system is implemented on two existing clustering algorithms for DSN- TCDC [38] and ACDA [107].

3.4.1 Simulation Environment

The experiments have been carried out in a discrete event network simulator ns-3 [77, 78]. Sensors are randomly deployed (unless otherwise explicitly mentioned) in a region of 1000m×1000m^2 and the grid distance d is kept 1 m. For different experiments, we have varied the number of sensors from 200 to 1000. YansWifiPhy model is used for adjusting the channel properties like the propagation delay model, data rate, delay loss model and other channel properties. The simulation parameters are shown in Table 3.2. For event generation, we use OnOff application type; each event happens randomly at different places, time-overlaps with other events, and lasts for different simulation durations (Table 3.3). The size of generated packets by each event is 512 bytes.

We have kept the weight factor values $g_1 = 0.55$, $g_2 = 0.45$, $w = 2$, $\delta = 0.75$ and run simulation experiments for various node densities, network sizes, node distributions and initial node energy values as in [44, 113, 114] . For the parameter settings of clustering protocol TCDC [38], we take the values as referred to sections 6.1 and 6.2 of [38]. Similarly, simulation parameters for ACDA [107], the values are taken as described in section VI (B) of [107]. In the network, all the α-OAC nodes, be it a cluster head (CH) or cluster member (CM) use the same transmission range in all transmission attempts irrespective of location of the destination node. The energy consumption is calculated following equations in [38] and [115]. Each simulation was run for 1000 seconds and the

Table 3.2: Network Simulation Parameters

Parameters	**Value**
Area of deployment	$1000m \times 1000m$
Grid distance d	1m
Type of deployment	Random (Uniform)
Sensor nodes deployed	$200 \sim 1000$
Sensing and communication sectors	$2 \sim 6$
Field of view	$60^o \sim 180^o$
Transmission range	$100m$
Sensing range	$50m$
Node energy (initial)	6 J
E_{th}	1 J
Network bandwidth	512 Kbps
Data packet size	512 bytes
ACK size	14 bytes
Control packet size	16 bytes
Physical layer model	YansWifi Model
Application type	OnOffApplication
Simulation time	1000 Seconds

Table 3.3: Events and Traffic Bursts

	Event 1	Event 2	Event 3
Burst 1	50s-80s	70s-100s	130s-190s
Burst 2	160s-230s	250s-330s	340s-450s
Burst 3	540s-750s	700s-850s	820s-960s

graph data points are plotted for the average of the results from 20 simulation runs.

3.4.2 Performance Metrics

- *Coverage percentage:* The coverage percentage is measured as the ratio of total number of covered grids to the total number of grids in the terrain.
- *Network lifetime:* The network lifetime is defined as the time difference from the deployment time of the network nodes to the time at which the first node dies out of energy. This is a reasonable assumption in sensor networks since it is expected

that the energy of other nodes will also be exhausted some time after the first node.

- *Percentage of active sensor nodes:* After deploying nodes in the terrain, the percentage of active sensor nodes to cover the grid area perceived by the studied systems is measured. The lower the number of active sensor nodes for the coverage of the terrain, better is the corresponding coverage algorithm, because it reduces the energy consumption and increases the network lifetime.

- *Standard deviation of residual energy:* The standard deviation of energy states the average variance among the residual energy levels on all nodes and can be calculated as follows,

$$\sigma = \sqrt{\frac{1}{|\mathcal{N}|}\sum_{i=1}^{|\mathcal{N}|}(E_r(i) - \nu)^2}, \tag{3.32}$$

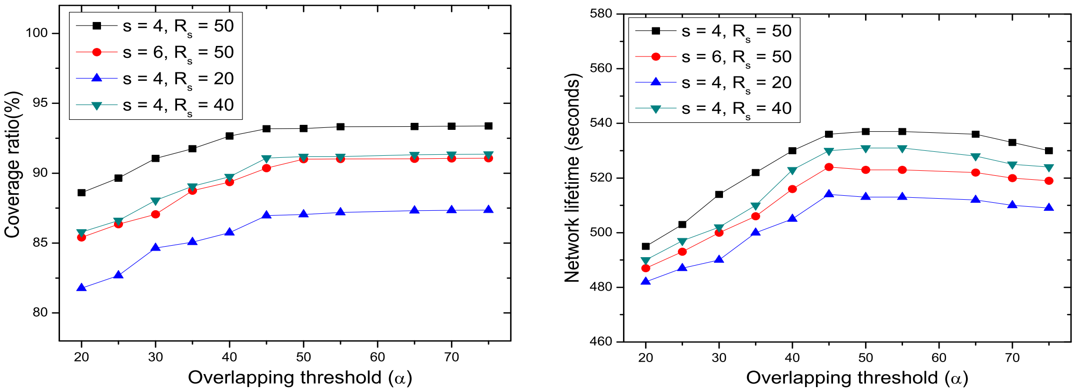
  where, $E_r(i)$ is the node i's residual energy and the mean residual energy of all nodes is indicated by ν. Hence, the σ value specifies the distribution of the energy consumption among the sensors. The σ value is expected to be small cause it indicates better ability of the α-OAC system to balance energy consumption.

- *Operation overhead:* We have also studied the amount of control bytes transmitted during the whole simulation period for successful transmission of each byte of user data to the sink to compare the operation overhead. A smaller value of operation overhead indicates better performance.

3.4.3 Simulation Results

3.4.3.1 Impacts of overlapping threshold (α)

We first vary the overlapping threshold (α) to study the performances of α-OAC using TCDC for different sensing radius (R_s) and sectors ($s \in \Psi_s$). The graphs in Fig. 3.9(a) depict that the coverage ratio initially increases with the overlapping threshold (α) since



(a) Coverage percentage

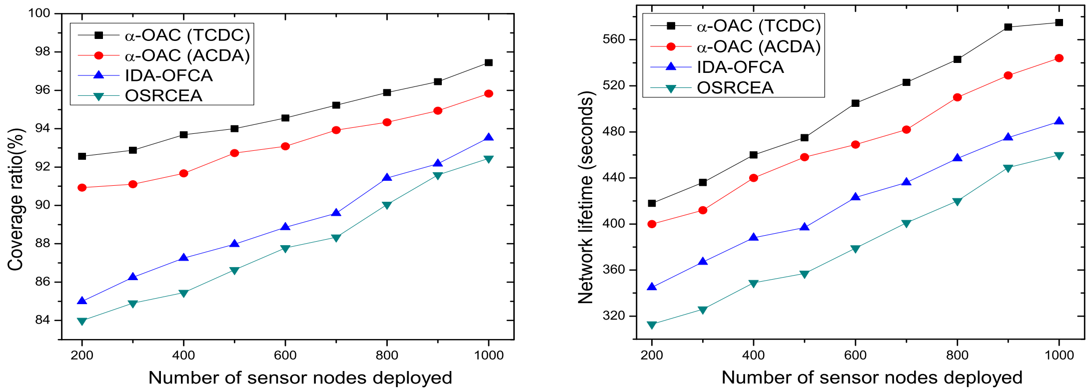
(b) Lifetime of the network

Figure 3.9: Performance studies of the systems for increasing overlapping threshold (α)

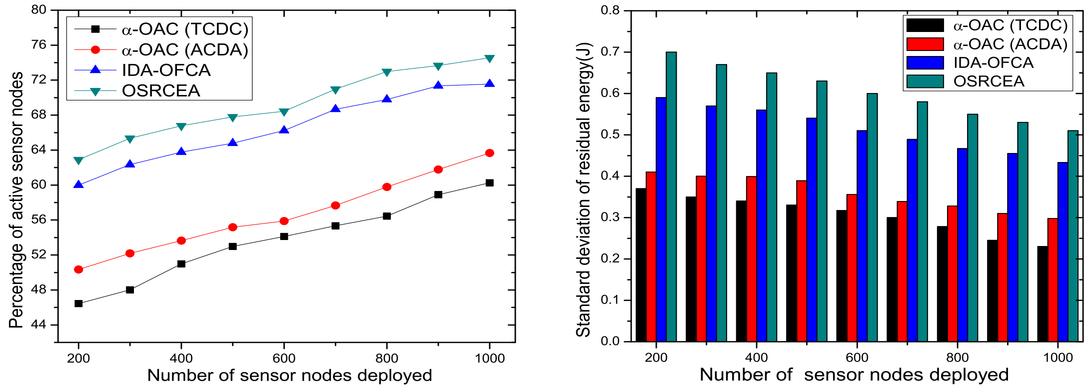
higher α value allows more nodes to take part in coverage enhancing method. However, the coverage ratio does not increase after reaching the α value at a certain point. But, the number of active nodes upsurges to cover the same area, which in turn decreases the network lifetime, as shown in Fig. 3.9(b). Observing the comparative performances, the experimental results reveal that for $\alpha = 45\%$ proposed α-OAC performed well than the other values. Therefore, the rest of the experiments have been carried out using $\alpha = 45\%$.

3.4.3.2 Impacts of node density

By varying the node deployment density, we have measured the performance metrics discussed above. Here, the number of sectors is kept at 4, sensing radius is 50m and $\alpha = 45\%$. From the graphs in Fig. 3.10(a), we have found that there is a substantial improvement in terms of area coverage percentage for α-OAC. This result is achieved because of, opposing to OSRCEA and IDA-OFCA, the CHs in α-OAC administer the coverage activities of their member nodes. In IDA-OFCA and OSRCEA, individual sensors are responsible for taking decisions and due to the less synchronization among the nodes they are incapable to offer better area coverages. On the other hand, in α-OAC, the CHs not only control their member nodes but also they cooperate with neighbor clusters so as to minimize the overlapping coverage by detecting and sending



(a) Coverage percentage (b) Lifetime of the network



(c) Percentage of active sensors (d) Standard deviation of residual energy

Figure 3.10: Performance studies of the systems for increasing node densities

corresponding sensor nodes to sleep mode. Moreover, the threshold α limits overlapping and offers additional opportunity to select the sectors for better coverage. The graphs of Fig. 3.10(a) reveal that the α-OAC with TCDC clustering algorithm provides better coverage than that with ACDA. The cluster formation strategy of TCDC takes into account the number of neighbor nodes, energy of nodes and communication cost with the sink. As a result, α-OAC (TCDC) provides better lifetime and coverage compared to α-OAC (ACDA).

The network lifetime behaviors of the algorithms α-OAC, IDA-OFCA and OSRCEA are shown in Fig. 3.10(b). As expected theoretically, the network lifetime upsurges linearly with extra deployed sensors in the network for all the systems. However, compare to others, the α-OAC system attains improved lifetime as it uses clustered network to lessen overhead of the network. More explicitly, in IDA-OFCA and OSRCEA, the energy level is not considered when selecting active nodes. On the contrary, proposed α-OAC considers the energy level of nodes and hence, there is balanced energy consumption that enhances the network lifetime. Compare to α-OAC (ACDA) system, α-OAC (TCDC) achieves better lifetime due to reduced communication overhead for cluster formation and renewal of CHs and gateways considering nodes' residual energy values. Furthermore, the selection of CHs considering the residual energy and distance from sink to node, helps the α-OAC (TCDC) to achieve improved lifetime.

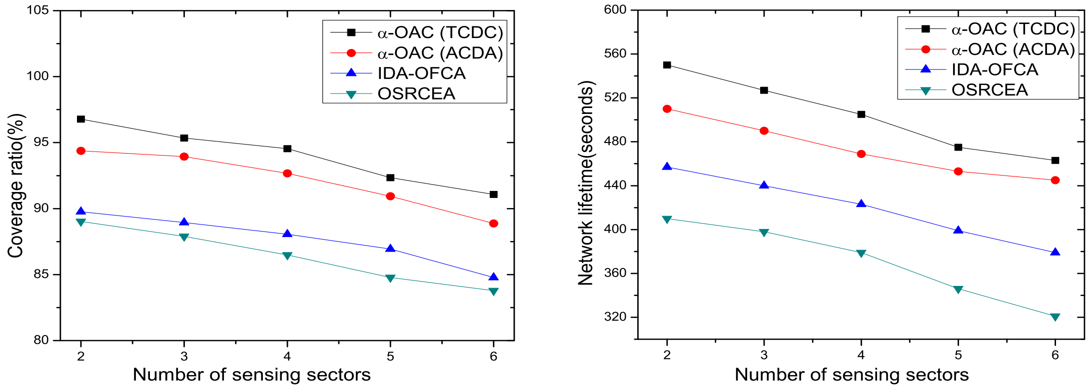
The graphs of Fig. 3.10(c) state that the percentage of active nodes are much higher for IDA-OFCA and OSRCEA systems compare to α-OAC. This happens as the proposed α-OAC executes at the CH, not an individual nodes. Each CH first minimizes the number of active member nodes ensuring its communication region is fully covered and overlapping nodes are reduced using CH-CH communication. For the same reason, as stated previously, α-OAC (ACDA) performs worse than the α-OAC (TCDC) for the activation of sensor nodes. The graphs in Fig. 3.10(d) depict that the standard deviation of residual energy level lessening gradually with the growing amount of sensors in all the studied algorithms. The proposed α-OAC system achieves enhanced result than the IDA-OFCA and OSRCEA algorithms. The reason behind this is that the IDA-OFCA and OSRCEA don't study the effect of energy level when picking active nodes; on the contrary, balanced energy consumption is achieved in α-OAC for taking care of remaining energy of nodes. However, α-OAC (TCDC) shows better performance than α-OAC (ACDA). Our in-depth look into the simulation trace files reveals that, the energy overhead due to the constitution and maintenance of cluster and gateways are relatively small in TCDC compared to that of ACDA, as expected theoretically.

3.4.3.3 Impacts of sector numbers

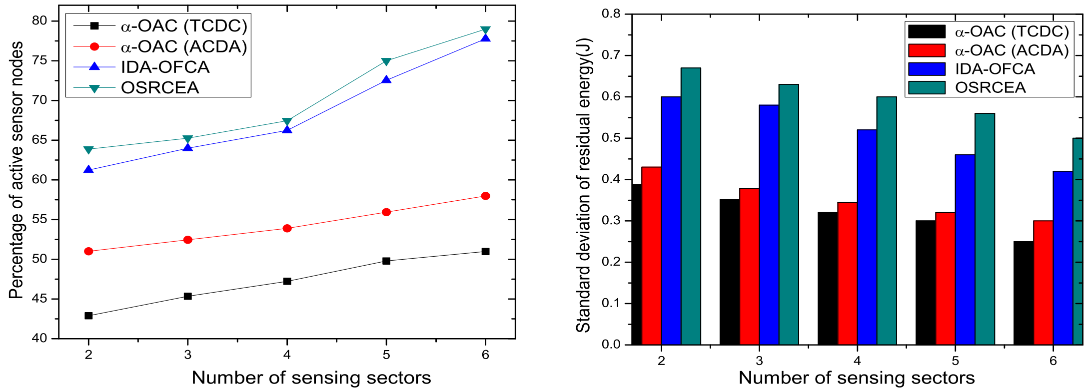
In this section, we assess the performances of the system by varying the field of view (FoV) from 180^o to 60^o. Varying the FoV allows us to use different amount of sensing as well as communication sectors, changing from 2 to 6. In this experiment, the number of deployed sensor nodes is 600. The graphs in Fig. 3.11(a) state that the coverage percentage decreases with increasing number of sectors in all the studied systems. Less number of sectors means higher size of FoV and better area coverage. The graphs also reveal that despite of increasing number of sectors, α-OAC algorithm achieves better results than OSRCEA and IDA-OFCA algorithms. In α-OAC, the coverage percentage is much better as the CHs run the coverage algorithm to decide the sensor nodes for activation along with directions in distributed fashion.

As shown in Fig. 3.11(b), the network lifetime is gradually reduced with the increasing number of sensing sectors for all the studied algorithms as it upsurges the possibility of activating huge amount of nodes primarily. However, our α-OAC shows better result as CHs select the active nodes considering their energy levels. The policy of selection of nodes helps α-OAC to overcome the overhead of clustering. Furthermore, the inter-cluster communication among the CHs assists to enhance the network lifetime. The energy-aware selection of CHs and gateways offer better network lifetime of the α-OAC (TCDC) compared to that of α-OAC (ACDA).

For increasing number of sectors, the quantity of active sensor nodes increases as depicted in Fig. 3.11(c). However, less number of nodes remain active in α-OAC compared to others since cluster formation optimizes the node activation policy co-ordinated by CHs. Besides the efficient selection of the communication sectors and the rescheduling mechanism of the cluster head and gateway nodes increase the performance of the α-OAC (TCDC) over α-OAC (ACDA). The graphs in Fig. 3.11(d) indicate that, for all systems, the standard deviation of residual energy level lessen gradually for growing number of sectors. The proposed α-OAC system achieves improved performance than others. As expected, relatively large value of sectors also enhances the choices for the CH to select nodes to keep in active or in sleep state. Consequently, this preserves the



(a) Coverage percentage (b) Network lifetime



(c) Percentage of active sensors (d) Standard deviation of residual energy

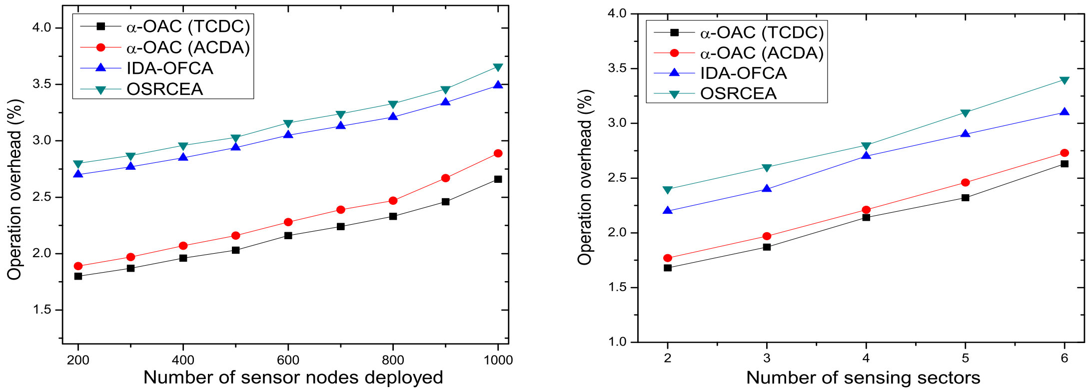
Figure 3.11: Performance studies of the systems for increasing number of sectors

energy. As stated previously, the energy-aware selection of CHs, active member nodes, reduced message passing, considering hop distance to the sink assists the α-OAC (TCDC) to distribute the energy load evenly over α-OAC (ACDA).

3.4.3.4 Operation overhead analysis

In this section, we have evaluated the operation overhead performances of the systems by varying the node density and number of sectors.

The graphs of Fig. 3.12(a) depict that our α-OAC system outperforms than the IDA-OFCA and OSRCEA since the former can significantly decrease the number of



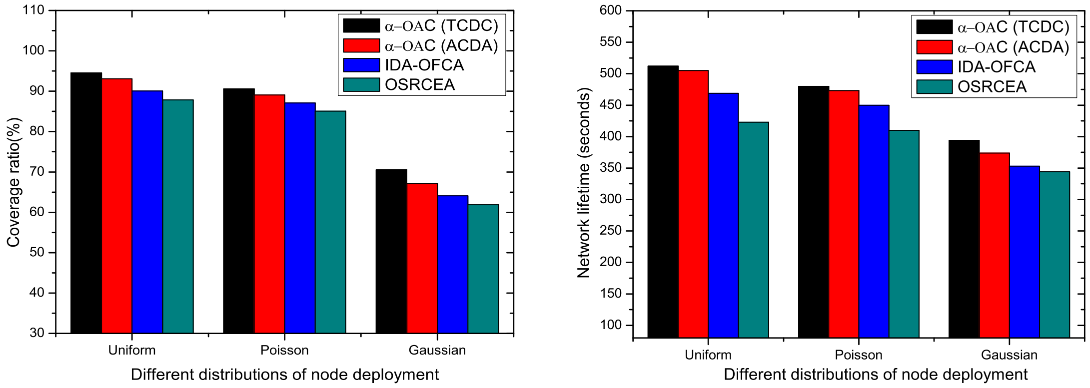
(a) Operation overhead (b) Operation overhead

Figure 3.12: Impacts of number of sensor nodes and their sectors on operation overhead

message passing by introducing one central cluster head for many sensing nodes. In fully distributed systems, IDA-OFCA and OSRCEA, the computation and communication costs are increased for exchanging messages among individual nodes. Therefore, proposed α-OAC performs better. Introducing the random waiting time in α-OAC (ACDA) incurs a number of message passing in the network, results more operation overhead in α-OAC (ACDA) compare to α-OAC (TCDC). The graphs of Fig. 3.12(b) state that our proposed system has a small overhead compared to IDA and OSRCEA, since the former needs to send few control bytes to build the cluster and communicate among the CHs.

3.4.3.5 Impacts of different node distributions

In a network, nodes can be deployed using different distributions based on application requirements. In this experiment, we observe the network lifetime and coverage performances of our proposed α-OAC system compared to those of IDA-OFCA and OSRCEA for three different node distributions- uniform random, Poisson and Gaussian. The number of nodes, sectors and sensing radius are kept at 600, 4 and 50m, respectively. From the graphs of Fig. 3.13(a) and Fig. 3.13(b), we observe that the coverage ratio and network lifetime are better for uniform distribution compare to those of Poisson and Gaussian distributions. The result is as expected theoretically, because uniform distribution helps



(a) Coverage percentage

(b) Lifetime of the network

Figure 3.13: Performance studies of the systems for different node distributions

to have more flexibility in activating sensor nodes. The results of Poisson distribution are very close to those of uniform distribution as it offers similar node distribution [116, 117]. However, Gaussian distribution causes nodes congested to some points, resulting in poor coverage and network lifetime. On the other hand, we have found that the proposed α-OAC performs well than the other state-of-the-art works for its better decision making capability using CHs.

3.5 Summary

This work develops a network lifetime-aware novel area coverage mechanism, α-OAC, has been developed for clustered DSNs. The α-OAC solve the area coverage problem using clustering mechanism by taking into account an acceptable sensing overlapping amount α among the nodes and their residual energy levels. In α-OAC system, each CH first selects the active nodes and their sensing directions within its covering region to ensure a fully covered communication region considering overlapping threshold α. The redundant sensor nodes for overlapping regions among CHs are also minimized by CH-CH communication. The residual energy-aware selection of sensing nodes and limiting the coverage overlapping help α-OAC to achieve balanced energy consumption among network nodes and thereby extends the network lifetime significantly. Moreover, the inter-cluster communication among the CHs helps to lessen the number of active nodes, resulting in higher network lifetime.

Chapter 4

Maximizing Target-Coverage Quality

4.1 Introduction

Directional Sensor Networks (DSNs) are proven to provide better network lifetime and sensing coverage compared to their omni-directional counterpart [9, 38]. These two cutting-edge features help DSNs attracting interests of research and industrial communities, particularly for the areas of high quality sensing in Smart City applications including healthcare, infrastructure security, traffic and access monitoring, etc. [9, 118]. Designated targets in Smart City are monitored to ensure more privileged and smarter living environments for the dwellers.

Target coverage is one of the fundamental research problems in DSNs, where a large number of sensors are dropped to monitor dispersed targets of interests within a given terrain. Conventional researches on target coverage mainly focus to enhance the network lifetime ensuring continuous monitoring of as maximum targets as possible [11, 12, 38]. However, in reality, distinct targets may have different significance and their required coverage qualities might differ from each other [30, 31]. Providing heterogeneous sensing qualities to all the targets in the network throws the following two major challenges that are to be carefully addressed.

1. **Coverage quality**: Traditional researches on target coverage have been carried out based on binary disk model [10, 11, 12, 22, 33], where a target is said to be covered by a sensor if the former is located within sensing range of the later. However, the quality of sensing of a target may vary due to many reasons including the exact distance between the target and the sensor, the rate of signal attenuation [30, 31, 99]

etc. In [30, 31, 106] sensing quality is quantified by an inversely proportional function of distance between a sensor and a target. The authors in [99] determined the sensing coverage quality as a function of signal attenuation factor. In reality, sensing quality is imprecise and inhomogeneous and mostly follows probabilistic model [22, 32, 79] and thus a more realistic measurement might boost up the system performance. Besides, it is also noticeable that, for some applications (e.g., emergency rescue operation), we need to focus on enhancing the coverage quality. Nevertheless, achieving high quality sensing requires to engage more number of nodes in the operation that consequently decreases the network lifetime.

2. **Network lifetime**: Many works in the literature focused on strategies to maximize the network lifetime. As far as sensing quality is concerned, the problem is transferred to maximize the network lifetime ensuring the required quality of each targets. In [31], nodes of the network are divided into non-disjoint cover sets so that each set maintains the required coverage quality of the targets. Then, the scheduling of the cover sets are optimized in such a way that the network lifetime is maximized. Similarly, in [99], the network lifetime is maximized through optimal choosing of non-disjoint cover sets that can ensure minimum sensing quality for the targets. In addition to formulating MILP (Mixed Integer Linear Programming) to achieve optimal solution, heuristic or greedy solutions are also developed in [31, 99]. However, these works mainly focus on network lifetime, overlooking the enhancement of quality. From the graphs of Figure 4.1, we observe that an inverse relationship exists between quality and lifetime. The reason is that, extended network lifetime requires to keep the number of active nodes as less as possible. On the contrary, if we try to increase the quality, it hinders to enhance the network lifetime. Therefore, an efficient solution is needed to address both the quality and lifetime that can reflect the true demands of the applications.

Based on the above observations, in this study, we explore the following research questions, develop optimal and sub-optimal greedy solutions and present the analytical

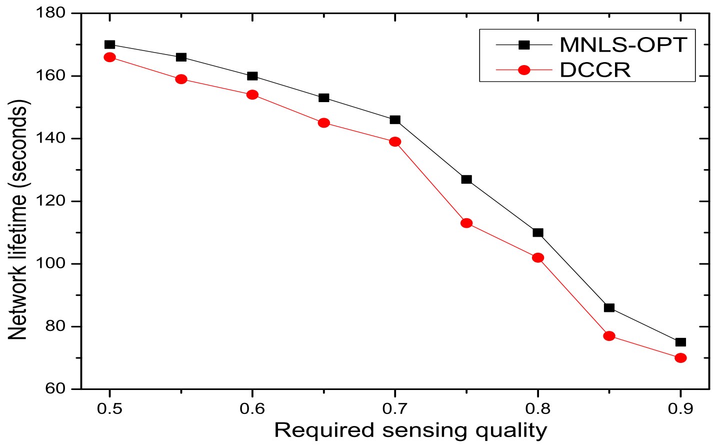


Figure 4.1: Impacts of sensing quality on network lifetime (Experiments are conducted in ns-3 with area = 100m × 100m, sensor nodes = 100, sensing radius = 25m, target = 20, sensing sector = 4)

results.

- How to maximize the target coverage quality while ensuring balanced energy consumption among the sensor nodes?
- What strategies can further optimize the network lifetime while satisfying the required sensing coverage qualities for all targets in the terrain?
- How to schedule and re-schedule the sensor nodes and their sensing directions so as to make an efficient tradeoff between the sensing coverage quality and network lifetime?
- What measurement methodology is more effective for maximizing the sensing qualities of targets?

We observe that, focusing on only coverage quality or network lifetime without considering both, failed to reflect the actual requirements of diverse applications. Applications may require to give emphasis on enhancing coverage quality or network lifetime or both based on the significance of the application. For example, an emergency rescue operation may need high coverage quality; on the other hand, remote monitoring of elderly people at home using multimedia sensor networks may demand longer network lifetime maintaining a certain coverage quality [15]. We also find that, if the residual energy and the coverage quality are not considered jointly, it is difficult to achieve enhanced network lifetime since the energy depletion rates of different sensor nodes vary greatly from each other.

In this work, we develop a general framework, namely MQMS-DSN (Maximizing Coverage Quality with Minimum Number of Sensors in DSN), that is applicable to maximize the target coverage quality or the network lifetime or to make an efficient tradeoff between the two following application demands. The proposed MQMS-DSN framework is a Mixed Integer Linear Programming problem (MILP) that facilitates to achieve multiple objectives by using a suitable tuning parameter. Indeed, obtaining the optimal solution is a combinatorially hard problem to solve as the basic target coverage problem is NP-hard [12, 31]. Thus, to obtain meaningful insights and overcome the complexity of the original problem, we provide sub-optimal and greedy heuristic solutions for clustered DSN. Each cluster head (CH) takes coverage decisions independently following current situations of its vicinity. Measuring the coverage quality using a probabilistic sensing model (i.e., Elfes probabilistic model [32]), the residual energy-aware selection of active nodes helps our MQMS-DSN formulation to achieve enhanced network lifetime. We also present schemes to mitigate the redundancy of active nodes for common covered targets by inter-cluster communications. Finally, the performance results of the proposed solutions, carried out in ns-3 [77, 78], show that the proposed MQMS-DSN outperforms state-of-the-art-works in terms of network lifetime, coverage quality, percentage of active sensor nodes, and standard deviation of residual energy.

The rest of this Chapter is organized as follows. We have described the network model in Section 4.2 and our proposed MQMS-DSN architecture is detailed in 4.3. In Section 4.4, the simulation results are presented and finally, we have summarized the work in 4.5.

4.2 System Model and Assumptions

4.2.1 Network Model

We consider a Directional Sensor Network (DSN) consisting of a set $\mathcal{N}$ of large number of stationary directional sensor nodes in a 2-D Euclidean plane. A set $\mathcal{M}$ of targets with known locations is also positioned in the same terrain. Sensor nodes are randomly deployed maintaining large density to achieve high coverage ratio. We also assume a sink node is located at a fixed point in the terrain for collecting data from sensor devices through multi-hop data communication. We also consider that, in terms of number of communication and sensing sectors, corresponding radius and initial energy E_o, all nodes are homogeneous. However, individual targets $m \in \mathcal{M}$ have different sensing coverage quality requirements, $\varrho(m)$. We also assume that each sensor node is aware of its location and its neighbors by using GPS or any other localization method [109]. The tasks of sensing and transmission are directional and the reception is omni-directional for the nodes.

To support implementations of sub-optimal and greedy alternate solutions to our optimal MQMS-DSN problem, we also assume that the network nodes are clustered. That is a suitable clustering algorithm [38, 107], is running in the network that selects cluster heads (CHs) and gateways (GWs) to develop a communication backbone for the network. Let $\mathcal{N}_k$ denotes the set of member nodes of a CH k, $k \in \Upsilon$. As discussed in the previous Chapter 3 Section 3.2, in the literature, a very good number of clustering algorithms exist that consider the coverage problem for omni-directional sensor networks [46, 47]. However, those are not applicable for directional sensor networks since there are some basic differences between the operational procedures of omni and directional sensor nodes. In the literature, we have found two leading clustering techniques that work with directional sensor networks - ACDA [107] and TCDC [38]. In autonomous clustering algorithm (ACDA) [107], individual nodes exchange messages for a random waiting time period to select cluster heads and gateway nodes. At the beginning, ACDA does not consider residual energy levels of nodes; however, later it renews the cluster heads

Table 4.1: List of Notations for MQMS

Symbol	**Definition**
$\mathcal{N}$	Set of all sensor nodes in the network
$\mathcal{M}$	Set of all targets in the network
θ_s, R_s	Sensing angle and radius
Ψ_s	The set of sensing sectors of a node, $\lvert\Psi_s\rvert = \frac{2\pi}{\theta_s}$
ϕ_i	The set of directions of sensor i, $\phi_i = \{< i, s > \mid s \in \Omega\}$
Ψ	The set of directions of all the sensors, $\Psi = \cup\ \phi_i,\ \forall i \in \mathcal{N}$
$\varrho(m)$	The sensing coverage quality requirement for target $m \in \mathcal{M}$
$\rho_{i,s}(m)$	Given sensing coverage quality for target $m \in \mathcal{M}$ by sector s of node i
$\rho(m)$	Aggregated sensing quality for target $m \in \mathcal{M}$
$\vec{V}_i^s$	Working direction of a node i in sector s
Υ	Set of all cluster heads
$\mathcal{N}_k$	Set of member nodes of CH $k \in \Upsilon$
$\mathcal{M}_{i,s}$	Set of targets for which the sensing coverage quality value $\rho_{i,s}(m_k) \neq 0$ in the sensing sector s for node i
$\mathcal{M}_k$	Set of targets covered by member nodes of a CH k i.e., $\mathcal{M}_k \leftarrow \cup\ \mathcal{M}_{i,s}, \forall i \in \mathcal{N}_k, \forall s \in \Psi_s$
Γ_k	Set of one hop neighbor CHs of CH k

and gateways studying the residual energy levels. On the other hand, the TCDC [38] selects a node as cluster head (or gateway) considering its residual energy level, number of neighbor nodes and its distance from the sink. The renew process is performed by existing CHs and gateways when their energy levels fall below a certain threshold. Both the ACDA and TCDC systems use gateways to route data packets from CHs toward the sink using the shortest hop single path routing strategy. The performances of the proposed suboptimal and greedy MQMS solutions may vary depending on the clustering technique. However, previous study reveals that, TCDC outperforms between the two and thus we carry out performance evaluation using TCDC [38] as underlying clustering algorithm. Throughout the paper, we have adopted the notations described in Table. 4.1.

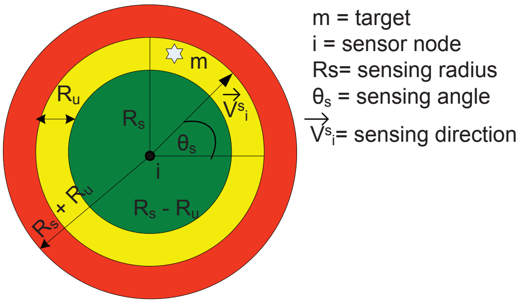


Figure 4.2: Probabilistic sensing model

4.2.2 Probabilistic Sensing Models

Each sensor has a set Ψ_s of non-overlapping sensing directions (Fig: 4.2), where each direction of a node is a sector of a disk centered at the sensor with sensing radius R_s and angle $\theta_s = \frac{2\pi}{|\Psi_s|}$. The directional vector $\vec{V}_i^s$ represents a center line on the sensing sector $s \in \Psi_s$. To determine the presence of a target $m \in \mathcal{M}$ in sector s of node i, we use the target in sector (TIS) test [9, 10, 75] and thus build a set Φ_m that contains the tuple $< i, s >$ for all nodes that can cover the target as follows,

$$\Phi_m \leftarrow \{< i, s > \mid d(i,m) \leq R_s,\ \vec{im}.\vec{V}_i^s \geq d(i,m)\cos\frac{\theta_s}{2}\}, \tag{4.1}$$

where, $d(i, m)$ is the Euclidean distance between the node i and target m. Depending on the sensing range R_s, an individual sensor node is able to sense only a subset of the observing area, where it is deployed.

4.2.3 Sensing Coverage Quality Measurement

Unlike binary disk model [10, 22, 33], the quality measurement for a target offered by any node in probabilistic model [22, 32, 79], depends on the observing region of the node where the target is located. According to Elfes model [22, 32, 79], the probabilistic sensing quality $\rho_{i,s}(m)$ for a target $m \in \mathcal{M}$ covered by a node i in sector s can be calculated as follows,

$$\rho_{i,s}(m) = \begin{cases} 0 & R_s + R_u \leq d(i,m),\ <i,s>\in \Phi_m, \\ e^{-\mu\xi^{\beta}} & R_s - R_u < d(i,m) < R_s + R_u,\ <i,s>\in \Phi_m, \\ 1 & R_s - R_u \geq d(i,m),\ <i,s>\in \Phi_m, \end{cases} \tag{4.2}$$

where, $R_u(\leq R_s)$ is the measure of sensing uncertainty of a target; $\xi = d(i,m)-(R_s-R_u)$, β and μ are parameters $(0 \leq \mu, \beta \leq 1)$ that measure detection probability when a target is at distance greater than R_u but within R_s (Fig: 4.2(a)). Therefore, the aggregated sensing coverage quality of a target m offered by all nodes in the vicinity is measured by,

$$\rho(m) = 1 - \prod_{<i,s>\in\Phi_m} (1 - \rho_{i,s}(m)). \tag{4.3}$$

Our proposed MQMS-DSN system aims to maintain the required sensing coverage quality, *i.e.*, keeping $\rho(m) \geq \varrho(m)$, for all targets $m \in \mathcal{M}$ in the network by activating different sensors in certain directions.

4.3 Proposed MQMS-DSN Systems

In this section, at first, we develop a centralized optimal MQMS-DSN system, namely CMQMS, which is a generalized framework for either maximizing the network lifetime while supporting the required coverage quality or maximizing the coverage quality only or orchestrating a tradeoff between the two. Then, we develop a suboptimal system (SMQMS) for a clustered network to enhance the scalability of the solution, where each cluster head decides the activation of member nodes and their sectors in distributed way. Finally, GMQMS is proposed that greedily chooses the sensor nodes so as to increase either the coverage quality or the network lifetime. What follows next, we explore the operation of the aforementioned MQMS-DSN systems in detail.

4.3.1 Centralized Optimal MQMS-DSN System

The CMQMS system is formulated as a Mixed Integer Linear Programming (MILP) problem, where a central controller chooses the nodes that provide optimal performances.

The central controller (sink node) first generates candidate sets, consisting of some nodes and their sectors, that meet the required coverage quality, as described below.

4.3.1.1 Formation of coverage candidate sets

Let Ψ be a set of tuples $< i, s >$ for all sensors $i \in \mathcal{N}$ and for all directions $s \in \Psi_s$. A *candidate set* ψ is a subset of Ψ that can satisfy the required coverage quality $\varrho(m)$ of all targets $m \in \mathcal{M}$ in the network. We define a boolean variable $x_{i,s}$ that represents whether a tuple $< i, s >$ is present in a candidate set or not; the value is determined as,

$$x_{i,s} = \begin{cases} 1 & \text{if} < i, s > \in \psi,\ i \in \mathcal{N},\ \psi \subseteq \Psi\ , \\ 0 & \text{otherwise.} \end{cases} \tag{4.4}$$

Note that, a node i can't exist multiple times in a particular candidate set, $\psi \in \Psi$. Many such coverage candidate sets can be formed in the network, where the elements in the set altogether satisfy the condition in Eq. 4.5.

$$1 - \prod_{<i,s>\in\psi} (1 - \rho_{i,s}(m)) \geq \varrho(m), \quad \forall m \in \mathcal{M} \tag{4.5}$$

The complete process of forming coverage candidate sets is presented in Algorithm 2. In line number 1, we filter out the tuples $< i, s$ that can't cover any target, helping us to reduce the complexity of the algorithm. The complexity of the algorithm can further be lessened by sieving out the nodes that have residual-energy smaller than a threshold value (E_{th}), as depicted in line 2. In line numbers 4-10, in each iteration, we take a subset ψ' from the power set, $P(\Psi)$, and test whether it can satisfy the required coverage quality using Eq. 4.5, whether the subset contains no more than one $< i, s >$ entries for a single node i and whether the cardinality of the subset limits within the size of the network or not. In the case, all the above conditions return true for a subset ψ', it is declared as a candidate set $\psi \in \Psi'$, where Ψ' is the set of all coverage candidate sets.

The complexity of this algorithm is quite straightforward to follow. The lines 4-10

Algorithm 2 Formation of Coverage Candidate Sets

```
INPUT: Set $\Psi'$ of tuples $< i, s >$ for nodes $i \in \mathcal{N}$
OUTPUT: Candidate sets $\psi \subseteq \Psi'$

$\Psi \leftarrow \Psi \setminus \ < i, s >$, where the tuple $< i, s >$ can't cover any target $m \in \mathcal{M}$
$\Psi \leftarrow \ \Psi \setminus < i, s > for\ E_r(i) \leq E_{th}$
$\Psi' \leftarrow \phi$
for all $\psi' \subseteq P(\Psi)$ do
  if $(|\psi'| \leq |\mathcal{N}|$ AND $\sum_{<i,s>\in\psi} x_{i,s} \leq 1)$ then
    if Eq. 4.5 returns TRUE for $\psi'$ then
      $\psi \leftarrow \psi'$
      $\Psi' \leftarrow \Psi' \cup \psi$
    end if
  end if
end for
```

are enclosed in a loop which iterates at most $2^{|\mathcal{N}|\times|\Psi_s|}$ times having a computational complexity of $O\big(2^{|\mathcal{N}|\times|\Psi_s|}\big)$. Here, $2^{|\mathcal{N}|\times|\Psi_s|}$ is actually the computational complexity of generating the subsets. The rest of the lines have constant time unit complexities. Therefore, to formulate the candidate sets the overall time complexity is $O\big(2^{|\mathcal{N}|\times|\Psi_s|}\big)$.

4.3.1.2 MILP formulation

Out of the competent coverage candidate sets, the proposed CMQMS system finds an optimal set ($\psi^* \in \Psi'$) that achieves our goals through exploring all possible ways using an MILP optimization function, expressed as follows,

$$\underset{\psi\in\Psi'}{arg\ min}\left\{\gamma \times \sum_{<i,s>\in\psi} x_{i,s} - (1-\gamma) \times \sum_{m\in\mathcal{M}} \Big(1 - \prod_{<i,s>\in\psi} \big(1-\rho_{i,s}(m)\big)x_{i,s}\Big)\right\} \tag{4.6}$$

subject to,

$$\sum_{s\in\Psi_s} x_{i,s} \;\leq\; 1, \quad \forall < i,s > \in \psi,\; \psi \in \Psi' \tag{4.7}$$

$$1 - \prod_{<i,s>\in\psi} (1-\rho_{i,s}(m))x_{i,s} \geq \varrho(m), \quad \forall\; m \in \mathcal{M} \tag{4.8}$$

$$E_{th} \leq E_r(i) \;\leq\; E_o(i), \quad < i,s > \in \psi,\; \psi \in \Psi' \tag{4.9}$$

$$0 \leq \gamma \leq 1. \tag{4.10}$$

The constraint (4.7) ensures that a node can participate in at most one sector in a particular candidate set. The constraint (4.8) satisfies the coverage quality constraint, i.e., all targets are covered with required coverage qualities by the sensors in the candidate set. A node is activated only if its residual energy $E_r(i)$ is larger than a threshold value E_{th}, implemented by the constraint (4.9). The constraint (4.10) sets the value of the tuning parameter γ. Therefore, based on the constraints, the objective function finds an optimal candidate set for activation that can maximize the aggregated coverage quality of targets (when $\gamma = 0$) or the network lifetime (when $\gamma = 1$) or make a trade off in between the two, depending on the value of $0 < \gamma < 1$. In other words, the proposed objective function, depicted in Eq. (4.6), implements a generalized framework. In the case $\gamma = 0.5$, both the performance metrics- coverage quality and network lifetime get equal importance; the network lifetime can be given more priority by setting $0.5 < \gamma < 1$ while maintaining the minimum coverage quality for targets and the reverse case happens when $0 < \gamma < 0.5$.

In the above MILP formulation, the central controller finds a set ψ^* and activates the nodes to their corresponding sectors, $< i,s > \in \psi^*$. However, producing only one optimal set does not guarantee enhanced lifetime; we have to rotate the responsibilities among other nodes so as to increase the network lifetime. The central controller initiates generation of a new optimal set ψ^{**} when the following condition holds true for any active

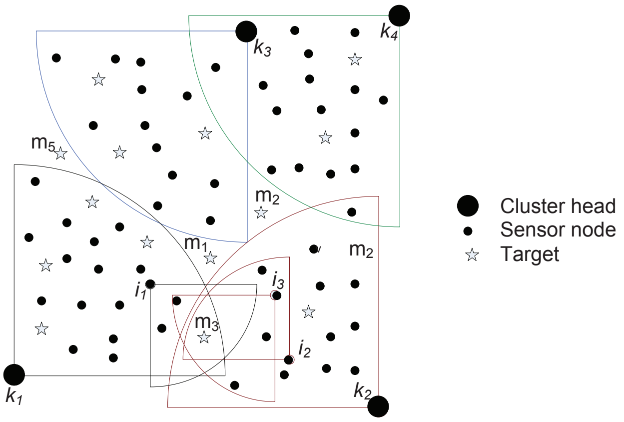


Figure 4.3: Target coverage by member nodes of cluster heads

node $i \in \mathcal{N}$,

$$E_r(i) \leq E_{th}, \quad < i, s > \in \psi^*. \tag{4.11}$$

Note that the value of energy threshold E_{th} is not kept fixed; rather, its value is updated using Eq. 4.12 every after running the objective function, where, the weight parameter $0 < \zeta < 1$ allows new nodes to come into the optimal candidate set.

$$E_{th} = \zeta \times E_{th} \tag{4.12}$$

Now, the key limitation of the proposed CMQMS system is that it requires all nodes in the network to send their instantaneous status (location, residual energy, etc.) to a central controller (typically, a sink); it is very expensive in terms of computation and communication costs as the number of targets and nodes is increased. Furthermore, the CMQMS is an NP-Hard problem and thus polynomial-time solution for CMQMS often will not be possible, like that in [30, 31]. What follows next, we present a suboptimal system for covering targets.

4.3.2 Distributed Sub-optimal MQMS-DSN System

In this section, we develop a sub-optimal MQMS system, namely SMQMS, that distributes the responsibility of running target coverage algorithm to many nodes in the network, unlike at a central node in CMQMS system. The key philosophy is to divide the network into many clusters, where each cluster head (CH) is given the duty to select a set of active nodes and their sensing sectors so as to maximize the coverage quality with minimum number of sensors. One naive solution is to run the same objective function (i.e., the Eq. 4.6) at CHs as if a CH acts like a central controller for reduced set of sensors and targets located within its working communication sector. However, it introduces some new challenges to achieve our goals:

- *Some targets may remain uncovered-* Targets located in void zones (i.e., not located within the communication range of any of the CHs in the neighborhood) will not be covered. For example, the targets m_1, m_2 and m_5 are out of the communication boundaries of CHs and they might not covered by any of the CHs, as shown in Fig. 4.3. This is happened due to the reduction of visibility on the network by individual CHs and participation of only sensor nodes in cluster formation process without considering target locations [38, 107].

- *Redundant activation of sensors-* As individual CHs are activating their sensor nodes for covering targets within their communication regions, a target (located at boundary zones) may be covered by excessive sensor nodes than it requires. For example, in the Fig. 4.3 suppose, alone the node i_1 or nodes i_2, i_3 jointly can satisfy the sensing requirement of target m_3. If CHs k_1 and k_2 work independently, the activation of all the three sensors are unnecessary here.

To mitigate the above challenges, we reformulate the previous MILP (in Eq. 4.6 to 4.10) to develop the sub-optimal MQMS-DSN system. Note that, we can mitigate the first problem neither by including targets in the cluster formation process nor compelling those to be located within the communication region of any of the CHs, since it's not realistic. Therefore, we redefine the set of targets, $\mathcal{M}_k$, that will be considered by a CH

$k \in \Upsilon$ as,

$$\mathcal{M}_k = \bigcup_{\forall i \in \mathcal{N}_k} \mathcal{M}_{i,s}, \quad \forall s \in \Psi_s \tag{4.13}$$

where, $\mathcal{N}_k$ is the set of member nodes of CH k and $\mathcal{M}_{i,s}$ is the set of all targets covered by a sensor node i focused in direction $s \in \Psi_s$, defined as, $\mathcal{M}_{i,s} = \{m \mid m \in \mathcal{M}$ and $\rho_{i,s}(m_k) \neq 0\}$. This redefinition of the target set, at different CHs, ensures that, every target in the terrain must be a member of any of target sets $\mathcal{M}_k,\ k \in \Upsilon$, as proved in Lemma 1.

To address the second challenge, *i.e.*, redundant activation of sensor nodes, we allow a CH to share the set of targets that are already covered by it along with their one hop neighbor CHs, Γ_k, after each time it selects a set of sensors for covering the targets. Like in CMQMS system, a SMQMS CH k calculates the values, $\rho(m)$ and $\rho_{i,s}(m)$ using Eq. 4.1 to Eq. 4.3 $\forall m \in \mathcal{M}_k$ and generates a set of candidate sets $\Psi'_k = \{\bigcup \psi \mid <i,s> \in \psi,\ \forall i \in \mathcal{N}_k\}$ using Algorithm 2. The MILP for the SMQMS system is reformulated as follows,

$$\underset{\psi_k \in \Psi'_k}{arg\ min} \left\{ \gamma \times \sum_{<i,s> \in \psi_k} x_{i,s} - (1-\gamma) \times \sum_{m \in \mathcal{M}_k} \Big(1 - \prod_{<i,s> \in \psi_k} (1 - \rho_{i,s}(m)) x_{i,s} \Big) \right\} \tag{4.14}$$

subject to,

$$\mathcal{M}_k = \mathcal{M}_k \setminus \mathcal{M}_l, \quad \forall l \in \Gamma_k, \tag{4.15}$$

$$\sum_{s \in \Psi_s} x_{i,s} \ \leq \ 1, \quad \forall <i,s> \in \psi_k,\ \psi_k \in \Psi'_k \tag{4.16}$$

$$1 - \prod_{<i,s> \in \psi_k} (1 - \rho_{i,s}(m)) x_{i,s} \geq \varrho(m), \quad \forall\ m \in \mathcal{M}_k \tag{4.17}$$

$$E_{th} \leq E_r(i) \ \leq \ E_o(i), \quad <i,s> \in \psi_k,\ \psi_k \in \Psi'_k \tag{4.18}$$

$$0 \leq \gamma \leq 1. \tag{4.19}$$

Here, the constraint (4.15) helps the SMQMS system to minimize redundant coverage of targets, *i.e.*, it further minimizes the active number of sensor nodes in a neighborhood. The rest of the constraints (4.16), (4.17), (4.18) and (4.19) follow the similar interpretation as before but for reduced set of sensors $i \in \mathcal{N}_k$ and targets $m \in \mathcal{M}_k$.

Lemma 1: *The distributed SMQMS system can offer the required coverage quality for all targets in the terrain as maintained by the CMQMS system.* □

Proof: We show the correctness of the lemma *using proof by contradiction.* We first assume that, after execution of SMQMS system, there remains a target $m \in \mathcal{M}$ in the network, which is not covered by its required quality.

Note that, the required coverage quality $\varrho(m)$ of a given target $m \in \mathcal{M}$ in the network may not be fulfilled if any of the following two conditions holds true:

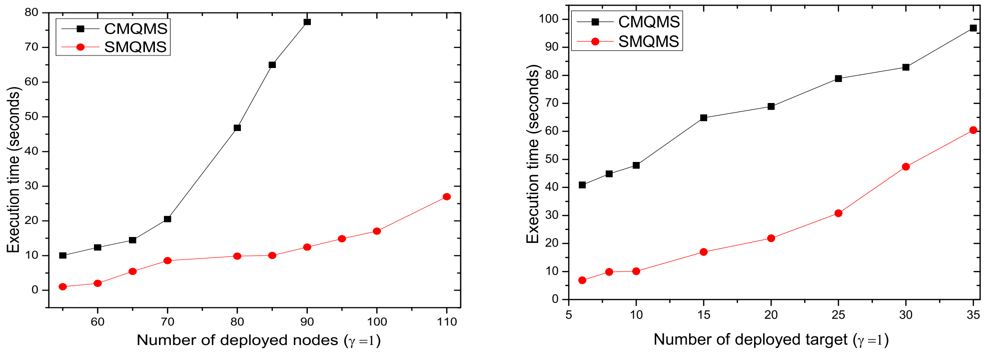
(a) Sufficient number of sensor nodes are not available in the network to satisfy the coverage quality of the targets.

(b) The given target is not visible by the entity executing the sensing coverage algorithm.

Typically, in wireless sensor network, the nodes are deployed with high density so as to schedule those alternately to extent the network lifetime [9, 26]. Furthermore, since every node in SMQMS works either as CH or a member node and given that the CMQMS system ensures the required coverage quality of all targets in the network, there is no reason that the SMQMS system suffers from insufficiency of sensor nodes to cover targets. Thus, the first condition (a) does not hold true.

Similarly, the second condition (b) cannot be held for SMQMS system since we consider all targets are covered by each and every member nodes of a CH $k \in \Upsilon$ (using Eq. 4.13). Moreover, the constraint (17) ensures that, all targets are covered by their required qualities. Therefore, our initial assumption contradicts with the achievable properties of SMQMS system. ■

Now, like CMQMS, the SMQMS system also becomes intractable one for increasing number of nodes, targets and monitoring area. We simulate the objective function of



(a) Execution time vs. number of nodes

(b) Execution time vs. number of targets

Figure 4.4: Impacts of execution time with varying number of (a) nodes and (b) targets for CMQMS and SMQMS system.

CMQMS and SMQMS systems in NEOS Optimization server (2x Intel Xeon E5-2698 @ 2.3GHz CPU and 92GB RAM) for given 20 snapshots of the network environment, and the results are shown in Fig. 4.4. The results reveal that, on an average, several seconds are required to execute the CMQMS and SMQMS systems for around 60 $\sim$ 110 number of nodes and 5 $\sim$ 35 targets. Also, as the node size in the network upsurges, it is difficult to find the results in polynomial time rather it requires exponentially high execution time (Fig. 4.4(a)). The reason is that, both the systems, calculate the number of subsets of the directions of nodes which increases as a power of nodes. However, since each CH distributedly selects the active nodes in the network, the SMQMS system has the ability to show better performance than the CMQMS system for larger number of nodes. The same is true for increasing number of targets (Fig. 4.4(b)). Nevertheless, it is quite challenging to provide results in polynomial time using SMQMS system for some real-time applications as sensors have very limited processing power and memory (nearly 5 $\sim$ 8 MHz and 2 $\sim$ 108 KB [34]). This challenge has motivated us to design a distributed greedy system to cover the targets.

4.3.3 Distributed Greedy MQMS-DSN System

In this section, we design a distributed greedy system, GMQMS-DSN for clustered networks. The GMQMS-DSN greedily maximizes either the network lifetime or sensing quality, implemented by two algorithms- (a) First-fit lifetime maximization (GMQMS-L, $\gamma = 1$) and (b) First-fit quality maximization (GMQMS-Q, $\gamma = 0$).

At first, each CH k finds a target set $\mathcal{M}_k$ using Eq. (4.13) by exchanging the nodes' and targets' information with neighbor CHs $l \in \Gamma_k$. The target set $\mathcal{M}_k$ constitutes three different types of targets in terms of coverage status, defined as follows,

$$\mathcal{M}_k = \mathcal{M}_k^F \cup \mathcal{M}_k^P \cup \mathcal{M}_k^U \tag{4.20}$$

where, $\mathcal{M}_k^F$ is the set of targets having coverage requirements fulfilled, $\mathcal{M}_k^P$ is the set of targets partially covered and $\mathcal{M}_k^U$ is the set of uncovered targets. The CH k also updates direction set Ψ_k as follows.

$$\Psi_k \leftarrow \Psi \backslash < i, \omega >, \quad E_r(i) < E_{th}, \quad \forall i \in \mathcal{N}_k \tag{4.21}$$

where, $E_r(i)$ is the residual energy value of node i and E_{th} is the energy threshold, updated using Eq. (4.12). What follows next, is the detail description of the two strategies.

4.3.3.1 First-fit lifetime maximization (GMQMS-L)

The key philosophy of designing GMQMS-L is to activate as minimum number of sensor nodes as possible to ensure required sensing coverage qualities of all targets in the networks. Each CH $k \in \Upsilon$ calculates a metric $\mathcal{L}_{i,s}$ for each sector $< i, s > \in \Psi_k$, as follows,

$$\mathcal{L}_{i,s} = q_1 \times \frac{|\tau_{i,s}|}{|\mathcal{M}_k^P \cup \mathcal{M}_k^U|} + q_2 \times \frac{\sum\limits_{m \in (\mathcal{M}_{i,s} \backslash \tau_{i,s})} \rho_{i,s}(m)}{\sum\limits_{m \in (\mathcal{M}_k^P \cup \mathcal{M}_k^U) \backslash \tau_{i,s}} \varrho(m)} + q_3 \times \frac{E_r(i)}{E_o(i)}, \tag{4.22}$$

where, q_1, q_2, q_3 are weight parameters and $\tau_{i,s} \subseteq (\mathcal{M}_{i,s} \cap (\mathcal{M}_k^P \cup \mathcal{M}_k^U))$ s.t. $\rho_{i,s}(m) \geq \varrho(m), \forall m \in (\tau_{i,s} \cap \mathcal{M}_k^U)$ or $\rho_{i,s}(m) \geq (\varrho(m) - \rho(m)), \forall m \in (\tau_{i,s} \cap \mathcal{M}_k^P)$. In other words, $\tau_{i,s}$

is the set of uncovered and partially covered targets whose remaining required coverage quality can be fulfilled by the sector $< i, s >$.

Note that, the computation of the metric $\mathcal{L}_{i,s}$ in Eq. (4.22) is done by weighted linear combination of three sub-metrics: the number of targets ($|\tau_{i,s}|$) whose requirements can be fulfilled, the contribution of the sector to cover more uncovered targets ($\rho(m) < \varrho(m)$) and the residual energy of the sensors ($E_r(i)$). Now, the CH k greedily activates a sensing sector $< i, s >$ that has maximum $\mathcal{L}_{i,s}$ value. The activation process of sensing sectors has been summarized in Algorithm. 3. One sector can be activated in only one direction at a time (line 9 of Algorithm. 3). After activating a sensor device, the value of $\rho_{i,s}(m)$ and $\rho(m)$ are updated $\forall m \in \mathcal{M}_{i,s}$; subsequently, the target sets $\mathcal{M}_k^F$, $\mathcal{M}_k^P$ and $\mathcal{M}_k^U$ are also updated (lines 11 $\sim$ 15). The CH k continues the above process until the required coverage qualities for all targets in the network are achieved or there is no other sensing sectors that can be activated (line 18).

4.3.3.2 First-fit quality maximization (GMQMS-Q)

In this section, we present our strategy for enhancing quality of sensing coverage for all targets in the network. The key philosophy is to greedily activate a sensing sector that gives the highest coverage quality to the targets. Thus, each CH $k \in \Upsilon$ calculates a quality metric $\mathcal{Q}_{i,s}$ for all sector $< i, s > \in \Psi_k$ as follows,

$$\mathcal{Q}_{i,s} = q_4 \times \frac{\sum\limits_{m \in \tau_{i,s}} \rho_{i,s}(m)}{\sum\limits_{m \in (\mathcal{M}_k^P \cup \mathcal{M}_k^U)} \varrho(m)} + (1 - q_4) \times \frac{\sum\limits_{m \in (\mathcal{M}_{i,s} \setminus \tau_{i,s})} \rho_{i,s}(m)}{\sum\limits_{m \in (\mathcal{M}_k^P \cup \mathcal{M}_k^U) \setminus \tau_{i,s}} \varrho(m)}, \tag{4.23}$$

where, q_4 is a weight parameter. Similar to Algorithm. 3, the steps of first-fit-quality maximization has been summarized in Algorithm 4.

The complexity of the two algorithms 3 and 4 can be calculated as follows: lines 5 to 21 are enclosed in a while loop that can run $O(|\Psi_k|)$ times. Inside the while loop, there is a for loop that has complexity $O(|\mathcal{M}_k|)$ (line 10 to 17)). Therefore, the overall complexity of the algorithms 3 and 4 is $O(|\mathcal{M}_k| \times |\Psi_k|)$.

Algorithm 3 First-fit lifetime maximization algorithm at each CH $k \in \Upsilon$

```
INPUT: $\Psi_k, \mathcal{M}_k, \mathcal{N}_k, \varrho(m), \rho(m)$
OUTPUT: The set of nodes with active sensing sectors, $\psi'_k$
Update $\mathcal{M}_k$, $\Psi_k$ using Eq. (4.13) and Eq. (4.21) respectively
$\Psi'_k \leftarrow \Psi_k$
$\mathcal{M}^F_k \leftarrow \phi,\ \mathcal{M}^P_k \leftarrow \phi,\ \mathcal{M}^U_k \leftarrow \mathcal{M}_k$
$\rho(m) \leftarrow 0,\ m \in M_k$
while (1) do
  Calculate $\mathcal{L}_{i,s},\ \forall <i,s> \in \Psi_k$ using Eq. (4.22)
  Find $<i,s>$ having the maximum $\mathcal{L}_{i,s}$,
  $\psi'_k \leftarrow <i,s>$
  $\Psi'_k \leftarrow \Psi'_k \setminus <i,s>,\ \forall s \in \Psi_s$,
  for all $m \in \mathcal{M}_{i,s}$ do
    Calculate the quality $\rho_{i,s}(m)$, $\rho(m)$, using Eq. (4.2) and Eq. (4.3) for $<i,s>$
    if $(\rho(m) \geq \varrho(m))$ then
      $\mathcal{M}^F_k \leftarrow m,\ \mathcal{M}^U_k \leftarrow \mathcal{M}^U_k \setminus m,\ \mathcal{M}^P_k \leftarrow \mathcal{M}^P_k \setminus m$
    else
      $\mathcal{M}^P_k \leftarrow m,\ \mathcal{M}^U_k \leftarrow \mathcal{M}^U_k \setminus m$
    end if
  end for
  if (($\mathcal{M}^U_k == \phi$ AND $\mathcal{M}^P_k == \phi$) OR $\Psi'_k == \phi$) then
    EXIT
  end if
end while
```

4.3.4 Determination of weighting parameters

In this section, we discuss on values chosen for factor values ζ, q_1, q_2, q_3 and q_4 that are used in Eq. (4.12), Eq. (4.22) and Eq. (4.23).

Introducing ζ in Eq. (4.12), helps more nodes to participate in activation process, upsurging network lifetime. Over the course of time, the residual energy of a node gradually decreases and keeping the energy threshold (E_{th}) at a fixed point, restraints to form new active sets. Determining the value of ζ depends on dynamic nature of the network parameters and it leads us to a new research dimension. In this work, we have done extensive simulations for choosing a suitable value for ζ and set $\zeta = \frac{1}{2}$ for all experiments .

Algorithm 4 First-fit quality maximization algorithm at each CH $k \in \Upsilon$

```
INPUT: $\Psi_k, \mathcal{M}_k, \mathcal{N}_k, \varrho(m), \rho(m)$
OUTPUT: The set of nodes with active sectors, $\psi'_k$
Update $\mathcal{M}_k$, $\Psi_k$ using Eq. (4.13) and Eq. (4.21), respectively
$\Psi'_k \leftarrow \Psi_k$
$\mathcal{M}_k^F \leftarrow \phi,\ \mathcal{M}_k^P \leftarrow \phi,\ \mathcal{M}_k^U \leftarrow \mathcal{M}_k$
$\rho(m) \leftarrow 0,\ m \in M_k$
while (1) do
  Calculate $\mathcal{Q}_{i,s},\ \forall < i,s > \in \Psi_k$ using Eq. (4.23)
  Find $< i,s >$ having the maximum $\mathcal{Q}_{i,s}$,
  $\psi'_k \leftarrow < i,s >$
  $\Psi'_k \leftarrow \Psi'_k \setminus < i,s >,\ \forall s \in \Psi_s,$
  for all $m \in \mathcal{M}_{i,s}$ do
    Calculate the quality $\rho_{i,s}(m)$, $\rho(m)$, using Eq. (4.2) and Eq. (4.3) for $< i,s >$
    if $(\rho(m) \geq \varrho(m))$ then
      $\mathcal{M}_k^F \leftarrow m,\ \mathcal{M}_k^U \leftarrow \mathcal{M}_k^U \backslash m, \mathcal{M}_k^P \leftarrow \mathcal{M}_k^P \backslash m$
    else
      $\mathcal{M}_k^P \leftarrow m,\ \mathcal{M}_k^U \leftarrow \mathcal{M}_k^U \backslash m$
    end if
  end for
  if $((\mathcal{M}_k^U == \phi$ AND $\mathcal{M}_k^P == \phi)$ OR $\Psi'_k == \phi)$ then
    EXIT
  end if
end while
```

Similarly, the optimal values of weight factors q_1, q_2, q_3 and q_4 used in Eq. (4.22) and Eq. (4.23) are corresponding to complex multivariable functions, highly depend on the network size and shape, node density, initial node energy, etc. In the design of GMQMS system, we have gone simulation based approach for setting the values of these parameters which is one of our key limitations. We run our simulations by setting the values as $q_1 = 0.42$, $q_2 = 0.32$, $q_3 = 0.26$ and $q_4 = 0.55$.

4.4 Performance Evaluation

In this section, we present comparative performances of the proposed MQMS-DSN systems and maximal network lifetime scheduling (MNLS) system [31], a mixed integer

Table 4.2: Network Simulation Parameters

Parameters	**Value**
Area of deployment	$500m \times 500m$
Type of deployment	Random (Uniform)
Sensor nodes deployed	$100 \sim 400$
Number of targets	$15 \sim 50$
Sensing sectors	$2 \sim 6$
Field of view	$60^o \sim 180^o$
Sensing range	$30 \sim 80m$
Transmission range	$60 \sim 160m$
Node energy (initial)	6 J
E_{th}	1 J
Network bandwidth	512 Kbps
Data packet size	512 bytes
ACK size	14 bytes
Control packet size	16 bytes
Physical layer model	YansWifi Model
Simulation time	1000 Seconds

programming problem.

4.4.1 Simulation Environment

The experiments have been carried out in a discrete event network simulator ns-3 [77]. Sensors and targets are deployed in a region of $500 \times 500 m^2$ with uniform random distribution. For different experiments, we have varied the number of sensors from 100 to 400 and targets from 15 to 40. YansWifiPhy model is used for adjusting the channel properties like the propagation delay model, data rate, delay loss model and other channel properties. For the cluster-based solutions (SMQMS and GMQMS), we use a clustering algorithm for directional sensor network, described in [38]. The simulation parameters are shown in Table 4.2.

The required coverage quality, $\varrho(m)$ for a target $m \in \mathcal{M}$ is randomly chosen from the range [0.7,1]. The value of μ, β are set as 0.5 and 0.5 following the discussion in [32]. In measuring performances of proposed CMQMS and SMQMS, the value of γ is set to 0 for maximizing coverage quality and to 1 for maximizing network lifetime. The clusters are formed using TCDC algorithm [38] with parameters specified in section 6.1 and 6.1 of [38]. All nodes in the network use the same transmission range in all transmission attempts irrespective of location of their destination nodes. Each simulation was run for 1000 seconds and the graph data points are plotted for the average of the results from 30 simulation runs.

4.4.2 Performance Metrics

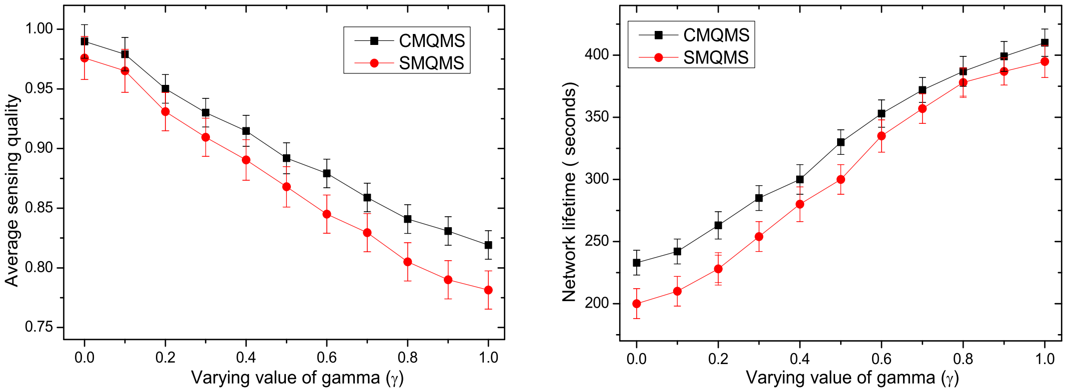
- *Average sensing quality:* It is measured as the average of sensing qualities given to all targets by a system. Higher value of this metric indicates better capability of the system to provide quality coverage to the targets.
- *Network lifetime:* It is calculated as the summation of the lifetime of all active sets ([31, 119]) in the network.
- *Percentage of active sensor nodes:* It is defined as the ratio of number of sensor nodes activated by a system to the total number of sensor nodes in the network.
- *Standard deviation of residual energy:* It represents how well the energy consumption load of the network nodes is distributed and is calculated as follows,

  $$\sigma = \sqrt{\frac{1}{|\mathcal{N}|}\sum_{i=1}^{|\mathcal{N}|}(E_r(i) - \nu)^2}, \tag{4.24}$$

  where, $E_r(i)$ is the node i's residual energy and the mean residual energy of all nodes is indicated by ν. The lower value of σ represents better energy-load balance in the network.

4.4.3 Simulation Results

In this section, we discuss on the results of performance evaluations for varying values of control parameter γ, number of sensor nodes, number of targets, sensing ranges and



(a) Average sensing quality (b) Network lifetime

Figure 4.5: Impacts of control parameter γ on the performances of CMQMS and SMQMS systems

number of sensing sectors.

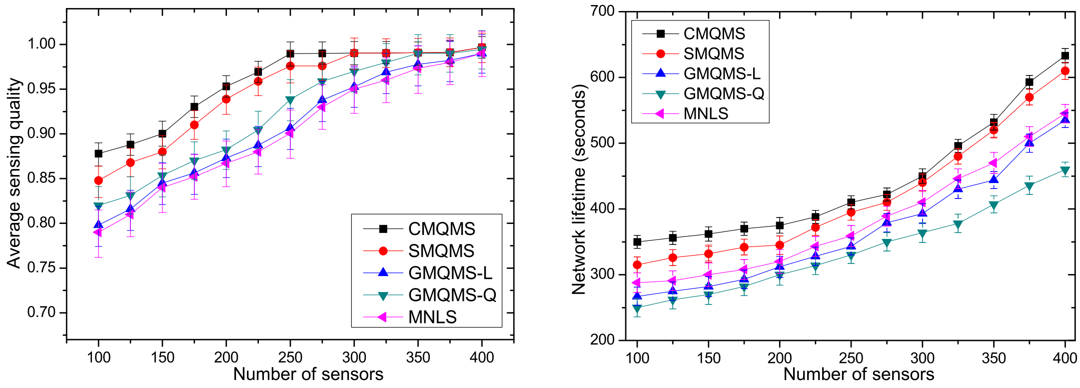
4.4.3.1 Impacts of varying values of control parameter, γ

We have varied the value of γ and assessed the performances on network lifetime and average sensing quality achieved by CMQMS and SMQMS systems. The value of γ controls the level of importance an application requires on sensing quality and network lifetime. For this experiment, the area, number of targets, sensor nodes, sensing sectors and sensing radius are kept constant at 500m × 500m, 25, 250, 4 and 50m respectively. From the graphs Fig. 4.5(a) and Fig. 4.5(b) it is clear that, sensing quality and network lifetime are inversely related to each other for increasing values of control parameter γ. Both CMQMS and SMQMS maximize the network lifetime when $\gamma = 1$ while keeping the required sensing qualities for all targets in the network. Similarly the overall sensing quality for all targets are maximized when $\gamma = 0$ while ensuring balanced energy consumption across all sensor nodes in the networks. However, other values of γ facilitate the systems to make a trade off between lifetime and quality. Thus the values of γ is set by the system administrator following the requirements of intended application.

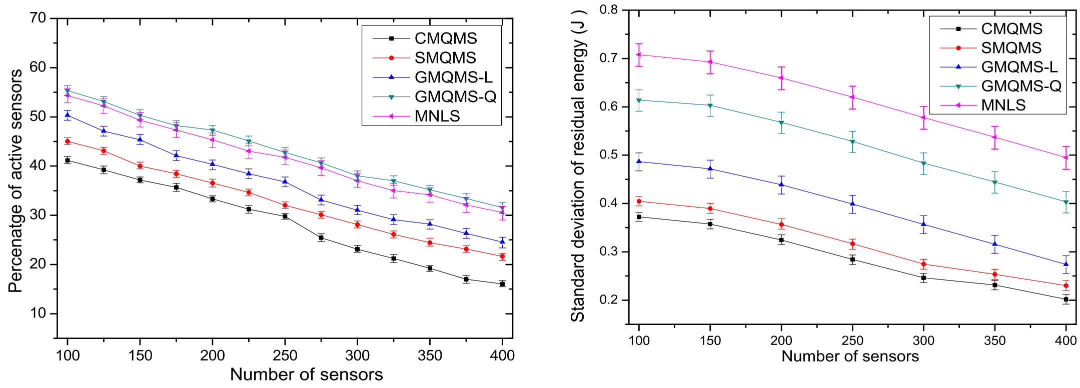
4.4.3.2 Impacts of varying number of nodes

We have varied the number of sensor nodes in the network to analyze the scalability of our proposed MQMS-DSN systems. For this experiment, the number of sectors, sensing radius and number of targets are kept constant at 4, 50m, 25, respectively. From the graphs of Fig. 4.6(a), we observe that, our proposed MQMS–DSN systems offer better average sensing quality than the state-of-the-art-work MNLS [31] for increasing number of nodes. Compared with our MQMS-DSN systems, the MNLS achieves poor coverage quality ratio since its primary objective is to enhance the network lifetime. We have noticed that, the proposed CMQMS system achieves full sensing coverage with less number of nodes compared to all other systems. The results are as expected theoretically , because CMQMS has the ability to pick the optimal solution from all the combinations to enhance the coverage quality (for $\gamma = 0$). However, the greedy solution GMQMS-Q offers improved performance compared to that of MNLS and GMQMS-L as it is designed to enhance the quality rather than lifetime. The most interesting outcome of this experiment is that the performance gap in between the studied systems are decreased with the increasing node densities. The suboptimal and greedy solution reach the performances of the optimal solution when the number of nodes in the network crosses 300. The reason behind achieving these result is the lack of information in the current status of the network at the central node.

For increasing the node density, the network lifetime upsurges in all the studied systems as coherent with the theory. However, from the graphs of Fig. 4.6(b), we observe that, the CMQMS performs better compared to the other systems for different node densities. Nevertheless, MNLS achieves quite inferior result than CMQMS and SMQMS. Although SMQMS is a cluster based-distributed solution, the energy-aware selection of nodes, dynamic updating of energy threshold value and instantaneous decision making help the SMQMS system to provide better lifetime than the MNLS. On the contrary, the GMQMS-L system has low performance than the CMQMS and SMQMS as the former greedily chooses local optimal nodes and thus often fails to achieve global optimal results.



(a) Average sensing quality (b) Network lifetime

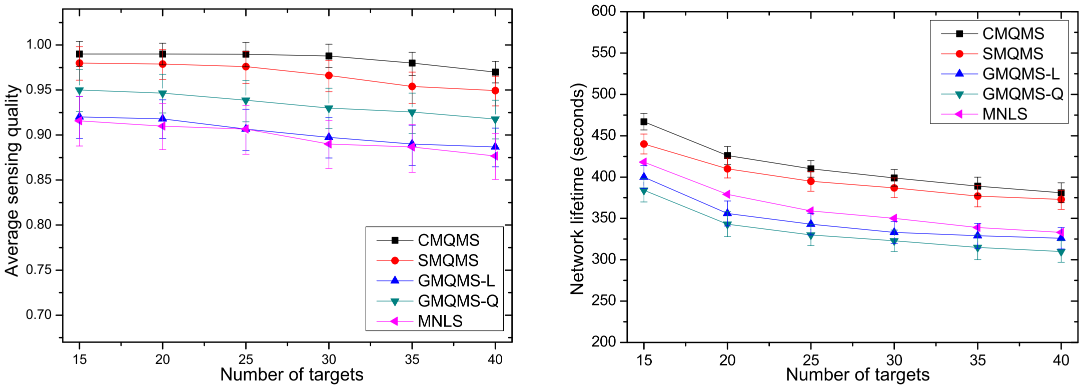


(c) Percentage of active sensor nodes (d) Standard deviation of residual energy

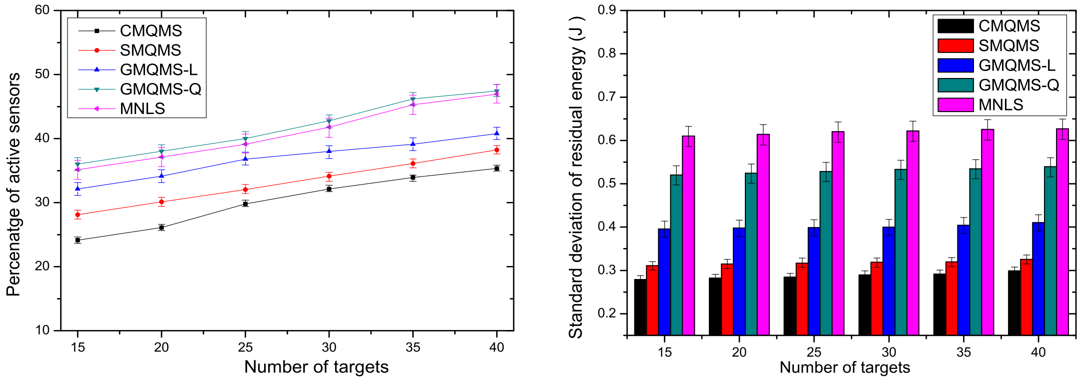
Figure 4.6: Impacts of varying sensor nodes (area = 500m × 500m, sensing radius = 50m, target = 25, sensing sector = 4)

We also plot the performance results of percentage of active sensor nodes for different systems varying the node densities. The graphs of Fig. 4.6(c) reveal that the optimal and suboptimal formulation of the MQMS-DSN system i.e., CMQMS and SMQMS achieve better outcomes compare to all others. This happens due to the strategy of the MILP formulation of the two, that aims to minimize the number of sensor nodes. However, MNLS achieves poor performance than the GMQMS-L as it does not consider to minimize the number of sensor nodes.

The standard deviation of residual energy values for all nodes in the studied systems are plotted in Fig. 4.6(d). We observe that, our MQMS-DSN systems outperform than



(a) Average sensing quality (b) Network lifetime



(c) Percentage of active sensor nodes (d) Standard deviation of residual energy

Figure 4.7: Impacts of varying targets (area = 500m × 500m, sensing radius = 50m, number of nodes = 250, sensing sector = 4)

the state-of-the-art-work MNLS. The results are achieved due to the minimization of number of sensor nodes, residual energy-aware selection of nodes, updating threshold value dynamically and instantaneous decision making on selecting active nodes.

4.4.3.3 Impacts of varying number of targets

We gradually increase the number of targets in the network and study its impact on the performances of the studied systems. Employing the proposed algorithms for various targets would shed light to the robustness of the proposed MQMS-DSN systems. The number of sectors, sensing radius and number of nodes are fixed at 4, 50m, 250 for this experiment. The graphs in Fig. 4.7(a), portray the relationship between the number of average sensing quality and number of targets of the evaluated systems. For increasing number of targets, the average sensing quality remains almost same or decreasing very slightly for all the systems which is sensible as average value is taken. However, the proposed MQMS systems have the ability to achieve better quality with respect to MNLS [31] for varying number of targets, where as the performance of GMQMS-L is close to MNLS. The objectives of MNLS and GMQMS-L are to enhance network lifetime rather quality, which restricts those to achieve high sensing quality compare to others.

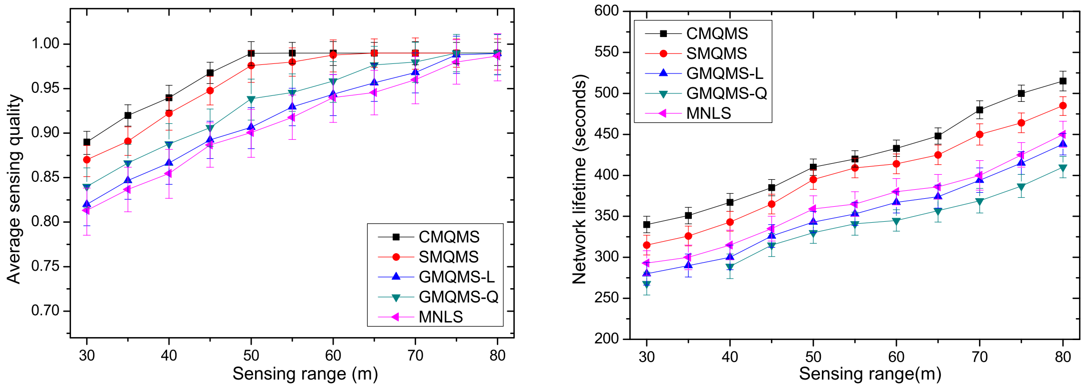
For upsurging the number of targets, the network lifetime lessens for all the systems that are consistent with the theoretical results as shown in Fig. 4.7(b). We also notice an interesting phenomenon, initially the decreasing rate of lifetime is very high; however, after certain number of targets (here it is 25) the rate declines slowly. The reason is that, as we are enhancing the targets maintaining fixed number of sensor nodes, it increases the chance to cover more number of targets by the active nodes.

From the graphs in Fig. 4.7(c), it is clear that the percentage of active nodes increases for all the systems with the growing number of targets. The reason is straight forward, as increasing the number of targets demands more nodes to be activated, resulting increased number of active nodes. Nevertheless, our proposed CMQMS, SMQMS and GMQMS-L show improved results for their working approach to minimize the number of sensor nodes over MNLS and GMQMS-Q ($\gamma = 1$).

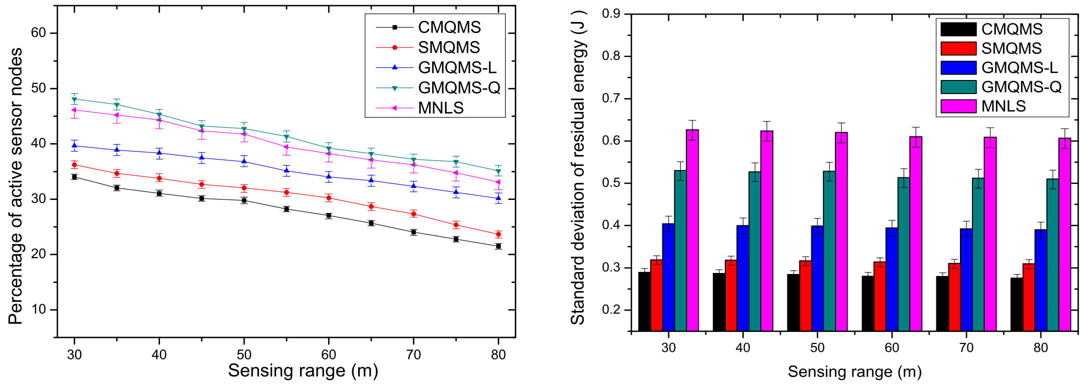
For varying number of targets, the standard deviation for all the systems are shown in Fig. 4.7(d). The experimental outcomes reveal that, the proposed MQMS-DSN systems have better capacity to balance the energy consumption compare to MNLS for its working strategy to select the active nodes considering residual energy, dynamically updating energy threshold value and instantaneous decision making of active nodes.

4.4.3.4 Impacts of varying sensing ranges

We have also studied the comparative performances for varying sensing ranges. For this experiment, we have deployed 250 number of nodes with 25 targets, keeping the number



(a) Average sensing quality (b) Network lifetime



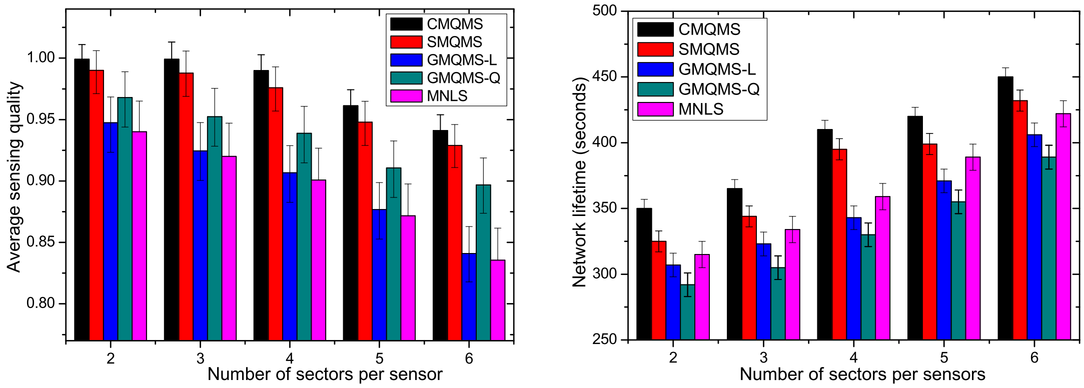
(c) Percentage of active sensor nodes (d) Standard deviation of residual energy

Figure 4.8: Impacts of varying sensing ranges (area = 500m × 500m, number of targets = 25, number of nodes = 250, sensing sector = 4)

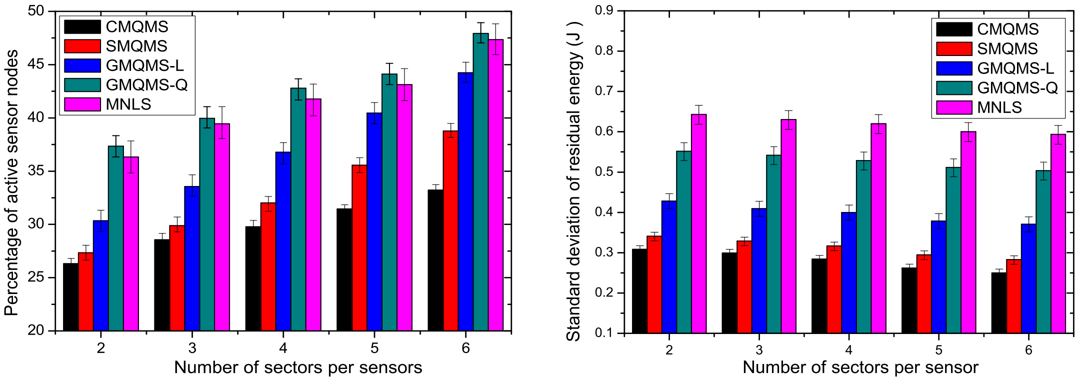
of sensing sector fixed at 4. Increasing the sensing range enhances the chance to cover more targets by the nodes that results increasing the average sensing quality and the network lifetime. For the same reason, the percentage of active nodes also decreases. The other reason for achieving better results by the proposed MQMS-DSN systems, as depicted in Fig. 4.8, are already stated before.

4.4.3.5 Impacts of number of sectors

In this experiment, we evaluate the impacts of the number of sensing sectors (ranging from 2 to 6) of the sensor nodes on the performances of the studied systems. The number



(a) Average sensing quality (b) Network lifetime



(c) Percentage of active sensor nodes (d) Standard deviation of residual energy

Figure 4.9: Impacts of varying sensing sectors (area = 500m × 500m, number of targets = 25, number of nodes = 250, sensing radius = 50m)

of targets, sensor nodes and sensing range are fixed at 25, 250, 50m, respectively. The graphs in Fig. 4.9(a) state that, the average sensing quality decreases with increasing number of sectors in all the studied systems. High number of sectors means lower size of FoV that limits to cover more targets. The graphs also reveal that despite of increasing number of sectors, MQMS-DSN systems achieve better results than the MNLS. As shown in Fig. 4.9(b), the network lifetime is gradually increased with the increasing number of sensing sectors for all the studied systems. This happens as, sensors with small FoV size consume low energy. For increasing number of sectors, percentage of active sensor nodes increases, as depicted in Fig. 4.9(c). However, less number of nodes remain active in CMQMS, SMQMS and GMQMS-L compared to those of MNLS and GMQMS-Q.

The graphs in Fig. 4.9(d) indicate that, for all the systems, the standard deviation of residual energy level lessen gradually for growing number of sectors. The proposed MQMS-DSN systems achieve improved performance than other. As expected, relatively large value of sectors also enhances the choices for the central controller to select nodes to keep in active or in sleep state that consequently preserves the energy.

4.5 Summary

In this chapter, we have addressed the joint problem of maximizing the sensing coverage quality and the network lifetime for covering heterogeneous targets. At first, we develop a general framework studying the boundary analysis, both for the coverage quality and network lifetime, in addition to making an efficient tradeoff between the two. The results of the experiments reveal that, rather than executing precomputed coverage decisions, instantaneous situation-aware dynamic coverage plans are more effective to enhance the network performance. The outcome of this research also states that, the optimal coverage algorithms are not practically usable for large scale application networks with enormous sensor nodes and targets; in such situations, greedy coverage algorithms with probabilistic sensing quality measurements provide with performances near to that of optimal solution.

Chapter 5

Conclusions

5.1 Summary of Research

This dissertation has addressed two of the most crucial challenges in Directional sensor networks (DSNs), namely *area coverage* and *target coverage* with quality. The proposed mechanisms, in this thesis is expected to facilitate many crucial real life applications of DSNs.

In this thesis, we have developed a network lifetime-aware novel area coverage mechanism, α-OAC system for clustered DSNs. To the best of our knowledge, the α-OAC is the first approach to solve the area coverage problem using clustering mechanism by taking into account an acceptable sensing overlapping amount α among the nodes and their residual energy levels. We have designed the α-OAC in such a way that, at first each CH selects optimal set of active nodes and their sensing directions within its covering region to ensure a fully covered communication region considering overlapping threshold α. However, the generated optimal solution using MILP formulation is more applicable for small networks. To overcome the scalability issues, later we have exploited greedy approach to select the set of active nodes. However, individual decision making by the CHs, may create void regions, therefore, inter-cluster communication among the CHs is applied to mitigate void zones and redundant activation of nodes. The simulation results show that our proposed α-OAC system offers higher network lifetime, consistent with the theoretical results. This balanced energy consumption among the network nodes is carried out for the residual energy-aware selection of sensing nodes and limiting the coverage overlapping that also extends the network lifetime significantly. Also, proposed

α-OAC exhibits higher coverage ratio compared to state-of-the-art works.

Next, we have addressed the joint problem of maximizing the sensing coverage quality and the network lifetime for covering heterogeneous targets in different smart applications. To the best of our knowledge, this work first develops a general framework that studies boundary analysis, both for the coverage quality and network lifetime. In addition to this, the proposed framework has the ability to make an efficient tradeoff between the two. The optimal coverage algorithm CMQMS formulated using MILP in Section 4.3.1.2 is not practically suitable for networks with large number of sensor nodes and targets, and also it fails to take a real-time decisions due to being computation intensive. Later, we have formulated a suboptimal solution SMQMS that also suffers from non-polynomial execution time. Therefore, to accommodate with large network scenario, greedy coverage algorithms with probabilistic sensing quality measurements are proposed in Section 4.3.3. The GMQMS-L tries to maximize the lifetime maintaining the required coverage quality of each targets; on the other hand, the GMQMS-Q enhances the quality as much as possible. The results of the experiments reveal that, rather than executing precomputed coverage decisions, instantaneous situation-aware dynamic coverage plans are more effective to enhance the network performance. Simulation results show that our proposed MQMS offers higher coverage quality and network-lifetime compared to state-of-the-art works.

5.2 Discussion

The journey started with the aim to work with Wireless sensor networks (WSNS). Studying with the state-of-the-art works, we find the promising field of Directional sensor networks (DSNs). Although DSN, is a special kind of WSN, the solution strategies are different for the same problem. It is also observed that, DSNs are quiet useful for our real-life applications. Later we search that, the solutions of the coverage problems are required for any surveillance task problems. Therefore, we focus our research to find efficient solutions on coverage problems.

To find efficient solutions, all we need is to study and familiar with new techniques. For searching the optimal solutions, we explore different optimization techniques. To verify the theoretical results, it requires to learn matlab. Also, the network simulator tool (ns-3), which is a new environment to me, has to be worked with.

Truly speaking, during this PhD period, I have finally learned about the research techniques, i.e., how to read the state-of-the-art works, answer of what questions should be searched, how to criticize the existing works, what one should do when it is difficult to find an answer. In other words, how research is conducted, I have got to know the overall process, which is a lifetime opportunity for me I believe. However, as we can say everything is not as beautiful as it seems. To complete this thesis, we had to work hard and definitely hurdles came along the way. I had to give a lot of efforts and spent sleepless nights. Also, had to bear a lot of pressure from the work place, family, all around and it was really difficult to hold the patience for a long time. However, organizing everything in a planned way and proper utilization of time assisted me to reach at this stage.

5.3 Future Work

Although our proposed mechanisms α-OAC and MQMS-DSN achieves better coverage ratio, quality and network lifetime, further theoretical and experimental extensions are possible. In future, investigating the problem of finding suitable clustering and routing algorithms that works the best with the proposed α-OAC and MQMS-DSNs system, would be an interesting problem.

The proposed coverage mechanisms presented in this thesis have been evaluated using simulator tool. Although, for studying the behavior of any proposed solution mechanisms, simulation study is a good starting point; however, real life situations may be provided different scenarios. Even with the most sophisticated network simulation tools, however, it is hard to anticipate how these solutions perform in real hardware. Therefore, proposed mechanisms in a real test-bed environment would be a good contribution to the literature.

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Appendix A

List of Acronyms

α-OAC	α Overlapping Area COverage
ADCs	Analog to digital converters
ACDA	Autonomous clustering algorithm
CGA	Centralized Greedy Algorithm
CH	Cluster head
CMQMS	Centralized MQMS
DCCR	Directional cover sets with coverage reliability
DSN	Directional sensor network
EFCEA	Electrostatic field-based coverage-enhancing algorithm
GSP	Grouping scheduling protocol
GMQMS	Greedy MQMS
GWs	Gateways
FoV	Field of View
IDA	Inter-cell working direction adjustment
IDS	Intra-cell working direction
ILP	Integer Linear Programming
IoT	Internet of things
IR	Infrared sensor
LMIP	Linear Mixed Integer Programming
MCMS	Maximum Coverage with Minimum Sensors
MCRS	Maximum Coverage with Rotatable Sensors
MCS	Maximum cover sets

MDAC	Maximum Directional Area Coverage
MDCS	Multiple Directional Cover Set problem
MeCoCo	Minimum-Energy Connected Coverage
MEMS	Micro-electro-mechanical systems
MIC	Move Inside Cell Algorithm
MILP	Mixed-integer linear programming
MKDSC	Maximum K Directional Sensor Coverage
MNLS	Maximal network lifetime scheduling
MQMS-DSN	Maximizing Coverage Quality with Minimum Number of Sensors in DSN
OCDSN	Optimal coverage problem in directional sensor networks
OFCA	Out-of-field coverage avoidance
OSR	Overlap-sense ratio
QoS	Quality of service
RDS	Rotating Directional Sensor
RB	Rotation based on boundary
RWD	Rotate Working Direction Algorithm
SCSG	Sensing Connected Sub-graph
SDP	Sensing direction partition
SMQMS	Suboptimal SMQMS
SNCS	Sensing Neighborhood Cooperative Sleeping Protocol
SDMP	Service Delay Minimization Problem
TCDC	Target coverage through distributed clustering
TQC	Target Q-coverage
VCA	Voronoi based centralized algorithm
VCFCEA	Virtual centripetal force-based coverage-enhancing algorithm
VDA	Voronoi based distributed approximation
WCGA	Wighted Centralized Greedy Algorithm
WSNs	Wireless sensor networks

Appendix B

List of Notations

Parameter	Description
α	Maximum overlapping threshold
$\mathcal{N}$	Set of all sensor nodes
$\mathcal{N}_k$	Set of cluster member nodes of CH k
Ψ_c	Communication sectors set for a node $i \in \mathcal{N}$
Ψ_s	The set of sensing sectors of a node, $\lvert\Psi_s\rvert = \frac{2\pi}{\theta_s}$
$<i, s>$	Sector s of node i
$n_{i,s}$	The set of i's neighbor nodes in sector $s \in \Psi_s$
$E_o(i)$	Node i's initial energy
$E_r(i)$	Node i's residual energy
E_{th}	Energy threshold value
$\mathbb{A}_k$	The set of grids that are inside total communication sector of CH k
$\mathbb{A}_{k,C}$	The set of grids that are inside active communication sector $C \in \Psi_c$ of CH k
$\mathbb{A}^T_{i,s}$	The set of grids that can be fully covered by a sector s of a node $i \in \mathcal{N}_k$
$\mathbb{A}_{<i,s>}$	The set of grids that are covered by a sector s of a node $i \in \mathcal{N}_k$
$O(i, j, s)$	The set of common grids between nodes i and j for a sector s
η_k	The set of active member nodes of CH k with active sector
Υ	Set of all cluster heads
$\chi^s_{i,j}$	The percentage of overlapping grids between node i and j for a sector s
α'	New value of α
ϖ	A descending ordered sorted list of $< i, s >$ based on the metric $\varepsilon_{i,s}$
λ_k	Set of sensor nodes i, initialized to $\mathcal{N}_k$

$\mathcal{M}$	Set of all targets in the network
θ_s	Sensing angle
R_s	Sensing radius
ϕ_i	The set of directions of sensor i, $\phi_i = \{< i, s > \mid s \in \Omega\}$
Ψ	The set of directions of all the sensors, $\Psi = \cup\ \phi_i,\ \forall i \in \mathcal{N}$
$\varrho(m)$	The sensing coverage quality requirement for target $m \in \mathcal{M}$
$\rho_{i,s}(m)$	Given sensing coverage quality for target $m \in \mathcal{M}$ by sector s of node i
$\rho(m)$	Aggregated sensing quality for target $m \in \mathcal{M}$
$\vec{V}_i^s$	Working direction of a node i in sector s
$\mathcal{M}_{i,s}$	Set of targets in the sensing sector s for node i and $\rho_{i,s}(m_k) \neq 0$
$\mathcal{M}_k$	Set of targets covered by member nodes of a CH k
Γ_k	Set of one hop neighbor CHs of CH k
d	Length of a grid
(x, y)	Co-ordinate of a grid
(x_i, y_i)	Location co-ordinate of a sensor node i
$\mathcal{A}$	Total area
$\vec{V}_i^s$	A directional vector that divides a sensing sector into two equal parts.
θ_c	Communication angle,
$\vec{V}_i^c$	The directional vector which is the center line of a communication sector
R_c	The maximum communication radius
Π_k	A two dimensional matrix for the entire area $\mathcal{A}$
$b_{i,s,k}$	Represents whether a sector s of a sensor $i \in \mathcal{N}_k$ is activated or not
η_k	Set of active sensor nodes with sectors for area coverage
$\varepsilon_{i,s}$	Intregated metric
g_1, g_2	Weight factors used to calculate $\varepsilon_{i,s}$
w	A multiplication factor used to reduce the value α
G(x,y)	Denotes a grid
P_1, P_2, P_3, P_4	Cartesian co-ordinate points of a grid G(x,y)
$z_{(x,y)}$	A true value indicates a grid G(x,y) is fully covered

C	Center of a grid
P'	The farthest corner of a grid from the center C
P''	The nearest corner point of the grid
$u_{(x,y)}$	A true value determine (x,y) is a border grid
δ	A grid is a boreder grid if δ portion is covered
$t_{(x,y)}$	Value is 1 if δ portion is covered
$H^b_{x,y}$	The covered area by a border grid
ϑ_k	List of active sensor nodes that have overlapping with neighbor CH $l \in \Gamma_k$ larger than the overlapping threshold α
n	The number of grids covered by a sensing sector s
ϵ	Multiplication factor used to determine the value n
κ	Factor for error correction.
α_{min}	Minimum value of overlapping factor
R_u	Measure the sensing uncertainty of a target
β, μ	Parameters that measure detection probability when a target is at distance greater than R_u but within R_s
$x_{i,s}$	Represents whether a tuple $< i, s >$ is present in a candidate set or not
$P(\Psi)$	Power set of Ψ
γ	The tradeoff parameter
ψ^*	Optimal set of active nodes with sector
ζ	Weight parameter used to set the new value of E_{th}
q_1, q_2, q_3	Weight parameters used to calculate $\mathcal{L}_{i,s}$
q_4	Weight parameters used to calculate $\mathcal{Q}_{i,s}$
$\tau_{i,s}$	The set of uncovered and partially covered targets whose remaining required coverage quality can be fulfilled by the sector $< i, s >$.
$\mathcal{L}_{i,s}$	Metric parameter
$\mathcal{M}^F_k$	The set of targets having coverage requirements are fulfilled
$\mathcal{M}^P_k$	The set of targets partially covered
$\mathcal{M}^U_k$	The set of uncovered targets.

$\mathcal{Q}_{i,s}$	Metric parameter
ν	The mean residual energy of all nodes
σ	The distribution of the energy consumption among the sensor nodes

Appendix C

List of Publications

International Journal Papers (SCI-indexed)

1. _______________, "Tradeoff Between Sensing Quality and Network Lifetime for Heterogeneous Target Coverage Using Directional Sensor Nodes", IEEE Access, vol.PP, no.99, doi: 10.1109/ACCESS.2017.2718548.

2. _______________, "α-Overlapping Area Coverage for Clustered Directional Sensor Networks", Computer Communication (Elsevier), Volume 109, 1 September 2017, Pages 89-103, ISSN 0140-3664.

3. _______________, "Collaborative Neighbor Discovery in Directional Wireless Sensor Networks: Algorithm and Analysis", EURASIP Journal on Wireless Communications and Networking (2017): 119. doi:10.1186/s13638-017-0903-6.

4. _______________, "A Low Duty Cycle MAC Protocol for Directional Wireless Sensor Networks.", Wireless Personal Communications, Springer, Volume 96, Issue 4, pp. 5035-5059, Oct 2017.

International Conference Papers

5. _______________, "Target Coverage-Aware Clustering for Directional Sensor Networks" In IEEE International Symposium on Parallel and Distributed Processing with Applications (IEEE ISPA 2017), Guangzhow, China, 12-15 December 2017. [Accepted].

6. _______________, "Quality-aware Directional MAC Protocol for Multi-channel Wireless Sensor Networks" In IEEE International Symposium on Parallel and Distributed Processing with Applications (IEEE ISPA 2017), Guangzhow, China, 12-15 December 2017. [Accepted].

7. _______________, "Network Lifetime Aware Coverage Quality Maximization for Heterogeneous Targets in DSNs." In IEEE TENCON 2016 - Technologies for Smart Nation, Marina Bay Sands, Singapore, 22-25 November 2016, pp. 3030-3033.

8. _______________, "Collaborative Neighbor Discovery in Directional Wireless Sensor Networks." In IEEE TENCON 2016 - Technologies for Smart Nation, Marina Bay Sands, Singapore, 22-25 November 2016, pp. 1097-1100.

9. _______________, "Area coverage for clustered directional sensor networks using Voronoi diagram." In 2015 IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE), BUET, Dhaka, Bangladesh, 19-20 December 2015, pp. 370-373.

10. _______________, "Network lifetime aware area coverage for clustered directional sensor networks." In Networking Systems and Security (NSysS), BUET, Dhaka, Bangladesh, Jan 2015, pp. 1-9.

11. _______________, "A duty cycle directional mac protocol for wireless sensor networks." In Networking Systems and Security (NSysS), BUET, Dhaka, Bangladesh 2015, Jan 2015, pp 1-9.

12. _______________, "Congestion Aware Fair Data Delivery in Wireless Multimedia Sensor Networks", 8th WSEAS International Conference on Computer Engineering and Applications, Tenerife, Spain, 10-12 Jan, 2014.