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MECHANISMS FOR EFFECTIVE UTILIZATION OF MOBILE NODES IN WIRELESS SENSOR NETWORKS

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DISSERTATION SUBMITTED 2015

AALBORG UNIVERSITY
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I earned my bachelor's and master's degree in engineering from University of Pune, India, and University of Bradford, United Kingdom respectively. In addition to sensor networks, I have a keen interest in internet of things, and green communications.

Abstract

Wireless sensor networks are expected to provide rich information from future applications that necessitate deployment across a large area, possibly over a harsh or inhabitable terrain. Utilizing mobile nodes for such deployments is highly desirable. However, their usability is doubted as they are costlier compared with static nodes, and their movement-actuation consumes a significant amount of energy. Mobile nodes have other operational constraints in the form of need for navigation assistance through localization services, and favorable deployment conditions. In addition, a mobile node addressing a certain network attribute could negatively impact another network attribute. This thesis examines the possible mechanisms for effective utilization of mobile nodes operating within the aforesaid operational constraints.

Using geometric models based techno-economic evaluation it was concluded that mobile nodes are cost effective for use in sensor networks. It is possible to relocate mobile nodes without use of localization services, and collectively address two network attributes - coverage and clustering. A hybrid network comprising only partial mobile nodes is sufficient to fulfill coverage requirements for the network, deduced by determining the multi-parameter relations that govern node mobility. An operational mechanism that supports sensor networks to operate on undulating-harsh terrain has been put forward, relying on data collection by flying sensors and bypassing the need for multi-hop communication between clusters and the base station. It was also found that seemingly non-related applications of sensor networks can be addressed collectively, utilizing passive node mobility. Proving the immense utility and possible applications relying on non-active actuation mechanisms, in addition to active node mobility.

The thesis effectively concludes that mobile nodes have immense utility in sensor networks in spite of the operational constraints.

Dansk Resumé

Trådløse sensornetværk forventes at bringe værdifuld information fra fremtidige applikationer, der kræver implementering over et stort område, eventuelt i barsk eller ubeboelig terræn. Brug af mobile sensorer til sådanne implementeringer kan have mange fordele. Dog er deres anvendelighed ikke bevist, da de er dyrere sammenlignet med ikke-mobile sensorer, og deres evne til at bevæge sig kræver en betydelig mængde energi. Mobile sensorer har andre operationelle begrænsninger i form af behov for navigationsbistand gennem lokalisering, og gunstige implementeringsbetingelser. Derudover kan en mobil sensor ved at adressere en parameter i netværket have negativ indflydelse på et andet parameter. Denne afhandling undersøger mulige mekanismer til effektiv udnyttelse af mobile sensorer indenfor de ovennævnte operationelle begrænsninger.

Ved hjælp af teknisk-økonomisk evaluering baseret på geometriske modeller er det blev konkluderet, at mobile sensorer er omkostningseffektive til brug i sensornetværk. Det er muligt at flytte mobile sensorer uden brug af lokalisering, og kollektivt adressere to netværk parametre - dækning og klyngedannelse. Et hybrid-netværk kun delvist bestående af mobile sensorer er tilstrækkeligt til at opfylde dækningskravevene for netværket, udledt ved at bestemme de forskellige parameter relationer, der styrer sensor mobilitet. En operationel mekanisme, der understøtter at sensor netværk kan operere på kuperet og barsk terræn er blevet fremsat på baggrund af dataindsamling ved hjælp af flyvende sensorer og uden behov for kommunikation gennem flere hop mellem klynger og basestationen. Det blev også konstateret, at tilsyneladende ikke-relaterede anvendelser af sensornetværk kan adresseres kollektivt ved at udnytte passiv sensor mobilitet. Dette beviser de enorme fordele og mulige applikationer der afhænger af ikke-aktive aktiveringsmekanismer, foruden aktiv sensor mobilitet.

Afhandlingen konkluderer, at mobile sensorer har stor anvendelighed i sensornetværk på trods af de operationelle begrænsninger.

Acknowledgements

I am grateful to Prof. Ramjee Prasad for providing valuable guidance, encouragement and support throughout my doctoral research.

I am indebted to my supervisor, Dr. Neeli R. Prasad for guiding me through this work and keeping faith in me. Without her guidance, motivation and support I would not have completed my PhD.

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The real driving force for me to accomplish the PhD were my parents, I am grateful to them for playing this key role. I am also grateful to my other family members for their encouragement and support.

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List of Acronyms

AoI	area of interest
ASN	active sensing node
BS	base station
CAPEX	capital expenditure
CBA	cost benefit analysis
CH	cluster head
FR	functionality round
GPS	global positioning system
IRR	internal rate of return
LWR	long welded rail
MAV	miniature aerial vehicle
MSN	mobile sensor network
NPV	net present value
OPEX	operational expenditure
PSN	passive sensing node
RBS	regional base station
RSSI	received signal strength indicator
SWR	short welded rail
TDMA	time division multiple access
UASN	underwater acoustic sensor network
VTOL	vertical take off and landing
WSN	wireless sensor network

Chapter 1

Introduction

Wireless sensor networks (WSNs) offer a promising approach for collecting data covering possible applications and areas that cannot be catered by conventional wired/wireless communication networks. WSNs are expected to be deployed and rendered operational with minimal human involvement, and operate unattended for a long duration relying on minimal energy reserve.

1.1 Fundamentals of WSNs

WSNs are composed of sensor nodes, which are low power, multi-functional, capable of sensing a phenomenon and transferring the measured value to a base station (BS). WSNs are considered a promising technology expected to transform the future world, with the whole globe dotted with billions of nodes to address diverse applications such as: structural health monitoring, industrial monitoring, habitat and wildlife monitoring, battlefield surveillance and natural disaster monitoring among others [1]. However, large scale use of WSNs is hampered due to typical constraints related with their operational capacity and any substantial use of WSNs is feasible if the envisioned applications can become commercially viable [2]. WSNs are primarily considered to stay at the place of deployment and thereby the sensor nodes that they are composed of are referred as *static* nodes. The layout obtained with such a deployment comprising of only static nodes imposes functional limitations on the overall performance of the network, as it cannot adapt with changes that may occur across the network's lifetime, *e.g.*, the network might be partitioned or rendered useless due to a coverage hole emerging because of a dead sensor node. The network might also be impacted in an undesirable way due to changes in the environment at the deployment site [3].

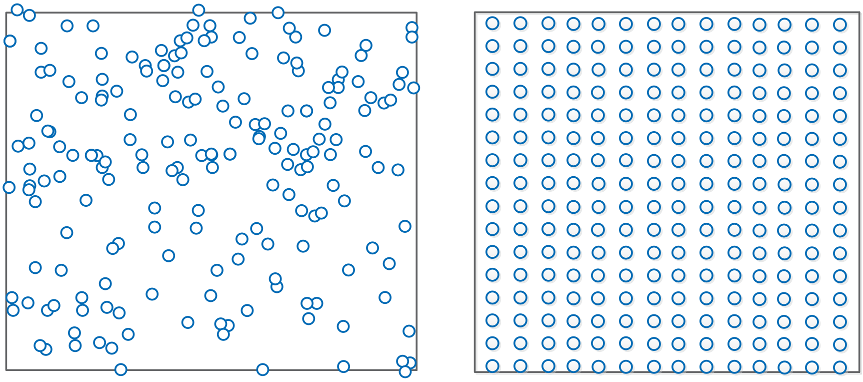

Figure 1.1: Non-uniform and deterministic deployments

1.2 Deployment of WSNs

Deployment of WSNs is expected to be done in a deterministic manner, it refers to placing the sensing nodes in a pre-determined manner across the area of interest (AoI). Therefore, a deterministic deployment requires manual placement of sensing nodes. However, some of the envisioned applications of WSNs as stated earlier would span across a large AoI and it would be infeasible to manually deploy the network. Inhabitable or harsh terrain could be an additional factor that could render manual deployment infeasible, alternative to *deterministic* (*uniform*) deployment of the network is to deploy it in a *non-deterministic* manner (*non-uniform*). The non-deterministic deployment of the network could be done remotely by air dropping the sensing nodes in the AoI from an air plane [4], [5]. The word *non-uniform* has been used throughout this thesis referring to a deployment that is opposite to a deterministic deployment. Non-uniform deployment has also been commonly referred as *random* deployment in the existing literature. Non-uniform deployment leads to formation of certain regions in the AoI that have excess nodes and at same time there could be certain regions in the AoI that could be without any nodes - vacant spaces [6]. The coverage of an AoI describes the overall quality of monitoring / sensing provided by all the nodes collectively. Therefore, it is expected that the sensor nodes cover the complete AoI such that they have the capacity to monitor / sense as per the application requirement in any part of the overall AoI. However, as stated earlier, this is much lower for a remotely deployed network due to overlapping nodes and vacant spaces. The difference between a non-uniform deployment and an organized deployment can be depicted as shown in Fig. 1.1. This can be compensated by utilizing more nodes than the minimum required to cover the AoI. However, this is not feasible considering the manufacturing cost of the sensor nodes. Alternatively, *node mobility* can be explored to improve the coverage of an AoI, with relocation of sensor nodes possessing mobility, *i.e.*, usability of mobile node [4]. Node mobility in WSNs refers to sensor nodes which are capable of moving and relocating in the network deployment region, also referred as sensor mobility [4],[7]. The term node mobility is used throughout this thesis to refer to the utilization of mobile nodes for relocation in the network for addressing various functionalities that include: coverage improvement (area, barrier and target), clustering, network lifetime, and network connectivity.

1.3 Structural Organization of WSNs

Structural formation in respect to WSNs refers to the manner in which the nodes in the AoI are organized. WSNs can be deployed with a tree based structure for transfer of information in which the final aggregation point of data is the BS, other nodes are leaf nodes to the root. Information routed in the network can be aggregated at the parent node to certain leaf node(s) or relayed as it is to the further parent node in direction to the BS [8, 9]. An other prominent structure formation for WSNs is the organization of sensor nodes into clusters, which can be classified as a specific type of tree structure. Clustering the sensor nodes forms a hierarchical structure in the network, such that the sensor nodes relay their messages to the elected cluster head (CH) in the lower tier. The CHs form the upper tier in the network and the CHs are collectively responsible for delivery of the packets at the BS [10],[11]. WSNs can also be deployed in the AoI without proper structural formation, called as a flat structure, both types are shown in Fig. 1.2. A flat structure is not preferable as sensor nodes possess a very limited energy and possibly no option to renew / replace the battery reserve. Nodes will consume more energy in transmission of messages as there will be no clear routes for transmission of messages to the BS. There can be excessive undesired transmissions of data packets across the network [12]. In a hierarchical structure achieved with clustering of the nodes the packets received at the CH can be aggregated before onward transmission to the BS, thereby, decreasing the overall traffic in the network in comparison with a flat network.

Mobile CH based organization of nodes in the network for improving network lifetime has been presented with three mobility strategies based on remaining energy of sensors or occurrence of an event [13]. While after a non-uniform deployment caused by remote dropping of nodes, it is expected that mobile nodes would relocate to improve coverage of the network over an AoI as the primary task. Therefore, clustering of nodes is related to the manner

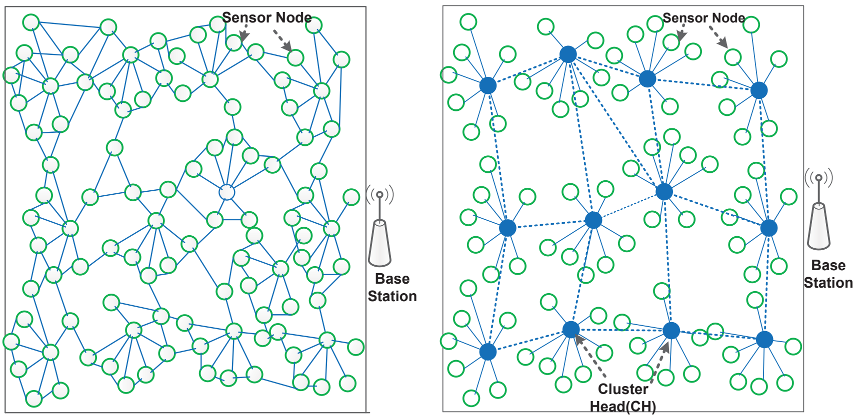

Figure 1.2: WSN structure i) flat ii) hierarchical (clusters)

in which nodes are deployed in the AoI. Despite of this implicit relation between the two network attributes they have been analyzed individually in the literature [14].

1.3.1 Types of WSNs Based on Node Mobility

Based on the node mobility available in the network, WSNs can be classified into three types: static, hybrid and mobile [5],[15]. They are discussed in the following subsections:

Static WSN

A network with none of the nodes having mobility, *i.e.*, composed of only static nodes is called a static WSN. A network composed with all static nodes can not adapt with dynamic changes that may occur in the network over its lifetime. In the event of non-uniform deployment of the network in the AoI, the number of static nodes required would be much larger than a critical density that would be sufficient to cover the AoI [3], [15]. Critical density is described as an over positioning metric in [5]. It would be necessary to attain a k-coverage across the AoI, with k referring to the number of sensors expected to cover all point in the region. Such a network can be partitioned resulting from outage of a few nodes relaying traffic for other nodes. Such a network is also not capable to address a condition in which a certain region generates information at a higher rate than the rest of the network. Additional resources required by a certain region can not be provided by a static nodes based network [7]. Therefore, it can be said that the overall performance of a static sensor network is limited to the initial deployment [16]. Reorganizing the network would be achievable only by manually placing the nodes as per the need.

Hybrid WSN

A hybrid network comprises a mix of static and mobile nodes, also referred as a mixed WSN [4]. Such a network can also be classified as a special class of mobile sensor network (MSN), as out of the total nodes in the network only some possess mobility. This is justifiable, considering the difference in cost between mobile nodes and static nodes [16] on a per unit basis. Even in respect to energy costs involved, it is undesirable to have a large number of mobile nodes in the network [2]. In [17], it is stated that a mix of static and mobile nodes should be used for maintaining a balance between the sensor cost and coverage. Therefore, hybrid sensor networks are expected to function considering this trade-off between sensor cost and benefit garnered with node mobility in the network.

Mobile WSN

Mobile WSNs is a network composed such that all nodes possess the capacity to relocate, *i.e.*, node mobility. In such a network it is intended that all the nodes are continuously moving throughout the network region, and throughout the network lifetime [18]. This differentiates mobile WSN from hybrid WSN, where the usual intention is to utilize mobile nodes to supplement network performance provided by static nodes and node mobility is utilized restrictively. In a MSN the mobile nodes may possess passive mobility also referred as parasitic mobility [19], instead of active mobility provided by the node itself. This is feasible with mobile nodes moving based on: river currents, ocean currents, air currents or other forces of fluid. Alternatively, the nodes can be mounted on vehicles, attached to animals or carried by people [18],[19],[20]. Mobile WSN applications based on passive node mobility are much more acceptable compared with applications based on active node mobility considering in terms of the applicable cost to accomplish them.

1.3.2 Energy: Resource and Consumption

Energy is a scarce resource in sensor nodes due to limited battery reserve. Movement of sensor nodes consumes a lot of energy compared to energy consumption for radio communication in the network. Many studies in the literature state this and propose applications and uses of node mobility considering this constraint [2], [21]. In some of the literature works, it is assumed that node mobility is unlimited [22]. Some studies consider static and mobile nodes as heterogeneous entities (difference in their operational capabilities apart from node mobility), with mobile nodes possessing more energy reserve (battery) compared with static nodes. Similarly, there are studies that consider energy spent in movement of the mobile nodes to be replenished by means of energy harvesting mechanisms provided on the sensor node platform. Alternatively, feasibility of energy replenishment with periodic approach of mobile node to the BS or a recharging docking station [23]. Use of mobile nodes in the network such that they are considered as low cost and disposable nodes has also been proposed [24]. Both movement of nodes and transmission of information are highly energy intensive resources in WSNs, the latter as such being a fraction of the other. The energy consumption for movement of mobile node and transmission of information have been compared in [24], and described as below. The energy consumption by a mobile node En_M to move a certain distance (d) is represented as:

$$En_M(d) = kd$$

For an optimal speed of the node, $k = 2$, energy consumption for transmission En_T of bits over a distance (d) is represented as:

$$En_T(d) = m(a + bd^2)$$

Here m represents the number of bits transmitted, while a and b are constants based on the environment. Based on this representation, constant $a = 0.6 \times 10^{-7} J/bit$ and $b = 2 \times 10^{-10} Jm^{-2}/bit$ for a radio platform (CC1000) to achieve a packet reception ratio of 95% at the receiver. It can be noted that the factor k governing the mobility of a node over a distance is 10^{10} times larger than b governing the transmission over the same distance d. This justifies that utilizing node mobility in a controlled manner is better compared with unrestricted node mobility in the network.

Navigation and Path Planning

Energy consumption due to node mobility depends on the distance moved by the node. Therefore, stressing on the requirement for proper navigation and path planning for mobile nodes to minimize the total distance moved by the nodes. An obvious inference can be drawn based on fact, *i.e.*, a mobile node moving seldomly and remaining stationary during the remaining time would require less navigation / path planning resources, compared with a node continuously moving. Due to this, coordinating the movement of mobile nodes in a WSN is a major issue [15]. For navigating mobile nodes in the network, path planning incurs an overhead in terms of message transmission. This can be handled in a centralized or distributed fashion. The cost of path planning with a centralized implementation is much higher than distributed schemes, considering the transmission cost of multi-hop messages involved across the network. Location mechanisms provided by network elements internally or externally by global positioning system (GPS) have usually been considered for path planning and navigation of mobile node across the network [21],[24],[25]. Alternatively, it is considered that nodes in the network and the network as a whole are aware of their locations [22]. This consideration simplifies the solution of path planning involving mobile nodes in the network. However, path planning of mobile nodes is complex without these assumptions. These observations further stress on the requirement to utilize node mobility in a controlled manner within the network.

1.3.3 Mobility Mechanisms

Many mobile node platforms have been proposed in the literature such as Robomote, CotsBots, Racemote, Millibots, Khepera [26],[27], and some of these mobile nodes are shown in Fig. 1.3. These mobile node platforms rely on a

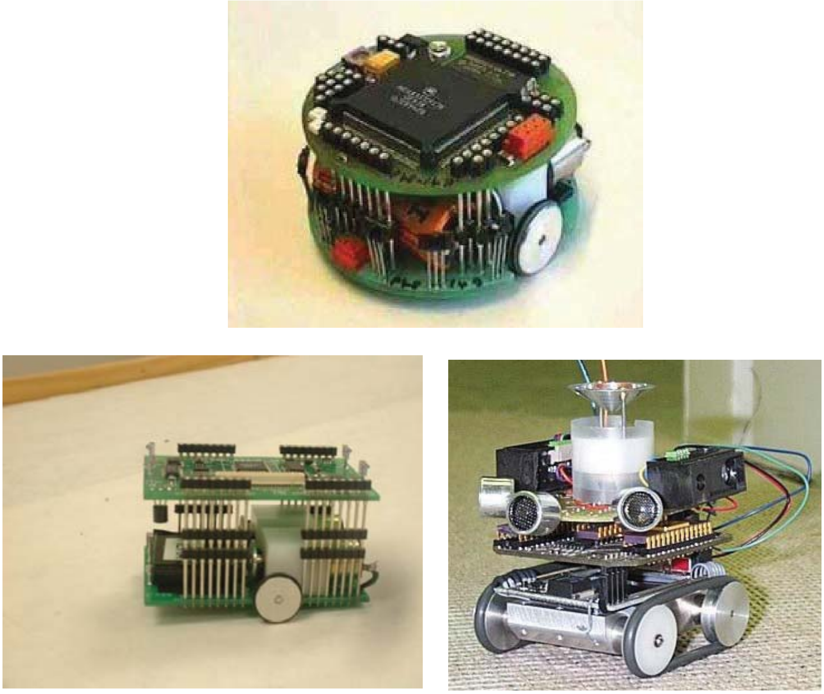

Figure 1.3: Mobile sensor node platforms
Robomote, Khepera and Millibot (clockwise from left) [26],[27],[28]

mobility mechanism of motor driven wheels. These mobile node platforms, in generalized terms, have a cuboid like shape (modular in shape) and relate with popular static node platform which also have a cuboid shape structure. Although, a majority of the aforesaid mobile node platforms are custom designed, in a generalized sense, they can be considered as a static node platform + modules for actuation (motor) and movement (wheels). Coiled spring based mobility for mobile node has been proposed in [21], where a mobile node hops from one location to another by uncoiling of spring. Mobility in this case is *limited* with mobile nodes managing to hop only once in the network lifetime. However, the hop distance can be adjusted by altering the amount of coiling of the spring. Hop *height* as a means for coverage improvement has been presented in [28]. Mobility with magnetic wheels for structural health monitoring of structures made with ferromagnetic material has been presented in [29]. Crawling locomotion and mobility by means of legs attached to the mobile node have also been presented. Utilizing hybrid locomotion of leg-wheel or crawl and jump have also been proposed. The significance of hybrid locomotion mechanisms is to help mobile node to relocate on rough terrain or obstacle hindered terrain. The wheel based mobile node can relocate only on levelled terrain, which cannot be provided in many WSN applications [30],[31]. Mobility in the form of wings has also been proposed in literature. Flying mobile nodes or miniature aerial vehicles (MAVs) mimicking flying behavior of similar sized insects have been proposed [32]. Overall size and weight of a mobile node are greatly influenced by the actuation module for mobility. These aspects in turn influence the possible applications and service limit of mobile node once deployed in the network.

As stated earlier, node mobility can rely on active or passive mobility mechanisms. The various node mobility mechanisms stated above are active mobility mechanisms. In passive mobility mechanisms, nodes relocate with external forces acting on them (energy expense on node mobility is zero). Energy resources can be utilized completely for on-board computation and transmission. Detecting leakages and monitoring condition of internal pipelines with a mobile node as a capsule traversing the pipeline with propulsion by liquid flow has been presented in [33]. Passive mobility is usually uncontrolled compared with active mobility mechanisms. In [34], the authors present a method for sea surface monitoring using a mix of controlled mobility and uncontrolled mobility, coined *c-mobility* and *u-mobility.* Use of mobile phones as mobile nodes for urban sensing for monitoring parameters such as noise, pollution, and the crowd has been presented in [35]. It is uncontrolled as movement of people can not be regulated, and passive as no energy consumption for mobility. Monitoring road conditions for potholes with sensor mounted on vehicles is presented in [36]. Mobility mechanisms influence the mobility limit and feasible functionality of a mobile node to a significant extent. It can be said that design of efficient mobility mechanisms for node mobility is a diverse area of research in itself. This is evident clearly in case of flying mobile nodes / MAVs, wherein actuation for mobility dominates the weight of a MAV, and forces other sensing functionalities to a bare minimal [32]. Similarly for the influence of other *active* mobility mechanisms. Based on this, the majority of studies concerned with utilization of node mobility for some functionality within the network or application of the network, are restricted around utilization of node mobility in the best way possible.

1.4 Problem Definition

This thesis is centred around finding mechanisms through which node mobility can be utilized effectively in the network for addressing some of the aspects stated earlier. However, the node mobility utility is expected to comply with certain constraints. Node mobility is considered as a limited resource in terms of operational limit of the mobile node due to high actuation cost, and number of mobile nodes out of total nodes in the network (hybrid network) (**constraint 1**). Similarly, the mobile nodes are expected to relocate in the network without direct access to localization services provided from other entities within the network or by external means, *e.g.*, using GPS (**constraint 2**). The mobile nodes are expected to relocate in the network, wherein the network is deployed possibly remotely on undulating ground (**constraint 3**). The relocation of mobile nodes in the network for enhancing and positively impacting a certain network aspect/parameter should not impact another aspect/parameter in a negative manner (**constraint 4**). The overall objective therefore is to find mechanisms that can ensure utilization of mobile nodes for realistic deployment conditions, considering possibly a large AoI, that can have an inhabitable - harsh terrain.

1.4.1 Hypothesis

The research addressed in this thesis can be summarized into the following hypothesis - ”utility of mobile nodes in sensor networks is cost effective (monetarily and operationally), and their utility is not limited to assistance from other network entities, and deployment conditions of the network in the AoI”.

1.4.2 Research Questions

Based on the problem definition and hypothesis, the questions this thesis answers are formulated as follows:

- How useful are mobile nodes for use in WSNs in comparison to static nodes?

- How can mobile nodes be utilized for improving the coverage of the network in the AoI, considering the network organized in clusters?
- How can mobile nodes be relocated within the network without active localization services?
- What parameters govern the total node mobility based coverage improvement in the network and how are these parameters related with each other?
- What can be possible mechanisms for relocating mobile nodes apart from the usual active mobility mechanisms?
- How can mobile nodes be utilized for data gathering from a deployed network, without impacting the network organization and operation?

1.4.3 Research Methodology

The research carried out in this thesis to examine the aforesaid hypothesis and the research questions is broadly based on quantitative research methodology. The research questions have been addressed by carrying out geometric modeling, simulation based evaluation of network operations, and numerical analyses.

1.5 Original Contributions

The contributions of this thesis addressing the problem definition through the research questions stated above are mentioned below, specific chapter and the corresponding publication(s) relating with the contribution is stated in brackets.

- The utility of mobile nodes in comparison with static nodes is presented. The two types of nodes have been evaluated for their capacity to carry out certain network functionalities based on a techno-economic evaluation (Chapter 2, publication: *a*).
- Inter-parameter relation between node mobility and coverage for a certain AoI considering parameters which govern these two network aspects, they include: total number of nodes, percent of total nodes as mobile nodes and permissible distance a mobile node can relocate (Chapter 3, publication: *f*).
- A new mechanism for utilizing node mobility to achieve a positive influence on network coverage under the consideration that the network is organized in a hierarchical structure. The mobile nodes are considered

to have a limited mobility capacity and no access to any active localization service, additionally, the underlying hierarchical structure is not hampered by the relocation of mobile nodes (Chapter 4, publication: *e*).

- A new mechanism for data collection from a deployed network utilizing novel node mobility. The mobile node collects data from the deployed network without hampering any other network operation aspect. The data collection mechanism is specifically adapted to collect data from a network deployed in harsh and inhabitable terrain (Chapter 6, publications: *b,c*).
- A new mechanism to address two seemingly non-related applications using a single network deployment. Additionally, the mechanism utilizes passive node mobility, and the mechanism demonstrates the immense utility of passive node mobility in comparison (Chapter 5, publication: *d*).

1.5.1 Publications

Journals

a) P. Mathur, R. H. Nielsen, N. Prasad and R. Prasad,"Cost benefit analysis of utilising mobile nodes in wireless sensor networks," *Wireless Personal Communications*, doi[10.1007/s11277-015-2529-5], 2015 (Chapter 2)

b) P. Mathur, R. H. Nielsen, N. Prasad and R. Prasad,"Data collection using miniature aerial vehicles in wireless sensor networks," *IET Wireless Sensor Systems*, 2015 (Chapter 5).

Conference

c) P. Mathur, R. H. Nielsen, N. Prasad and R. Prasad,"Novel framework for data collection in wireless sensor networks using flying sensors," *Advanced Networks and Telecommuncations Systems (ANTS), 2014 IEEE International Conference on*, (Chapter 5).

d) P. Mathur, R.H. Nielsen, N.R. Prasad, and R. Prasad.,"Wildlife conservation and rail track monitoring using wireless sensor networks," *Wireless Communications, Vehicular Technology, Information Theory and Aerospace Electronic Systems (Wireless VITAE), 2014 3rd International Conference on*, IEEE Xplore, May 2014 (Chapter 6).

e) P. Mathur, R. H. Nielsen, N. Prasad and R. Prasad, "Coverage improvement in clustered wireless sensor networks by relocating mobile nodes based on waypoints," *Wireless Personal Multimedia Communications Symposium, Global Wireless Summit*, New Jersey, USA, IEEE Xplore, 2013 (Chapter 4).

f) P. Mathur, R. H. Nielsen, N. Prasad and R. Prasad,"Coverage improvement for wireless sensor networks using grid quorum based node mobility," *Networking and Electronic Commerce Research Conference*, Riva Del Garda, Italy, October, 2012. (Chapter 3).

1.6 Thesis Outline

An outline of the thesis is shown in Fig. 1.4, with the aforestated publications linked with their respective chapters. The current chapter (chapter 1) presented a basic overview about WSNs and utility of mobile nodes along with problem definition based on various utilities that can be attained by effective utilization of mobile nodes in WSNs, and the original contributions of this thesis in line with it.

In Chapter 2, the capacity of mobile nodes to fulfil a certain functionality in comparison with static nodes has been presented. The two node types are evaluated to fulfil the given functionality based on a techno-economic evaluation. The various functionalities have been represented by relevant geometric models

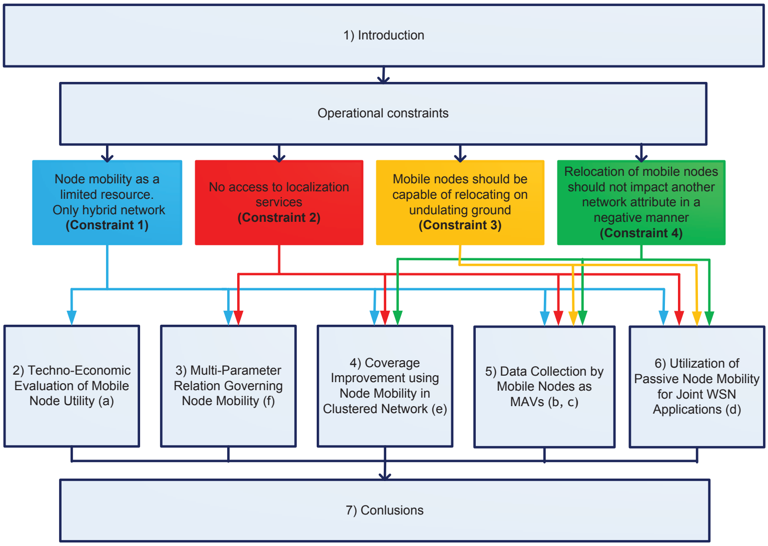

Figure 1.4: Structure of the thesis

for carrying out the evaluation. The need to evaluate the two types of nodes on a techno-economic basis stems from the fact that high operational cost is stated as one of the main reasons for low acceptability of mobile nodes for use in WSNs. The outcome of the evaluation is that mobile nodes are substantially beneficial for use in comparison with static nodes in the network.

Chapter 3 presents the relation amongst the various parameters that govern the overall node mobility feasible in the network. The evaluation is presented based on node mobility usage for covering a given AoI. The outcome of this chapter is the multi-parameter relation that can conveniently serve as a yardstick for planning the network resources before deployment.

Chapter 4 presents a mechanism for coverage improvement for a cluster based network deployed in the AoI. The outcome of the chapter is that coverage and clustering should be considered in a combined manner and not individually. The proposed mechanism in the chapter also demonstrates that without utilizing any localization service the mobile nodes are able to relocate to the destination location for improving the coverage.

Chapter 5 presents a novel mechanism for data collection using miniature aerial vehicles (MAVs) for a network organized in a clustered manner and deployed in a harsh and inhabitable terrain. The specific outcome of the chapter is that the proposed mechanism allows data collection from the network, without hindering the normal operations. Moreover the requirement of resource intensive operation of multi-hop communication is largely avoided within the network as the CHs are not required to communicate with the BS.

Chapter 6 presents a mechanism to address seemingly non related applications using passive mobility of mobile nodes, achieved using a novel deployment and collection agent. The specific outcome of the chapter is that it proves that WSNs can be used to serve more than one purpose (application), similar to the ideal utility of mobile nodes within the network, *i.e.*, to serve more than one network parameter. Another significant outcome of the chapter is the promising utility of passive mobility in WSNs.

The overall conclusions based on the research contributions presented in this thesis, and the possible future work based on current work are discussed in Chapter 7.

1.7 References

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Chapter 2

Techno-Economic Evaluation of Mobile Node Utility

2.1 Introduction

As elaborated in Chapter 1, high manufacturing cost and operational cost are two major limitations cited for usability of mobile nodes in wireless sensor networks (WSNs). This chapter presents a cost benefit analysis for comparing the utility of static and mobile nodes in WSNs. Based on the analysis, it is determined whether the aforesaid statement that is holding back the possible utility of mobile nodes in sensor networks due to high manufacturing and operational cost is justifiable or not. The cost benefit analysis necessitates monetizing all relevant costs for the comparison, this chapter discusses novel geometric models that represent the functionalities to be undertaken by mobile nodes for determining the applicable economic cost. Accordingly, it is centred around addressing primarily constraint 1 stated in the problem definition (Section 1.4) of this thesis.

2.2 Related Work

To the best of the knowledge of the author there has been no work in which utility of mobile nodes in WSNs has been evaluated. Economic feasibility of deploying a static sensor network to work as a parking monitoring system has been proposed by authors in [1]. Techno-economic evaluations have been carried out for access network technologies and architecture [2]. Techno-economic evaluation of access networks technologies for FiWi networks comparing between WiMax and EPON has been presented in [3]. Access networks involve high infrastructure cost and this justifies evaluating the design of access networks on an economic basis, also economic analysis is easier to carry out as the applicable cost and benefit likely to be reaped can be monetized, (*i.e.*, represented in monetary terms) conveniently [4]. Techno-economic feasibility framework to evaluate utility of Internet protocols developed by Internet Engineering Task Force to determine the potential incentives for adopting a given protocol has been presented in [5]. Techno-economic aspects concerning cognitive radio regulatory and policy aspects has been presented in [6].

The costs governing the possible utility of mobile nodes are not easy to monetize. This can be justified as the reason for no existent techno-economic evaluation of their utility in WSNs. The comparison of related works with the presented contribution have been summarized in the Table 2.1.

Table 2.1: Comparison of related works and presented contribution

Factors	Geometric models	Techno economic evaluation	Collectively considering communication cost and relocation cost	All functionalities of mobile nodes
Parking sensor network [1]	×	✓	✓	×
Comparison access networks and the infrastructure [2]	×	✓	×	×
Access networks - WiMax and EPON [3]	×	✓	×	×
Utility of Internet protocols [5]	×	✓	×	×
Cognitive radio regulatory policy [6]	×	✓	×	×

Techno-Economic Modeling

Techno-economic modeling is a method used for evaluation of economic feasibility of complex technical systems [7]. It can help determine the potential economic viability of a process or technology, and used to determine technologies that have the highest likelihood of economic success. The economic competitiveness of a technology is assessed by evaluating its implementation costs for a given process compared to the costs incurred by current technology. A number of methods that are used in the modeling to determine economic viability include: trend analysis, expert opinion, cost benefit analysis (CBA), cash flow, and process modeling. Techno-economic modeling is mostly used in areas of power generation and biotechnology. Based on derived costs and likely benefits from the techno-economic modeling, various indicators are used to judge the profitability likely from the process / projects, *e.g.*, net present value (NPV) and internal rate of return (IRR) [7].

Cost Benefit Analysis

CBA can be utilized to determine the outcome of a program or policy by expressing the applicable cost and likely benefit to be garnered represented in monetary terms. The costs can generally be split into capital expenditure (CAPEX) and operational expenditure (OPEX). Similar to CBA there is cost effectiveness analysis (CEA). The difference between CBA and CEA is that in CEA only costs are monetized, benefits are not taken into account. Technical limitation of utilizing the CBA is that all aspects relevant to the project/process should be quantified - monetized. Major steps in a CBA require the determination of the benefits and costs (monetized), computation of NPV, sensitivity analysis, and recommendation based on the overall analysis [4]. CBA is employed here to evaluate the use of mobile nodes in the network to complete a certain functionality, compared to static nodes. Manufacturing cost of mobile nodes is considered as CAPEX, completing a certain functionality within the network. OPEX of mobile nodes comprises energy consumption for navigation, and communication overhead for coordinating the navigation. Benefit of using mobile nodes in a network intuitively depends on the functionality it can complete in comparison with static nodes. In the CBA, deployment cost of the network has not been taken into account, based on the consideration that there would be no difference between deploying a static node or a mobile node. Similarly, the cost for collecting the nodes after the deployment objective is accomplished has not been considered as is the environmental damage the nodes cause to the environment [8]. Inclusion of these costs can be suggestible future work in regard to economic feasibility of sensor networks. Geometric models have been proposed that model the functionality for which mobile nodes are used in the network for determination of OPEX incurred, and are discussed in subsequent sections.

2.3 Geometric Model to Represent Network Functionality

As stated earlier, the cost of completing a functionality (OPEX) depends on the total distance moved by the mobile node and the communication held with other nodes for coordinating the navigation. Various functionality within the network for which mobile nodes can be used in the network are: coverage improvement, network lifetime as: mobile base station (BS), mobile relay, and data mule. It would be fair to say that other network functionality for which mobile node can be used in the network, *i.e.*, clustering and network connectivity are sub-aspects of aforesaid functionalities, and therefore the proposed geometric models are sufficient to model possible functionalities of mobile nodes in WSNs. The only functionality that can not be modeled by a geometric shape is mobile target coverage. The size of geometric model influences OPEX (node mobility and communication cost) for mobile nodes to complete the functionality. The mobile nodes accomplish the objective of relocating if it relocates to any point within the geometric shape including its perimeter. The mobile nodes perform a certain functionality multiple times over its lifetime, a single instance of it is referred as *functionality round* (FR).

2.4 Benefit of Using Mobile Nodes

As stated earlier the benefit of using mobile nodes in a network depends on the functionality it can complete compared with the use of static nodes to accomplish the same. It is stated in [9] that static nodes have to be *over-positioned* to complete the deployment objective, compared with a network having hybrid deployment (static nodes + mobile nodes). The density of static nodes that are required to guarantee k-coverage are derived as follows:

$$\lambda = \log \ell^2 + (k+2) \log\log \ell^2 + c(\ell) \tag{2.1}$$

$$c(\ell) \to +\infty \quad as \quad \ell \to +\infty \tag{2.2}$$

$$c(\ell) = o(\log \ell^2) \tag{2.3}$$

The density of nodes required for a hybrid deployment is:

$$\lambda = 2\pi k + \sqrt{2\pi k} \tag{2.4}$$

In the above equation λ represents the density of nodes, and ℓ represents the length of the area of interest (AoI). Based on the equations, additional static nodes required if there are no mobile nodes, are the difference of (2.1) and

(2.4). Equation (2.3) holds for all positive constant which is ε, as the applicable condition of little o notation, here we considered it as 1. Considering the length of the area (ℓ) to be 100 and k as one (only one node to cover a given point in the AoI, derived difference in density requirement is $5.49 \simeq 5$. This derivation is also complemented by the observation stated in [10] to attain full coverage for a region when all nodes can move unconditionally, and for a deployment with only static nodes in the network. The number of nodes required are 100 and 480 respectively *i.e* $\approx$ 1:5. Difference in manufacturing cost (CAPEX) of mobile nodes and static nodes in this proportion, is the benefit of using mobile nodes in the network. The derivation of geometric models to discuss the various functionalities is discussed in the following subsections.

Area Coverage

Area coverage describes how well the AoI is covered collectively by the sensor nodes. Mobile node can be relocated to fill a coverage hole resulting anywhere in the network. A coverage hole is described as a region which is not under the sensing coverage of any sensor node, and it results due to initial non-uniform deployment or death of a node during the lifetime of the network [11], [12]. Coverage holes can be determined by using Voronoi Diagrams. The procedure to determine coverage holes has been stated in [11] using the diagram as shown in Fig. 2.1, where the shaded region in the figure represents a coverage hole. Area of the hole in the above figure is determined as follows:

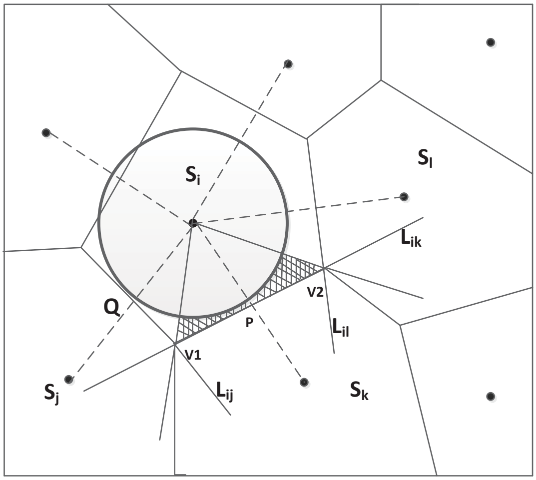

Figure 2.1: Voronoi diagram for determination of coverage hole

$$\text{Area coverage hole}(S_i) = \frac{l_{ik} d(s_i, s_k)}{4} - \frac{x_{ik} R_s^2}{2} \tag{2.5}$$

Where l_{ik} is related with line segment V_1 and V_2 which are to be derived by solving equations of L_{ik}, L_{ij} and L_{il} which are perpendicular lines connecting S_i, S_k, S_j and S_l (sensor nodes) respectively. x_{ik} is determined by the cosine rule once aforesaid line equations are determined. The term $d(s_i, s_k)$ can be safely assumed to be the transmission distance between the sensor nodes. Since the line equations cannot be determined unless all the deployment details are known, the coverage hole area cannot be calculated using (2.5). It is also stated in [11] and [12] that mobile node relocation should only take place when the coverage hole size is larger than a threshold given by $\rho \pi R_s^2$, where $(0 < \rho \leq 1)$. This is considered for determining the functionality area (size). That is 75 m^2 for area coverage-functionality, considering $\rho = 1(max)$ and sensing radius (R_s) as 5 m and communication radius (R_c) is considered as $2R_s$, *i.e.*, 10 m. The same value for R_s and R_c are used for determining size of geometric models to represent other functionalities.

Mobile Relay / BS / Data Mule

Mobile relay/BS/ data mule cane assist the network operations by relocating within the network to assist nodes in their data communication, and assist in enhancing the network lifetime. Mobile nodes are necessitated to be repositioned within communication range (R_c) of the node that is to be assisted (mobile relay) or from which the data is to be collected (mobile BS/data mule). In order to accomplish these functionalities, mobile nodes follow a path and traverse around the network, as shown in Fig. 2.2, if the mobile node has to collect data from node B or relocate itself in its vicinity to relay multi-hop traffic, and it is approaching it from node A. Therefore, if node B is in communication range of the mobile relay / BS (R_c) functionality objective is accomplished. There can be variation in the actual path undertaken by the mobile node as shown by the possible paths based on the availability of way-points. It can be safely assumed that the possible width while traversing from one node to another node would be $\leq R_s$. The actual route adopted by the mobile node can vary, as shown in the figure. The geometric model to represent this functionality is a rectangle of size:

$$R_c \times R_s = 50m^2 \tag{2.6}$$

Target Coverage

It is stated in [13] that when a node has to transmit information to some destination it will look for a neighbor in the destination direction within a sector angle θ as shown in Fig. 2.3, and subsequently that neighbor will look for a neighbour in a sector region in direction of the destination, thereby forming

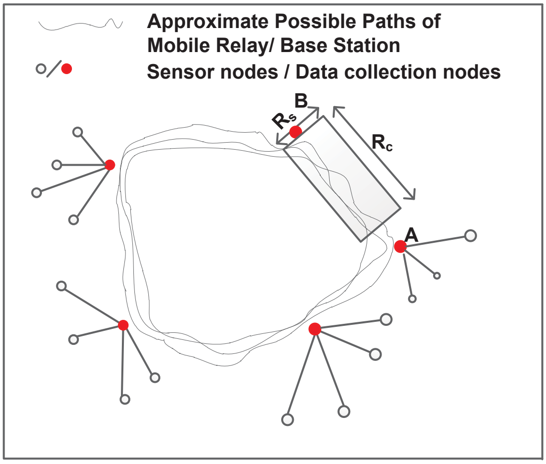

Figure 2.2: Possible mobile relay / BS path in network layout and geometric model representing functionality

a multi-hop route. Based on this it is inferred that mobile nodes look for the target within a similar sector region when the distance to the target $(D_t) \leq R_s$, as shown in Fig. 2.4. The possible angle θ has been considered as 90° as that

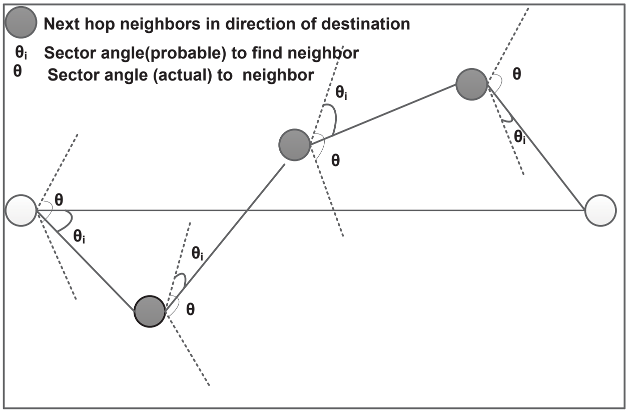

Figure 2.3: Node looking for a neighbor in a sector region towards the destination

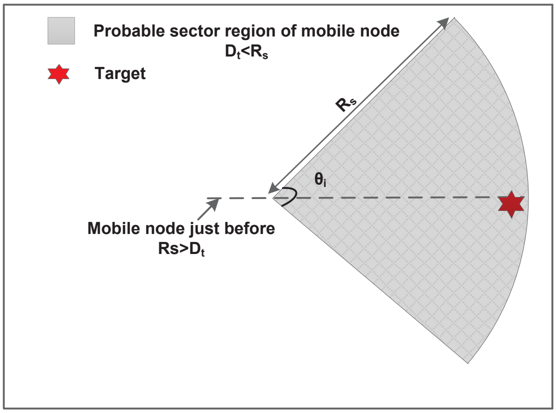

Figure 2.4: Geometric model for target coverage functionality

is the maximum feasible sector angle, and the size of the geometric model to represent the functionality is derived as:

$$\frac{\theta}{360}\pi R_s^2 = 19.62m^2 \tag{2.7}$$

Barrier Coverage

In the barrier coverage, functionality mobile nodes are required to relocate to fill in any gaps in the barrier, to prevent a possible intruder undetected crossing the barrier region. Barrier coverage with deterministic and non-uniform deployment is shown in Fig. 2.5. It can be observed that in the non-uniform deployment the nodes have to overlap to ensure barrier protection and total nodes required are more. The functionality area is modeled based on the desirable area within which mobile nodes should relocate. As can be observed in Fig. 2.6, the node can move to an extent leftward or rightward (w) and upward or downward (l_u and l_d) with reference to the neighboring nodes in the barrier region.

The maximum movement in upward (l_u) and downward (l_d) will happen till the point the mobile node has a maximum distance $2R_s$ with the neighbor node. The initial distance between nodes is 4.75 ($< R_s$) with overlap 0.25 m. The term l_u is determined by Pythagoras Theorem as 8.8 m. Considering that a node can have a maximum overlap of 20%, *i.e.*, 1 m (w=1 m), the size of the functionality geometric model is given as:

$$(l_u + l_d) \times w = 17.60m^2 \tag{2.8}$$

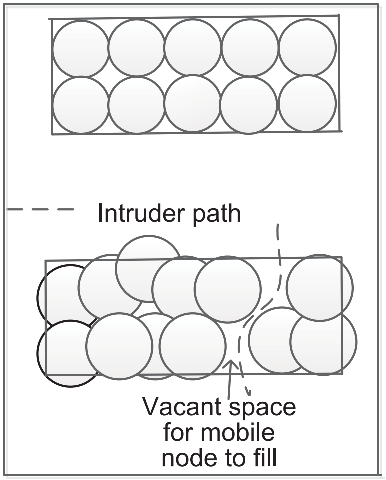

Figure 2.5: Barrier coverage i) Deterministic ii) Non-uniform, possible intruder escape route

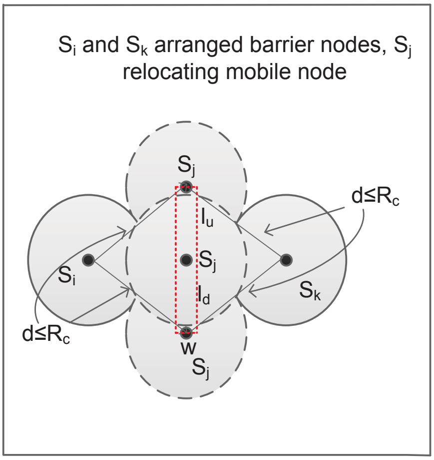

Figure 2.6: Geometric model representing Barrier coverage functionality

2.5 Operational Expenditure of Accomplishing Functionality - Distance

As stated earlier in Section 2.3, OPEX comprises of total distance moved by the mobile node to complete the functionality and information exchange to coordinate the navigation. In the previous sections, geometric models to represent the functionalities were determined. Relocation of mobile nodes anywhere within the geometric model is sufficient to accomplish the functionality. If the geometric models derived for various functionality were to be stacked on top of each other collectively, they appear as shown in Fig. 2.7. From the figure it can be observed that the various functionalities differ significantly in size. The geometric shapes are redrawn into concentric circles with the same size to get a fair comparison and representation of the various functionality for which mobile nodes are used. With concentric circles and a common starting point for the mobile node, the distance to accomplish the functionality is the distance to circumference of a particular circle as shown in Fig. 2.8. The concentric circles are considered to be centred in the AoI, size of AoI is 100× 100 m. The length of the line joining the starting point and the center of AoI is derived by Pythagoras Theorem as 70.71 m. Based on this, the distance to reach the

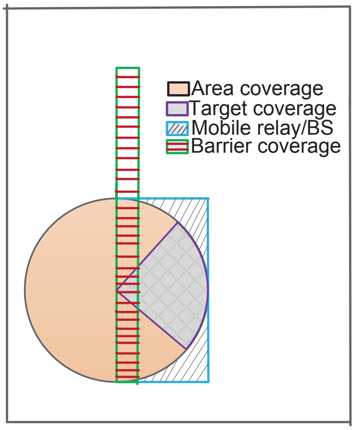

Figure 2.7: Geometric model (actual) representing various functionality stacked together

circumference of functionality - area coverage is 70.71 - 5 = 65.71 m ($R_s = 5$). Similarly, distance to other circles representing mobile relay - BS / data mule, target coverage and barrier coverage are 66.82, 68.31, 68.43 m respectively.

2.6 Operational Expenditure of Accomplishing Functionality - Communication

Mobile nodes are required to exchange information with other nodes in the network for coordinating its movement to the functionality area. Intuitively, communication cost is inversely related with the functionality area, considering the fact that it is harder to relocate into a small area than a large area. This is represented as the *complexity factor* of accomplishing the functionality, as derived in equation (3.9). It is summarized in Table 2.2 along with functionality area and applicable distance.

$$\frac{1}{\text{functionality area}} \times \text{size of AoI} \tag{2.9}$$

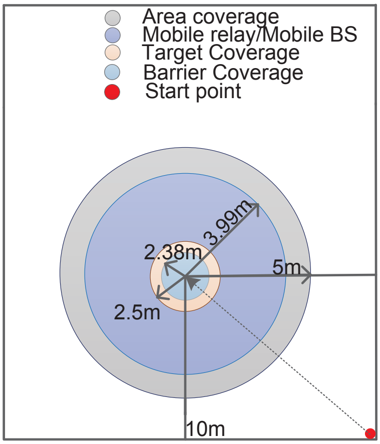

Figure 2.8: Geometric model as concentric circles and starting point of mobile node

Table 2.2: Functionality Details

Functionality Type	Functionality Area	Distance	Complexity Factor
Area coverage	75.00	65.71	133
Mobile relay/BS	50.00	66.82	200
Target coverage	19.63	68.31	509
Barrier coverage	17.60	68.43	568

2.7 Energy Capacity of Mobile Nodes - Operational Expenditure

OPEX for a mobile node directly relates with the battery capacity possessed by the node. In the analysis, battery capacity is considered as $2,800\ mAh$ with operating nominal voltage of 1.5 V based on common rating of an alkaline AA battery, *i.e.*, 4.2 Wh (2800 × 1.5). This can be expressed in Joules as 15,120 J ($4.2 \times 3,600$). Considering that at least 20% capacity of the node would be lost for carrying other network management task,*e.g.*, clustering - cluster head (CH) elections and encryption of the transferred data for security. Therefore, available capacity for node mobility to accomplish functionality is 12,096 J, active sensing is considered an integral part of the functionality. The power consumption for unit distance(m) in Joules is calculated based on battery specifications given for Robomote in [14] as 345 mAh and nominal voltage of 3.7 V. Total capacity in Joules based on the aforesaid specification is 4595.4. It is stated that Robomote moves 180 m on fully charged battery. Therefore the cost of moving 1 m in Joules is 25.53 J (4595.4 ÷ 180). Considering that with improvements in motor and wheel design for mobile nodes, today this would reduce by 10%, *i.e.*, 22.97 J. Overall communication cost is considered to be directly related to the complexity factor. Normalized rate of 1 μJ per bit is considered to take into account other indirect transmission cost consumed in the radio circuit of the sensor node (actual one bit T_X cost is much less). Packet size is considered as 128 bytes, and to take into account both T_X and R_X the overall value is multiplied by 2. Overall complexity cost is therefore given as:

$$\text{complexity factor} \times 128 \times 8 \times 1\mu J \times 2 \tag{2.10}$$

2.8 Results and Discussions

Based on the OPEX of utilizing mobile nodes determined based on the geometric models to represent the functionalities, and considering the benefit of using mobile nodes in comparison to static nodes, CBA to determine the effective utility of mobile nodes is presented. The detailed factors in reference to area coverage functionality are presented in Table 2.3 and all the functionalities collectively in Table 2.4.

In the previous section the cost implied for distance moved and the complexity factor of a particular functionality have been determined. The cost of a static node is considered as \$100 (based on Micaz mote cost given in [15] for 2009, to hold even today). Cost for mobile node is considered as \$150 accounting for the extra cost due the peripherals and packaging, as stated earlier 1 mobile node = 5 static nodes. The overall economic benefit of using a mobile node against static nodes is therefore \$500 - \$150 = \$350. Total benefit is incurred across the lifetime of the node, and benefit per functionality round (FR) depends on the number of FRs that can occur. The detailed table for CBA for the area coverage application is shown in Table 2.3. The possible FRs are 8 in the evaluation, derived dividing the total energy capacity available for node mobility by the total cost for a FR in Joules. Positive cash flow can be observed from the 6^{th} round of the functionality and the net benefit at the end of the lifetime of the node is \$85.52. Similarly for the other functionalities, specifications for the first round and the net benefit at the end of the lifetime is shown in Table 2.4. The positive cash flow in the other functionality also occur from the 6^{th} round and mobile node lifetime ends after 8^{th} round. The distance cost increases by 1.69, 3.85 and 4.03 (%) for mobile relay/BS, target coverage and barrier coverage compared with the area coverage. Similarly, the complexity cost in the same sequence with reference to area coverage area are 48, 285 and 329 (%) higher respectively. The net-benefit at the end of area coverage and barrier coverage functionality differ by \$4.8 ≈ \$5. The difference between the end net-benefit of the functionalities and the complexity factor, explains that various functionality of mobile node differs significantly. CBA also involves a step for determination of NPV of a project, and the NPV is determined by the following expression [4]:

$$NPV = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{2.11}$$

Where B_t and C_t represent benefit and cost for period t and n represents total number of benefits and costs in the project. In normal course, time period is considered in years, in our case definite time period is not available. Therefore, the time period is considered as the number of FRs that can be performed, *i.e.*, $t = 8$. Discount rate i is considered as 5% as this is the most widely accepted discounted rate. Overall benefit B_t=350 and cost C_t=114.48, and putting the values in (2.11), the NPV is 159.41. A positive value of NPV signify that implementation of the project is useful and vice versa applies for negative NPV [4].

Table 2.3: Cost Benefit Analysis for Functionality - Area Coverage

Specification \ FR	-	1	2	3	4	5	6	7	8
Initial static node cost ($)	100								
Additional mobile node cost ($)	50								
Cost area coverage (dist) (J)		1445.62	1445.62	1445.62	1445.62	1445.62	1445.62	1445.62	1445.62
Complexity cost (J)		0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Total functionality cost (J)		1445.89	1445.89	1445.89	1445.89	1445.89	1445.89	1445.89	1445.89
Cost ($)		14.31	14.31	14.31	14.31	14.31	14.31	14.31	14.31
Benefit ($)		43.75	43.75	43.75	43.75	43.75	43.75	43.75	43.75
Net benefit(cost) ($)		-120.56	-91.12	-61.68	-32.24	-2.80	26.64	56.08	85.52

Table 2.4: Cost Benefit Analysis for Various Functionalities

Specification \Functionality type	Mobile relay/BS	Target coverage	Barrier coverage
Initial static node cost($)	100	100	100
Additional mobile node cost ($)	50	50	50
Functionality cost (dist)(J)	1470.02	1502.82	1505.46
Complexity cost(J)	0.40	1.04	1.16
Total functionality cost(J)	1470.42	1503.86	1506.62
Cost ($)	14.55	14.88	14.91
Benefit ($)	43.75	43.75	43.75
Net benefit (1^{st}FR)($)	-120.80	-121.13	-121.16
Net benefit(end)($)	83.60	80.96	80.72

2.9 Conclusions

It can be observed based on CBA that mobile nodes are economically beneficial for use in WSNs in comparison with static nodes apart from their functional utility. The geometric models that have been utilized for determining the applicable costs have proven to be an effective method to represent the functionalities. Geometric modeling can be utilized to represent other sensor network aspects for the purpose of comparison. Additionally, CBA between static and mobile nodes also justifies that it is possible to monetize the applicable cost in areas/aspects that are usually considered infeasible. The current CBA can be extended taking into account parameters such as deployment cost, and recollection cost of nodes after completion of the deployment objective.

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Chapter 3

Multi-Parameter Correlation Governing Coverage Improvement Using Node Mobility

3.1 Introduction

It has been elaborated in the problem definition in Chapter 1, that a primary objective expected to be examined in this thesis is to find suitable mechanisms for relocation of mobile nodes within the area of interest (AoI) such that minimal undesired navigation and communication cost occur, and only limited node mobility is considered feasible. Coverage improvement is the foremost functionality that is addressable by utilizing mobile nodes in WSNs. The node relocation schemes for coverage improvement utilizing mobile nodes can be classified into: virtual force, coverage pattern or graph based, and grid quorum. There are certain parameters that govern the coverage improvement possible relying on any of these schemes using node mobility, and this chapter examines these parameters and determine their interrelations. This chapter addresses constraints 1 and 2 stated in the problem definition (Section 1.4) of this thesis.

3.2 Related Work

The objective of coverage improvement differs based on the type of underlying network, *i.e.*, a hybrid sensor network or mobile sensor network. The operational difference between hybrid and mobile sensor network has been discussed in Chapter 1. A hybrid sensor network with *limited* node mobility is considered here for determining the inter-parameter relations. The movement schemes for coverage improvement classified based on relocation of the mobile nodes are described below [1], [2]:

- *Virtual force*: This coverage improvement technique is based on the consideration that there exists a repulsive or attractive force between two nodes. The direction of the force is specified as a vector, and whether the force between two nodes is attractive or repulsive is based on the distance. The force would be an attractive force if the distance is more than a prefixed threshold and vice versa if the nodes are too close. Vector addition of all forces acting on a given node decides the resulting direction, and distance that a mobile node moves. In order to determine the resultant direction, it is considered that the nodes are aware of their locations.

- *Coverage pattern*: Under this coverage improvement technique the mobile nodes are expected to move for meeting a predetermined coverage pattern, and also meet the network connectivity requirements. The coverage pattern requirement can be either global or local, global coverage pattern refers to achieving, in a way, deterministic deployment as the movement locations for the nodes are suppose to be specific. Similarly, a local level coverage requires that the mobile node is assigned and is feasible only to fill a specified location in its neighboring area. In both the coverage types the whole network is considered to be tiled by hexagonal polygons, vertices of these polygons are the possible locations to which the mobile node is expected to relocate. This method is also described as Voronoi method with the tile up polygons referred as Voronoi polygons [2].

- *Grid quorum*: This coverage improvement technique considers the AoI as a grid, *i.e.*, sub-divided into sub regions. Grid quorum is less complex compared with the other two techniques: virtual force and coverage pattern. This is due to the relocation destination of the node not being specific, a node is required to relocate anywhere in the target grid cell. As stated in Chapter 1, research work in this thesis is centred around utilizing node mobility to achieve a positive influence on the network attribute (coverage), along with the consideration that only limited node mobility is feasible. Based on these consideration the coverage improvement using node mobility for a grid quorum based network deployment has been considered for further determining inter-parameter relations [3].

Grid Quorum Based Coverage Improvement

This method for relocation of the mobile nodes is also referred as a load balancing problem. The grid cells are categorized based on the number of nodes contained in a cell, referred as the weight of the cell. Therefore, the node relocation is intended to minimize the weight difference between the grid cells, nodes are relocated from cells with excess nodes to cells that have no nodes at all or minimal nodes. Further, it is desirable that the relocation of the nodes is such that the total relocation distance is minimal [1]. A scan based movement - assisted sensor deployment method, SMART has been described in [4]. This method involves identification of over-loaded, under-loaded and balanced grid cells based on a two step scan process, first for all rows and then the columns. Based on the first scan, average number of nodes that should be in each cell for a balanced state are obtained, the second scan is in the direction opposite to that of the first scan on the same row. Considering w_i to denote the number of nodes in the cell i, and v_i to denote the number of nodes in a certain number of i cells, *i.e.*, $v_i = \sum_{j=1}^{i} w_j$. With the first scan in one direction, the average load of a cell is $\vec{w} = v_n/\mathrm{n}$, and with the second scan in the opposite direction the cell determining the state comparing its number of nodes w_i with $\vec{w}$. $w_i^{\rightarrow}$ denotes nodes to be sent from a given cell in the right direction and $w_i^{\leftarrow}$ to the left direction, these are computed as follows [4]:

$$w_i^{\rightarrow} = \min\{\ w_i - \vec{w},\ \{\ \max v_i - \vec{v_i},\ 0\ \}\ \}$$
$$w_i^{\leftarrow} = (\ w_i - \vec{w}\ ) - w_i^{\rightarrow}.$$

After determining $w_i^{\rightarrow}$ and $w_i^{\leftarrow}$ the scan algorithm is executed to dispatch nodes from overloaded cells to under-loaded cells. This approach for balancing the load across the cells does not take into account the energy consumption that is incurred by the mobile nodes to relocate. The authors in [5] extend this underlying grid based layout for relocating mobile nodes relying on flip based movement between the cells, with the flipping possible only once across the lifetime, considering only *limited* mobility based relocation of mobile nodes. The flip based movement of the node is brought about by unwinding of springs. The process is shown in Fig. 3.1 (i) and (ii), redrawn based on the figure presented in [5]. To decide the flip movement for all mobile nodes such that the coverage is maximized by relocating nodes to vacant cells (under balanced) translates into a problem of minimum-cost maximum flow. Cells are considered to be in three states similar to the SMART method as a *source* if it possess two or more nodes, *forwarder* if it has just one node and as a *sink* if it has no node. The cells with a single node function as a forwarder as they would send their node to an adjoining cell, and another adjoining cell provides them with one node. The minimum-cost maximum flow problem in relation to flipping of nodes is addressed in [5] using a virtual graph, with each cell represented with

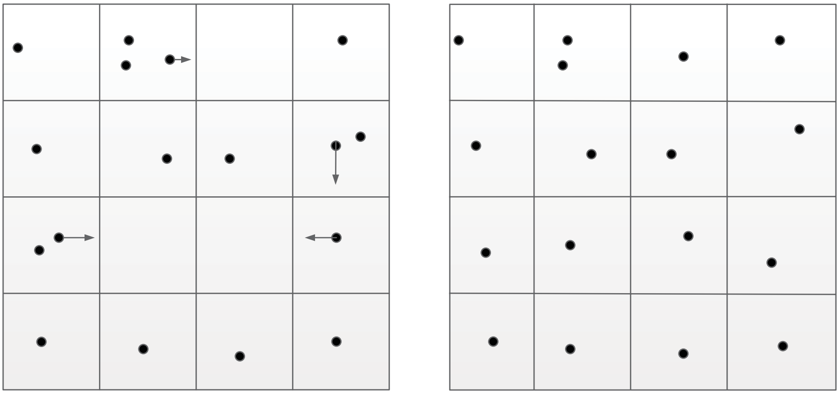

Figure 3.1: i) Loaded and unloaded cells in the grid, nodes shown with arrow relocated to the adjoining cells (left) ii) Balanced grid after relocation of nodes (right)

three vertices: base vertex (v^b) to track number of nodes in a cell, in vertex (v^i) to track number of nodes flipped into the cell, and out vertex (v^o). Similarly, another strategy adopted for determining the optimal movement planning for nodes is by converting the grid quorum load balancing problem into a perfect matching problem over a bipartite graph. Determining the perfect matching by enumerating all the possible combinations may not be convenient and even infeasible for a large grid, *i.e.*, large number of cells. Hungarian method is adopted to determine the perfect matching and thereby decide the optimal movement strategy for the nodes between the cells. The Hungarian method has been discussed in detail in the following section as it has been utilized in determining the inter-parameter relations.

Parameters Influencing Coverage Improvement

Balanced load of nodes amongst the grid cells can be achieved based on the aforestated methods, however, the actual cost implied in terms of node mobility has not been taken into account in these methods for load balancing the nodes and improving network coverage. It was observed from these methods, that apart from the prime node mobility cost, *i.e.*, cost incurred due to movement of mobile node, the amount of load balancing and thereof the coverage improvement feasible are also governed by the ratio of mobile nodes to static nodes. Further, the maximum distance a mobile node is permissible to move will govern the load balancing - coverage improvement feasible. As stated earlier, it is considered throughout this thesis that limited mobility is feasible for the mobile nodes, this has been discussed in the previous chapters. The total

Table 3.1: Comparison of related works and presented contribution

Factors	Grid quorum	Limited mobility	Total nodes -mobile nodes	Average distance	Variation node density
Flip based node deployment [5]	✓	✓	×	×	×
Trade-offs mobility and coverage [6]	×	×	✓	×	×
Mobile node density and detection performance [7]	×	×	×	×	×
Connectivity guaranteeing deployment [8]	×	✓	×	×	×
Coverage enhancement virtual force [9]	×	×	×	✓	✓
Coverage improvement with directional nodes [10]	×	×	×	×	✓
Coverage improvement based on swarm optimization [11]	×	×	×	✓	✓
Coverage improvement with mobile nodes [12]	✓	×	✓	×	×

number of nodes (static + mobile) deployed govern the coverage improvement feasible. These critical parameters have not been considered in the aforesaid grid quorum based coverage improvement - load balancing methods. Therefore, experiment evaluation was carried out to determine the interrelation between these parameters that would govern the coverage improvement possible using node mobility. However, there are other related work that have studied the relation of coverage improvement with other network attributes apart from the attributes mentioned above. The upper bound on mobile node density required for attaining a k - coverage has been presented in [6], however, the influence of aforesaid mobility constraints applicable on mobile nodes have not been considered. The trade-off between mobile node density and network performance parameters of detection probability, detection latency, and mean first contact distance for target detection have been presented in [7], however, the coverage

- node mobility interrelation parameters has not been evaluated. Coverage improvement with connectivity guarantee utilizing mobile nodes based on virtual forces has been presented by the authors of [8]. The authors state that mobile nodes are considered to move only short distances for improving the network deployment, and interrelation between the node types (total nodes - static and mobile) has not been considered to determine the coverage improvement attained by the mobile nodes. The mobile nodes could be subjected to continuous movement (loop) due to the operation relying on virtual forces. Virtual force based coverage improvement using mobile nodes has also been presented by the authors in [9], where they discuss the average distance moved by the nodes in reference to the coverage attained. Coverage improvement in sensor network comprising of directional sensor nodes based on Voronoi diagram is proposed by the authors in [10]. The sensors shift their respective directional coverage to enhance the overall coverage of the network. Influence of variation in number of sensor nodes, sensing radius, and angle of view (directional coverage) have been taken into consideration for deployment in an AoI. The authors, however, assume that the sensor nodes have access to localization services and all the nodes are considered to be static in nature. Coverage improvement based on swarm optimization is presented in [11], impact of number of nodes on coverage achieved and the distance moved by the nodes to attain given coverage have been evaluated by the authors. However, the node movement is governed by virtual forces existing between the nodes and the network is considered to comprise only of mobile nodes, expected to reorganize across the network after deployment from a central location in the AoI. For the sensing region considered to be divided into grid (square cells) and utilizing a bidding protocol to determine the mobile node that moves to fill a coverage hole (uncovered cells) has been presented in [12]. The mobile nodes are considered to be assisted by static nodes for relocation, in addition to the assumption that all nodes are aware of their locations. The analysis takes into account the influence of virtual forces between the mobile nodes and the static nodes, it is also assumed that nodes are aware of their locations. Although, not directly related, use of grid quorum for determining the location of mobile nodes/hosts has been presented in [13], stressing on the utility of grid quorum for easy distributed location determination utility. The comparison between related works and the presented contribution based on certain governing factors have been summarized in Table 3.1.

3.3 Hungarian Method

In a bipartite graph based classification of the grid cells, left side represents the over-loaded grid cells, and the right side represents the under-loaded cells. Hungarian method is used to determine the perfect matching between the two sides of the graph. The matching problem is represented mathematically with x_{ij} *(i,j = 1...n)* representing the set of variables, n is number of nodes in the vertices set of the complete bipartite graph A = *(V, U, E)*, where V, U represents the set of vertices and E the set of edges. X_{ij}=1 means the edge v_i, u_j is included in the matching and vice versa is applicable for X_{ij}=0. Therefore, the perfect matching can be derived solving the following optimization problem [4]:

$$Minimize \sum_{ij} C_{ij}\ X_{ij} \tag{3.1}$$

subject to $\sum_{i=1} X_{ij} = 1,\ i = 1,2,...n,$

$\sum_{j=1} X_{ij} = 1,\ j = 1,2,....n.$

Based on the above formulation the bipartite graph problem is converted into a matrix problem. This is shown in the Fig. 3.2, where the intention is to choose one unique entry for each row and column respectively [14]. Rows of the matrix represent the nodes in over-loaded cells (vertex set V) and the columns the under-loaded cells (vertex set U). The value of entry C_{ij} is the cost of assigning nodes from cells in v_i to cells in u_j (cost is in terms of distance implied for relocating). Therefore, the objective is to match the nodes between the two sets such that the overall cost is minimum.

Under-loaded cells (vertex set U)

Over-loaded cells (vertex set V)

$$\begin{array}{c|cccc} & p & q & r & s \\ \hline a & 2 & 4 & 6 & 8 \\ b & 1 & 2 & 3 & 4 \\ c & 5 & 6 & 9 & 12 \\ d & 4 & 8 & 12 & 16 \end{array}$$

Figure 3.2: Matrix representation of bipartite graph based two sets

3.4 Results and Discussions

In this section, first the simulation setup is discussed followed by the results categorized in three categories: unconstrained distance mobility and number of mobile nodes, constrained distance mobility, and constrained distance mobility and number of mobile nodes.

Simulation Setup

The experimental setup to determine the aforesaid parameters in relation with coverage improvement attained in the network has been determined based on simulations. [3]. The simulation experiment has been carried out using MATLAB, a uniform deployment region (grid) of 100 × 100 is considered with 100 grid cells each of size 10× 10, in a manner similar to as shown in Fig. 3.1. A grid cell is considered covered if it has at least one node, nodes are assumed to be at the center of the grid cell as the precise location of the nodes is not considered. The Euclidean distance between the grid cells is used to populate the cost matrix, C, in (3.1). The experiment is conducted varying the number of nodes from 10 to 500 in increments of 10 and the number of mobile nodes as a ratio of total nodes is varied from 10 % to 100 %. The experimental results are mean values obtained over 100 simulation runs. The mobile nodes are considered to possess only limited mobility capacity and accordingly the constraint on maximumum moveable distance are considered as 7.5, 5.0 and 2.5 units respectively. Unconstrained (unlimited) mobility is represented with a permissible moveable distance of 15 units (diagonal length across the grid region), and a single unit represents one cell. Precise distance based determination is not feasible, considering that actual deployment conditions and the mobile node specifications can vary from case to case.

Unconstrained Distance Mobility and Number of Mobile Nodes

The relation between the coverage obtained with non-uniform deployment of nodes and unconstrained node mobility is shown in Fig. 3.3. The figure shows a critical observation about the functionality difference between a static node and a mobile node. For full coverage, 460 static nodes are required, and in comparison only 100 mobile nodes are sufficient to obtain full coverage. Based on this observation it can be inferred that 1 mobile node $\approx$ 5 static nodes. The total distance moved by all the mobile nodes combined, and the highest distance moved by a node to attain this coverage pattern (Fig. 3.3) is shown in Fig. 3.4. The graphs should be looked at collectively to obtain the interrelation between the various parameters governing coverage improvement with node mobility.

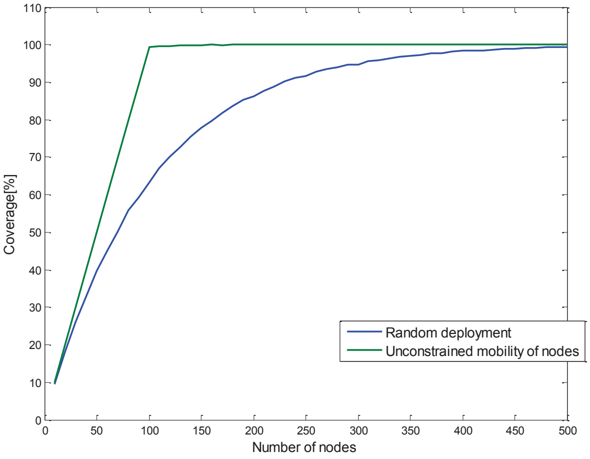

Figure 3.3: Coverage percentage for non-uniform deployment (initial) and based on node mobility

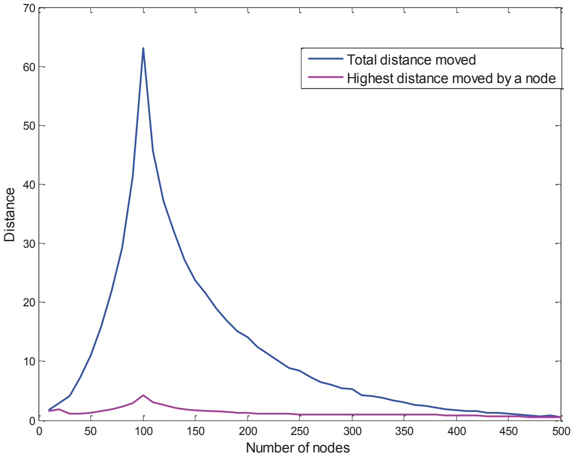

Figure 3.4: Total distance and highest distance moved for corresponding coverage shown in Fig 3.3

Constrained Distance Mobility

To understand the influence of constrained mobility, alone, the experimentation was carried out varying the maximum permissible distance the nodes can move.

The number of nodes required to attain the coverage with varying constrained mobility can be observed from the figures, when all the nodes are considered to be mobile. The effect of constrained distance mobility of mobile nodes on: coverage improvement achieved, total distance, and highest distance required to be moved by an individual node to attain the given coverage are shown in Fig. 3.5, 3.6 and 3.7 respectively. It can be observed from Fig. 3.5 that as expected, with permissible mobility distance of 15 units (unconstrained mobility), the network attains full coverage with 100 non-uniformly deployed nodes. Based on the figures, it can be observed that there is an increase in the number of nodes required to attain full coverage with decrease in the maximum permissible distance the nodes can move. For the lowest moveable distance of 2.5 units the number of nodes required is as high as 350.

Constrained Distance Mobility and Number of Mobile Nodes

In the previous sub-section, the influence of maximum permissible distance a mobile node can relocate has been observed. A low permissible distance for relocation of mobile nodes in a non-uniformly deployed network increases the total number of nodes required substantially. We are interested in a hybrid sensor network, with the consideration that a mobile sensor network (MSN) is not feasible, due to the high cost for movement of mobile node and the

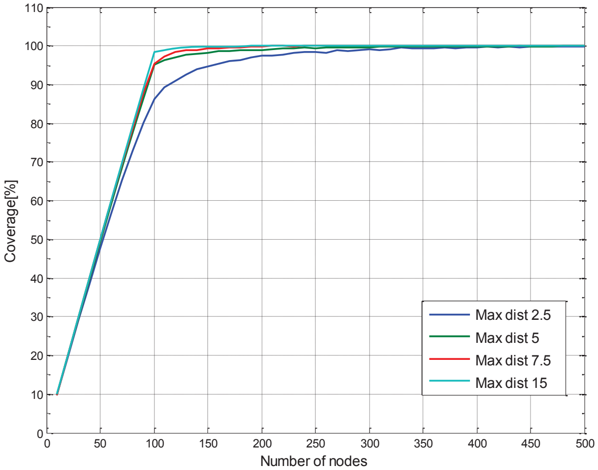

Figure 3.5: Coverage percent for constrained mobility distance

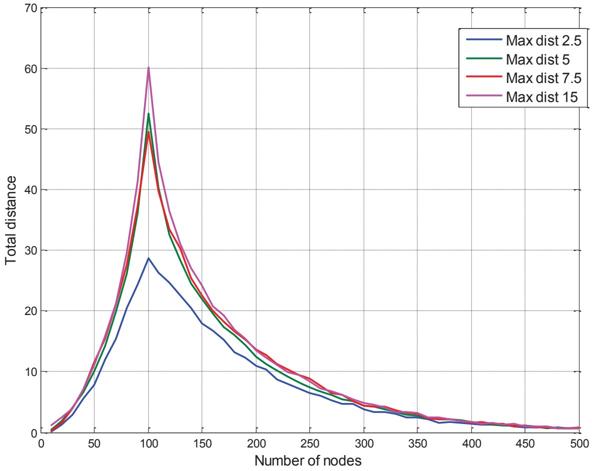

Figure 3.6: Total distance moved by nodes for corresponding coverage improvement shown in Fig 3.5

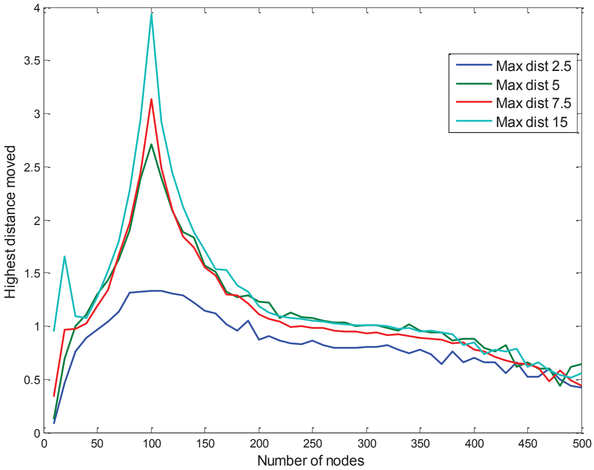

Figure 3.7: Highest distance moved by a node for corresponding coverage improvement shown in Fig. 3.5

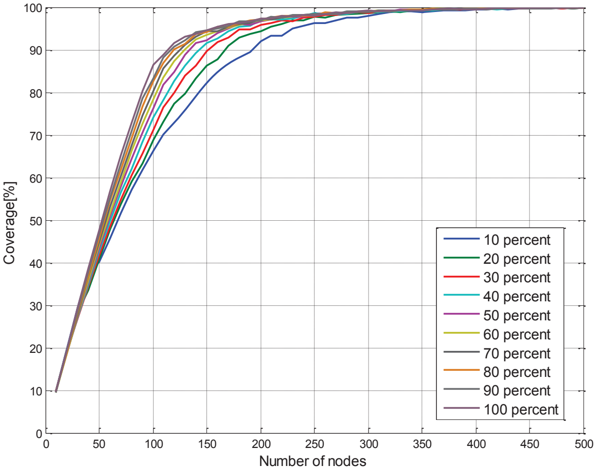

Figure 3.8: Coverage percentage with constrained mobility distance 2.5 units

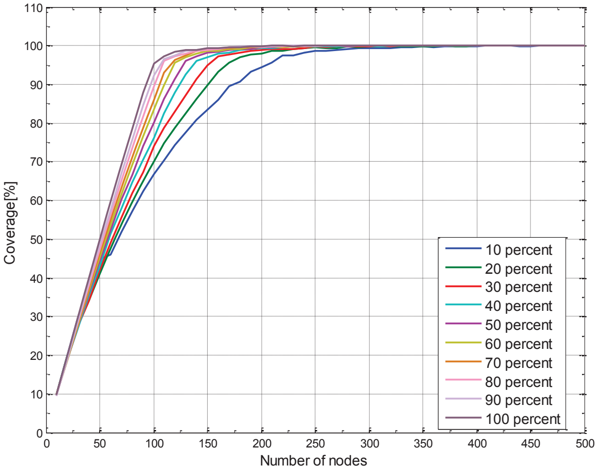

Figure 3.9: Coverage percentage with constrained mobility distance 5 units

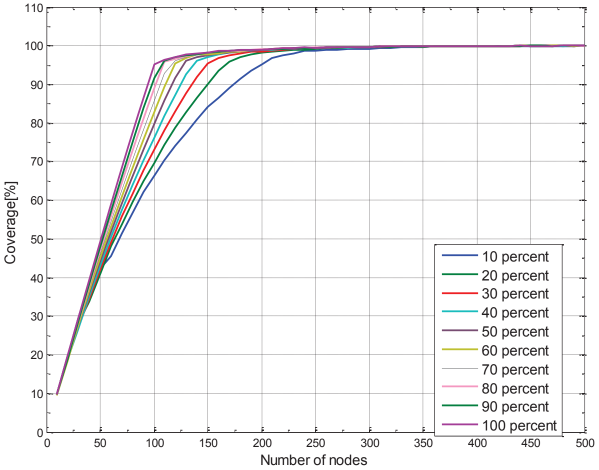

Figure 3.10: Coverage percentage with constrained mobility distance 7.5 units

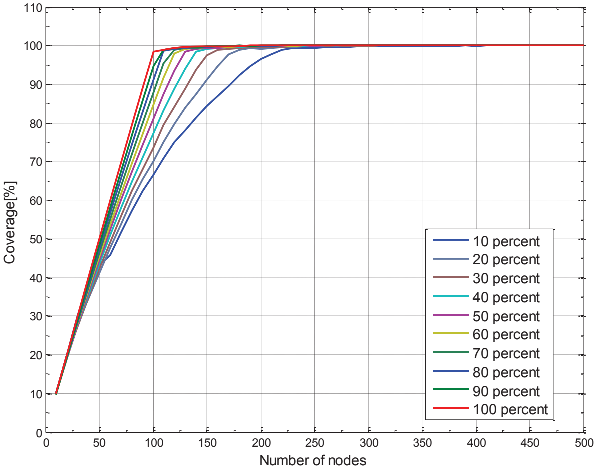

Figure 3.11: Coverage percentage with constrained mobility distance 15 units

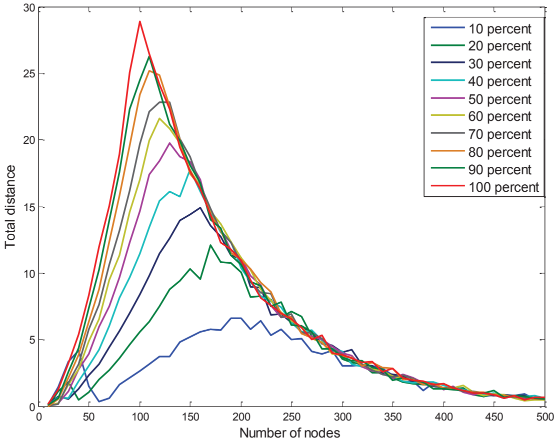

Figure 3.12: Total distance moved by the nodes for constrained mobility (2.5 units) and varying of mobile nodes, corresponding coverage shown in Fig 3.8

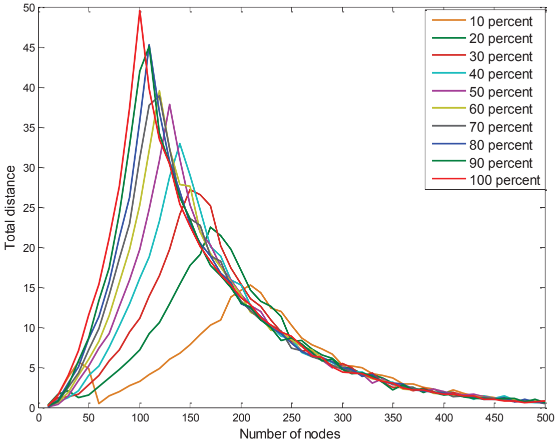

Figure 3.13: Total distance moved by the nodes for constrained mobility (5 units), varying % of mobile nodes, corresponding coverage shown in Fig 3.9

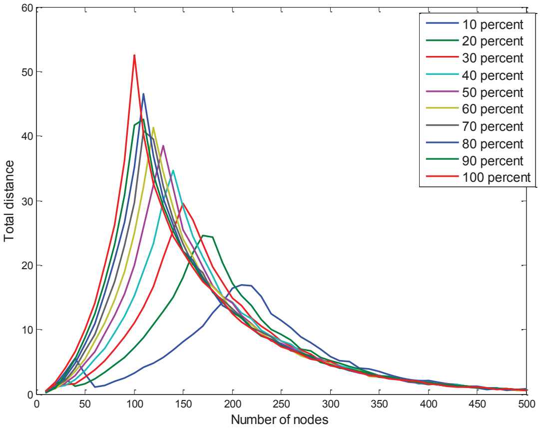

Figure 3.14: Total distance moved by the nodes for constrained mobility (7.5 units), varying % of mobile nodes, corresponding coverage shown in Fig. 3.10

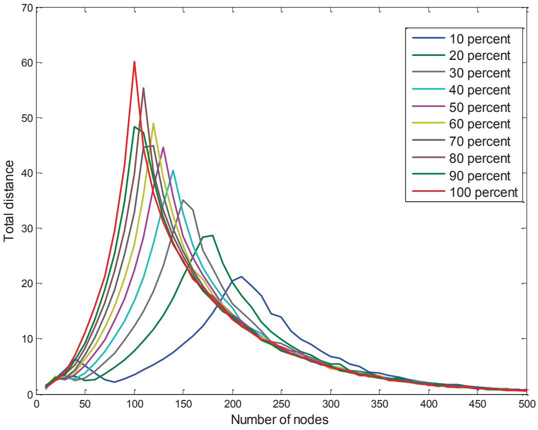

Figure 3.15: Total distance moved by the nodes for constrained mobility (15 units), varying % of mobile nodes, corresponding coverage shown in Fig. 3.11

high manufacturing cost of a unit. The experimentation was carried out to determine the inter-parameter relation with varying '%' of mobile nodes out of the total nodes (static + mobile), along with variable maximum permissible distance the mobile nodes can move. The coverage improvements achieved under these parameter constraints are shown in Fig. 3.8, 3.9, 3.10, and 3.11. The total distances moved by the nodes for attaining the coverage are shown in Fig. 3.12, 3.13, 3.14,and 3.15 respectively. The added effect of only a certain proportion of the total nodes being mobile nodes can be demonstrated by an example: considering permissible distance mobility of 2.5 units, the number of nodes required to attain a 90% based on Fig.3.5 is 120. In order to attain the same coverage with 10% of the total nodes as mobile node, number of total nodes required is 180 (Fig. 3.8). From the figures it can also be observed that variation in % of total nodes as mobile nodes has insignificant influence on the coverage improvement when 50% or more of the nodes are mobile nodes.

3.5 Conclusions

The inter-parameter relations that govern the coverage improvement feasible are derived by the experimental evaluation and can be used to serve as a yardstick for network planning. This is especially significant considering the fact that network resource planning would be necessitated considering large scale sensor deployments in the future for anticipated applications, and per unit cost of a sensor node and its operational limitations. The inter-relation between the parameters governing the coverage improvement possible using mobile nodes also justify a key aspect, *i.e.*, a hybrid network is sufficient to suffice deployment objective. This work can be enhanced especially to include deployment conditions in the AoI, addressing constraint 3 stated in the problem definition of the thesis, and thereby attain further effectively planning of the required network resources.

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Chapter 4

Coverage Improvements using Node Mobility in Clustered Networks

4.1 Introduction

In Chapter 3, the inter-parameter relations governing the coverage improvement feasible using node mobility have been elaborated. The core objective of Chapter 3 was to determine the relation between number and type of nodes (total nodes, proportion of mobile nodes); distance mobility permitted in the network (total distance movable by all mobile nodes collectively and maximum distance movable by a single node), and the coverage improvement feasible. Therefore, a centralized implementation to determine the matching between the grid cells is acceptable. However, a centralized implementation imposes a high communication cost as all nodes are involved in multi-hop communication. It has been stated in Chapter 1 that a hierarchical structure in the network is useful for reducing the overall communication cost and it has a positive impact on the network lifetime. Nodes are grouped in clusters with an elected cluster head (CH) that represents them, and communicates with the rest of the network and the base station (BS) on their behalf. Both coverage and clustering are important QoS attributes of a deployed network. Despite their extreme significance, proposed methods/mechanisms have addressed them individually. This chapter elaborates a mechanism to collectively address them taking into consideration the node mobility operational constraints 1, 2 and 4 stated in the problem definition (Section 1.4) of this thesis.

4.2 Related Work

In Chapter 3, classification of coverage improvement schemes based on node mobility have been elaborated. Necessity for utilizing node mobility arises due to insufficient coverage of the area of interest (AoI) attained with non-uniform deployment of nodes. A possible way to attain the complete coverage under these condition is to deploy the nodes in a much larger number than the critical density. Clustering of nodes in the network helps in attaining a hierarchical structure. Clustering mechanisms stated in the literature have been designed to achieve some additional purpose apart from achieving a hierarchical structure such as better load balancing, fault tolerance, and network connectivity [1], [2]. In [3], the authors have stated that clustering and coverage should be considered in an integrated manner and not as individual attributes in reference to network deployment. The authors have also proposed an algorithm for CH elections and thereby clustering of nodes, based on coverage properties (metrics) of the area. However, coverage improvement feasible with reorganization of the nodes has not been evaluated as node mobility is not considered and all nodes are considered to be static. Coverage optimization with relocating of mobile nodes has been presented in [4], wherein the nodes are clustered by maximum entropy clustering method. It is however assumed that the nodes are aware of their location using global positioning system (GPS) and the actual movement of mobile nodes is not considered. A coverage preserving clustering algorithm has been presented in [5], clusters are formed such that there is minimum overlap between the clusters. Achieving coverage improvement and utilizing mobile nodes for this purpose have not been taken into consideration. Utilizing mobile nodes to monitor the occurrence of an event, with static nodes functioning as guiding waypoints has been presented in [6]. The actual cost incurred for the movement of mobile nodes has not been considered and the mobile nodes are assumed to have a communication range twice that of the static nodes. Dynamic clustering is considered only around the occurrence of a phenomenon and not across the rest of the network, direction and extent of relocation of mobile nodes are decided based on cumulative virtual force of neighbouring nodes acting on the mobile node. Utilizing mobile nodes for coverage improvement in a mobile sensor network (MSN) has been presented in [7], nodes are considered to be continuously mobile in the network and therefore the coverage attained is dynamic, leading to a certain area covered at a given instant of time to be exposed in future and vice versa. Utilizing jumping mobile nodes to improve the coverage possible for a network deployed in inhabitable terrain has been presented in [8]. However, with such use of mobile nodes only temporary increment in coverage is obtained, additionally, the organization of the network is not taken into account. Utilization of mobile nodes for improving coverage in regions within the AoI that do not have any static node has been presented in [9]. The mobile nodes are expected to relocate only with local information provided by static nodes, however, all nodes are assumed to be aware of their coordinates. Mobile nodes relocating in a step wise motion to fill void cells has been presented in [10]. The mobile nodes are primarily expected to serve for target coverage (intrusion detection) in the network, their relevant detection metrics are presented, but, the organizational structure of the network has not been considered. A similar target tracking (target coverage) method using mobile nodes has been presented in [11] based on ant colony optimization. The authors assume that there are enough static nodes to cover the complete AoI, and the mobile nodes can be used for target tracking purpose solely without examining the changes in network coverage their relocation may incur. CH election considering residual energy and mobility of nodes is presented in [12], such that with mobility of nodes, links with non-cluster nodes and message transmission can be sustained. However, the authors do not consider the influence of node mobility on coverage and consider that all nodes are aware of their location. Coverage improvement utilizing a glowworm swarm optimization (GSO) algorithm, considering each node as a glowworm emitting luciferin (illuminating substance) is presented by the authors of [13], where intensity of the luciferin depends on the distance between the node and its neighbours. The node is expected to move towards neighbours emitting less light and vice versa for strongly illuminating nodes. The authors evaluate the impact of variation in sensor nodes on the coverage attained and the impact of moving distance of a mobile node. However, the proposed algorithm in the basic sense is an underlying virtual force algorithm, and is therefore subjectable to limitations of virtual force based movement of nodes as covered in the previous chapter. The structural layout of the network has not been stated and all nodes are considered to possess mobility. Utilizing a bidding protocol for determining the mobile node that moves to fill in a coverage hole and enhance the coverage has been presented in [14]. The analysis takes into account the influence of virtual forces between the mobile nodes and the static nodes, and it is also assumed that nodes are aware of their locations.

In the contribution presented in this chapter, coverage improvement and clustering of nodes have been considered collectively. The objective is to relocate mobile nodes in a manner such that the clustering and CH election is done considering their relocation activities, and relocation is carried out such that overall network coverage is maximized [15]. The comparison between related work and the presented contribution based on certain critical factors has been summarized in Table 4.1.

Table 4.1: Comparison of related works and presented contribution

Factors	Coverage and clustering	Limited mobility	Localization service utilized	Hybrid network
Cluster head election coverage preservation [3]	✓	×	×	×
Coverage optimization with maximum entropy clustering [4]	✓	×	×	×
Waypoint based navigation [6]	✓	✓	×	×
Coverage in mobile sensor network [7]	×	✓	×	×
Coverage leveraging jumping height of nodes [8]	×	×	×	✓
Dynamic coverage in hybrid network [10]	×	✓	×	✓
Target tracking using mobility [11]	×	×	×	✓
Target tracking using mobility [12]	×	×	×	✓
Coverage enhancement based on swarm optimization [13]	×	×	×	×
Coverage improvement using mobile nodes [14]	×	×	✓	✓

4.3 Network and Node Mobility Model

Based on the observations stated in the previous chapter regarding number of mobile nodes that are sufficient for the network, it is considered that a maximum of 50 % of the nodes can be mobile (layout of the network shown in Fig. 4.1). As stated earlier in Chapter 1 of the thesis, mobile nodes are considered to possess only limited mobility and there is no provision of GPS or other localization mechanisms. All nodes in the network are considered to be equal in operational capacity, except for the actuation - movement capacity possessed by mobile nodes. However, it is considered that the nodes can determine the Euclidean distance between themselves, and radio communication between the nodes relies on free space radio propagation model. Coverage of nodes is represented by a binary disk model with the radius of the disk equal to the sensing range of the node, R_s, considered as 5 m. The communication range, R_c, is considered as twice the sensing range, *i.e.*, 10 m. A sample non-uniformly deployed network is shown in Fig. 4.1.

Node Mobility Model

Relocation of mobile nodes has been proposed based on waypoints, as access to localization mechanisms is not available to the nodes in the network. Mobile nodes are relocated between clusters such that the mobile node has capacity to volunteer as a future CH candidate in the destination cluster. The simulation

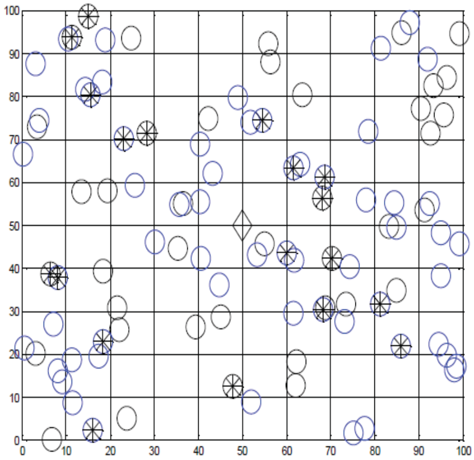

Figure 4.1: Non-uniform network deployment (circle - static node, black circle - mobile node, asterisk - cluster head, diamond in center of region - base station)

results of the actual distance traversed by the mobile nodes have been evaluated considering the movement capacity of Robomote, that can move for a maximum of 20 minutes in full motion and full battery, with a speed of 15 cm/sec and a total range of 180 m [16].

4.4 Coverage Improvement Mechanism

The presented mechanism comprises of two phases: i) to match the clusters as source and destination for individual mobile nodes, and ii) determination of waypoints for an individual mobile node for navigating from source to destination cluster. These have been elaborated in the following sub-sections.

Cluster Matching

Coverage improvement is sought by relocating mobile nodes between clusters in the network. The CHs are elected based on execution of the low-energy adaptive clustering hierarchy (LEACH) protocol as stated in [3], election is based on residual energy of the nodes. Each node in the network is accounted for its coverage contribution to the overall network, based on whether the node has an overlap with adjoining nodes in the network or not. Maximum coverage contribution of a node is considered as 1 and it decreases with the number of overlapping node(s), and the degree of overlap (distance) of the node(s) for a certain given node in the network. Coverage contribution of all nodes combined is the overall coverage of the network. The various clusters in the network are classified into three types based on the number of nodes they have, and the cumulative coverage contribution of the nodes they possess. Regions with only a CH are classified as *empty regions*; regions with only a CH and static nodes as a *normal empty region*; and a region with both static and mobile nodes in the cluster as a *normal region*. According to this classification the clusters are prioritized as *recipients* of mobile nodes from the clusters that could provide them referred as *suppliers*. The actual implementation for matching the clusters is elaborated through flowcharts as shown in Fig. 4.2 and Fig. 4.3.

Waypoints Determination for Relocating Mobile Node

Subsequent to matching the source and destination clusters as node suppliers and recipients, a given mobile node is assigned for relocation to a specific cluster. Waypoints are determined such that they guide the specific mobile node from the source to destination cluster. Therefore, the goal is to maximize the number of waypoints available to the mobile node for relocation, more the number of waypoints the less random would be the path from source to destination cluster. Initially, the nodes that can assist the mobile node are determined as helper nodes in source and destination clusters, waypoints are elected from

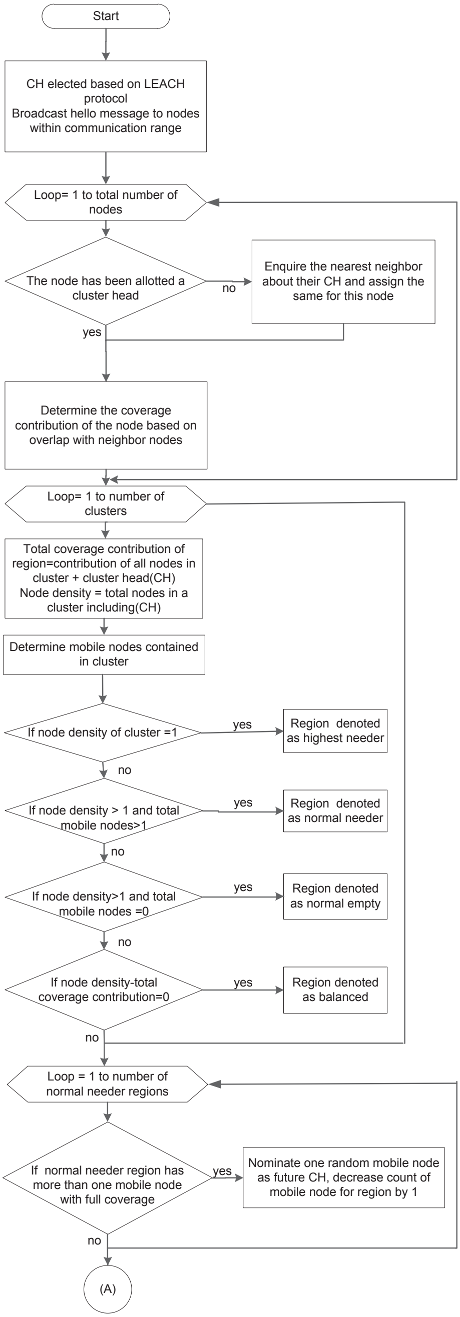

Figure 4.2: Matching of clusters for relocating mobile nodes

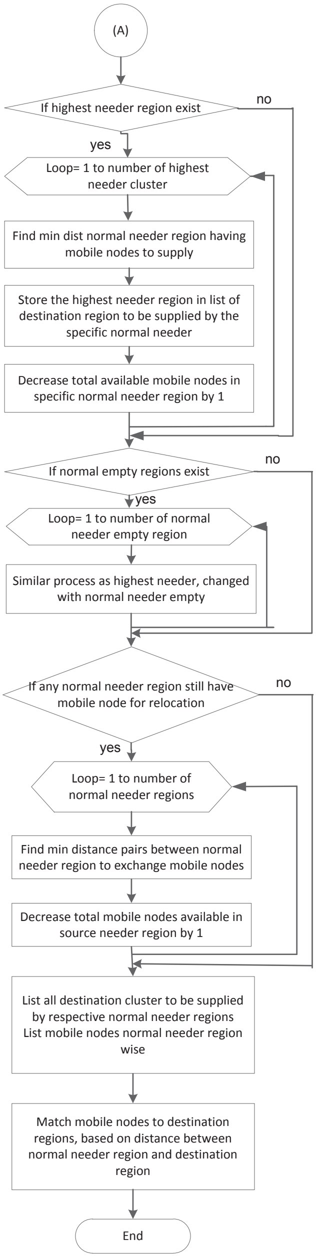

Figure 4.3: Matching of clusters for relocating mobile nodes (contd.)

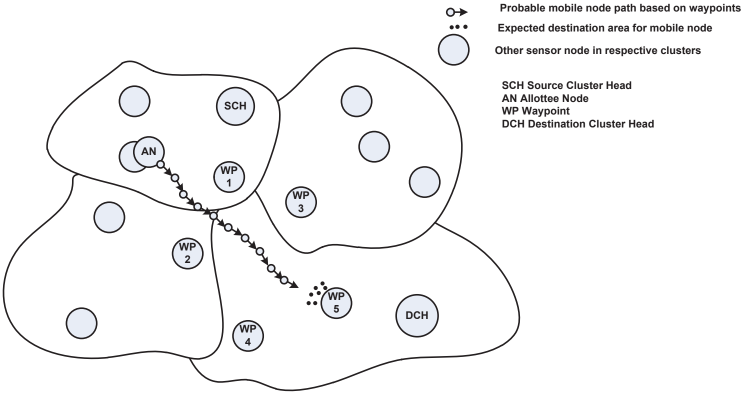

Figure 4.4: Path of mobile node following waypoints

amongst the helper nodes. This selection is done such that there is at least one waypoint within the source and destination cluster. Waypoints issue hello message in pairs (two waypoints) so that the mobile node can approximate its movement based on received signal strength indicator (RSSI), and the waypoints issue multiple hello messages. A waypoint based relocation of mobile node between the clusters is shown in Fig. 4.4.

The hello messages in pairs ensure that the mobile node can reliably relocate based on them compared with only a single hello message issuer. The process for waypoint guiding is terminated when the mobile node is within the communication range of the final waypoint. Considering the reliability of RSSI the relocation is permitted if direct distance between the mobile node and the destination CH is < 65 m. The detailed procedure for determination of waypoints has been elaborated in Fig. 4.5.

4.5 Results and Discussions

Simulation Set-up

The simulation based evaluation of the proposed mechanism has been carried out in MATLAB. The total number of nodes in the AoI is varied in increments of 10 from 100 to 150, and the proportion of mobile nodes to total nodes is varied from 10% to 40% in increments of 10%. The AoI considered is a square,

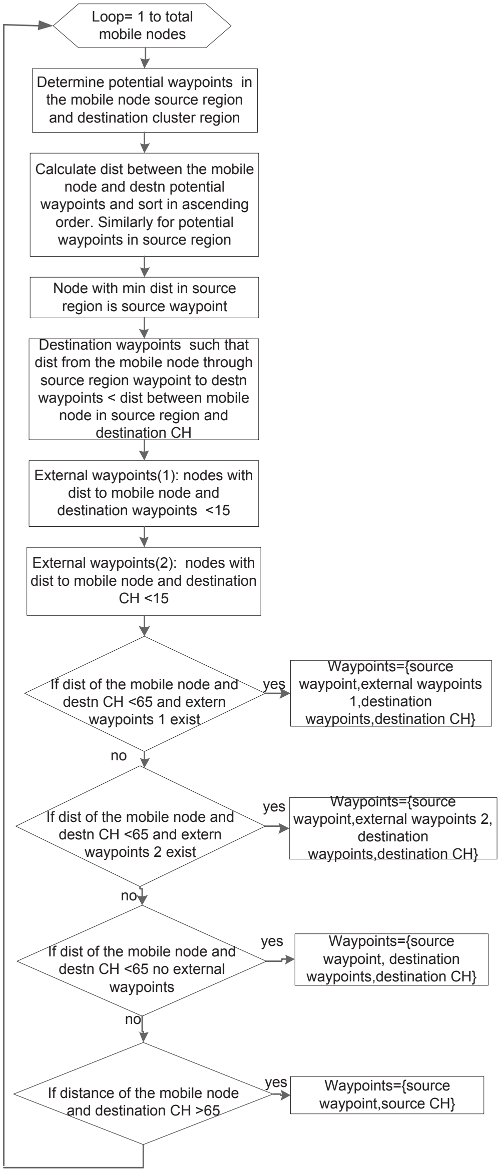

Figure 4.5: Determination of waypoints for a mobile node

i.e., $l \times l$, with l equal to 100 m. The presented results are mean values for all parameters obtained based on 50 runs of the simulation.

Simulation Results

Based on the simulations, it is was observed that full coverage in the network is attained with 150 nodes deployed in the AoI, with 40% of the total nodes as mobile nodes. This is in line with the experimental observations drawn in Chapter 3 regarding the acceptable proportion of total nodes and mobile nodes for a hybrid sensor network. With 40% of the total nodes as mobile nodes, the coverage attained is more than 90% over the complete range of variation in total nodes. These observations have been shown in Fig. 4.6, along with the initial coverage attained with the non-uniform deployment of nodes. The maximum distance moved by a mobile node for attaining the respective coverage improvement shown in Fig. 4.6 has been shown in Fig. 4.7, and is in the range of 51 to 72 m. Further, it can be observed that there is not a significant difference in the distance moved by a given node compared with the shortest path distance between initial and destination location of the mobile node. This justifies that there is minimal random movement of the mobile nodes from the source to destination cluster and that waypoints are effective in guiding the mobile nodes. The maximum distance moved by a mobile node is approximately one third of the maximum distance that a Robomote can move. The total distance moved by all the mobile nodes to attain the coverage improvement

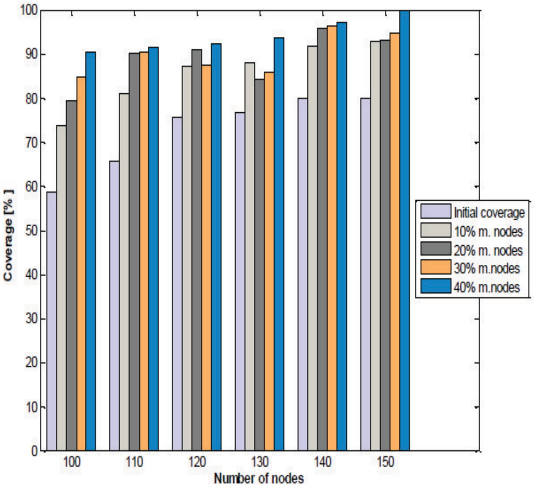

Figure 4.6: Coverage improvement with relocating mobiles nodes

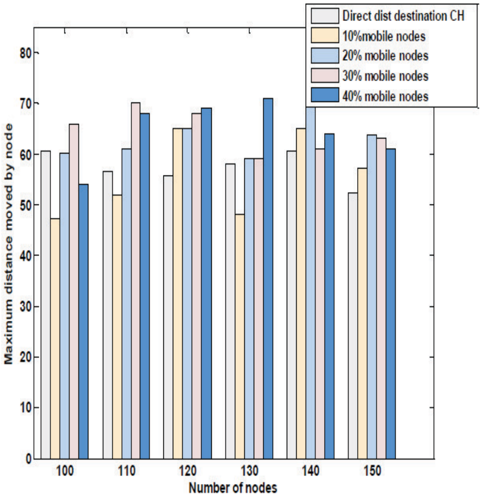

Figure 4.7: Maximum distance a single node moved for coverage improvement

has been shown in Fig. 4.8. It represents the summed up distance of waypoints following the nodes from source to destination cluster. However, it is to be noted that as the relocation to the destination cluster is terminated when the mobile node is within the communication range of the destination cluster waypoint, the actual distance moved by a node can be less than the presented distance, but on the other hand some nodes can encounter extra random movement while following the waypoints. This justifies the total distance moved by a mobile node to be considered for the distance upto the final waypoint. It should be noted that actual behavior of the node in response to RSSI has not been taken into account here, as it is considered that reliable RSSI reception to the mobile node is feasible. This, however, requires alterations to the algorithm in field experimentation to take into account environmental influence on the RSSI. The cluster matching has a centralized implementation as it is only after determining the distribution of nodes throughout the network in various clusters, that a decision can be made regarding the suppliers and recipients. However, once a pair of clusters has been matched there is distributed execution across the network, with the source and destination cluster coordinating the exchange and movement of mobile nodes.

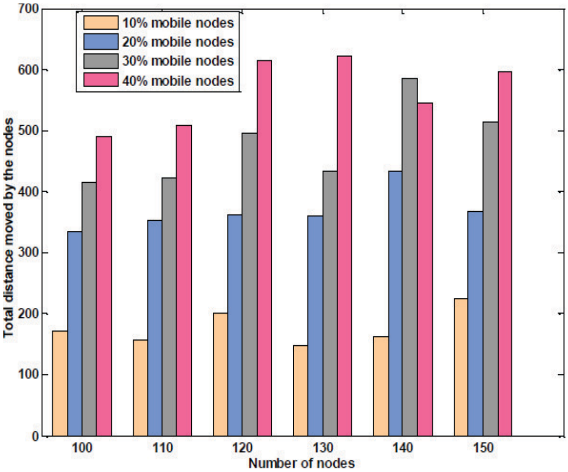

Figure 4.8: Total distance moved by all relocated mobile nodes for coverage improvement

4.6 Conclusions

Based on the experimentation it can be concluded that relocating mobile nodes between the cluster regions by waypoints is an effective method for coverage improvement. The method justifies that relocation of mobile nodes can be carried out without use of GPS or other localization mechanisms. The proposed method also demonstrates that clustering and coverage are complementary attributes of a deployed network and therefore should be considered in a collective manner. In the proposed mechanism, the LEACH protocol was used for election of the CHs. Relocation of mobile nodes has been planned such that they can volunteer as CHs in the destination cluster. A single mobile node is left behind in the original cluster only if it has a full coverage contribution and there are other mobile nodes being relocated from that cluster. Such a node can offer to be utilized for other functionality such as target tracking in the network. The LEACH protocol can be replaced with a clustering protocol that takes into account these attributes of mobile nodes for electing CHs. The proposed mechanism addresses constraints 1, 2 and 4 stated in the problem definition (Section 1.4). Constraint 3 has not been addressed, *i.e.*, deployment terrain conditions have not been taken into consideration for this proposed mechanism, and addressing this constraint will ensure further acceptability of the proposed mechanism. Based on the proposed mechanism, following the initial deployment, three network organization steps can be: i) clustering the nodes to determine distribution of nodes, ii) reorganize the nodes to balance clusters and improve coverage, and iii)subsequent election in clusters taking into consideration reorganized mobile nodes.

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Chapter 5

Data Collection by Miniature Aerial Vehicles as Mobile Nodes

5.1 Introduction

As discussed in Chapter 2, mobile nodes can be utilized in the network to assist certain nodes or a certain area in their data transmission to the base station (BS) or collecting the data on behalf of the BS; functioning as a mobile relay, mobile BS or a data mule. These functionalities of mobile nodes derive from the fact of limited energy resources possessed by the static nodes. The operational constraints applicable to mobile nodes have been discussed in the previous chapters. Instead of utilizing node mobility for carrying out aforesaid data collection and/or transmission tasks, other mechanisms for reducing the data transmission across the network have also been proposed by the researchers. They comprise of in-network computation techniques of data aggregation, compressive sensing, and network coding. Utility of active node mobility and passive node mobility for improving area coverage, and addressing dual network attributes have been elaborated in Chapter 4 and 6. Utilizing hovering nodes for sensing and actuation purposes has been put forward to address applications commonly referred as aerial sensing networks but not for data collection. The data collection mechanism presented in this chapter utilizes mobile nodes as miniature aerial vehicles (MAVs). It is referred as *DCFly* to symbolize that it is a flying data collection MAV [1],[2]. DCFly based data collection covers all the operational constraints stated in the problem definition of this thesis (Section 1.4).

5.2 Related Work

Mechanisms for reducing the energy consumption in the network can be broadly categorised into node mobility and in-network data processing. The DCFly based data collection approach collectively utilizes both node mobility and in-network processing.

Node Mobility

The utility of DCFly is similar to use of mobile BS and data mule in the network (referred in this chapter as mobile equipment (*ME*)). The ME is expected to visit certain nodes in the area of interest (AoI) (referred as data collection nodes). The data collection nodes serve as sub-sinks for other adjoining nodes, this is shown in Fig. 5.5(i). The underlying objective for data collection using MEs is to maximize the data collected traversing on the shortest path. This way it is basically a travel salesman problem (TSP) that is known to be NP hard. Accordingly, the ME based approaches presented in the related literature, address the problem in a heuristic manner. To address this problem path planning for MEs rely on shortest path - minimal spanning trees and their variations. In addition, the underlying deployment conditions of the terrain and the likelihood of encountering an obstacle/hindrance have not been taken into account [3],[4]. A cluster based path planning approach has been presented by authors in [5], with the ME guided by cluster heads (CHs) in the AoI. The advantage of hierarchical structure with cluster based path planning is there in the proposed mechanism, however, the limitation likely to be imposed due to ground terrain has not been considered. The mechanism does not consider optimal clustering (election of CHs) has not been considered, without optimal clustering (discussed in Section 5.3) the network would comprise of localized trees between data collection nodes and the adjoining nodes.

The concept of flying sensors has been presented by the authors in [6], intended to operate as an aerial sensor network. *SensorFlock* an aerial sensing network comprising flocks of MAVs for atmospheric sensing presence of toxic plume or studying distribution of chemical dispersion has been presented by authors in [7]. Aerial sensors have minuscule resources for sensing as actuation consumes substantial amount of energy resources similar to the other mobile node platforms. The DCFly serves as a data collection agent (ME) and therefore all the energy resources are available for actuation (prolonging the operational limit).

In-Network Processing

The deployed WSNs are expected to report the sensed/monitored data readings on regular intervals to the BS. The limited communication range necessitates the sensing nodes to communicate their sensed data to the BS in a multi-hop manner. Repeatedly relaying data in a multi-hop manner is not sustainable for nodes as they are energy constrained. In-network processing techniques to address these concerns are discussed in the following sub-sections.

Data Aggregation

As discussed in earlier chapters, nodes in the AoI should be organized in a clustered manner, since it reduces the total communication cost of the network. In a clustered organization, the CH is responsible for collecting and forwarding the data on behalf of all nodes in its cluster onward to the adjoining CH or the BS, depending on the clustering protocol. The sensor data usually possesses a certain amount of spatial and temporal correlation, considering the physical deployment of sensor nodes separated by just a few meters. Based on this useful characteristic, aggregating the data of certain nodes before forwarding to the BS has been suggested as a mechanism to mitigate the negative effect of transferring data from individual nodes. Data aggregation mechanisms exploiting spatial and temporal correlation and utilizing data aggregation functions such as sum and average have been put forward in the literature [8]. Apart from cluster based data aggregation, tree based, and structure free data aggregation mechanisms have been put forward in the literature [9],[10].

Network Coding

Network coding techniques rely on utilizing correlation in transmitted data by removing spatial redundancy in the data, thereby compressing the data to be transmitted to the BS, and avoiding the requirement for all nodes to transmit their data individually [11]. The most prominent network coding technique - Slepian Wolf has been demonstrated for effective reconstruction at the BS relying on minimal transmitted data. However, the BS requires the distribution pattern of the nodes in the network beforehand for this coding process, which is a limitation of this approach. In comparison to data aggregation techniques, the advantage is the shift of substantial computation activity from the nodes to the BS, which is normally considered not to be energy constrained [12]. Comparison of the related work with the DCFly based data collection considering certain critical parameters has been summarized in Table 5.1.

Compressive Sensing

Compressive sensing is an emerging alternative approach for addressing the efficient data collection and transmission of data in WSNs. In a way, compressive sensing combines the possible advantages of data aggregation and network

Table 5.1: Comparison of related works and presented contribution

Factors	Collectively in-network processing and node mobility	BS stationed away	Operation on undulating ground	MAVs for data collection	Multi-hop communication avoidance
Data aggregation approach [9]	×	×	×	×	×
Structure free data aggregation [10]	×	×	×	×	×
Slepian Wolf based data collection [12]	×	×	×	×	×
Flying sensors for urban monitoring [6]	×	×	✓	×	✓
Flying nodes indoor emergency [7]	×	×	✓	×	✓
Compressive sensing cell based [13]	×	×	×	×	×
Cluster based ME [5]	×	×	×	×	×
Tree based ME for data collection [4]	×	×	×	×	×

coding techniques. Utilizing compressive sensing for data gathering in WSNs has been proposed in [14]. Instead of a compressed sensing based approach applied on individual nodes, the authors in [13] extend this approach with the AoI partitioned into cells. The cell heads are responsible for implementing compressive sensing operations on the data received from the nodes in their respective cells. Compressive sensing theory makes it feasible for acquisition and reconstruction of the signal below the Nyquist sampling rate (under sampling), as compressive sensing relies on sparsity in signals for this operation [11].

Other details about compressive sensing and its emergence as a signal processing technique for under sampled signal reconstruction are presented in [11] and [15]. Under normal operation, nodes forward the data received from a neighboring node to the next node towards the BS, in addition to their own generated data. However, with such an approach, the relaying nodes carry out excessive radio communication transferring the packets. Instead, in compressive sensing the nodes combine their measurements with a random coefficient seed, and send it to the adjoining node that does the same on its measurements, and adds the random value generated with the random value received from the neighboring node. Therefore, instead of individual node values, the BS obtains sets of cumulative values from the nodes, reducing the total communication taking place in the network. The signal recovery relies on the BS being aware of the generating seed initially supplied to the cell heads. Cell heads generate the random measurements utilizing these random seeds. The number of measurement rounds (M) required is less than the total nodes (N) in the network.

In data collection utilizing DCFly, the AoI is divided into clusters. Instead of the CHs communicating the data in a multi-hop manner, it is collected directly from individual CHs. Specific details about operation of the DCFly have been presented in Section 5.4. It is, however, considered that for data collection using DCFly, the BS is aware of the domain in which the node data exhibits sparsity, and is capable of recovering the data from the random measurement sets. If compressive sensing is not implemented in the network, the DCFly can collect aggregated data from the CHs.

5.3 Optimum Number of Clusters in AoI

If there are an optimum number of clusters in the AoI, they can be represented as a circular region, with the CH located at the center of the circle [16],[17]. The radius of such a cluster is $\sqrt{(Area/CH_{opt})}$, where $Area$ represents the total AoI and CH_{opt} represents the optimum number of clusters. The optimum number of clusters can be derived as follows [16]:

$$CH_{opt} = \sqrt{\frac{N\epsilon_{fs}A}{2\pi\left(\epsilon_{amp}d_{toBS}^{n} - E_{elec}^{Rx}\right)}} \tag{5.1}$$

Where N represents the total number of nodes in the AoI, M or R represents the dimensions of the AoI, d_{toBS} represents the distance to the BS from the nodes, E_{elec}^{Rx} represents the energy consumed by the receiver circuit on the sensing node, ϵ_{amp} signifies the energy spent by the transmitter amplifier of a node, A represents the area of AoI, and ϵ_{fs} represents the free space radio propagation model. The various parameters that govern the optimal number of clusters possible in the overall AoI based on (5.1) are therefore:

$$CH_{opt} = f(N, MorR, d_{toBS}, E_{elec}^{Rx}, \epsilon_{amp}) \tag{5.2}$$

Based on these governing parameters, it is concluded that the optimum number of clusters reduces as the BS moves farther away from the AoI, and for a BS located significantly away from the AoI there will be a single optimum cluster spanning the whole AoI. Based on this observation, it becomes operationally infeasible for more than one cluster to communicate with a BS distantly located from the AoI. The consequence of a single CH for the whole network is that it necessitates all the nodes to be involved in a multi-hop manner to communicate with the given CH. Accordingly, it can be concluded based on this observation that a hierarchical structure with clustering of nodes (multiple CHs) cannot be supported for BS located away from the AoI. Various applications of WSNs especially in environment and habitat monitoring require operation of the sensing nodes in inhabitable conditions, and expecting a BS to be stationed close to the perimeter of the AoI or within AoI is not feasible under actual operational conditions. This is further supported by the fact that in harsh - inaccessible terrain it might not be feasible for the BS to relay the collected data from the network to a back-end control station, due to non availability of any communication network, especially if close to the AoI (within communication range of CHs). The presented mechanisms relying on DCFly based data collection addresses these operational aspects.

5.4 DCFly

A DCFly is a MAV that traverses across the AoI and collects data from the clusters (CHs). The DCFly is considered capable of performing a vertical take off and landing (VTOL) at every cluster descending from its flying height, referred as *cluster-hop*. Utilizing a DCFly for a forest monitoring application is illustrated through front and top (aerial) view across the AoI in Fig. 5.1, and Fig. 5.2. From the figures it can be observed that the DCFly is expected to collect data from the clusters in the AoI and deliver it to the BS located at a distance from the AoI (at least a distance greater than direct communication range of the CHs.

The DCFly flies at a height 2 m higher than the tree canopy to stay clear of any possible obstruction. In applications where there is no scope for the DCFly to land (static position) for collecting data it still descends from the normal flying altitude and hovers at the *cluster-hop* point with the intention of reaching within communication range of sensing nodes on the ground. The random seed required for generating random coefficients (if using compressive sensing) will be supplied to the CHs by the DCFly, while collecting previous round data. On commencement of network operations, the DCFly conducts an extra round to supply random seeds for the first round. In the DCFly based data, the optimum number of clusters in the deployed network will be governed by factors governing the DCFly's operations. The DCFly as a MAV has a maximum flying length so that it can traverse based on the power consumption rate and the total energy reserve available on board. The size of the cluster is a critical aspect

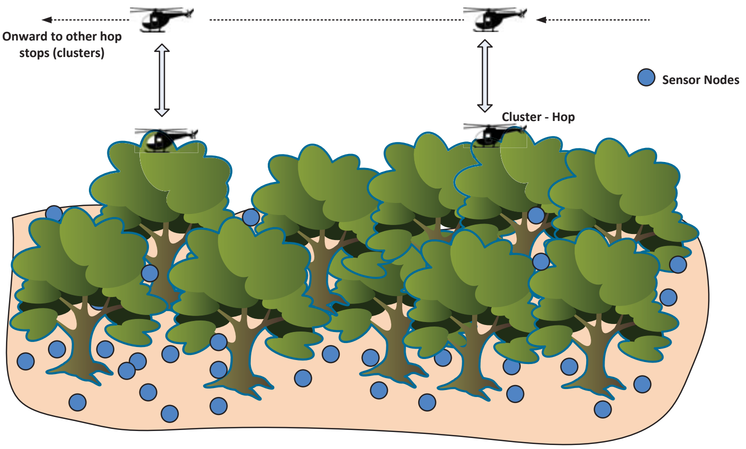

Figure 5.1: DCFly - forward flight and cluster-hops

as well, as large sized clusters imply lesser clusters in the AoI, and accordingly lesser cluster-hops, and vice versa implies for small sized clusters. Therefore, the optimal clusters in the AoI will have to take into account the DCFly's operational factors in comparison to the factors governing optimum clusters in the normal course as given by (5.1). Certain conditions are considered for the DCFly's operation in the AoI to collect data, and they are as follows [?] :

- The delivery deadline at the BS is high (10 - 15 min).

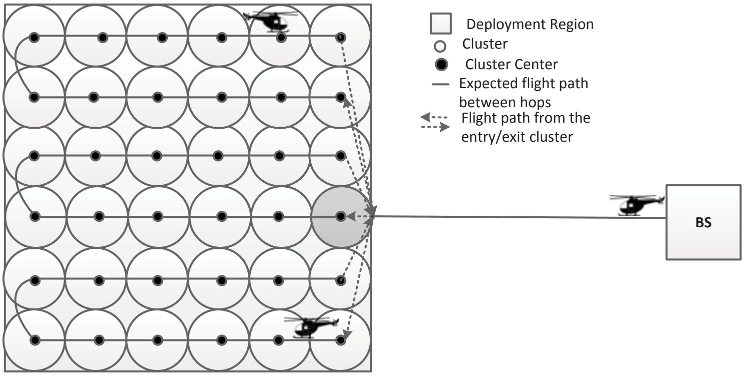

Figure 5.2: DCFly's path across the AoI

- The nodes have unique IDs and the CHs have access to the IDs of the nodes in their cluster.
- The DCFly has capacity to hook/cling to stay firmly at the cluster-hop.
- Nodes in the network are unaware of their location, including the DCFly.
- The AoI is square in shape so that it can be divided into even number of rows and columns, with one DCFly covering a pair of rows.
- Beyond the entry/exit cluster the DCFly is able to navigate to the BS without path guiding assistance, and it possible to recharge the DCFly at the BS between data collection rounds.
- The DCFly is assisted by the clusters in the first column from entry/exit cluster for navigating to its assigned rows (Fig. 5.2).
- The DCFly is not impacted by external factors such as wind while traversing the AoI.

5.5 Optimum Clusters - DCFly

As stated in the previous section the parameters that govern the optimum number of clusters in the AoI (for data collection by DCFly) are different compared with the normative factors governing clustering in a network. A DCFly is governed by the following factors in collecting data from the network, and accordingly the clustering of the nodes (CH election) should take them into account.

- Maximum serviceable range of the DCFly, taking into account power consumption for different flight operations, *i.e.*, forward and axial (cluster-hop).
- Total time taken by the DCFly to complete the designated round and return to the BS after collecting data.
- Size of the cluster (inversely related with number of cluster-hops)

To the best of the knowledge of the author, no other work has evaluated the operational capacity of MAVs for data collection and therefore the relation of the aforesaid factors on the operational capacity of a DCFly are required to be determined. Subsequently, taking into account the various factors, the optimum clusters that can be serviced by a single DCFly is formulated as an optimization problem.

Maximum Serviceable Range

The DCFly is considered capable of performing VTOL as stated earlier and the various flight operations include : forward, hovering, vertical (axial), rearward and sideward [18]. The DCFly's flying path across the AoI comprises of forward flight segments between clusters and vertical flight (two-way) at cluster-hops as shown in Fig. 5.1. Therefore, the power consumed for forward flight and axial flight operation on a per unit meter basis is required to determine the total service length that can be served by the DCFly. The relation between the two flight modes cannot be determined directly as it varies on a case by case basis, as well as on actual operational flight conditions. However, both forward (P_{fwd}) and axial power (P_{ax}) consumption are related with hover power (P_{hvr}) consumption, *i.e.*, power consumed at a static position on a certain height. They are related as explained below [19].

The relation between forward and hover power is given as:

$$P_{fwd} = \frac{V_\infty \sin\alpha + V_{ind}}{v_{hvr}} P_{hvr} \tag{5.3}$$

Here, V_∞ represents the magnitude of free stream velocity and V_{ind} the propeller induced velocity. The relation between axial and hover power is

$$\frac{P_{ax}}{P_{hvr}} = \frac{V_{ax}}{2v_{hvr}} + \sqrt{\left(\frac{V_{ax}}{2v_{hvr}}\right)^2 + 1} \tag{5.4}$$

$$\text{for} \qquad \frac{V_{ax}}{v_{hvr}} \geq 0$$

Additionally, the power ratios between axial and hover power, and axial and hover velocity are related by the universal power curve. For the normal working state, the axial power P_{ax} is twice the hover power P_{hvr}, when a certain value is selected for the evaluation from the universal power curve. The hover power is related differently with axial power (descend) and for certain descend rates the power consumption is lower than hover power. In the evaluation, power consumption for both axial climb and descend is considered the same to compensate for any additional power that might be consumed in real operational conditions. The forward flight power is lower than hover power due to existence of a translational lift that assists the forward flight with more air on the lower part of the rotor disk compared with the upper part, thereby saving energy. For the evaluation, forward power and hover power are considered to be related as $P_{fwd} = 0.5P_{hvr}$, and the relation between forward and axial power is therefore:

$$P_{ax} = 4P_{fwd} \tag{5.5}$$

The power consumption relations stated above apply for the DCFly on per unit distance traversed basis (per m). As stated earlier, the DCFly traverses in its forward flight at an altitude higher than the tree canopy height, to prevent the DCFly of any obstruction in the flight path. In the forest based monitoring, the DCFly is expected to fly 2 m above tree canopy height, and therefore for each cluster-hop axial power consumed based on (5.5) is:

$$P_{ax} = 16P_{fwd} \tag{5.6}$$

Accordingly, for full battery reserve E_{batt}, the distance that DCFly can traverse making cluster-hops CH_{hops} is given as:

$$\frac{E_{batt}}{16P_{fwd}CH_{hops} + 2CH_{rad}CH_{hops}} = Dist_{serv}(m) \tag{5.7}$$

The distance between the clusters (second term in denominator) should have been multiplied with (CH_{hops}-1), instead of the given term, but multiplication has been done with CH_{hops} to take into account the distance from entrance/exit cluster and turning sidewards to change between the rows as shown in Fig. 5.2 [?].

Time for Completing Data Collection Round

The total time for various activities that comprise one computational round and data collection by the DCFly is given as:

$$T^{n}_{slots} + T^{m}_{CH} + T^{DCFly}_{CH} + T^{round}_{DCFly} \tag{5.8}$$

Where T^{n}_{slots} represents the total time slots that are required for the nodes in the cluster to communicate their data with the CH following a time division multiple access (TDMA) based time slotted approach. T^{m}_{CH} represents the time for M rounds to be computed by the CH as per the compressive sensing requirement. T^{DCFly}_{CH} and T^{round}_{DCFly} represent the time spent by the DCFly at a cluster-hop to collect the data and the time for completing the whole data round across the AoI starting and terminating at the BS. The first two terms do not impact the DCFly operational deadline at the BS as these tasks execute in all clusters in parallel. Time spent on an individual cluster-hop and the total time traversing across the AoI between the cluster-hops are of greater significance. In relation to the time spent in traversing one round of the network, the applicable distance to be traversed by the DCFly is given as:

$$16CH_{hops} + 2CH_{rad} \tag{5.9}$$

The first term represents the distance equivalent (in forward flight) of axial flight distance in addition with the distance between two clusters. As stated earlier in Section 5.3, optimum clusters can be represented as circles, as also shown in Fig. 5.2. Accordingly, the distance between two CHs is twice the radius of a cluster (CH_{rad}). The DCFly is considered to traverse the radius equivalent distance between clusters at uniform speed, and the remaining half decelerating to reach at a halt (hover state) to transfer into axial flight mode (cluster-hop) at the next cluster. Based on these operational conditions and using *Equations of Motion*, the time required for traversing the two half distances (radius equivalent) between the clusters is determined. The DCFly is expected to cover half the distance between clusters at uniform speed (U_{DCFly}) and the remaining half decelerating to reach standstill condition at the next cluster-hop to transit into axial flight. Based on the determined time for navigating between clusters and time spent on individual clusters, (5.8) is modified into:

$$T^{n}_{slots} + T^{m}_{CH} + T^{DCFly}_{CH} CH_{hops} + CH_{hops} \left(\frac{3CH_{rad}}{U_{DCFly}} \right) \tag{5.10}$$

Cluster Size

The third condition governing the optimum clusters serviceable by DCFly is the radius of the cluster. As optimum clusters can be represented as circles, the size of a cluster relates with the radius of the circle representing it. The size of the cluster refers to the permissible distance between the CH (centre of circle) and the farthest node from the CH. The objective function based on the three factors, and the overall optimization problem is formulated as follows [**?**]:

$$\text{Maximize } CH_{hops} + CH_{rad} + T^{DCFly}_{CH}$$

s.t.

$$16P_{fwd}CH_{hops} + 2(CH_{rad})CH_{hops} \leq Dist_{serv} \tag{5.11}$$

$$T^{DCFly}_{CH} CH_{hops} + \left(\frac{3CH_{rad}}{U_{DCFly}} \right) CH_{hops} \leq T_{delv} \tag{5.12}$$

$$CH_{rad} \leq radius_{upper} \tag{5.13}$$

$$CH_{rad} \geq radius_{lower} \tag{5.14}$$

$$CH_{rad} T^{DCFly}_{CH} \leq ubound_{1} \tag{5.15}$$

$$CH_{hops} \in \mathbb{Z}, \text{ and } CH_{hops}, CH_{rad}, T^{DCFly}_{CH} \geq 0 \tag{5.16}$$

A maximization function is considering as the larger the number of clusters hops (clusters) serviced by a single DCFly, the better it is for the network, and this in turn influences the total number of DCFlys required to cover the overall AoI. Since it is not desirable to have the size of the cluster to be larger beyond a permissible limit as discussed earlier, an upper and lower bound is imposed on CH_{rad}. Similarly, inequality (5.15) ensures that time spent at individual cluster-hops is regulated. An additional restriction of being only a positive integer is imposed on CH_{hops} and accordingly the problem formulation is a mixed integer non - linear programming (MINLP) problem. It should be noted here that that specific operational parameters of the DCFly are not known. Therefore, the values considered for the bounds and inequalities have been considered to represent the generalized operation scenario anticipated from the DCFly, where U_{DCFly} is considered 0.5m/sec, $radius_{lower}$ as 20 m, $radius_{upper}$ as 25m (bounds on cluster radius), and upper bound $ubound_1$ as 200. The communication and sensing radius (R_c and R_s) of the sensing nodes are considered as 10 m and 5 m respectively.

The optimum number of clusters that can be serviced by the DCFly along with the maximum range (m) and the delivery deadline for data at the BS under which this can be attained have been stated in Table 5.2.

However, it should be noted that with the imposed constraints only even number clusters are determined. This way the DCFly is expected to cover half of clusters in one row and the remaining half in the other row as stated earlier. For the derived values as per constraint (5.15), CH_{rad} was 20 m and accordingly T_{CH}^{DCFLy} is 10 seconds. The dimensions of the AoI in relevance to the DCFly can be determined based on the maximum operational range of the DCFly. The DCFly covers the total length per cluster-hop as discussed earlier, *i.e.*, $16P_{fwd}CH_{hops}$. As stated earlier AoI is considered square, and the length of this square can be determined subtracting the total cluster-hop length (cluster-cluster distance) length from maximum length stated in Table 5.2 and divide by two. Based on the portion of AoI covered by two rows, the number of DCFly's can be determined before commencing network operations. The DCFly traverse across one row reaching the farthest cluster and switches to the adjoining row and traverses back to the entry / exit cluster as shown in Fig. 5.2. Whether the DCFly switches to an adjoining row rightwards or leftwards depends on the direction it turned while entering the AoI.

5.6 Results and Discussions

As stated and discussed in the related work, the DCFly collectively utilizes network processing and in-network processing mechanisms for effective data collection.

Table 5.2: DCFly across AoI

Clusters	Maximum range (m)	Delivery deadline time (sec)
4	224	520
6	336	780
8	448	1040
10	560	1300
12	672	1560

DCFly and Multi-hop Data Collection

DCFly based data collection is compared for its operational utility with compressive sensing based data collection as proposed by the authors in [13], referred here as *CS-DC*. Additionally, data collection with data aggregation implemented in the network is also considered for comparison, referred as *DA*. Since compressive sensing complements data collection by DCFly, data collection with DCFly without compressive sensing collecting only aggregated data from CH has also been considered for comparison (referred as *DCFly-DA*). The four approaches are evaluated on two accounts, *i.e.*, total energy consumed for completing one data collection round at the BS, and packet loss/throughput of the network in a multi-hop manner.

The energy consumed for one round of data aggregation in a network considering the energy consumed in a CH and a node in the network is represented as [16], [17]:

$$E_{CH} = lE^{Rx}_{elec}\left(\frac{N}{CH_{opt}} - 1\right) + l\epsilon_{DA}\frac{N}{CH_{opt}} + lElec^{Tx}_{elec} + l\epsilon_{amp}d^{n}_{toBS} \tag{5.17}$$

Where l is the packet data size, E^{Rx}_{elec} is the energy spent to receive a packet, E^{Tx}_{elec} is the energy spent to transmit a data packet, N is the number of nodes, CH_{opt} is the optimum number of clusters, ϵ_{DA} is the energy consumed for data aggregation operation at the CH, and ϵ_{amp} is the energy spent by the transmitter amplifier. The energy consumed by a non-CH node is:

$$E_{nonCH} = lE^{Tx}_{elec} + l\epsilon_{amp}d^{n}_{toCH} \tag{5.18}$$

The transmission amplifier, ϵ_{amp}, is considered based on a free space model as ϵ_{fs} and the path loss exponent as 2 for the comparison of the four approaches.

The total energy consumed for data aggregation relying on (5.17) and (5.18) is given as:

$$E_{round} = E^{Total}_{CH} + E^{Total}_{nonCH} \tag{5.19}$$

The aforesaid equation for energy consumed by the CH node is based on the consideration that individual CH nodes communicate directly with the BS.

This can be infeasible for the individual CHs in the network, especially those located far away from the BS. Therefore, for the comparative evaluation, CHs are expected to communicate in a multi-hop manner with adjoining CHs to reach the BS. In order to compare the four approaches, the optimal clusters aligned in a single row are considered (as shown in Fig. 5.2). In such a layout all CHs are involved with transmitting data (own data and/or relaying on behalf of other clusters). However, the farthest CH will only be transmitting data and not relaying data on behalf of other clusters. Based on this layout the energy spent by a CH for the DA approach can be represented as:

$$\begin{aligned} E_{CH} = {} & \left(lE_{elec}^{Rx} \left(\frac{N}{CH_{opt}} - 1 \right) + l\epsilon_{DA} \frac{N}{CH_{opt}} + l\epsilon_{fs} d_{nextCH}^{2} \right) CH_{opt} \\ & + lCH_{opt} E_{elec}^{Tx} + l(CH_{opt} - 1) E_{elec}^{Rx} \end{aligned} \tag{5.20}$$

The energy consumption for a single non-CH node is given in (5.18), and is applicable for all the four approaches. The energy consumption for all nodes in the network excluding the nodes designated as CHs can be represented as:

$$E_{nonCH} = lE_{elec}^{Tx} + l\epsilon_{fs} d_{toCH}^{2} \left(N - CH_{opt} \right) \tag{5.21}$$

The equation for total energy consumption remains the same for all four approaches. In the case of the CS-DC approach, the CH is required to communicate M sets of readings to the BS for recovery of actual data values. Energy spent by the CHs can be represented as:

$$\begin{aligned} E_{CH} = {} & \left(\left(lE_{elec}^{Rx} \left(\frac{N}{CH_{opt}} - 1 \right) + l\epsilon_{DA} \frac{N}{CH_{opt}} + l\epsilon_{fs} d_{nextCH}^{2} \right) CH_{opt} \right. \\ & \left. + lCH_{opt} E_{elec}^{Tx} + l(CH_{opt} - 1) E_{elec}^{Rx} \right) M \end{aligned} \tag{5.22}$$

can be represented as follows:

$$\begin{aligned} E_{CH} = {} & \left(lE_{elec}^{Rx} \left(\frac{N}{CH_{opt}} - 1 \right) + l\epsilon_{DA} \frac{N}{CH_{opt}} \right) \left(M \times CH_{opt} \right) \\ & + \left(l\epsilon_{fs} d_{tofly}^{2} + lE_{elec}^{Tx} \right) CH_{opt} \end{aligned} \tag{5.23}$$

For the sake of comparison, it should be noted that CHs were referred as optimum clusters CH_{opt} for the energy consumption equations of DA and CS-DC approaches, *i.e.*, to consider that if derived optimal clusters as per Table 5.2 were to operate under these approaches. As stated earlier, for the comparative evaluation a single row of clusters is considered, and therefore half of the optimal clusters derived in Table 5.2 are considered here as the optimal clusters derived are expected to be covered by a DCFly in two rows. The values for the various parameters considered in the aforementioned equations are given

Table 5.3: Parameters used for analytical evaluation

Parameter	Value
N	50
E_{elec}^{Tx}	100 nJ/bit
E_{elec}^{Rx}	100 nJ/bit
CH_{opt}/N_{hps}	2,3,4,5,6
ϵ_{DA}	5 nJ/bit/signal
d_{nextCH}	40 m
d_{toCH}	20 m
e_{fs}	10 pJ/bit/m^2
l	256 bytes
$M(CS-DC)$	5
$M(DCFly)$	2
p_{link}	0.05,0.2

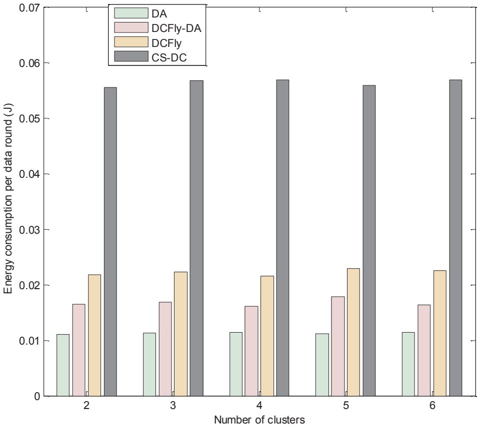

Figure 5.3: Energy consumption per round in the four approaches

in Table 5.3 The value of M (number of data sets) required for recovering the actual data depends on the number of nodes N that are included in the set. In the proposed DCFly mechanism, the number of measurement sets required depends only on a single cluster, and accordingly, the difference in M (CS-DC and DCFly) values as stated in Table 5.3. The energy consumed for one round of data collection for the four approaches is shown in Fig. 5.3. The energy saving due to a smaller M in comparison to CS-DC in DCFly is evident, although, per round energy consumption for the DA approach is less in comparison to DCFly and CS-DC. However, with one round, the information conveyed is highly compressed, and if the actual value for all nodes was to be determined it would require multiple rounds. Similarly, it can be inferred between DCFly (compressive sensing) and DCFly-DA (no compressive sensing - aggregated data at CH). Therefore, the proposed approach is manifold more energy efficient compared with both CS-DC and DA approaches. Multi-hop communication is subjected to path loss occurring due to environment and operational conditions and loss of packets necessitates re-transmission, which is highly resource intensive. The four approaches can be evaluated for possible transmission errors based on the following equation [20]:

$$p = 1 - (1 - p_{link})^{N_{hps}} \tag{5.24}$$

Where p is the probability of error on the entire path; p_{link} is the packet error rate of an individual link, and N_{hps} is the number of hops on the path. Two

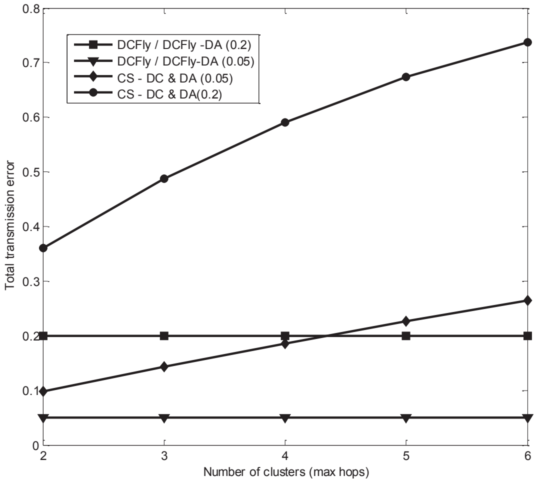

Figure 5.4: Transmission error in the four approaches

possible values are considered here for evaluation: 0.05 and 0.20 and based on these values the difference of transmission error in the four approaches is shown in Fig. 5.4. Since, individual clusters directly relay their data to the DCFly when it visits the cluster, the effective number of hops between the CH and the DCFly (at the cluster-hop) remains constant at one. This is also applicable for the DCFly-DA approach. Transmission errors due to multi-hop data transfer are accordingly applicable to the DA and CS-DC approaches.

DCFly and ME: Data Collection Points Covered

The data collection path for a ME is basically determined as the shortest path connecting the data collection points. As stated earlier, the most common method for determining the data collection path for a ME rely on the shortest path-minimum spanning tree and their variations. Considering the network to consist of a complete graph *G=(V,E)*, *V* is the set of data collection points and *E* is the set of edges between the data collection points. Also, let the set of nodes that serve as data collections points for the visiting ME be *M* and the set of other adjoining nodes (member nodes) that deliver their data to the data collection point be represented by *N*. The approaches are intended to be compared in terms of ratio of data collection points covered by the visiting DCFly/ME to the length of the DCFly/ME path. As stated earlier, in the DCFly approach the nodes are considered to be clustered with the CH located in the centre of a circle. The distance traversed per cluster is the diameter of the circle (twice of CH_{rad} i.e. 40 m) is considered for determining the number of nodes covered vs. the length of the DCFly/ME path. The average node degree (d) is given as [21]:

$$d = \frac{n\pi R_c^2}{A^2} = \mu\pi R_c^2, \tag{5.25}$$

where n is the number of nodes, and A the length of the AoI, μ the density of nodes (n/A^2). For the numerical analysis, the following values are considered: n = 100, A = 100 m, and $\mu = 0.01$. The average number of nodes in a cluster is given as [21]:

$$P_c = \frac{\pi k^2 R_c^2}{A^2}, \tag{5.26}$$

where k is the number of hops (considered k = 2), substituting from (5.25) for d

$$P_c = \frac{dk^2}{n} \tag{5.27}$$

The average size of a cluster is therefore [21]:

$$E(N_c) = nP_c = dk^2 \tag{5.28}$$

DCFly based data collection is compared with a ME moving based on a minimum spanning tree and Steiner minimal tree. Determining the number of data collection points for a given set of vertices and edges is not directly feasible for minimum spanning tree and Steiner Minimal tree, and for this reason approximation algorithms and heuristic approaches have been considered. Assuming the length served by the ME is L, and the average length of the edge connecting two vertices as l_{edge}, then $\frac{L}{l_{edge}} = w$, where w is number of edges, and number of vertices is w+*1*. In the case of the Steiner tree the number of vertices is known as some approximate points functioning as Steiner points [22]. However, for a given set of points, P, on the Euclidean plane, the length of the Steiner minimum tree (L_s) and the length of minimum spanning tree L_m are related as: $L_s(P) \geq (\sqrt{3}/2)L_m(P)$. The inequality is referred as the Gilbert-Pollak Conjecture [23]. Considering both the sides removing the inequality as:

$$L_s(P) = (\sqrt{3}/2)L_m(P) \tag{5.29}$$

It is appropriate to consider that number of vertices for both trees is related in the same proportion as the total length. The average length of the edge (l_{edge}) is taken as $\frac{R_s+R_c}{2} = 7.5$ m, considering that the minimum legitimate distance between two nodes is R_s (else they overlap) and the maximum distance is R_c (maximum communication range). The influence of changing the total length is shown in the Fig. 5.5(ii), and it can be inferred from the figure that with aerial data collection from an optimal cluster layout, the number of nodes covered is manifold higher than the Steiner minimal tree and minimum spanning tree.

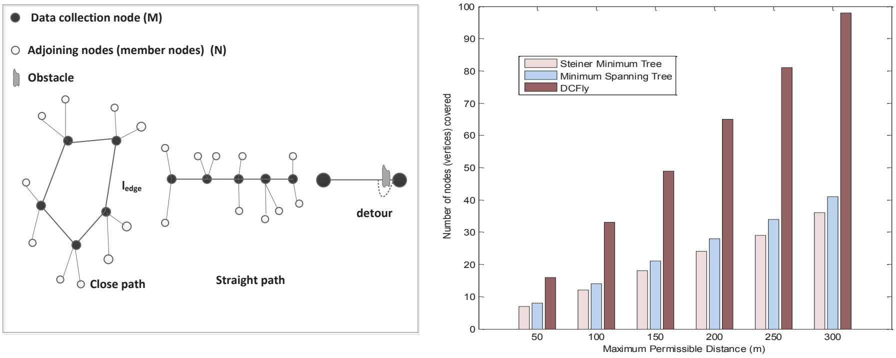

Figure 5.5: i) Data collection path and detour due to obstacle on l_{edge} ii) Total number of data collection points covered in reference to ME path length

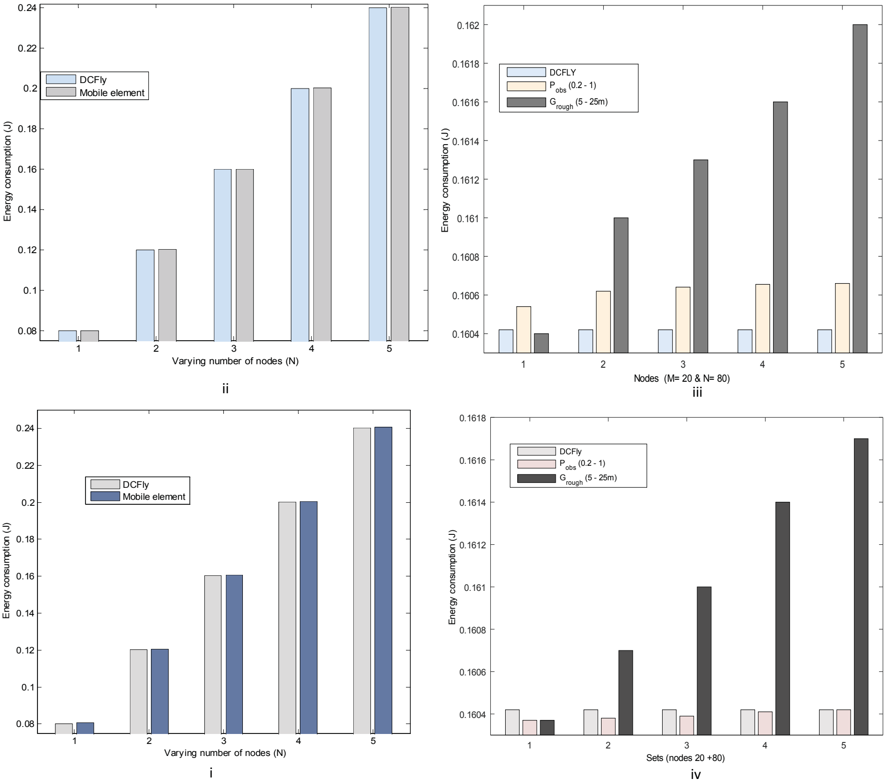

Figure 5.6: (clockwise from left i) DCFly and ME in close route path, ii) DCFly and ME on a straight line path, iii) Varying P_{obs} and G_{rough} influence on ME compared with DCFly on closed path iv) P_{obs} and G_{rough} based ME and DCFly on straight path

DCFly and ME: Energy Consumption and Network Lifetime

For data collection purpose, the ME is expected to reposition itself in the proximity of data collection points. The energy consumption for an individual node is given as [4]:

$$p \approx e(l_r + l_t), \tag{5.30}$$

where l_r and l_t represent the number of bits received and transmitted, and e represents the energy consumption per bit. Let λ represent the data generation rate of an individual node j during one data collection round of the ME, then $l_t^j = l_r^j + \lambda$, where l_t^j and l_r^j represent the amount of data transmitted and received by node $j \in N$, where all nodes are assumed to transmit their data to the nearest collection point. Representing the total data in terms of hop is given as:

$$\sum_{j=1}^{N} l_r^j = \sum_{j=1}^{N} h_j \lambda, \tag{5.31}$$

where h_j is the lowest number of hops from the node to the destination collection point. The total energy consumption of the nodes is [4]:

$$p = \sum_{j=1}^{N} p_j \approx e(l_r^j + l_t^j) = \sum_{j=1}^{N} e(2l_r^j + \lambda) = \sum_{j=1}^{N} e(2h_j + 1)\lambda \tag{5.32}$$

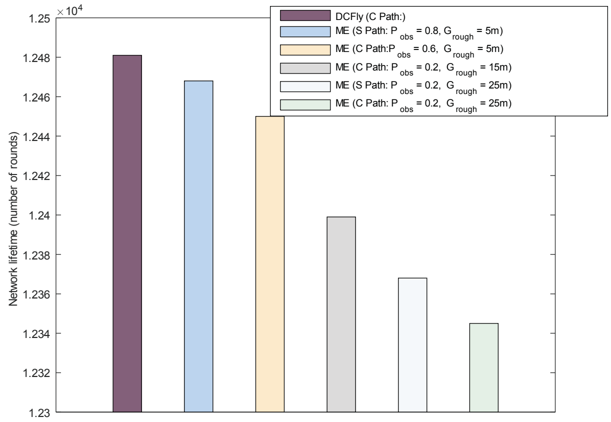

Figure 5.7: Network lifetime for the different approaches

However, in addition to transmitting the collected data, data collection points are assumed to be responsible for ME path planning. Each data collection point is responsible for its two edges and collectively for all edges, and the energy consumption can be given as $2M(e)$. The data collection by ME is prone to encountering obstacles and hindrances on ground that can force the ME into taking a detour from the shortest path and necessitate additional communication overhead (shown in Fig. 5.5 (i)). A ME traversing on the ground will also be hampered by ground roughness (undulating terrain) in the AoI in addition to possible hindrance due to obstacles and hindrances. However, predicting the likelihood of encountering an obstacle or the exact amount of roughness of ground terrain is hard to predict. The novelty of the proposed DCFly is centred on overcoming this underlying limitation of data collection by ground-based ME. Therefore, an appropriate model to take into account the likelihood of an obstacle and ground terrain conditions is necessitated. The probability of an obstacle represented P_{obs} can be based on the general profile of the AoI, an obstacle/hindrance could be anything, *e.g.*, a boulder, a log of wood, or a pothole that limits the movement on the shortest path between the collection points. The ground roughness can be determined based on radio propogation path loss relying on finite difference time domain (FDTD) analysis [24]. Accordingly, we propose an expression that represents the amount of overhead due to obstacles / hindrances and the ground terrain (roughness) as:

$$e(P_{obs} + G_{rough})l_{edge}w, \tag{5.33}$$

where G_{rough} represents the roughness of ground terrain, and w the number of edges. G_{rough} would be zero only for an absolutely levelled ground, and P_{obs} would be zero if there is no obstacle at all, therefore the expression would be zero only under ideal conditions. Accordingly, the overall energy consumption by all data collection point M(s) is:

$$Me(2h_j + 1)\lambda + 2M(e) + e(P_{obs} + G_{rough})l_{edge}w \tag{5.34}$$

The aerial data collection for the same route will, however, not encounter any obstacles/hindrances or impact of non levelled ground. It is, however, assumed that the path planning is the same for ME and DCFly (especially covering a closed irregular path ($c-path$) in the AoI). For the sake of comparison the data collection points organised in a straight line are also considered, assuming that movement across a straight line path ($s-path$) requires no path planning. The ME based data collection is, however, still impacted by the obstacles and hindrances. Energy consumption for all ME(s) presented in (5.34) changes for straight line path as:

$$Me(2h_j + 1)\lambda + e(P_{obs} + G_{rough})l_{edge}w \tag{5.35}$$

For DCFly, (5.35) is applicable in both *c-path* and *s-path*.

For the numerical analysis, it is considered that $M = 20$ (constant throughout), and number of adjoining nodes (N) varying between 2 and 6. All collection points are considered to have equal number of nodes. P_{obs} is varied between 0.2 and 1 in increments of 0.2, and G_{rough} between 5 and 25m in increments of 5. The data generation rate of nodes is $\lambda = 200$ bps and the nodes are expected to transfer data for 10 seconds for every data collection round. The radio energy factor is $e = 0.5\mu J$, l_{edge} is 7.5 m and w is 19. It can be observed from the figures that there is almost no difference for data collection between DCFly and ME (Fig. 5.6 (i) and (ii)), as $P_{obs} = 0.2$ and $G_{rough} = 5$ m are low, *i.e.*, 0.00037 J. In Fig. 5.6 (iii), the value for DCFly based data collection is kept constant (M=20 and N=80) and is compared with change in P_{obs} (keeping G_{rough} constant) and vice versa for G_{rough}. In comparison to Fig. 5.6 (i) and (ii), the influence of increasing P_{obs} and G_{rough} is evident in Fig. 5.6 (iii) and (iv). Between the two parameters, the energy consumption is more pronounced in the case of G_{rough} in comparison to P_{obs}. Based on the figures, it can be inferred that data collection using ME on obstacle ridden and undulating terrain is manifold higher than aerial data collection. The impact on the network lifetime has been determined considering the total initial energy of all nodes (M+N, initial energy of all nodes as 20 J), collectively, divided by the energy consumed by the nodes in one data collection round, shown in Fig. 5.7. The advantage of data collection by DCFly is amply evident in comparison with ME based approaches, and it can be concluded that with a larger number of data collection points and adjoining nodes the effect of ground roughness and obstacle/hindrance based overhead become even more pronounced.

5.7 Conclusions

The utility and effective reliability of data collection by DCFly in comparison to multi-hop data collection, and node mobility of a ground based ME for data collection is clearly evident. Reduced transmission errors due to avoidance of multi-hop communication for inter-cluster communication, and the possibility of the BS stationed distantly away from the AoI make the approach highly desirable for use in applications that require deployment in harsh and inhabitable conditions. Utilizing MAVs for data collection instead of active sensing and monitoring as proposed using a DCFly offers a great opportunity for advancement of MAVs for use in WSNs, as all the focus is usually concentrated alone on making the actuation of MAVs more efficient. Usually the design of MAVs has been centered on sensors that can be coupled to MAV apart from improving the MAV itself in terms of actuation efficiency. Further work based on the proposed approach includes finding possible applications apart from forest monitoring that can benefit from aerial data collection.

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Chapter 6

Utilization of Passive Node Mobility for Joint WSN Applications

6.1 Introduction

In Chapter 3 and 4, the various parameters governing active node mobility and coverage improvement have been discussed. Node mobility is of two types: active and passive, based on the mechanisms the mobile node utilizes for movement. Passive node mobility is advantageous in comparison with active node mobility as there is no requirement of battery powered actuation. However, passive node mobility can not be controlled in comparison to active node mobility, and due to this constraint utilizing passive node mobility effectively in the network is challenging. Utilizing passive node mobility, the possible utility of mobile nodes in sensor networks are limited only by imagination. This chapter presents utility of node mobility provided through a novel deployment/collection agent to address two seemingly non-related applications. The proposed mechanism in this chapter covers all the operational constraints governing the node mobility utility within the network as stated in the problem definition of this thesis (Section 1.4).

6.2 Related Work

Passive mobility of mobile nodes has emerged considering the limitations imposed by active mobility in terms of high movement cost, and the infeasibility to move under certain conditions. The authors in [1] present a floating sensor network for monitoring a river system, where movement of nodes is governed by water current. Similarly, underwater acoustic sensor network (UASN) comprising of floating sensors functioning as an intermediary between the base station (BS) and sensor nodes at the sea bed has been elaborated in [2]. Utilizing flow of water for steering sensing nodes through a pipeline system in a building for monitoring the condition has been elaborated in [3]. Passive node mobility in the form of a mobile sink affixed to moving trains for collecting data about structural health of railway bridges has been presented in [4].

The related work is discussed in two parts i) wildlife monitoring and ii) rail infrastructure as the proposed mechanism addresses these two application areas in a collective manner.

Wildlife Monitoring

A wildlife monitoring system for understanding the interaction among animals in their ecosystem has been presented in [5]. Determining social interaction and living patterns of European badgers utilizing wireless sensor network (WSN) has been presented in [6]. Similarly, monitoring white tail deer to alert any drastic changes in its population or habitation habits have been elaborated in [7]. Monitoring migratory birds such as Siberian crane, wild turkeys and whooping cranes through a cellular based sensor network has been presented in [8]. Preventing elephants to reach close to human settlement and cause damage to settlement or cultivated crops by determining their locations in relation to the human settlement using an acoustic sensor network has been presented in [9].

Rail Infrastructure Monitoring

The rail infrastructure constitutes critical infrastructure of a nation, considering its immense significance of connecting far flung areas and capacity to transport heavy freight. The rail infrastructure runs through thick forests, treacherous mountainous terrain, and across massive water bodies apart from traversing through populated human settlement areas, due to this rail infrastructure monitoring is not straight forward. In the event of any damage to the rail track structure the repair involves a complex process in comparison to road repairs. In addition, predicting the likely damage in a foreseen future is tougher in rail infrastructure by physical examination in comparison with monitoring road condition. Damage to the rail infrastructure can lead to huge loss of life and property, if it goes undetected, here rail infrastructure refers to only rail tracks and rail coach wheels. A number of mechanisms for monitoring the rail infrastructure have appeared in the literature addressing various aspects. Classifying the rail traffic and determining rail rake length based on vibrations induced in rail tracks has been presented by the authors in [10]. The classification is intended to design further sophisticated systems for infrastructure monitoring taking into account the properties of the various rail traffic classes. Rail bridges are a significant aspect of the rail infrastructure, monitoring rail bridges and utilizing passing trains as data mules for relaying the sensed data have been presented in [11]. As rail infrastructure (here rail bridges) are usually remotely located with no possibility for reliable communicating the sensed data. Similarly, a rail infrastructure monitoring system has been proposed in [12], wherein a WSN is intended to work as an early warning system. The proposed method relies on communicating the sensed data-warning signals through WSN gateway to the relevant back-end authority using communication through cellular links or fiber-optical cables. Comparison between the related works and the presented contribution have been summarized in Table 6.1.

Table 6.1: Comparison of related works and presented contribution

Factors	Passive node mobility	Limited mobility	Dual application
Interaction among animals and their ecosystem [5]	×	×	×
Tail deer population monitoring [7]	×	✓	×
Elephant monitoring - proximity to human settlement [9]	×	×	×
Classifying rail traffic and determining rake length [10]	×	×	×
Rail infrastructure monitoring system [12]	×	×	×

Collectively Addressing Wildlife Monitoring and Rail Infrastructure

Often the utility of deploying WSNs has been to address a single application. The disadvantage of setting up the complete network infrastructure to address a single application is that it necessitates setting up the whole network all together again for addressing another application. In the aforesaid two broad application areas of WSNs, it can be observed that the application targeted by deploying the network intends to serve a specific purpose. However, with careful examination it can also be observed that certain applications are closely related, *e.g.*, WSNs for monitoring animal ecosystems could be utilized for monitoring forests. In a similar manner the two broad application areas of sensor networks, *i.e.*, wildlife monitoring and rail track monitoring have been considered independently in the literature. However, there are conditions that necessitate a collective consideration of these two non-related application areas, these conditions form the motivation for the proposed approach.

Conditions that form the basis for this collective approach to address these two areas are relevant specifically in the Indian context. India has a rail system spanning across the country, serving as a pivotal link for connecting the nook and corner of the nation. Across numerous places in the country, the rail system runs through forests, some of these are reserved forest areas. Necessity for wildlife and habitat monitoring applications stems from the fact that many wildlife species are endangered, and there is a drastic rise in the species facing a extinction threat. India is home to the endangered species Asian Elephant (*Elephas maximus*) among many others, unfortunately in the last couple of years many elephants have been overrun by speeding trains in stretches running through reserved forest areas. The concerned government authorities for wildlife protection and conservation in India have repeatedly recommended to the railway authorities for decreasing the speed of trains running through reserved forest areas. However, the rail authorities are not keen on lowering the maximum permissible speed limits for the trains plying through reserved forest areas, as this would impact their overall operational timings, it would also increase their operational expenditure. On the other hand, the rail authorities are interested in a rail track monitoring system that can help them in averting an accident, in the event of intentional damage done to the rail track infrastructure. Therefore, a system which can help in prevention of elephants being overrun by the trains and monitor the rail track condition at the same time is highly beneficial. Since, a WSN deployed to meet these applications would serve the objectives of the concerned authorities related with wildlife conservation and rail traffic, both would be willing to support its deployment in monetary terms. It should be noted that the wildlife aspect of the proposed approach is stated as *wildlife conservation* and not as wildlife monitoring to stress on the point that the proposed approach is intended to prevent elephants deaths, and thereby implicitly contribute in conserving them.

6.3 Proposed Approach

The proposed approach to serve the dual purpose stated earlier consists of entities that collectively form the overall system, entities that form the system are as follows [13]:

- Active sensing nodes
- Passive sensing nodes
- Deployment and delivery agent
- Regional base station
- Maintenance and repair

As implied by the name, active sensing nodes (ASNs) are responsible for carrying out the significant part of sensing and monitoring operation of the overall system. The ASNs are placed on both rail tracks (referred as left and right rail tracks) firmly such that they stay clear of rail track area covered by the rail wheel. The ASNs are housed in a secure package to prevent any likely damage to be caused by severe vibrations induced in the rail track by passing trains. The ASNs comprise of a radio transceiver unit, ultrasonic emitter or ultrasonic receiver (only some ASNs will have both emitter and receiver). The distribution of ultrasonic receiver and emitters on ASNs is intended to minimize their cost, and the cost of the overall deployed network. Additionally, the ASNs comprise of a piezoelectric crystal that serves the dual purpose as an energy

Figure 6.1: Herd of elephant crossing rail track in an Indian forest with passive sensing nodes (PSNs) (encircled) and permissible width of collection agent [14]

harvester utilizing the induced rail vibrations and for detecting the onset of vibrations, *i.e.*, detect the presence of an approaching train. An acoustic sensor setup on the ASNs helps in determining any sound emissions from the PSNs, and additionally ASNs also comprise of an infrasonic sound emitter. The ASNs are intended to communicate with each other and their communication radius R_c is considered as 12 m. The utilities of ASNs for deterring elephants and monitoring the rail health have been discussed in individual Sections 6.5 and 6.6 respectively.

The PSNs are not involved in active sensing, and only assist the ASNs in the overall sensing monitoring operation. The PSNs are deployed on both sides of the rail, on the region comprising the *ballast* of the rail track as shown in Fig. 6.1. The deployment and collection process of the the PSNs has been discussed in the subsequent section. The external casing of PSNs is such that it resembles the adjoining pebbles forming the ballast, therefore the casing of the PSNs is irregular in shape and texture. However, the casing has sufficient rigidity to prevent damage to internal circuitry, additionally, the casing would be made of iron. The casing houses a pressure based piezoelectric crystal, button cell, timer circuit, and sound emitter circuit. The pressure based piezoelectric crystal is adjusted to the pressure likely to be exerted by an elephant stepping on it, leading to its activation. In the event of witnessing a desired external pressure on the PSN, a sound emitter beeps for a duration as set in the internal timer circuit. The button cell provides any supplemental power that could be required by the sound emitter, in addition, to that supplied by pressure induced piezoelectric crystal. The sound emitter is intended to operate at a frequency range inaudible to elephants as the emitted sound is only intended to serve as an input for the acoustic sensor on the ASN.

6.4 Passive Mobility - Deployment and Collection Agent

The PSNs are deployed along the rail track on two sides by a rail engine that works as a deployment and collection agent. The rail engine has dispensing tubes on either side that spray the PSNs on the rail track. A set of four dispensing tubes would ensure a uniform distribution of PSNs on either side of the rail track as shown in the Fig. 6.2. It can be interpreted as passive mobility of the PSNs, since their utility in the overall network operations is governed by mobility of the rail engine, and they are deployed in the area of interest (AoI) by it. Collection of PSNs is carried out using a novel method utilizing the electromagnetic principle, irregular shaped rigid PSNs have an outer iron casing. For collecting the PSNs an electromagnetic board is mounted on both sides of the rear coach of the rail rake referred as a guard coach/brake-van. The board in folded and unfolded position has been shown in the Fig.

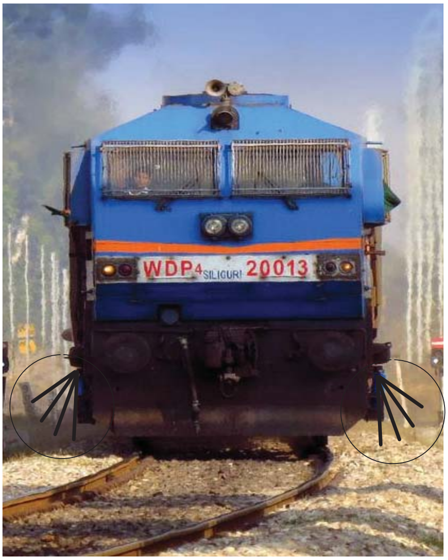

Figure 6.2: Rail engine - deployment agent
Spraying tubes (encircled)[15]

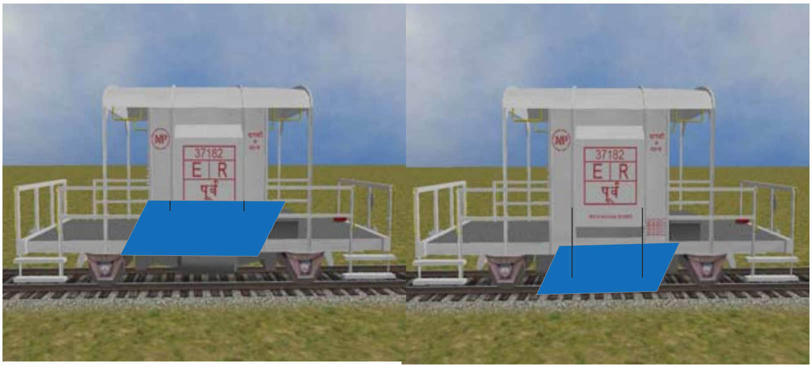

Figure 6.3: Electromagnetic board as collection agent on guard coach/brake-van

6.3. With the passage of current in the unfolded position the PSNs cling with the board due to magnetic attraction. Subsequent to collecting the PSNs the board retracts to folded position and current supply would be stopped, due to this the PSNs collect in a bag suspended under the retracted position of the board. As the two issues that are being addressed through the proposed approach are in Indian context, dimensions and other operational features of rail infrastructure considered here are applicable in the Indian context. The widely used rail gauge in India referred as *broad gauge* has a width of 1600 mm, maximum width of electromagnetic board is 2135 mm from the center of the rail track or 1335 mm from the edge of the rail as per the operational requirement for moving rail infrastructure [16]. This maximum permissible width restriction is imposed as the rail track have signalling and electric transmission fixtures in proximity to the rail tracks. However, the width of the electromagnetic board would be sufficient to cover the intended area on either side of the track, *i.e.*, ballast region of the rail track. The deployment/spraying of PSNs can be done by any rail engine pulled train passing through the designated AoI, collection will only be done by slower moving trains - goods train, this is necessitated as collection of PSNs using electromagnetic principle is not instantaneous and a slower moving train complements this attribute. Freight trains are expected to be utilized for this purpose as they have a lower sanctioned operational speed limit in comparison to passenger trains. A time difference of 12 hours between the deployment and collection of PSNs will be maintained considering their possible operational limits. Recollected PSNs are examined for any possible damage, and subsequent to rectification of possible damage the collected PSNs can be redeployed in the AoI. Recollection of deployed PSNs and redeployment prevent excessive accumulation of the PSNs in the ballast region of the rail tracks.

6.5 Wildlife Conservation

As stated earlier, one of the purposes of the combined approach is to protect elephants from being overrun by speeding trains. As an elephant steps on a passive sensing node (PSN) it activates the sound emitter. The emitted sound is in the frequency range 12 KHz to 20 KHz as this range is inaudible to elephants (audible to humans). The emitted sound is maintained in a frequency inaudible to the elephants, as it is intended to act only as an input to the ASNs, additionally, the emitted sound by PSNs can distract the elephants further towards the rail track. Emitted sound is picked up by acoustic sensors housed in the ASNs, it would be activated every minute to detect for any sound emission from PSNs. As a part of the daily routine, wandering in the forest for food and water, animals cover large spans of the forest (including elephants), and accordingly cross the rail line couple of times a day. It is undesirable to hinder the movement of elephants across the rail track in the absence of any approaching train. The piezoelectric crystal on the ASNs helps in determining an approaching train apart from utilizing the induced vibrations for energy harvesting. Therefore, the infrasonic sound emitter on the ASNs only emits a sound if the acoustic sensor reports sound emission from PSNs and the piezoelectric crystal detects an approaching train. An infrasonic sound emitter is utilized as elephants communicate in the infrasonic sound range, *i.e.*, 16Hz - 12 KHz. Elephants give distress calls in this frequency range and communicate long distances [9], [17].

6.6 Rail Track Monitoring

The ASNs collectively monitor the rail track, which is one of the purposes of the combined approach of deploying the sensor network. The deployment of ASNs to cover the rail track has been shown in Fig. 6.4, segments of rail tracks are usually welded together to form a section. In Indian Railway networks there are usually two types of welded rail sections, *i.e.*, short welded rail (SWR) and long welded rail (LWR). The SWR has a length of 36 m composed of three rail subsections each of 12 m length, while the LWR is a minimum of 250 m long [18]. In the proposed approach SWR based rail sections are considered as shown in Fig. 6.4 consisting of 5 SWR sections. A set of SWRs are intended to be terminated at a regional base station (RBS) on one or both side(s), depending on where the given section is placed in the overall rail track system.

The rail monitoring is intended to be carried out in two cycles namely odd and even. The ASNs are numbered from the edge of the rail, and their IDs are expected to justify their position on the track in reference to other nodes on the same track as well as the nodes on the other track (left and right pair of the rail tracks). As shown in Fig. 6.5, there are six ASNs placed equidistant and

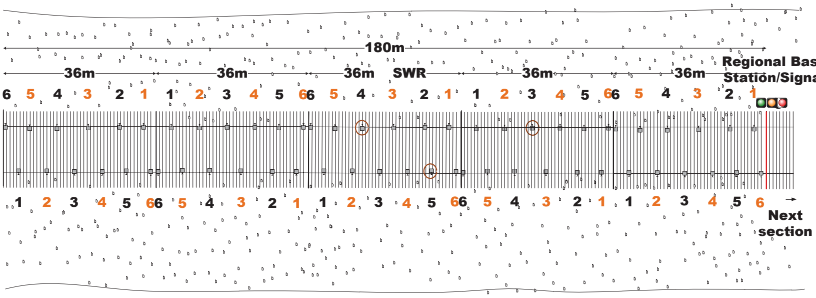

Figure 6.4: System as deployed on a set of SWRs, ASNs on rail track (encircled), PSNs on ballast

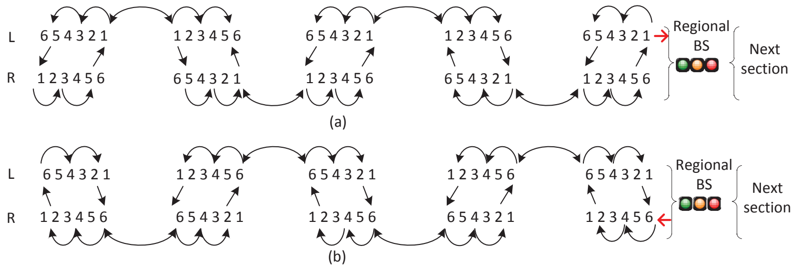

Figure 6.5: i) Odd (upper) and ii) even (lower) - monitoring cycles commencing and terminating at RBS

covering the entire length of the rail section. The ASNs have an address of the form, *e.g.*, 4AR that means the ASN is the fourth node on the right side rail in the *A* SWR section. The first node gains the address as the first node on the overall section once placed on the track, other nodes are expected to acquire their addresses by communicating with the first node placed on the track. The arrangement of ASNs on the two rails forms a criss - cross pattern that is intended for allowing nodes to communicate with nodes on the other side rail. The ASNs possess a communication range of 12 m, *i.e.*, a given ASN is capable of communicating with its two hop neighbour on the same rail, utilized in the odd and even cycle operation of rail monitoring. Only ASN1 and ASN6 nodes have an ultrasonic emitter apart from an ultrasonic receiver, this is intended to reduce the cost of an ASN unit as also stated earlier.

In order to demonstrate the operation of the monitoring system, consider that ASN1 on the right rail on the leftmost section starts the odd cycle, it emits an ultrasonic wave that is intended to be acknowledged by ASN3. Subsequently, ASN3 communicates with ASN5 on successfully receiving the ultrasonic wave emitted by ASN1, ASN5 also receives the wave initiated by ASN1. This is followed by communication of ASN5 with ASN1 on the other rail as shown in Fig. 6.5 (i). The left and right rail have been represented with symbols L and R in Fig. 6.5. The ASN1 on the left rail initiates communication in reverse direction communicating with ASN3, which in turn communicates with ASN5 on the left rail, subsequently for a normal cycle ASN5 communicates with ASN1, that in turn communicates with ASN3 and ASN5, and back to ASN1 on the left rail completing the odd cycle. The ASN1 on the left track will force trigger an even cycle if it does not hear from the ASN5 the initial message or hear back the message it conveyed through ASN3 and ASN5 on its own rail. In this sequence the even number nodes are involved following the sequence as shown in Fig. 6.5 (ii) for the left most section with ASN1 communicating with ASN6 on the right track to carry out a even cycle. The only difference compared to a routine even cycle is that ASN2 on the left track communicates with ASN1, as this cycle was initiated by it. If the even cycle reception is successful, it symbolizes faulty nodes on the odd cycle. Accordingly, ASN1 communicates with ASN1 on the adjoining SWR section. If both the odd and even cycles fail, ASN1 communicates with ASN1 of the adjoining section about an emergency condition, and this is relayed by all other nodes overriding any active cycles straight to the RBS. In a routine process the odd cycle commencement and completion take place at the RBS which subsequently initiates the even monitoring cycle as shown in Fig. 6.5. The even and odd cycle run collectively at intervals of 10 minutes at night and 15 minutes in the day. Monitoring at this periodic rate is considered sufficient to prevent any intentional damage to the rail track. The nodes synchronize, *i.e.*, correct clock drifts every few hours. Clock drift between the nodes can be tolerated for few hours as this is not a real time monitoring system, and the monitoring system is expected to alert the incoming traffic before hand by rail signalling. The RBS that serves as a representative for a given section of SWRs is expected to interface with rail signalling equipment to show the rail track condition with appropriate color signal, *i.e.*, green or red for permission to go or stop.

Maintenance and repair have been stated as an entity of the overall system as some ASNs require replacement, considering operational damage due to induced vibrations. All railway tracks are physically examined at least once every 8 hours in India by railway men. As elaborated earlier with a two cycle monitoring alternating between the set of ASNs used, the system has capacity to handle certain failed ASNs. The railway men carry spare sets of ASNs that can replace a faulty ASN. Nodes that are functional communicate about their neighbouring nodes that require replacement to a hand held device carried by the railway men that functions as a mobile BS, once it passes through their vicinity. The railway men also collect any PSNs lying in the ballast area beyond the region covered by the electromagnetic board.

6.7 Conclusions

The proposed collective approach offers a promising way to collectively address the two seemingly non related issues of wildlife conservation and rail track monitoring. The proposed approach stresses on an important observation to utilize WSNs for addressing multiple applications at the same time, instead of a dedicated WSN deployment to address an individual application. The enormous utility of utilizing passive node mobility in WSNs has been elaborated through novel node mobility provided in the proposed approach using rail engine/trains as a deployment and collection agent. The proposed approach requires extensive field verifications for its operational reliability. Specifically, to examine certain specific questions apart from the overall operation performance, such as the response of elephants to deter from the rail track with infrasonic sound emission from ASNs, and the precise frequency at which elephants are most deterred. Similarly, reliable spraying of PSNs across the two sides of the rail line by the rail engine, and subsequent reliable collection by the electromagnetic board mounted on brake-van/guard coach.

6.8 References

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Chapter 7

Conclusions and Future Works

Deployment of large scale wireless sensor networks (WSNs) for envisioned applications provides useful information about diverse physical parameters and aspects that are currently not covered by communication systems. The creation of Internet of Things (IoT) for an information rich future world depends heavily on WSNs deployed to sense and monitor in the most unexpected places, and supports a plethora of possible new applications. Utilization of mobile nodes offers diverse functionalities within the network and many WSNs are made feasible due to their use. On the other hand, effective utilization of mobile nodes has some operational constraints, that limit their possible utility for WSNs. This thesis addressed possible mechanisms for effective utilization of mobile nodes complying with operational constraints, detailed in the problem definition of the thesis in Section 1.4 of Chapter 1.

The thesis justifies, contrary to the common notion, that despite the operational expense (in monetary terms) to accomplish a functionality in the network, mobile nodes are better in performing them compared with static node. This observation has been presented in Chapter 2.

The possible use of node mobility for improving the coverage and the influence of various parameters governing the possible coverage enhancement have been presented in Chapter 3. The inter-parameter relations elaborated in this chapter are expected to collectively serve as a yardstick for network resource planning.

Coverage improvement in the area of interest (AoI) with clusters - cluster heads (CHs) governing the movement of mobile nodes under the constraints with no access to localization services, and only limited distance relocation capacity has been demonstrated in Chapter 4. The presented mechanism justifies that it is feasible to address more than one network attribute collectively using node mobility.

Utilizing flying sensor nodes for collecting data from a deployed network as put forward in Chapter 5 justifies that mobile node can serve specific functionalities in the network without hampering any other network operations. It is stressed through this work that possible uses of an entity in the network can be for a purpose which is completely different from its normative use, *i.e.*, using miniature aerial vehicle (MAV) for data collection instead of sensing and monitoring. Additionally, the proposed mechanism allows the network to maintain a clustered structure in spite of the base station (BS) located far from the AoI region. Additionally, the proposed mechanism is well suited for sensor network deployments in harsh - inhabitable terrain.

Chapter 6 stresses on an important observation that with wise planning a single WSN deployment can be be utilized to address more than one application. This way the resources incurred for deploying the network could be better optimized, as well as the possible acceptability of the application(s) addressed increases manifold as the possible stakeholders increases. Passive node mobility in the network provided through a deployment and collection agent in the form of rail engine/trains, demonstrates that passive node mobility is limited just by imagination.

In summary it can be concluded that, this thesis validates and justifies the hypothesis stated in Section 1.4.1 of Chapter 1.

Future Works

Based on the research work presented in this thesis, there are certain further directions (future work) that can be explored. Techno-economic evaluation of other aspects of WSNs can be explored, if relevant models to replicate the behavior could be enacted. The presented coverage improvement mechanism relies on a partial centralized approach (matching of the clusters). Instead of a centralized implementation, if the overall decision making is done amongst neighboring clusters in a distributed manner the proposed approach is more realistic to meet the deployment conditions. Possible passive mobility mechanisms can be utilized for addressing WSNs applications that cannot be fulfilled utilizing the existing and proposed node mobility mechanisms (active and passive). The passive node mobility based proposed approach for rail monitoring and wildlife conservation requires extensive field validation and this is a foreseen further work. The envisioned applications using node mobility and remote deployment in harsh inhabitable terrain involve hundreds of sensor nodes, appropriate re-usability or recycling of sensor nodes is necessitated to prevent accumulation of e-waste, and prevent possible environmental damage. Proper mitigation mechanisms that ensure that possible environmental damage with large scale deployments is averted are required to be explored. Additionally, mechanisms that reduce the number of nodes required in the first place are beneficial. This could be done by applying intelligent data analytics on data from sensor nodes. Utilization of environment friendly nodes, and effective energy harvesting mechanisms making the nodes energy neutral are also required to be studied further.

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