Chapter 1

Introduction

1.1 Overview

Wireless Sensor Networks (WSNs) have gained immense popularity due to their low-cost, low-power consumption, light-weight, and advancement in wireless communication and microcontrollers technologies. WSNs find their applications in a wide range of domains. A common example is monitoring a given Field of Interest (FoI), tracking of the moving objects, and capturing events in the FoI. A WSN consists of several sensor nodes which are self-governing entities. A sensor node consists the following units: sensor unit, which is composed of two subunits namely sensor unit and an analog-to-digital converter unit, data processing and storage unit, data transmission unit, and a power supply unit. The sensor nodes autonomously collaborate to sense, collect the sensory data, process into information, and transmit processed information to the destination.

The sensing unit of a sensor node in WSNs consists of the sensors which detect and respond to some type of input from the physical environment. Sensors can be directional and omnidirectional based on the architecture of the device. Directional sensors detect the events in a given direction whereas omnidirectional do not have any preferred direction. A directional sensor node specifies with its directional sensing region, sensing range, and the orientation of the sensing region. Due to the fixed direction sensing region, the directional sensor nodes consume less power than omnidirectional sensor nodes. This reduces the power consumption and prolongs the lifetime of the WSN.

The deployment of sensor nodes in WSNs can be classified into deterministic and random, based on the placement strategy of the sensor nodes. The sensor nodes in random deployment are scattered uniformly at random in the FoI. The deterministic deployment uses some given patterns of placement of sensor nodes in the given FoI. In some scenarios, deterministic deployment is not possible. Examples of such scenarios are forest fire monitoring, flood monitoring, or disaster monitoring, where man-made sensor nodes placement is not possible. The random deployment of sensor poses several challenges. The main issue in random deployment is the cost of the WSNs. A random deployment requires a large number of sensor nodes as compared with deterministic deployment for the monitoring of a given FoI. The requirement of a large number of sensor nodes increases the cost of the WSNs. The deterministic deployment, on the other hand, helps to reduce the cost of the network and provides the desired quality of the monitoring of the moving target. Triangles, squares, and hexagons are the only possible regular shapes which tessellate by themselves. The deterministic deployment of sensor nodes usually uses such regular geometry for placement of sensor nodes.

Target tracking is an important application of WSNs. The main objective of the target tracking is to detect the moving targets in the FoI as soon as possible. A sensor node in a WSN works as a tracking device if the device detects the moving targets inside the given FoI. Some applications of WSNs that a target must be detected by at least k sensor nodes. Such a network is known as k-target tracking WSN, where $k \geq 1$.

Communication between the sensor nodes in a WSN is another important aspect. A device in a WSNs is known as a routing device if the device relays the tracking information from the source node to the destination node. The process of selecting a path for establishing the communication link from the source node to the destination node in a network is termed as routing. In a fault tolerance WSN, when some sensor nodes go down or are not working perfectly the network still survives. In such scenarios, m-connectivity in WSNs may be required, where the networking consists of m edge disjoint paths between source node and the destination node, where $m \geq 1$. Routing is the process by which the WSNs relay the sensory data from the source node to the destination node. The main issues of the existing routing protocols in WSNs are reducing the energy consumption while providing the desired level of connectivity in WSNs.

1.2 Motivation of the Research Work

The objective of target tracking in WSNs is to track the moving targets in the FoI and relay the tracked information to the destination. The main issue in the deterministic deployment of WSNs is to deploy the minimum number of sensor nodes that providing the desired level of tracking and connectivity in the WSNs. The deployment process of sensor nodes in regular patterns is complicated when the tracking angle of the sensor nodes is fixed. Different from the omnidirectional, such directional sensor nodes consume less energy and provides an energy-efficient solution. The deployment geometry may consist of triangle, square, and hexagon regular patterns. The literature on the deterministic deployment of directional sensor nodes in WSNs mainly reports square regular deployment pattern. Although considering a fixed pattern is not a realistic assumption, since it loses the advantages of other regular deployment patterns.

Some target tracking applications may require that each moving target in the FoI is tracked by more than one directional sensor node. For example, deployment of sensor nodes in hostile or harsh environments, military applications, and health-care scenarios. Similarly, a fingerprinting based indoor localization technique requires that a target is simultaneously tracked by at least three sensor nodes. A network is called as k-target tracked if each moving target in the FoI is traced by at least k sensor nodes, where $k \geq 1$. The literature on determining the location of sensor nodes in the FoI for tracking the moving targets by one sensor nodes are not suitable for such target tracking applications.

Communication path of the tracking information from the source node to the destination is an important metric to measure the quality of connectivity in a directional WSN. An m-connected WSN consists of m disjoint paths from the source to the destination, where $m \geq 1$. Similar to k-target tracking, m-connectivity is also required by some fault-tolerant WSNs. Most of the literature considers k-target tracking and m-connectivity as two separate problems. If k-target tracking and m-connectivity are considered as a single problem it enhances the solution and reduces the cost of the network.

Finding a shortest-path for reducing the power consumption is a promising technique to enhance the lifetime of the WSNs. At the same time, minimizing the power consumption while ensuring the desired quality of target tracking is another challenge in directional WSNs because the sensor nodes in directional WSNs consist of a fixed direction tracking region. In some scenarios, a sensor node consists of a longer routing path but it provides the desired quality of target instance of a sensor node with a shorter routing path. The main objective of the existing routing protocols in the literature is to reduce the power consumption. Especially, they mainly focused on omnidirectional WSNs where the direction of the tracking region is not an issue. However, along with reducing the power consumption, the target tracking using fixed tracking region is a key issue in directional WSNs. Therefore, the work reported in the literature are not useful for target tracking in energy-efficient directional WSNs.

1.3 Contributions and Organisation of the Thesis

In this thesis, we consider the deterministic deployment of sensor nodes where the nodes are placed in various regular patterns. We consider the directional WSNs in which the tracking region of the deployed sensor nodes is fixed in a given direction. We derive the expressions for estimating the position of the sensor nodes in triangle, square, and hexagon regular deployment patterns. Such analysis provides a minimum cost WSNs for k-target tracking and m-connectivity of the network, where $\{k, m\} \geq 1$. We propose a routing protocol to find an energy-efficient path between the source and the destination while providing the desired quality of target tracking. The main research questions addressed by the thesis are summarised below:

- What is the optimal distance between two directional sensor nodes and tracking direction of the nodes for k-target tracking and m-connectivity of networks?
- How many, minimum numbers of directional sensor nodes (and their locations) are required for the desired level of target tracking and connectivity?
- How to determine the route selection metric in a directional WSNs which prolongs the lifetime of the network while providing k-target tracking and m-connectivity of networks?
- What are the effects of different target mobility models on k-target tracking in directional m-connected WSNs?

The thesis is organised as follows:

Chapter 2: This chapter presents the existing work on monitoring the FoI and connectivity in WSNs. Based on the requirement of monitoring of the targets, coverage can be classified into three categories: area coverage, point coverage, and barrier coverage. We mainly focus on area coverage of the FoI in this work. The research work for estimating the sensing coverage in the FoI using the deployed sensor nodes in WSNs has been studied and summarized. We describe issues and challenges for designing the coverage and connectivity by using computation geometry and probabilistic-based approaches. We consider the essential design issues such as the type of sensor nodes, deployment region, the shape of the FoI, and border effects. In addition to that impact of sensing models binary and probabilistic for sensing the FoI has been objectively discussed.

Chapter 3: In this chapter, we consider the regular directional node placement patterns for k-target tracking in m-connected wireless networks with a given segment length. *We* *address the problem: What are the regular directional node placement pattern and the distance between two nodes that use the minimum number of nodes for k-target tracking in an m-connected WSN and a given segment length, where $\{k, m\} \geq 1$?*

We address the problem of determining a regular directional node placement pattern, distance between nodes, and direction of the tracking region of the nodes for k-target tracking, m-connected WSNs, and a given segment length. The major contributions of our work in this chapter can be summarized as follows:

- We formulate a regular directional node placement problem for k-target tracking in m-connected WSNs. The object of the problem is to determine the direction of the tracking region and location of the nodes for the desired level of target tracking and connectivity in a given segment length. The direction and location help to estimate the minimum number of directional nodes in the FoI.

- It is difficult to estimate the location of nodes in the irregular geometric areas. We propose an algorithm that can be used to compute the tracking accuracy for any deployment. The correctness of the algorithm is validated by simulation results. The simulation results show that only one regular directional node placement pattern is suitable for tracking a target by k nodes in a connected WSN under different values of k, m, track range, communication range, segment length, and the area of the FoI.

- We develop a target tracking system using the proposed analysis for tracking moving targets in the FoI. We setup testbeds with different scenarios for conducting experiments. Real data is collected to evaluate our algorithm and validate our work. The experiments validate the analysis and demonstrate the impact of k, m, tracking range, connectivity range, segment length, and area of the FoI on the number of nodes, the distance between nodes, and placement pattern.

Chapter 4: In this chapter, we consider the regular sensor nodes deployment patterns for tracking of moving targets. *We address the problem: How to estimate the route* *selection metric which provides an energy-efficient routing path for relaying the moving target tracking information in a directional WSN?*

We address the problem of estimating the route selection metric, determining a regular node deployment pattern, and locations for tracking the moving targets in an energy-efficient directional WSN. Along with this, the major contributions of our work are as follows:

- We formulate a direction sensor node deployment problem for tracking of moving targets inside the FoI. The object of the problem is to estimate the locations and select the regular deployment pattern which provides the tracking and connectivity of the network.

- We use Fuzzy Logic System (FLS) for estimating the route selection metric. The transmission energy, neighbor energy consumption, hop count, target tracking percent, and residual energy are the input variables of FLS. The estimated location of the sensor nodes uses to calculate the inputs of FLS.

- We propose an energy-efficient routing algorithm by using the estimated route selection metric. The algorithm selects the shortest path for reducing the energy consumption, consider the residual energy for providing the stability of the selected path, and using tracking percent to maintain the quality of the tracking. The proposed routing algorithm can be integrated with any existing routing protocols.

- We demonstrate an application of the proposed energy-efficient routing algorithm in the deployment of a Moving Target Tracking System based on directional wireless sensor network called MTS. We consider indoor and outdoor scenarios for validation of our work. Using the directional tracking devices regularly deployed in such scenarios for estimating the energy consumption, the lifetime of the network, and stability of the network. We also demonstrate the application of the MTS for counting the moving objects pass from the deployed region.

Chapter 5: In this chapter, we consider the different mobility models of targets in the FoI. *We address the problem: What is the effect of mobility models of the targets on the accuracy of k-target in m-connected directional WSNs?* Along with this, the major contributions of our work are as follows:

- In this chapter, we used the proposed analysis to estimate the location of sensor nodes for k-target tracking in m-connected WSNs. We examine the following mobility models on target tracking in directional WSNs: random walk mobility model, random waypoint mobility model, random direction mobility model, and non-uniform spatial distribution model.

- We illustrate the impact of the different mobility models on the energy consumption of the network, lifetime of the network, residual energy of sensor nodes in the network.

Chapter 6: The main findings of the thesis are summarized in this chapter. We also discussed some future directions for this highly comparative approach to data analysis are discussed. Our main contributions put into a global perspective in this chapter.