Chapter 1

Introduction

1.1 Background

In recent years, the Internet of Things (IoT) has emerged as a pivotal area within computer science and technology that offers immense potential for future applications [1]. In IoT, physical objects such as air conditioners, fans, washing machines, industrial equipment and machinery, etc., are becoming smart with data processing capability and internet connection. Wireless Sensor Networks (WSNs) are one of the most important ingredients of IoT that help to collect data from physical objects [2]. IoT applications such as smart cities, environmental monitoring, agriculture, e-healthcare, transportation, and Industry 4.0 have substantially revolutionized our lifestyles [3]. IoT-enabled WSN is a collection of wirelessly connected small, low-priced sensor nodes that are randomly deployed in the monitoring environment. The sensor nodes sense the physical parameters like temperature, humidity, smoke, and fire from the environment and transmit the collected data to a Base Station (BS) or sink [4]. The sensor nodes in WSN have limited computation, power, and memory capacities. WSNs can be classified into two categories such as homogeneous WSNs or heterogeneous WSNs. In homogeneous WSNs, sensor nodes have similar capacities. However, sensor nodes have different capacities in heterogeneous WSNs [5]. IoT-enabled WSNs are often deployed in areas

Figure 1.1: Multi-hop data transmission in IoT-enabled WSNs.

that are difficult to reach or inaccessible to humans. Therefore, once the sensor node's battery is discharged, then it is very difficult to recharge and replace [6]. An energy-efficient data routing mechanism can help to enhance sensor nodes as well as network lifetime.

In general, sensor nodes consume their energy for sensing and data transmission. Energy consumed by sensor nodes at the time of sensing is constant. However, the energy consumed for data transmission varies depending on network topology and data load on sensor nodes [7]. Therefore, it is crucial to minimize energy consumption during data transmission to improve the network lifetime. Clustering is one of the popular data routing mechanisms in WSNs that helps to reduce the energy consumption of sensor nodes and improve network lifetime [8]. In clustering, sensor nodes are logically divided into different groups, and each group selects one node as a Cluster Head (CH) for inter-cluster communication. Cluster Member (CM) nodes transmit their data to the CH via single-hop or multi-hop communication. Once CH receives data from all CM nodes, it aggregates all data and transmits it to the BS either directly or through multi-hop communication [9]. Cluster-based data routing mechanisms significantly reduce the inter-cluster transmission distance of the CM nodes. It helps to improve the overall network lifetime as compared to direct data transmission to the BS. However, the clustering mechanism also increases the energy consumption rate of CH nodes. Therefore, CHs die early as compared to the CM nodes. Once CH dies, other CM nodes are unable to send their data to the BS due to the unavailability of a proper data routing path [10]. It is subject to the premature death of the network. To overcome this problem, some of the data routing approaches use the CH rotation mechanism, where the CH role is shifted from one CM to another CM with respect to time. It helps to balance the communication load among CM nodes. However, this mechanism is unable to reduce the inter-cluster communication load of acting CHs [11].

In clustering approaches, CHs near the BS transmit their data directly to the BS/sink through a single-hop communication. CHs that are far from BS send their data via BS nearest CH through multi-hop communication. Fig. 1.1 shows multi-hop data transmission in IoT-enabled WSNs. Therefore, CHs located within the nearest range of the BS relay more data packets than CHs that are far away from the BS. Therefore, BS nearest CHs consume more energy as compared to the faraway CHs. As a result, the BS nearest CHs die early as compared to the far away CH. Once the CHs near BS die, then CHs far from BS are unable to transmit their data to the BS due to the unavailability of paths. This problem is referred as the hot spot problem or the energy hole problem [10]. It is also one of the major causes of premature death of the network. To overcome this issue, some approaches divide the whole network into different unequal-sized clusters. The cluster size varies according to the intra- and inter-cluster load. If the load is very high, then the cluster size is small. On the other hand, if the load is less, then the cluster size will be bigger. Therefore, clusters near BS are small in size, and faraway clusters are bigger in size [12]. This approach is capable of solving the energy hole problem to some extent. However, these approaches suffer from high message overhead and high computational complexity. On the other hand, the management of unequal-sized clusters throughout the network lifetime is very challenging due to dynamic changes in network topology [13]. Furthermore, fault occurrence probability in IoT-enabled WSNs is higher as compared to wired-based traditional networks due to wireless communication and different environmental threats [14]. Sometimes, IoT-enabled WSNs also get divided into isolated sub-networks due to node faults in the network. It significantly reduces the lifetime and overall performance of the networks [15].

Nowadays, a Mobile Sink (MS) is used to collect data from sensor nodes in IoT-enabled WSNs. An MS is an intelligent device that traverses the network and collects data from sensor nodes. MS reduces the energy used in data transmission at sensor nodes. It improves network lifetime as well as the overall performance of the network [16]. MS-based data routing mechanism is more energy efficient as compared to the static sink-based data routing mechanism. Two types of mobility techniques are used for MS-based data gathering. One is random mobility, and the other is controlled mobility. In random mobility, MS moves in the network randomly and collects data from sensor nodes. However, random mobility does not guarantee data collection from all nodes in the network. In controlled mobility, a guided path is designed for MS. MS visits each sensor node through this guided path and collects data from sensor nodes [17]. In controlled mobility, MS traverses a long path for data collection that significantly increases data collection delay. High data collection delay causes buffer overflow and data loss at sensor nodes. To resolve this issue, a set of Rendezvous Points (RPs) is selected for MS-based data collection. RPs are some locations in the network where MS halts to collect data from sensor nodes [18]. Some approaches group sensor nodes into different clusters and select a CH for each cluster. These CHs collect data from CM nodes and send it to MS when MS visits the nearest RP. Fig. 1.2 shows MS-based data collection in IoT-enabled WSNs. MS-based data collection is more

Figure 1.2: MS-based data collection in IoT-enabled WSNs.

effective for solving energy hole or hot spot problems as compared to static sink-based approaches. However, an optimal number of RP selections and optimal data gathering path selection are very important for MS-based data gathering schemes. It significantly improves the lifetime and overall performance of the network. Other challenging issues that are required to be addressed during the design of an MS-based data routing scheme for IoT-enabled WSNs are mentioned in the following section.

1.2 Challenges

Data routing in IoT-enabled WSNs suffers from various challenges due to the unique characteristics and constraints of the network. Some of the major challenges that should be considered while designing the data routing mechanism are as follows.

- **Energy Efficiency:** Sensor nodes consist of batteries with limited capacity. Data transmission is a primary cause of energy consumption in nodes. Therefore, the data routing mechanism must minimize energy consumption at nodes to prolong the network lifetime [19]. Furthermore, the data routing technique needs to ensure balanced energy consumption among nodes to avoid the early death of sensor nodes.

- **Scalability:** The number of nodes in an IoT-enabled WSN may vary from hundreds to thousands. Sometimes, more new nodes are included within the network with time for better Quality of Service (QoS). Similarly, some sensor nodes are excluded from the current network topology due to the node fault. Therefore, the data routing scheme must adapt these changes with minimum changes in the existing network topology [20].

- **Heterogeneity:** In advanced IoT applications, sensor nodes are of different types in nature in terms of energy, storage, communication ranges, and data transmission rate [5]. The data collection scheme needs to take into account these variations to efficiently utilize the network resources.

- **Obstacle avoidance:** Physical obstacles such as buildings, trees, and large rocks can hamper communication among sensor nodes and create transmission faults [21]. Furthermore, these obstacles prevent MS mobility within the network. It hampers the data-gathering process. Therefore, the data routing scheme must consider the presence of obstacles within the network and ensure reliable data delivery.

- **Dynamic Network Topology:** In IoT-enabled WSNs, sensor nodes fail due to various reasons, such as hardware malfunction, software issues, or physical damage due to environmental effects [22]. Failure of nodes alters the network's topology. Node failure also creates disconnected segments in IoT-enabled WSNs. Therefore, the data routing scheme must be able to detect these dynamic changes. The data routing mechanism should also be able to recover the network without significant delays.

- **Load Balancing:** In IoT-enabled WSNs, some sensor nodes die early as compared to the other nodes due to an imbalanced communication load among sensor nodes [23]. It results in the early death of nodes and leads to premature death of the network. Data collection schemes need to distribute the load evenly among nodes, which can prevent early death of the node.

- **Latency:** Some IoT applications perform real-time monitoring, e.g., fire detection or health monitoring. In these applications, data collection and analysis are performed in real-time. These applications require low-latency communication. Therefore, the data routing scheme must ensure data collection with minimum delay, especially in time-sensitive applications [24].

Any IoT-based system demands high-performance WSNs that can effectively handle the above-mentioned issues. Traditional WSNs are unable to effectively handle the above issues. Therefore, IoT-enabled WSNs are very important to effectively handle the above-mentioned issues. Various applications of IoT-enabled WSNs are mentioned in the following section.

1.3 Applications

Recently, IoT-enabled WSNs have earned significant attention because they are able to monitor and collect real-time data from diverse environments. The integration of IoT-enabled WSNs has revolutionized monitoring, automation, and decision-making processes in various fields. This section depicts the key applications of WSNs across multiple domains.

- **Environmental Monitoring:** IoT-enabled WSNs play a critical role in environmental monitoring by gathering data on air quality, water pollution, and climate conditions [25]. IoT-enabled WSNs are deployed at various locations, such as forests, rivers, and urban areas, to track the changes occurring in the environment and detect hazardous conditions.

- **Smart Agriculture:** In smart farming, IoT-enabled WSNs enable precision agriculture by collecting real-time data on weather patterns, soil conditions, and crop health. This data helps optimize irrigation, pest control, and crop fertilization. It improves resource efficiency and increases productivity [26].
- **Industrial Automation:** IoT-enabled WSNs facilitate industrial automation by enabling machine health monitoring, predictive maintenance, and power optimization. Various sensors, such as vibration, temperature, and pressure sensors, monitor the industrial machinery to predict the faults and machine failures [27]. Smart meters are able to monitor power utilization data that helps to distribute power efficiently in industries.
- **Healthcare and Biomedical Applications:** IoT-enabled WSNs significantly transformed healthcare by enabling smart wearable devices, remote patient monitoring, and hospital automation [28]. Wearable devices monitor the patient's vital signs, such as heart rate, blood pressure, and oxygen levels. These sensors not only keep track of the patient's condition but also help to quickly alert doctors/nurses in case of emergency.
- **Military and Defense Applications:** IoT-enabled WSNs play a critical role in battlefield monitoring, surveillance, and border security. Motion sensors can be used to detect intrusion. Furthermore, WSN can be deployed to monitor the battlefield to get real-time data [29].
- **Disaster Management:** IoT-enabled WSNs are widely used for early detection and response to disasters such as fire, gas explosions, and hazardous gas leaks. Sensor nodes detect the presence of flame, smoke, and harmful gasses in the

environment and alert the authorities. IoT-enabled WSNs are also used to help evacuate people in an emergency situation [30].

1.4 Motivation

IoT-enabled WSN uses power-constrained sensor nodes to monitor the environment and collect data. Therefore, energy consumption minimization at sensor nodes is one of the critical requirements to prolong the lifetime of IoT-enabled WSNs [31]. Existing static sink-based data routing approaches increase network lifetime up to some extent. However, the static sink-based data routing approach is unable to fully utilize sensor node energy due to an imbalance in communication load among the sensor nodes. Therefore, static sink-based data routing approaches are unable to solve energy-hole problems in an efficient manner. It reduces the lifetime as well as the performance of the network [32]. Therefore, we do not achieve the expected output from the static sink-based data routing approaches in terms of network lifetimes, stability period, energy consumption and other performance matrices. MS-based data routing mechanism significantly reduces the communication load of sensor nodes and is capable of balancing energy consumption among the sensor nodes. MS-based data collection is more effective in handling the energy-hole problem. Furthermore, the MS-based data-gathering mechanism significantly reduces the data transmission distance of sensor nodes and increases overall network performance [33]. However, an optimal number of RP selections is one of the major challenging tasks in an MS-based data-gathering mechanism. It directly affects the delay and energy consumption of sensor nodes. Improper RP selection leads to premature death of the network. Therefore, an optimal number of RP selections is crucial to improving the lifetime and overall performance of IoT-enabled WSNs [34]. Direct communication between RP and sensor nodes minimizes the data transmission distance of sensor nodes. Single-hop communication requires less energy for data transmission and minimizes sensor nodes' energy consumption. However, single-hop communication between RP and sensor nodes increases the number of RPs in the network. The high number of RPs creates a long data-gathering path for MS. It results in a high data-collection delay for MS. Furthermore, it also causes buffer overflow at nodes, which leads to loss of data. On the other hand, multi-hop communication between RP and sensor nodes increases the load on intermediate nodes. Data aggregation and forwarding cause high energy consumption at intermediate nodes and lead to early network death. Therefore, a trade-off between the number of hops and the data collection delay is needed to improve network performance. This motivates us to do the thesis on MS-based data-gathering approaches for IoT-enabled WSNs.

IoT-enabled heterogeneous WSNs present a complex network environment compared to homogeneous WSNs. In a homogeneous network, all sensor nodes are similar types in nature. On the other hand, a heterogeneous WSN is a collection of different types of sensor nodes [35]. These sensor nodes are different in data transmission rate, sensing rate, energy capacity, and buffer capacity. MS-based data-gathering techniques that are designed for homogeneous networks do not perform well in heterogeneous networks [36, 37, 38]. Data routing approaches that are designed for homogeneous WSNs are unable to fully utilize the network resources of heterogeneous WSNs. Therefore, an MS-based data-gathering scheme for IoT-enabled heterogeneous WSNs is needed for advanced IoT applications. These advanced IoT applications use heterogeneous nodes for data gathering from physical objects. This motivates us to propose an MS-based data routing approach for IoT-enabled heterogeneous WSNs. In real-life scenarios, IoT-enabled WSNs contain various types of physical obstacles, such as rocks, trees, buildings, and high walls in the network. These obstacles hamper the MS movement as well as the data-gathering process. Furthermore, large-size obstacles also prevent communication among nodes and create transmission faults in the network [39, 40]. To resolve the above-mentioned issues, an MS-based obstacle-aware data routing scheme is needed. It motivates us to propose an obstacle-aware data routing scheme for IoT-enabled WSNs.

In WSNs, sensor nodes are highly susceptible to various faults that can significantly impact their operation and overall network performance. These faults can occur due to several internal and external factors. Internal factors refer to energy exhaustion and hardware malfunction [41]. After energy exhaustion, nodes are unable to perform sensing or data transmission. Hardware malfunctions, such as damage to node components or failure of the node circuit, also cause sensor node faults. External factors refer to severe weather conditions and natural disasters. Environmental factors, such as heavy rain, storms, fire, and earthquakes, cause permanent damage to nodes. Failure of some nodes can disrupt the data transmission of other active nodes. Node failure creates network cuts that divide the network into several disconnected segments [22]. These segments are unable to transmit their data to BS. It adversely impacts the network lifetime and overall network performance. Therefore, it is important to identify the formation of network cuts and perform recovery of the network. This motivates us to present a mobile data collector-based network cut detection and recovery scheme for WSNs.

IoT-enabled WSNs play a crucial role in planning escape routes for individuals in an emergency evacuation system. Existing emergency evacuation systems only consider static fire conditions and do not take into account the spread of fire with time. Also, these systems do not consider dynamic fire spread, which leads to inefficient or unsafe evacuation routes [42, 43]. It can cause long detours and sometimes may even trap individuals in hazardous regions. Furthermore, it is crucial to consider the dynamic spread of fire to ensure a safer and more efficient evacuation route for trapped individuals. Therefore, an emergency evacuation system that considers the future fire shape while designing the shortest safe evacuation routes for individuals is needed. IoT-enabled WSNs-based emergency evacuation system minimizes risks by continuously adjusting paths depending on the fire situation. This motivates us to propose an intelligent indoor emergency evacuation system using IoT-enabled WSNs for smart buildings.

1.5 Objectives

The primary objective of this research is to improve the lifetime of WSNs by improving the lifetime of battery-constrained sensor nodes. MS-based data collection significantly reduces the energy consumption of sensor nodes and enhances network lifetime. MS-based data collection can significantly improve overall network performance. However, data collection in heterogeneous WSNs presents complex challenges compared to homogeneous WSNs. Hence, an MS-based data collection scheme for heterogeneous WSNs is a necessity. The presence of physical obstacles in the network area is a major challenge for MS-based data collection. In IoT-enabled WSNs, sensor nodes are prone to various faults. Faulty nodes disrupt the network operation and divide the network into multiple disconnected segments. Therefore, the identification of faulty nodes and network recovery is a significant issue in IoT-enabled WSNs. An emergency evacuation system that considers both current and future fire conditions is crucial to ensure safe and quick evacuation of evacuees. To solve the above-mentioned problems, the following objectives are set for this thesis work.

1. **Objective 1:** To design and develop an MS-based data collection mechanism for homogeneous IoT-enabled WSNs.

   Realized by: Multi-Objective Gray Wolf Optimization based Data Routing Scheme for Wireless Sensor Networks.

2. **Objective 2:** To design and develop an MS-based data collection mechanism for heterogeneous IoT-enabled WSNs.

   Realized by: A Deep Policy Dynamic Programming based Intelligent Data Routing Scheme for IoT-enabled Wireless Sensor Networks.

3. **Objective 3:** To design and develop an obstacle-avoiding data routing scheme

for IoT-enabled WSNs.

Realized by: Obstacle Aware Energy Efficient Data Routing Scheme for Industrial IoT-enabled Wireless Sensor Networks.

4. **Objective 4:** To design and develop an MS-based network cut detection and recovery scheme for IoT-enabled WSNs to mitigate node failure effects within the network.

   Realized by: Mobile Data Collector-based Network Cut Detection and Recovery Approach for WSNs.

5. **Objective 5:** To design and develop an indoor emergency evacuation system using IoT-enabled WSNs.

   Realized by: An Intelligent Indoor Emergency Evacuation System using IoT-enabled WSNs for Smart Buildings.

1.6 Thesis Contribution

The key contributions of this study are presented as follows:

1. **Multi-Objective Gray Wolf Optimization based Data Routing Scheme for Wireless Sensor Networks:** This thesis proposes a Multi-Objective Gray Wolf Optimization based intelligent data routing mechanism for WSNs that prevents premature death of the network. It significantly improves network lifetime and performance. The proposed scheme divides the whole network into different optimal-size clusters and selects optimal RPs. The MS visits each RP through the optimal path and collects data from the sensor nodes. MS starts the data collection tour from BS, visits each RP, and delivers the data to BS. In this approach, an RP rotation scheme is also applied to balance the energy consumption throughout the cluster.

2. **A Deep Policy Dynamic Programming based Intelligent Data Routing Scheme for IoT-enabled Wireless Sensor Networks:** This thesis proposes A novel Energy Efficient Rendezvous Points Selection (EERPS) algorithm for an optimal number of RP selections in IoT-enabled heterogeneous networks. The proposed scheme also identifies an optimal number of CHs and forms clusters to reduce the energy consumption of the deployed sensor nodes. It helps to prevent the early death of sensor nodes. Furthermore, the proposed scheme applies a Deep Policy Dynamic Programming (DPDP) algorithm to design an optimal path for MS-based data collection. Optimal RP selection and path design algorithms prevent the premature death of the network and significantly improve the overall performance of the network.

3. **Obstacle Aware Energy Efficient Data Routing Scheme for Industrial IoT-enabled Wireless Sensor Networks:** This thesis proposes an obstacle-aware data routing scheme for industrial IoT-enabled WSNs using an MS. It uses a Manta-ray Foraging Optimization (MRFO) algorithm to identify optimal RPs. Furthermore, the EBS-A* algorithm is used to identify a smooth obstacle-avoiding optimal route for MS. The MS follows the obstacle-avoiding optimal route to visit RPs for data collection. It significantly increases network lifetime, QoS, and overall network performance. The proposed scheme is used to monitor industrial safety and machine conditions in the chemical industry.

4. **Mobile Data Collector-based Network Cut Detection and Recovery Approach for WSNs:** This thesis proposes a Mobile Data Collector (MDC) based data gathering approach for WSNs to collect data from isolated segments. This approach proposes an MDC-based novel network cut detection algorithm that identifies the formation of network cuts in WSNs. A network recovery algorithm is also proposed to enable data collection from the isolated segment. Furthermore, this approach proposes a Reinforcement learning Brain Storm Optimization

(RLBSO) algorithm for optimal RPs selection and optimal MDC path design. It significantly reduces data gathering time from isolated network segments.

5. **An Intelligent Indoor Emergency Evacuation System using IoT-enabled WSNs for Smart Buildings:** This thesis proposes a Dynamic emergency Evacuation system for Shortest-Safe path Navigation (DESSN). The proposed work computes the shortest path for an individual toward a safe exit by considering the future spread of the fire region over time. The proposed approach creates a $fireMap$ and a $routeMap$ to show the fire spread and find a safe evacuation path. A modified Dijkstra algorithm is used to find the shortest path for a safe exit. This system is implemented using IoT-enabled WSNs with sensor nodes, which are equipped with different types of sensors. Deployed sensor nodes communicate with the BS to plan every individual's shortest and safest evacuation path. Sensor nodes are used to detect fire within the monitoring public infrastructure. Furthermore, BS is used to compute all the logical and arithmetical operations on real-time data. The proposed approach finds the shortest safe path considering the future fire spread that enables quick evacuation of evacuees during an emergency. It also helps to avoid detours.

1.7 Thesis Organization

The rest of the chapters of the thesis are as follows.

1. **Chapter 2** provides a comprehensive review of relevant and recent research works on MS-based data collection schemes in IoT-enabled WSNs. It presents the current challenges and highlights the research gaps in the literature.

2. **Chapter 3** presents an MS-based data collection scheme for WSNs. It proposes an optimization algorithm that selects energy-efficient RPs in the homogeneous network. It selects RPs that minimize the energy consumption of sensor nodes

and improves network lifetime.

3. **Chapter 4** proposes an MS-based data collection scheme for IoT-enabled heterogeneous WSNs. In this work, RPs are selected on the basis of varying communication ranges, energy capacities, and buffer capacities of sensor nodes. Furthermore, a neural network based algorithm is applied to design a data gathering path for MS.

4. **Chapter 5** presents an obstacle-avoiding data collection scheme using MS for IoT-enabled WSNs. This work applies a meta-heuristic algorithm to select RPs. Furthermore, a grid-based obstacle-avoiding path is designed for MS. This approach designs a path for MS that keeps a safe gap between obstacles and the designed path to avoid the possibility of collision between MS and obstacles.

5. **Chapter 6** proposes an MS-based network cut detection and recovery scheme for IoT-enabled WSNs. This approach identifies faulty nodes in the network that create network cuts. It also proposes a recovery scheme that enables data collection from all isolated segments.

6. **Chapter 7** presents an emergency evacuation scheme using IoT-enabled WSNs. This work designs a short evacuation path for trapped evacuees while considering present and future fire spread. It dynamically designs a safe path that enables fast evacuation of evacuees.

7. **Chapter 8** provides a summary of major research outcomes and discusses the contributions of this study. It also suggests potential directions for future research.