THE EFFECTS OF HIERARCHY
ON MOBILE WIRELESS SENSOR NETWORK COVERAGE

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ABSTRACT

THE EFFECTS OF HIERARCHY ON

MOBILE WIRELESS SENSOR NETWORK COVERAGE

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Due to their economic potential and widespread application areas, wireless sensor networks have emerged as an active research topic during the last five years. One of the fundamental challenges in wireless sensor network research is the provision of sufficient coverage while maintaining energy efficiency and longevity under sensor mobility.

The purpose of this thesis is to observe the coverage and energy consumption dynamics of a mobile wireless sensor network in a hierarchical architecture. To achieve this goal we implemented a simulation environment with flat and hierarchical topologies.

Defining performance metrics and network parameters we performed simulations in MATLAB test-bed. With the help of results obtained from simulations and performance metrics' relation to networks parameters we investigated the effect of hierarchical organization on mobile wireless sensor network coverage.

Keywords: Coverage, Wireless Sensor Networks, Hierarchy, Mobility

ÖZ

HİYERARŞİNİN HAREKETLİ KABLOSUZ ALGILAYICI AĞLARIN
KAPSAMA ALANI ÜZERİNDEKİ ETKİSİ

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Sahip oldukları ekonomik potansiyel ve geniş kullanım alanları sebebiyle son beş yılda kablosuz algılayıcı ağlar önemli bir araştırma konusu olarak ortaya çıkmıştır. Günümüzde kablosuz algılayıcı ağların en önemli problemlerinden birisi, hareketli algılayıcılar söz konusu olduğunda, ağın enerji verimliliği ve uzun ömürlülüğünü muhafaza ederken yeterli kapsamanın sağlanmasıdır.

Bu tezin amacı hareketli kablosuz algılayıcı ağı hiyerarşik olarak düzenlemenin enerji verimliliğini ve / veya uzun ömürlülüğü geliştirip geliştirmediğini gözlemlemektir. Bu hedefe ulaşmak için düz ve hiyerarşik topolojiler içeren bir benzetim ortamı önerilmiş, performans ölçüleri ve ağ parametreleri tanımlanıp MATLAB ile kurulmuş sınama ortamında benzetimler gerçekleştirilmiştir. Benzetimlerden elde edilen performans ölçümleri ve bu ölçümlerin ağ parametreleri ile olan ilişkileri yardımıyla hiyerarşik düzenlemenin hareketli kablosuz algılayıcı ağların kapsama alanı üzerindeki etkisi incelenmiştir.

Anahtar Sözcükler: Kapsama Alanı, Kablosuz Algılayıcı Ağlar, Hiyerarşi, Hareketlilik

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LIST OF ABBREVIATIONS

2D	:	2 Dimensional
3D	:	3 Dimensional
AODV	:	Ad-hoc On-demand Distance Vector
DES	:	Discrete Event Simulation
DSR	:	Dynamic Source Routing
EU	:	Energy Unit
GB	:	Giga Byte
GHz	:	Giga Hertz
GPS	:	Global Positioning System
MANET	:	Mobile Ad-hoc Network
MEMS	:	Micro-Electro-Mechanical Systems
pdf	:	Probability Distribution Function
QoS	:	Quality of Service
RAM	:	Random Access Memory
RF	:	Radio Frequency
WLAN	:	Wireless Local Area Network
WSN	:	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

Recent advances in MEMS technologies, wireless communication and miniaturization have led to the emergence of small, low power, inexpensive sensors with processing and storage capacities sufficient for diverse applications. Thus the vision of a physical world embedded with networked sensors and actuators is becoming a reality. The interweaving of sensing with communication, computation with control and decision making has numerous applications with which wireless sensor networks (WSN) transform our lives [1,2].

Generally, WSNs are comprised of a large number of densely deployed, error prone sensors with limited power. The sensors are equipped with wireless communication, sensing, signal processing and data networking capabilities. The collaboration of sensors makes WSNs suitable for measuring the value of a physical phenomena, detecting and responding to occurrence of an event, classifying a detected object, and tracking an object [1].

In a typical WSN architecture, sensors scattered in the region of interest collect data and route it to the sink. And the sink communicates with the end user via a wired or satellite network as shown in Figure 1.1.

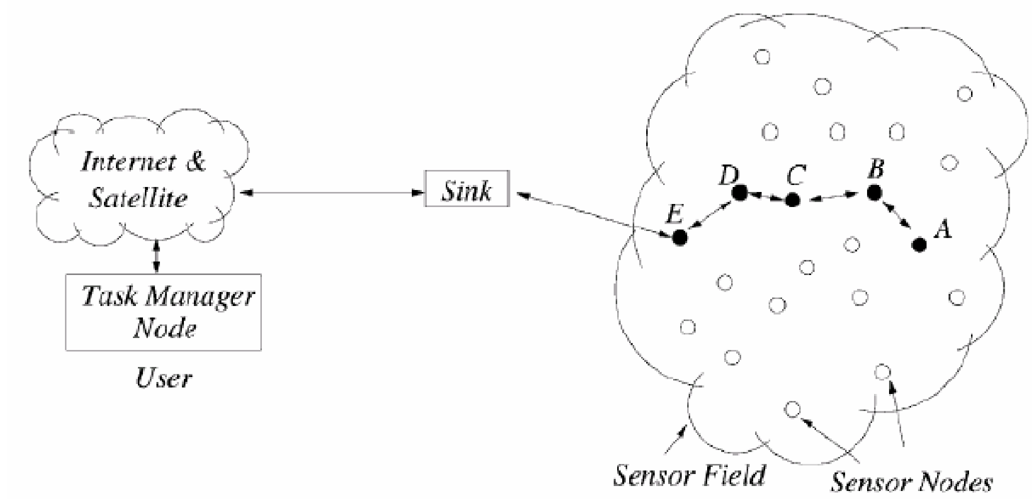

Figure 1.1: A Typical WSN Scheme [1]

Research on WSN has been steadily expanding for the last 5 years. Among the most active research topics are the relation between coverage, i.e., how well an area of interest is monitored by the network, sensor deployment/density, and energy efficiency [3-6].

WSNs are usually composed of sensor nodes equipped with limited power supplies that generally can not be replenished; therefore all operational requirements, such as coverage, must be met with efficient power consumption. A decrease in the number of available sensor nodes, due to power depletion and other effects such as physical damage, can seriously degrade the network performance in terms of coverage and connectivity. Some previous studies have addressed provision of coverage but most of them assume stationary nature for sensors [7-9], the few that consider mobility of sensors assume a flat network topology [3,10].

The effects of mobility and hierarchy on WSN coverage depend on various parameters such as node velocity, mobility pattern, geometrical properties of monitored area, transmission medium, sensing and coverage ranges of nodes. The degree of randomness inherent to some of these parameters further complicates the analytical investigation of the relation between coverage and mobility / hierarchy. In this work we describe a flat and a hierarchical architecture for mobile WSNs and, through simulations, we analyze the effect of introducing hierarchy and location awareness with regard to sensing coverage and energy efficiency. In our scheme, sensing coverage is characterized by the time in which the mobile WSN senses all stationary target points distributed within the monitored area. Energy efficiency, on the other hand, is measured by the total amount of energy consumed by the mobile WSN in order to sense all target points. By utilizing transmission ranges that are just sufficient for ensuring connectivity to the sink, we narrowed the scope of the work down to coverage only.

The objective of this thesis is to observe the effect of introducing hierarchy on the coverage of mobile WSNs, and to analyze the relation between network parameters and coverage properties. The hierarchy is introduced via a set of relay nodes which perform no sensing but probe other nodes to sense the environment.

In particular, we measure the network performance using total coverage time and the energy consumed until the area is covered. These measures usually display conflicting effects. In general changing a network parameter, like transmission power, decreases coverage time and it tends to increase energy consumption.

The thesis is organized as follows:

Chapter 2 briefly presents basics of WSNs and some applications. The chapter includes a detailed survey on WSN coverage, hierarchical architectures in WSNs, and mobility models in mobile network research.

Chapter 3 describes the problem we analyzed in the thesis and its context, and states the objective of the study together with assumptions.

Chapter 4 covers the details of the design, development, and implementation of the simulation environment.

Chapter 5 demonstrates simulation results and plots, and presents their analysis.

Chapter 6 concludes by summarizing the findings and contributions of the work.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Wireless Sensor Networks (WSN)

A WSN is a network made up of many sensors each containing units of battery, RF adapter, microcontroller, and sensor board. In general a sensor node is capable of sensing a physical quantity, processing and storing that information and communicating with other nodes. WSNs have ad-hoc nature and the nodes self-organize, rather than depending on an infrastructure. Due to their limited battery life, nodes generally spend most of their time in a low-power mode. Yet, WSNs outperform conventional sensor systems which use large and expensive macrosensors linked to end user with wires. With large number of densely deployed nodes, WSNs are fault tolerant and provide greater accuracy. Furthermore they are less expensive because of lower unit price of nodes and the ease of their deployment [2].

Some of WSN applications are as follows:

- *Environmental applications:* soil composition detection and precise agriculture, ecosystem monitoring, flood detection, exploration of minerals and reserves etc. [1,11-13].

- *Military applications:* reconnaissance, unmanned robotic vehicles, targeting systems, remote sensing of nuclear, chemical and biological weapons [1,14].
- *Medical applications:* artificial retina, organ monitoring for organ transplantation, general health monitoring, cancer detection for high risk persons, glucose level monitoring for diabetes patients [1,15].
- *Commercial applications:* remote metering, smart spaces, local climate control in large office buildings, automatic warehouse inventory tracking, robot control and factory instrumentation, structural health monitoring, [1,15,16].
- *Social applications:* smart kindergartens, interactive museums and voting platforms, traffic monitoring and smart roads [17,18].
- *Emergency applications:* identification of trapped personnel, detection of victims, potential hazards and sources of emergency detection and tracking of targets, identification of intruders, fire detection [14,19].
- *Scientific applications:* space exploration, chemical process control, geophysical studies [1,12,16].

Some of the challenges for WSN research are: limited resources, error-prone communication medium, dynamic topologies, adverse environment, requirement for ad hoc architecture and unattended operation, massive and random deployment, data safety and privacy, data redundancy, and quality of service (QoS) restrictions etc. [11,14,20,21].

Constrained by their limited physical size, sensor nodes can only have small batteries as energy supply, and their batteries are generally neither rechargeable nor replaceable. Due to the same reasons, computational and storage capacities of a sensor are restricted. These facts require WSN to be power efficient so as to maximize network lifetime. Furthermore WSNs, in many cases, operate under severe environmental conditions such as high pressure, low temperature, high moisture (even in water) etc. Even in the case of stationary nodes, topology of the network may change frequently. In addition, a WSN can be randomly dropped and left to operate in hazardous or inaccessible regions, yet it should configure itself without human intervention while ensuring operational functions. If sensors are densely deployed, redundant data sensed in the neighborhood would waste the scarce bandwidth and energy. Some applications with strict QoS requirements further increase the burden on the WSN [2].

To overcome such challenges researchers strive to achieve smaller microsensor devices, adaptability, fault tolerance, scalable and flexible protocols, resource efficient designs and self configuration.

Despite significant progress in the development of WSNs, several issues remain to be explored further [2]:

- Development and improvement of tiny hardware and compatible software
- Efficient protocols and algorithms for WSNs with heterogeneous sensor nodes
- Security issues
- Analytical models to evaluate and predict WSNs' performance characteristics

- Optimization of sensor node selection and allocation, discovery, localization, and network diagnosis in order to address deployment, coverage, connectivity, energy and communication efficiency
- Protocols with mobility consideration and dynamic group communications

2.2 Hierarchical Architectures in WSN

The notion of a flat network with interchangeable nodes seems appealing. However, in real life WSNs are seldom flat either due to their phased deployment (newly added sensors tend to have higher processing and storage capacity) or different task requirements [22]. In a hierarchical WSN functions such as sensing, communication, and computation are unevenly distributed among the nodes; energy intensive functions are assigned to resource rich sensors. Hierarchical WSNs are composed of heterogeneous sensors where heterogeneity stems from either physical or logical characteristics of the node. A WSN which is made up of sensors with differing characteristics and capabilities are said to have physical hierarchy; e.g. some nodes have long range communication and processing capability with no sensing and others have sensing and short range communication capability. On the other hand, a WSN can be made up of same physical nodes and yet be hierarchical; some of the sensors may perform services on behalf of the other sensors and take on the burden of computation, data and routing aggregation etc., leading to a functional hierarchy. In such networks logical roles may need to be periodically rotated to ensure fairness and smooth operation [22].

Hierarchy can be introduced to a WSN by manually configuring the topology via software (logical hierarchy) and hardware (physical hierarchy) installed on the sensors. However, under ad hoc deployment autonomous organization of nodes into hierarchies is highly desirable. Another method to form a hierarchical structure is to get some nodes to carry the burden of traffic, computation etc. in expense of routing delay. Readily available ad hoc routing protocols such as AODV may be altered so as to take into account node power and other metrics while building up routes [22]. Forming clustered architecture is another way of imposing hierarchy on the system. A cluster is comprised of a small group of spatially close nodes and a cluster head. In a cluster the data collected by sensors are transmitted to the cluster head and cluster head performs computation, data fusion and communicates the result to another cluster head or a base station [22].

In practice, hierarchical architectures are preferred over flat architectures for their cost-effectiveness, scalability and prolonged lifetime [22-27]. Various applications require different sensors to be deployed having dissimilar cost of purchase, maintenance, and installation. The sensors in a WSN are required to carry out different tasks in most of the applications; some nodes perform data analysis and storage which are resource hungry while some others are only assigned to perform sensing and short range transmission. If sensors are kept identical then the software and hardware of the nodes have to meet minimum resource requirements necessary for all tasks. Thus the total cost of network would increase. By allocating required resources only where they are utilized, hierarchical WSN increases return on investment to render the WSN feasible [22].

Another contribution of hierarchical architecture is the improved network operation time. Power consumption of sensors varies according to performed functions; sensing and computation consume less battery whereas communication depletes batteries faster [28]. The optimal hardware also differs in accordance with the tasks; faster processors are more energy efficient for computation intensive tasks whereas slow processors are more effective for sensing tasks [22]. Hierarchical WSNs provide the chance to select optimal hardware and software configuration for sensors with different tasks. Additionally, in hierarchical WSNs nodes communicate data over shorter distances, as a result the energy spent for transmission tends to be substantially lower than energy spent for transmission in flat topologies where each node directly communicates to the sink [26]. The power savings brought about by using hierarchy result in longer network operation time.

It is known that bandwidth in flat WSNs does not scale; [29] analytically proves that per node throughput of a flat WSN is $O(1/\sqrt{n})$ where n is the number of nodes. Experimental results demonstrate that the per node throughput decays even faster as $c/n^{1.68}$, where c is a constant [22]. For the case of a clustered hierarchical WSN high correlation between data gathered from neighboring nodes can be utilized to achieve higher rate of data compression [30]. Processing and digesting redundant data reduces the number of packets to be sent [22]. [31] shows that if the number of clusters grow as $\sqrt{n}$, where n is the number of nodes, the introduction of hierarchy in via a network of cluster heads causes the network capacity grow linearly as new nodes are deployed. [25]

evaluates the performance of DSR for WSNs with hierarchical and flat topologies; based on simulations they demonstrate significant capacity increase in hierarchical topology. Regarding the spatial aspects of scaling a flat WSN results in low density and poor connectivity, however in a hierarchical counterpart that includes high level nodes with long transmission ranges improves connectivity thus positively effects spatial scaling [22].

Although in many cases WSNs with hierarchical topologies outperform WSNs with flat topologies, introduction of hierarchy may have adverse effects on some other aspects of the network. With the provision of clusters and hierarchy, hotspots are introduced to the network and resource rich nodes may attract traffic and inadvertently drain energy of low powered neighbors leading to a decrease in the network lifetime [22]. Additional drawbacks might originate from intrinsic inefficiencies of hierarchical structure; e.g. two neighboring nodes can not directly communicate if they belong to different clusters. Hierarchy formation induces overhead which may further increase under high mobility.

2.3 WSN Coverage

Due to the variety of sensors and their applications, coverage is subject to different interpretations. But in general, the coverage of a sensor network is defined as a QoS measure characterizing the quality of surveillance that the network can provide in a designated region [3,19]. Coverage has different types such as area, point and barrier coverage. In area coverage the goal of WSN is to cover an area constrained by some limiting factors like sensing quality, connectivity etc. In point coverage the objective is to cover either a predetermined or a randomly chosen set of points. Barrier coverage is defined as the probability that an intruder can wonder around the monitored area without being detected by any of the sensors [4].

Based on the objectives to be achieved, different coverage problems can be formulated. Among the most common are choosing an optimum deployment method, optimizing sensing and communication ranges, providing energy efficiency and connectivity, maximizing WSN lifetime, minimizing the number of sensors etc. [4]. However defined, coverage is an active area of research in WSNs [5-10,32,33].

Focusing on barrier coverage, [19] investigates coverage under deterministic and stochastic approaches; the first approach stipulates a static network to be deployed according to a predefined shape whereas the latter assumes a stochastic random distribution of sensors. In WSN coverage literature, [19] is one of the first to combine computational geometry constructs (i.e., *Voronoi diagrams* and *Delaunay triangulation*) and graph theoretical algorithmic techniques. *Voronoi diagram* of a set of discrete sensors partitions the plane (in 2D) into a set of convex polygons in such a way that any point that falls inside a polygon are closest to only one sensor and there is only one sensor in the polygon, thus the diagram produces polygons with edges that are equidistant from neighboring sensors. *Delaunay triangulation*, on the other hand, is obtained by connecting the sensors in Voronoi diagram whose polygons share a common edge [19]. The dotted lines in Figure 2.3.1 correspond to Voronoi diagram and continuous lines correspond to Delaunay triangulation.

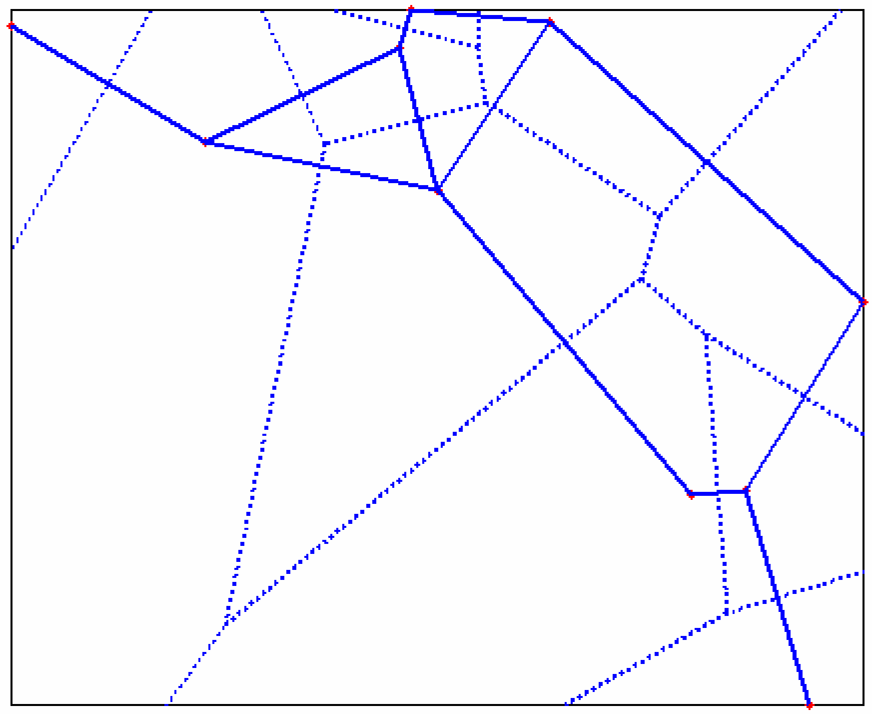

Figure 2.3.1: Voronoi Diagram and Delaunay Triangulation

In [19] algorithms for the determination of *maximal breach path* and *maximal support path* are proposed. *Maximal breach path* is the path between two points which maximizes the distance between any point on the path and the closest sensor. In a similar manner *maximal support path* is the path which minimizes the distance between any point on the path and the closest sensor. [19] proves that maximal breach path lies on line segments of Voronoi diagrams and maximal support path lies on line segments of Delaunay triangulation.

The formal justification of the aforementioned claims is presented in [7]. [7] mainly focuses on the *best coverage problem* (which is shown to be the same as maximal support path problem introduced in [19]) and tries to design localized algorithms to find a path connecting two points which maximizes observability of all points on the path. The authors assume static sensor nodes each of which knows its location either through low-power Global Positioning System (GPS) receiver or though ad hoc location detection algorithms based on incoming signal delay of neighbors [34-36].

In [8], coverage is formulated as a decision problem which aims to determine whether every point in the service area of a WSN is covered by at least k sensors, where k is a given parameter. The motivations of the work in [8] are to prolong lifetime of the network and to detect insufficiently covered areas. Some of the sensors sharing common sensing regions and tasks can be put alternatingly to sleep mode to save energy, while new sensors are being deployed to replenish depleted regions. The paper proposes a novel and decentralized method for the solution of k-coverage problem, and introduces the concept of *perimeter-coverage*. A point residing on the perimeter of a sensor is said to be *perimeter-covered* if this point is within the sensing range of another sensor. Instead of determining the coverage of sub-regions, the algorithm first determines the coverage of each sensor's sensing perimeter then relates perimeter-coverage property to coverage of entire area. Authors demonstrate that the same method can be extended to accommodate dissimilar sensing ranges for each sensor, and irregular sensing regions.

[5] suggests a static sensor deployment algorithm which takes both coverage and connectivity of the nodes into account. The work considers the sensing field as an arbitrary shaped region with obstacles. The approach presented in the paper partitions the sensing region into sub-regions based on the geometrical shapes of the region and then deploys sensors in sub-regions. Authors do not assume any relationship between sensing and coverage ranges, or any predetermined shape for obstacles. A point is defined to be covered by a sensor if it is within the sensing range of a sensor and line of sight exists between the sensor and the point, likewise two sensors are defined to be connected if they are within communication range of each other and line of sight exists between them. Under different relations between sensing and communication ranges, the deployment algorithm proposed in [5] is shown to require fewer sensors to achieve full coverage of monitored area compared to two native deployment approaches; *connectivity first* and *coverage first* methods.

Coverage is closely related with issues such as connectivity, power awareness, and network reconfiguration. In many applications long network life time is sought, where network lifetime is defined as the time until all sensors deplete their batteries or the network can no longer meet acceptable level of QoS. When coverage level is a constraint, network lifetime can be increased by turning off nodes that do not contribute towards coverage. [32] proposes a method to determine the optimal number of sensors to switch to sleep mode while meeting coverage requirements. The method computes coverage through central angles of nodes instead of coverage area, where both sensing and communication range of sensor nodes are equal. The nodes decide on going off-duty or on-duty based on the information gathered from the neighbor nodes. If a node calculates that on-duty neighbors can monitor its sensing area then the node turns itself off. To circumvent situations in which two neighboring nodes jeopardize coverage by dozing at the very same time, random back-off time is introduced. An off-duty node wakes after sleeping for an amount of time and probes its neighborhood to determine whether its sensing range is monitored by neighbor nodes. If sensing range is covered by other nodes then it sleeps again, otherwise it goes on-duty.

Building on [32], [6] proposes an “Optimal Coverage Preserving Scheme”. The method in [32] requires global clock synchronization and back-off times do not guarantee the absence of coverage breaches. To overcome these, [6] proposes a method to improve the calculation of the perimeter coverage, the decision mechanism, and the wake up strategy. The guarantee on coverage is achieved at the expense of message redundancy in the initial setup phase of the network. The wake up strategy, on the other hand, assumes that a low battery on-duty sensor broadcasts a wake up message to awaken neighboring off-duty nodes. While eliminating chances of accidentally allowing uncovered regions, this solution wastes energy by requiring the channel to be sensed even when the nodes are off-duty. Nevertheless sensing consumes much less energy than transmitting a message [4].

Some WSN applications may require dynamic coverage requirements due to changes in environmental conditions. For instance a surveillance WSN may initially require a low degree of coverage until an intruder is suspected, but upon suspicion of an intruder, network may have to reorganize itself to closely track the target [33]. In [33] a protocol that can dynamically configure a WSN to achieve certain degrees of coverage and connectivity is devised. In addition, geometrical analysis of relationship between connectivity and coverage is presented. The work shows that when communication range is at least twice the sensing range coverage implies connectivity for static WSNs, the same observation is also emphasized in [9]. In the protocol proposed in [33], the nodes execute an eligibility algorithm to determine whether they can sleep or not, however this algorithm requires information about the locations of all active neighbors. Such a neighborhood table is based on beacons of communicating neighbors. A sleeping node enters listening mode after its sleep time expires, and based on the beacons received in the listening period it decides either to sleep again or to enter active mode. This algorithm is valid only when communication range is at least twice the sensing range, otherwise the protocol needs to be integrated with a connectivity maintenance algorithm.

The "Optimal Geographical Density Control" algorithm proposed in [9] maintains a degree of sensing coverage and connectivity with minimum number of active sensors in a WSN. But, it is not designed to accommodate different levels of coverage intensity. The authors argue that if nodes have different sensing ranges the number of active nodes in the area may not be related to the power consumption, however the overlap of each node's monitored region is still a valid indicator for measuring power consumption in the network. [9] proves that minimizing overlap is equivalent to minimizing number of active nodes when all nodes have the same sensing range. The introduced algorithm requires global time synchronization because time is divided into slots and it assumes communication range to be greater than twice the sensing range. At the beginning of each round sensors wake up to an undecided state and by the end of the round active sensors are elected. When a sensor receives a power-on message it sleeps if its power is below a threshold, otherwise it checks if its coverage area is covered by neighbors. If so, it sleeps, otherwise it activates and broadcast a power on message. This scheme requires the nodes to know their global locations or their locations relative to their neighbors.

When a WSN is comprised of stationary nodes, the coverage depends on the initial deployment of the sensor nodes. Should nodes be mobile, however, coverage also depends on the movements. In recent years there have been many applications where sensors are mounted on mobile platforms such as mobile robots. One of the interesting problems in mobility in WSN is finding efficient algorithms to relocate sensor nodes in order to improve network coverage [3,10]. In essence, these works employ sensor mobility to achieve a new but stationary configuration that enhances coverage after sensors settle in their new locations.

Rather than attempting to attain a better network configuration as the end result of sensor movement, [3] analyzes and evaluates the dynamic aspects of network coverage that depend on sensor mobility. A particular coverage aspect originating from mobility is that previously uncovered areas become covered as sensors move, as a consequence a location is not always covered but instead it alternates between being covered and uncovered. Another coverage aspect is that intrusion detection capability of WSN is significantly enhanced under mobility: an undetected intruder will never be detected in a static WSN if it stays stationary or moves along an uncovered path. In a mobile WSN on the other hand intruder is more likely to be detected as sensors move about. [3] demonstrates that, as sensors patrol, the ratio of covered area to entire area remains unchanged, yet the area being covered during a time interval is improved. Authors identify coverage and covering time tradeoff by the fraction of time a location is covered and prove that this tradeoff is independent of sensor mobility. [3] models the initial deployment of sensor nodes by a Poisson Boolean model $B(\lambda,r)$ where λ is sensor density and r is sensing range. The random mobility of sensors assigns to each sensor a random direction θ in a sub-interval of $[0, 2\pi)$ with a probability density function $f(\theta)$ and speed is chosen from an interval of $[0, v_{max}]$ with a probability density function $f(v)$. The work analyzes the relation between the detection time and the target and sensor velocities through simulations and it is observed that the optimal sensor mobility strategy is to move uniformly at random in all directions. The corresponding mobility strategy for the intruder is shown to be staying still in order to postpone detection time.

Mobility strategies utilized in WSN literature are either deterministic or probabilistic. In deterministic approaches a region is partitioned into pieces and these sub-regions becomes home area of the sensor node. A node patrols in its home area with a deterministic pattern. [10] discusses random mobility strategies in terms of coverage efficiency, communication efficiency and reliability. The work studies the distribution of detection time of a slowly moving target under Brownian motion random mobility model for the sensors and the work can be extended to 3D domain as well [10].

2.4 Mobility Models for Mobile Networks

In wireless computer and communication networks the mobility of users plays an important role in the determination of algorithm and protocol validity and in performance evaluation of the communication system [37,38]. For the case of cellular networks end user's mobility behavior has a direct impact on signaling traffic for handover and location management which influence database query loads, channel holding time and call blocking and dropping probability [37]. On the other hand mobile ad hoc networks (MANET), having dynamic topology and no preexisting communication infrastructure, are affected by end user mobility in terms of link change rate, link and path duration, energy consumption and network performance [39-41].

Although real life usage of a mobile system can provide valuable insight, unfortunately it can not form a basis for experimentation because real movement in physical world is nondeterministic and unrepeatable [42]. At the moment, a universal model encompassing real node movements in MANET environment is lacking, as a consequence, probabilistic properties of MANETs can not be studied without simplifying assumptions [37,43,44]. However, there are researches on trace based mobility models in wireless local area networks (WLAN) and cellular networks [39]. To realistically mimic node movements in MANETs numerous synthetic models are proposed [37,38,40,41,43].

In the literature, synthetic mobility models for MANETs are generally classified according to two independent criteria; a node's degree of dependence on other nodes [37] and the movement's degree of randomness [39]. According to the first classification the models are categorized as entity and group mobility models, and according to the latter they are categorized as trace based, constrained topology based and statistical mobility models. In entity mobility models each node moves independently of the other nodes, whereas in group mobility model nodes move in groups [39]. In trace based mobility models nodes are bound to move to predetermined destinations with predetermined velocities. Constrained topology based models relatively relax the restrictions on the movement of nodes; nodes are bound to move along streets, paths etc. but at the crossings they can randomly alter their velocities in a limited way. Finally in statistical mobility models nodes are allowed to randomly move anywhere with any velocity [45].

One of the oldest and the simplest mobility models used in MANET research is the *Random Walk Mobility Model* [37,46]. In the literature this model is sometimes referred to as Brownian motion due to its resemblance to random movement of gas particles. In this mobility model the node choose a random direction from the interval of $[0,2\pi]$ and a random speed from the interval of $[v_{min}, v_{max}]$ in accordance with a uniform probability distribution function (pdf) (for both direction and speed), then the node moves with this velocity either for a predetermined time or for a predetermined distance. After the time elapses or the distance is traveled the node chooses another couple of direction and speed in the same manner. Should node try to cross the boundary of simulation area it bounces off the boundary into the area with the same speed and a corresponding reflection direction [37].

The most commonly used mobility model in MANET research is the *Random Waypoint Model*. The model hads become so popular that [42] claims that Random Waypoint Model has become de facto standard in the research. In this model the node chooses a random point within the simulation area and a speed from an interval of [v_{min}, v_{max}]. In general the destination (waypoint) and the speed are selected randomly according to uniform pdfs (probability distribution function). Then the node moves to its destination with the chosen speed. Upon reaching its destination, the node waits for a random amount of time chosen from an interval of [t_{min}, t_{max}] then chooses another waypoint and speed as described above [37]. Some extensions to Random Waypoint Model are *Soccer Player Model* and *Homing Pigeon Model* described in [38]. Both models are very similar to Random Waypoint Model. In Soccer Player Model the node selects a random point within the simulation area with a pdf in which probability of selecting a point is inversely proportional to the square of its distance. After choosing its destination, in accordance with a uniform pdf the node draws a speed from the interval [v_{min}, v_{max}] and moves towards its destination with the chosen speed. Once node reaches the destination it waits for a random amount of time drawn from the interval [t_{min}, t_{max}] and repeats the process. Homing Pigeon Model is almost the same as Soccer Player Model except that in Homing Pigeon Model every node has a stationary home location which does not change during the entire simulation. And in the pdf utilized, probability of selecting a point is inversely proportional to the square of its home location distance.

Another derivative of Random Waypoint Model is *Random Direction Model*. In this model the node in the simulation area chooses a random direction from the interval of [0,2π] and a random speed as in Random Waypoint Model and then the node moves until it reaches the boundary of the simulation area. The node rests on the boundary for a given time and then it chooses an appropriate direction and speed as before and repeats the pattern [37].

Aforementioned mobility models are non-smooth in the sense that sudden stops and sharp turns of a node are possible. To eliminate such abrupt changes *Gauss Markov Mobility Model* was proposed. In this model the node is assigned speed and direction at the beginning. At fixed intervals of time (t) the speed and direction of the node is updated based on its previous speed and direction. Namely the speed and direction of the node at instant t depends on the nodes speed and direction at instant t-1. Following equations are used to calculate speed and direction [37]:

$$s_t = \alpha s_{t-1} + (1-\alpha)\bar{s} + \sqrt{(1-\alpha^2)s_{x_{t-1}}}\,; \qquad \text{(Equation 2.4.1)}$$

$$\theta_t = \alpha \theta_{t-1} + (1-\alpha)\bar{\theta} + \sqrt{(1-\alpha^2)\theta_{x_{t-1}}}\,; \qquad \text{(Equation 2.4.2)}$$

where s_t and θ_t are speed and direction at t instant respectively, α is a randomness tuning parameter and $0 \le \alpha \le 1$, $\bar{s}$ and $\bar{\theta}$ are long run speed and direction averages, finally $s_{x_{t-1}}$ and $\theta_{x_{t-1}}$ are random variables from a Gaussian distribution. In above formulas α = 0 and α = 1 corresponds to Brownian motion and linear motion respectively. When the node gets close to boundary edges $\bar{\theta}$ is modified to push the node into the center of simulation area [37].

Above mentioned mobility methods were purely probabilistic, however MANETs are required to operate in constrained topologies as well. Several mobility models with constraints on the mobility pattern are demonstrated in [46]. *Location Model* is an extension of Random Waypoint Model and assumes that not all but certain points in a simulation area are visited by the nodes. A node does not randomly pick a waypoint but rather picks a destination from a set of predetermined locations, the rest of the model is same as the original Random Waypoint Model [46]. *Home-work Model* is similar to Location Model but the set of possible destination locations is further reduced to capture the fact that people frequently travel to only a few places. In both of the models destination locations are selected randomly with a uniform pdf. In *Path Model* there are paths connecting specific locations. A node at any specific location can not designate any other location in the simulation area as its waypoint, instead the node chooses its destination from the predetermined set of locations which are connected to its current location via a path. The remainder of model is the same as Random Waypoint Model.

Among the mentioned mobility models Random Waypoint Model deserves more attention because it is by far the most widely used model in MANET research. Despite its popularity, Random Waypoint Model suffers from a few serious drawbacks [37,41,42,44,45]. [42] proves that if v_{min} is selected as zero, network can not achieve a steady state, the average speed decay does not stop and mobility eventually drops to zero. The most simplistic solution to this problem is not choosing v_{min} as zero. Another solution is to adopt an appropriate speed for the choice of destination: when a distant destination is chosen the algorithm should tend to select high speed and vice versa [42].

[41] approaches the average speed decay problem similarly; the method demonstrated in the paper modifies the pdfs according to which nodes select destination, and speeds and provides a mathematical background and formulas.

Another shortcoming of the Random Waypoint Model is that the initial distribution of the nodes is not representative of long run stochastic behavior of the model. Initially nodes are uniformly distributed throughout the simulation area whereas in the long run the nodes are shown to concentrate in the center of simulation region due to border effect [37,41,45]. The border effect decreases as the pause time gets larger [44]. As another way of overcoming initialization problem, [37] proposes to run a long simulation and save the node locations to be used as initial locations for other simulations to be carried out. [37] also suggests discarding the initial 1000 seconds of the simulation and distributing nodes in a triangle distribution during initial phase.

Random Waypoint Model has sudden stops and sharp turns which are not realistic in the physical world. To address this problem *Smooth Random Waypoint Model* is presented in [45]. In the original Random Waypoint Model speed and direction change upon reaching the destination, however in Smooth Random Waypoint Model speed and direction change occurs at discrete time intervals obeying an exponential pdf. Another enhancement is that the node does not choose a velocity from a continuous interval, instead it selects its speed from a set of preferred velocities and the speed is not immediately changed to the new value. An acceleration value is designated from an interval of maximum and minimum acceleration values and speed is adjusted smoothly.

Direction change is smooth as well: when a direction change occurs, the node stochastically chooses an angular acceleration value from an interval and direction changes accordingly. Speed and direction of the node do not necessarily change at the same time but they are correlated so that direction is likely to change when speed changes and vice versa thus the model mimics real life better.

CHAPTER 3

PROBLEM DEFINITION

3.1 Problem Statement

As the preceding discussion shows, mobility and hierarchy improves WSN systems in various aspects such as scalability, longevity, connectivity, and coverage. To further exploit the advantages of mobility and hierarchy in WSNs relations between mobility / hierarchy and various metrics of performance need to be studied. In this thesis, we consider two such measures, namely, total coverage time and energy consumption.

There are many scenarios where WSNs are used in mobile hierarchical settings. A war theatre where dozens of tanks distributed among platoons of soldiers may form a mobile and hierarchical WSN scheme. Soldiers wearing intelligent outfit made of e-textiles can be interpreted as limited capacity sensors with small communication range and processing capabilities, in a similar manner tanks may be interpreted as high capacity sensors that do not have sensing but long range communication and high computation capabilities. Assuming that the group of soldiers and tanks scan the battlefield to discover targets, one may be interested in determining coverage properties and energy consumption of such a network.

Another example may be a network of vehicles with mounted sensor nodes. Such a structure can be used to monitor gas emissions and traffic congestion conditions. Civil vehicles can act as dummy sensors with little communication capabilities while vehicles belonging to municipality or the police may act as processing and data collection nodes.

In monitoring habitats with different interacting species mobile hierarchical sensor architectures can be used. In such a case, biological characteristics of a species dictate what capabilities can be incorporated on a sensor node. A small bird might bear only a small node while a large animal can be equipped with a bulkier device with more capabilities.

We investigate the relationship between the performance metrics of the mobile WSN and network parameters. Among the network parameters are the probing / sensing frequency of the nodes, the node density in the monitored area, the location awareness of the nodes, and the transmission power of probe packets and corresponding reply packets.

Among the independent variables that we changed in the network are the transmission power and how often the network is probed.

As a model in our study we consider a set of n mobile sensor nodes $S = \{s_1, s_2, \ldots.. s_n\}$ distributed over a two dimensional area. Nodes begin moving at time $t = 0$ according to a random mobility model. Each sensor has a sensing radius r_i^s and a communication radius r_i^c such that a sensor s_i can monitor any point within a radius of r_i^s and can transmit to any sensor within a radius of r_i^c.

Within the two dimensional area, m stationary target points, $P = \{p_1, p_2, \ldots.. p_m\}$ are placed. As sensor s_i moves about randomly it senses its vicinity either periodically or when probed. The sensor retrieves data from target point p_i if p_i falls within s_i's sensing range. We define total coverage time as the earliest time by which all of the target points are sensed at least once by a sensor. We also define the energy consumption as the total amount of energy spent in communication until total coverage time.

We investigate how total coverage and energy consumption change with varying sensing frequency of the nodes in a flat architecture. In the case of hierarchical architecture we envision a 2-level hierarchy where a group of nodes probe others to sense the environment and make readings. The multi-level hierarchy is kept out of the scope. We analyze the effect of probing frequency on total coverage time and energy consumption of the mobile WSN and compare these results with those of the flat architecture. In addition, for hierarchical architecture we examine the variation of total coverage time with the power level of probing packet and its corresponding reply signal.

We also analyze the relationship between node density and the performance metrics of the mobile WSN. Besides, we investigate the effect of location awareness on the total coverage time and energy consumption of the mobile WSN. In this case we assume that nodes can adjust their transmission powers just enough to transmit to the recipient.

3.2 Assumptions on the model

- For the investigation of the effect of hierarchy in mobile WSNs we assume functional hierarchy among the sensors. This difference in functionality might be reflected in hardware to reduce cost and increase efficiency.
- There are no obstacles to block the communication or sensing.
- The noise in the transmission medium is negligible.
- The sensors do not run out of battery throughout the simulation period.
- The sensors are always mobile and never get stuck. Also there is no pause interval between successive movement segments.
- The sensing quality and transmission range of the nodes do not change over time.
- No energy is spent on maintaining mobility.
- Energy consumption is mainly due to communication and the energy consumed in sensing and processing tasks is ignored.
- Overhead incurred during channel acquisition and contention is ignored.
- Nodes do not leave the simulation area.
- Nodes do not crash.

- The attenuation of signal strength is proportional to the square of the transmission distance.

CHAPTER 4

SIMULATION DESIGN AND IMPLEMENTATION

4.1 Mobile WSN with Flat Topology

In the flat network topology we consider a WSN composed of identical sensor nodes. Sensor nodes are assigned identical tasks and have identical capabilities. Every sensor node is configured to have identical sensing and communication ranges r^s, r^c respectively. The sensing range of the nodes and the distribution of target points are chosen such that a sensor can not simultaneously sense more than one target point.

Sensor nodes moving randomly within the rectangular simulation area monitor the environment and retrieve data from the stationary target points. If the target point p_i is within the sensing range, r^s, of the sensor node s_j, node s_j can measure data from the target point. Whether it actually does depends on the probing state. A target is labeled as “sensed” when the data acquired from the target point reaches the sink. The arrival of sensed data to the sink is related to the connectivity of the sensors. In an attempt to confine the scope of this study to coverage and energy consumption, we assume that each sensor node can directly communicate with the sink.

In order to conserve energy and reduce redundancy, nodes do not continuously scan and sense the environment. Instead they take measurements at fixed intervals. If a target point is within the sensing range of a node while the node is in sensing mode, the target point is labeled as sensed since the sensor can immediately pass the data to the sink. The first time a sensor acquires data from a target point, the sensor communicates this information to the sink and flags the target point as sensed in its memory buffer. If a target point is sensed by the sensor again, the sensor does not communicate to the sink since this target point has already been sensed. This way energy consumption due to data redundancy is reduced, though not eliminated: the sink may receive same target point information from different sensors. The *total coverage* is attained when the sink receives data from all target points at least once. And the *total coverage time* is the instance this happens.

In this scheme the sensor nodes are assumed to be globally synchronized. When a sensor is in sensing mode so is the rest of the WSN; as a consequence the simulation area is periodically sensed by all sensors simultaneously.

4.2 Mobile WSN with Hierarchical Topology

To model a hierarchical mobile WSN, we consider a network comprised of two different types of sensors accomplishing different duties. The first group of sensors, which we call *sensor nodes*, has limited communication and sensing ranges. As in the flat topology, a sensor node can not sense more than one target point at the same time. The other group of sensors, which we call *relay nodes*, has longer ranges and greater computing and storage capabilities but can not perform sensing.

In the hierarchical architecture, sensor nodes perform sensing only when they are prompted by relay nodes. For this, relay nodes periodically transmit beacon packets. A relay node picks transmission range r^c for its beacon. This is also the communication range of the sensor node. Sensor nodes that are at most r^c away from the relay node hear the beacon and immediately sense the environment. If a prompted sensor node is less than r^s away from a target point it takes relevant measurement and transmits this to relay nodes with one hop.

Relay nodes contain two transceivers; one used for communicating with sensor nodes, the other for communicating with the sink. These transceivers operate in separate channels so that communication with sensor nodes does not interfere with communication with the sink. The power level of the transceiver used for transmitting to sink is adjusted such a way that a relay node is always connected to the sink with one hop.

As in flat topology, a sensor node transmits data from a target point to the relay node just once, even if the sensor node actually senses the target point many times. A relay node may receive data for the same target point corresponding to measurements by different sensor nodes, however the relay node forwards only the first of these to the sink thus introduces another layer of data aggregation. The simulation ends when the sink receives data from all target points at least once.

We assume global time synchronization between relay nodes so that each relay node broadcast beacons at the same time and when prompted sensor nodes sense the environment simultaneously. No global time synchronization is required for sensor nodes because sensor nodes are always in the listening mode when they are not sensing or communicating thus no time dependent sleep or wake up mechanism are necessary.

4.3 Simulation Implementation

The simulations are run on a computer with 1 GB RAM and a 2.21 GHz, AMD Athlon 64 3200+ processor. The simulation test bed was implemented in MATLAB.

MATLAB is chosen because of its powerful set of utilities designed for technical computing. In many universities, it has become a standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. MATLAB provides an interactive system whose basic data element is an array with generic type that does not require dimensioning. This allows one to solve many technical computing problems in a fraction of the time it would otherwise take to write a program in a lower level language such as C or FORTRAN.

Moreover MATLAB integrates computation, visualization, and programming in an easy-to-use environment.

MATLAB is typically used for [47]:

- Mathematics and computation
- Algorithm development
- Data acquisition
- Modeling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics

For both flat and hierarchical schemes the movements of sensors are modeled with Random Waypoint Model due to its wide usage and generality in modeling unknown mobility patterns described in Chapter 2.

In the general mobility model each node is initialized at a random position within the rectangular simulation area. Then the subsequent movements are calculated using the Random Waypoint Mobility Model. For more accurate results we did not use random initial deployments. Instead, we ran a separate simulation to achieve long run spatial distribution. The final locations of the nodes are used as initial locations for the subsequent simulations. The Table 4.3.1 displays an abstract pseudocode of the movement function used in the simulations:

The simulation area is chosen as a 50m x 50m square. Since under Random Waypoint Model nodes are known to concentrate in the center of the simulation area we carried out five trial simulations to determine a proper location for target points in order to speed up subsequent simulations.

Table 4.3.1: Pseudocode for Movement Function

```
FOR all nodes
        Set the node at its initial location
        Assign a destination at random
        Compute distance and direction to be covered at each time step
END LOOP
WHILE true
        FOR all nodes
                IF destination not reached
                        Move the node towards its destination
                ELSE
                        Assign a destination at random
                        Compute distance and direction to be covered at each time step
                        Move the node towards its destination
                END IF
                Increment time
        END LOOP
END LOOP
```

Both in flat and hierarchical topologies node speed is selected as 20 m/s. In flat architecture the numbers of nodes are taken as 20, 40, 60, 80, and 100. In the hierarchical architecture, on the other hand, the number of relay nodes is kept fixed at 5 and the numbers of sensor nodes are selected as 20, 40, 60, 80, and 100. The beacon ranges of relay nodes are chosen as 7.07m, 4.71m, 3.54m, and 2.83m.

In these simulations nodes are initialized at final locations taken from the results of the long run spatial distribution simulation. After running for another 1.500 seconds sensors begin recording their positions every 0.03 seconds in the flat topology. Likewise relay nodes begin broadcasting beacons every 0.03 second and if a sensor node hears the beacon its position is recorded for further processing. The simulations are stopped when a total of 300.000 location data is collected. Table 4.3.2 is the pseudocode of the long run spatial distribution simulation for flat topology.

Table 4.3.2: Pseudocode for Long Run Spatial Distribution in Flat Scheme

```
Initialize time
FOR all nodes
    Set the node at its initial location
    Assign a destination at random
    Compute distance and direction to be covered at each time step
END LOOP
WHILE time is less than 1.500
    FOR all nodes
        IF destination not reached
            Move the node towards its destination
        ELSE
            Assign a destination at random
            Compute distance and direction to be covered at each time step
            Move the node towards its destination
        END IF
        Increment time
    END LOOP
END LOOP
WHILE length memory buffer is less than 300.000
    FOR all nodes
        IF the remainder of time divided by sensing interval equals zero
            Append the node location to memory buffer
        END IF
        IF destination not reached
            Move the node towards its destination
        ELSE
            Assign a destination at random
            Compute distance and direction to be covered at each time step
```

Table 4.3.2 (cont'd)

```
                Move the node towards its destination
                END IF
                Increment time
        END LOOP
END LOOP
```

Similarly Table 4.3.3 displays the pseudocode of the long run spatial distribution simulation for hierarchical topology.

Table 4.3.3: Pseudocode for Long Run Spatial Distribution in Hierarchical Scheme

```
Initialize time
FOR all nodes
        Set the node at its initial location
        Assign a destination at random
        Compute distance and direction to be covered at each time step
END LOOP
WHILE time is less than 1.500
        FOR all nodes
                IF destination not reached
                        Move the node towards its destination
                ELSE
                        Assign a destination at random
                        Compute distance and direction to be covered at each time step
                        Move the node towards its destination
                END IF
                Increment time
        END LOOP
END LOOP
WHILE length memory buffer is less than 300.000
        IF the remainder of time divided by sensing interval equals zero
                Find sensor nodes that are within the beacon range of relay nodes
                IF there is any found sensor node
                        FOR all found sensor nodes
                                Append the location of found sensor node to memory buffer
                        END LOOP
                END IF
        END IF
        FOR all nodes
```

Table 4.3.3 (cont'd)

```
                IF destination not reached
                        Move the node towards its destination
                ELSE
                        Assign a destination at random
                        Compute distance and direction to be covered at each time step
                        Move the node towards its destination
                END IF
                Increment time
        END LOOP
END LOOP
```

Figure 4.3.1 shows the normalized 2D histogram images of the sensor positions collected from the simulation area. As can be seen more data is collected from the central regions, meaning that nodes tend to wander at the center rather than at the edges.

Considering the uneven distribution of visited locations in the simulation area, in order to reduce simulation time we decided to place target points uniformly in a 20m x 20m area at the center, as shown in Figure 4.3.2.

We assume that the amount of energy required to transmit a data packet for 1 m corresponds to one "energy unit" (EU). And since the signal attenuation is assumed to be proportional to the square of the distance to be transmitted, the amount of energy required to transmit a packet for 2 m is 4 EU, for 3 m it is 9 EU etc.

In the flat topology;

- All of the nodes have sensing range of 1 m to ensure that no two target points can be sensed at the same time.

- In different simulations the sensing interval of the nodes takes on values from 0.005 seconds to 1 second.
- Unless declared otherwise sensors have a speed of 20 m/s.
- The data sink is located at the geometrical center of the simulation area.
- The number of sensors range between 20 and 100.
- The communication ranges of nodes ensure one hop connectivity to the sink.
- All of the simulation results are the average of 100 rounds of distinct simulations.

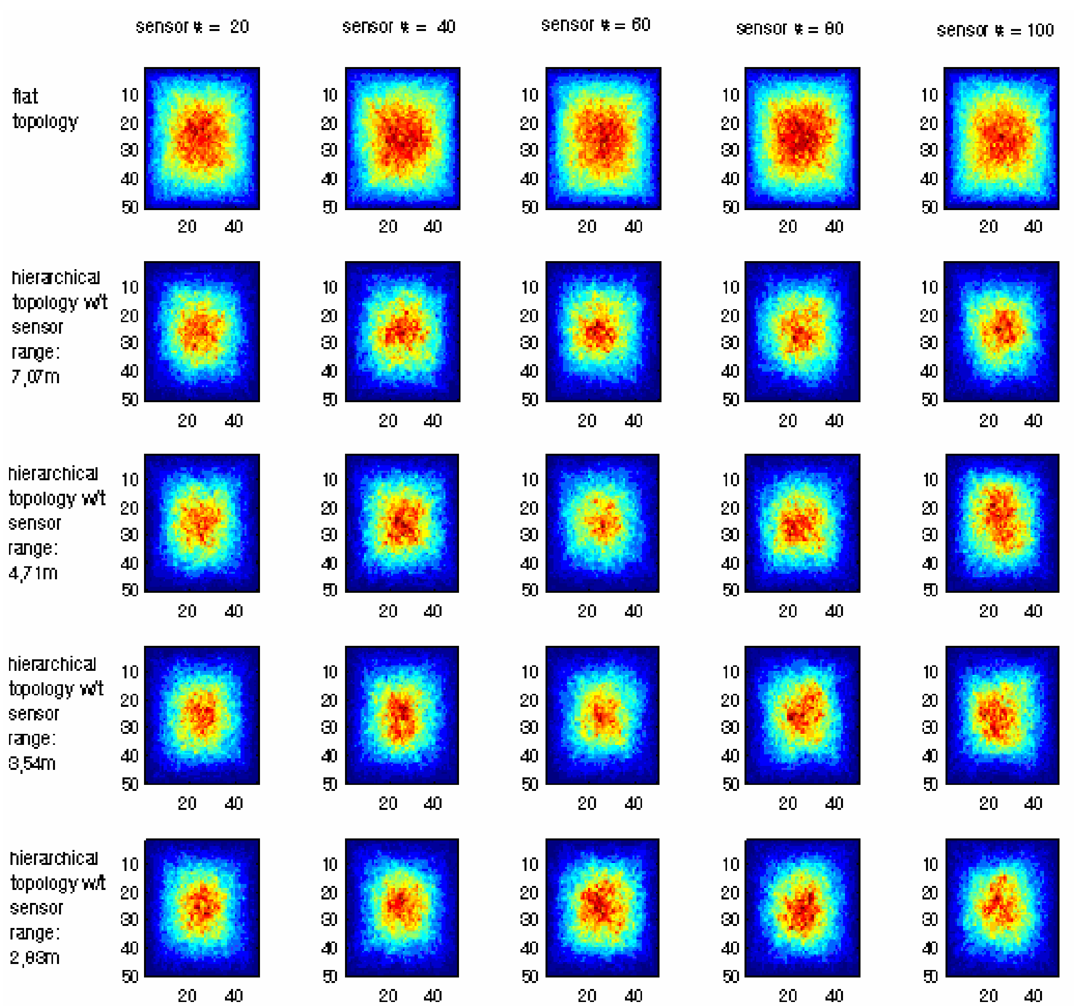

Figure 4.3.1: 2D Histogram Images of Position Distribution

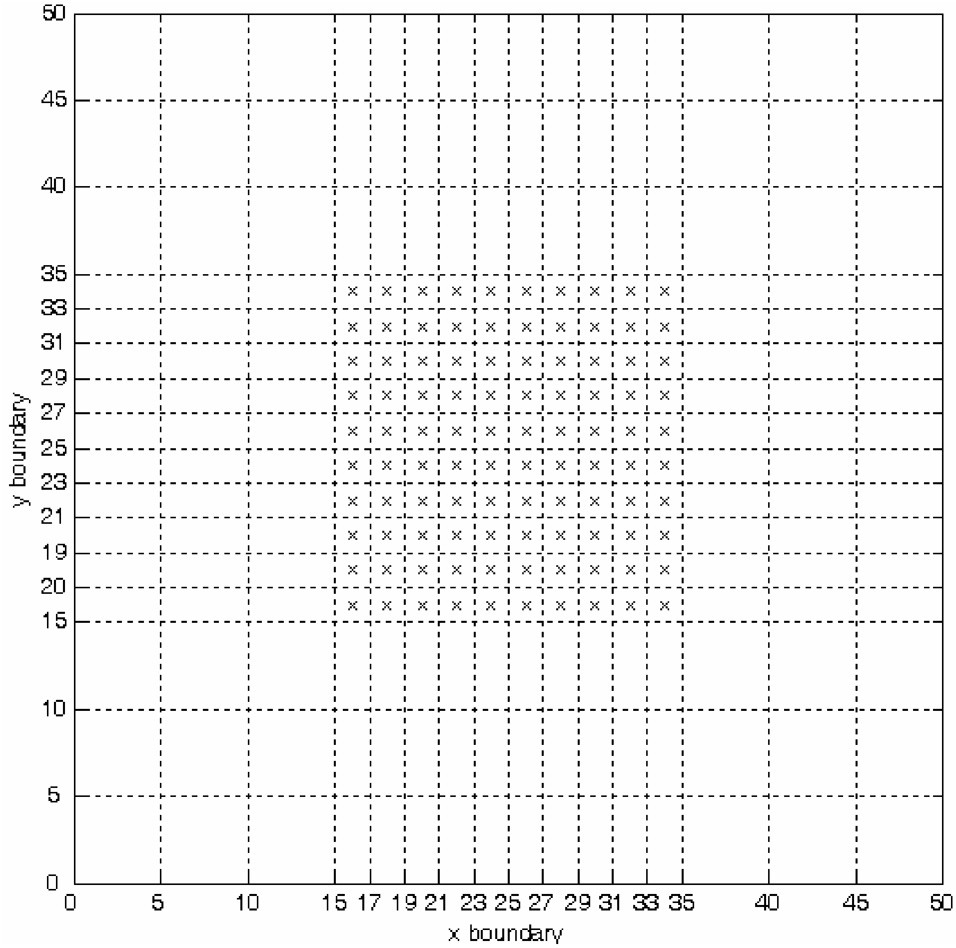

Figure 4.3.2: Target Point Locations

A snapshot of the flat topology simulation is shown in Figure 4.3.3. The circles drawn with dotted lines around the nodes illustrate sensing range of nodes, and circles drawn with continuous lines illustrate communication range of the nodes. The square at the center represents the data sink.

Table 4.3.4 is the pseudocode for simulation with flat topology where nodes transmit to the data sink with a fixed transmission power.

Table 4.3.4: Pseudocode for Flat Topology Simulation

```
Initialize time and energy
FOR all nodes
        Set the node at its initial location
        Assign a destination at random
        Compute distance and direction to be covered at each time step
END LOOP
WHILE data sink has not received data from all target point at least once
        FOR all nodes
                IF the remainder of time divided by sensing interval equals zero
                        Find target point within node's sensing range
                        IF there is any found target point
                                IF the found target point is not flagged
                                        Transmit target point data to the data sink
                                        Flag the target point
                                        energy  =  energy + (sensor communication range)^2
                                END IF
                        END IF
                END IF
                IF destination not reached
                        Move the node towards its destination
                ELSE
                        Assign a destination at random
                        Compute distance and direction to be covered at each time step
                        Move the node towards its destination
                END IF
                Increment time
        END LOOP
END LOOP
```

Table 4.3.5 is the pseudocode for simulation with flat topology where nodes are assumed to know their distance to the sink (via GPS) and adjust their transmission power accordingly.

Table 4.3.5: Pseudocode for Flat Topology Simulation with Location Awareness

```
Initialize time and energy
FOR all nodes
        Set the node at its initial location
```

Table 4.3.5 (cont'd)

```
        Assign a destination at random
        Compute distance and direction to be covered at each time step
END LOOP
WHILE data sink has not received data from all target point at least once
        FOR all nodes
                IF the remainder of time divided by sensing interval equals zero
                        Find target points within node's sensing range
                        IF there is any found target point
                                IF the found target point is not flagged
                                        Compute node distance to the data sink
                                        Transmit target point data to the data sink
                                        Flag the target point
                                        energy  =  energy + (node's distance to data sink)^2
                                END IF
                        END IF
                END IF
                IF destination not reached
                        Move the node towards its destination
                ELSE
                        Assign a destination at random
                        Compute distance and direction to be covered at each time step
                        Move the node towards its destination
                END IF
                Increment time
        END LOOP
END LOOP
```

Note that in the latter simulation, the energy consumed at each transmission is just enough for the packet to reach the sink.

In the hierarchical topology;

- The communication ranges of sensor and relay nodes vary and may be dynamic. Yet the ranges are such that relay node can always communicate with the sink.
- The sensing range of sensor nodes is 1 m.

- In different simulations the beacon interval of relay nodes takes on values from 0.005 seconds to 1 second.
- The number of sensor nodes range between 20 and 100 respectively, whereas the number of relay nodes is 5.
- Unless declared otherwise both sensor and relay nodes have a speed of 20 m/s.
- The data sink is located at the geometrical center of the simulation area.
- All of the simulation results are the average of 100 rounds of distinct simulations.
- The relay to sink communication ranges of relay nodes ensure one hop connectivity to the sink.

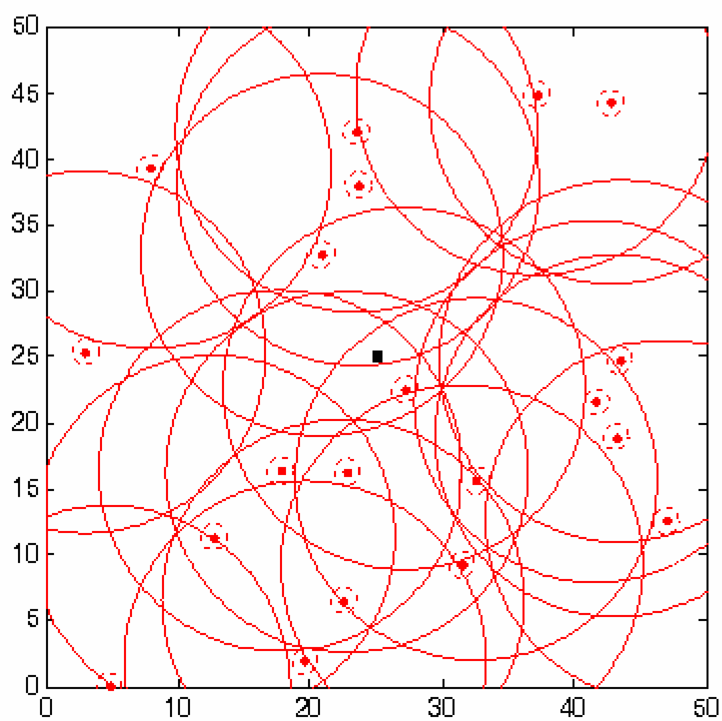

Figure 4.3.3: Snapshot for Flat Topology

The simulations for flat and hierarchical topologies were run 100 times in order to alleviate variations and have more accurate insight. We chose to run the simulations 100 rounds because most of the time 100 rounds provided sufficient accuracy and further increasing simulation rounds took so long since the simulations are continuous time.

Figure 4.3.4 is a snapshot from hierarchical topology simulation. The bold nodes with continuous circle around them are relay nodes and the circle illustrates the range after which beacons die out which is the same as sensor nodes' communication range, the larger dotted circles on the other hand display relay to sink communication range of relay nodes. The smaller filled circles denote sensor nodes. The dotted circles and continuous circles around the nodes denote sensing and communication range respectively. The square at the center represents the data sink.

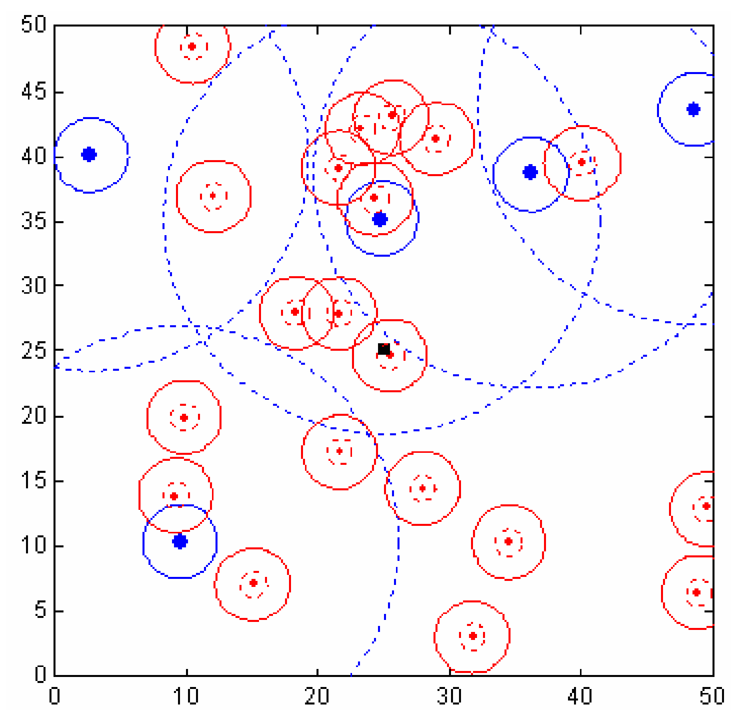

Figure 4.3.4: Snapshot for Hierarchical Topology

Table 4.3.6: Pseudocode for Hierarchical Topology Simulation

```
Initialize time and energy
FOR all nodes
    Set the node at its initial location
    Assign a destination at random
    Compute distance and direction to be covered at each time step
END LOOP
WHILE data sink has not received data from all target point at least once
    IF the remainder of time divided by sensing interval equals zero
        Find sensor nodes that are within the beacon range of relay nodes
        IF there is any found sensor node
            FOR all found sensor nodes
                Find target points within sensor node's sensing range
                IF there is any found target point
                    IF the found target point is not flagged
                        Transmit target point data to the corresponding
                        relay node
                        Flag the target point
                        energy = energy + (beacon range)^2
                    END IF
                END IF
            END LOOP
            FOR all relay nodes that received target point data
                IF the found target point is not flagged
                    Transmit target point data to the sink
                    Flag the target point
                    energy = energy + (relay communication range)^2
                END IF
            END LOOP
        END IF
    END IF
    FOR all nodes
        IF destination not reached
            Move the node towards its destination
        ELSE
            Assign a destination at random
            Compute distance and direction to be covered at each time step
            Move the node towards its destination
        END IF
        Increment time
    END LOOP
END LOOP
```

Table 4.3.7 is the pseudocode for another hierarchical topology simulation. In this simulation relay nodes are assumed to know their distance to the sink (via GPS) and adjust their transmission power accordingly. However senor nodes transmit to relay nodes with fixed transmission power.

Table 4.3.7: Pseudocode for Hierarchical Topology Simulation with Location Aware Relay Nodes

```
Initialize time and energy
FOR all nodes
    Set the node at its initial location
    Assign a destination at random
    Compute distance and direction to be covered at each time step
END LOOP
WHILE data sink has not received data from all target point at least once
    IF the remainder of time divided by sensing interval equals zero
        Find sensor nodes that are within the beacon range of relay nodes
        IF there is any found sensor node
            FOR all found sensor nodes
                Find target points within sensor node's sensing range
                IF there is any found target point
                    IF the found target point is not flagged
                        Transmit target point data to the corresponding
                        relay node
                        Flag the target point
                        energy = energy + (beacon range)^2
                    END IF
                END IF
            END LOOP
            FOR all relay nodes that received target point data
                IF the found target point is not flagged
                    Compute relay node's distance to the sink
                    Transmit target point data to the sink
                    Flag the target point
                    energy= energy + (relay distance to the sink)^2
                END IF
            END LOOP
        END IF
    FOR all nodes
        IF destination not reached
```

Table 4.3.7 (cont'd)

```
            Move the node towards its destination
            ELSE
                  Assign a destination at random
                  Compute distance and direction to be covered at each time step
                  Move the node towards its destination
            END IF
            Increment time
      END LOOP
END LOOP
```

Finally, Table 4.3.8 is the pseudocode for hierarchical topology simulation where both sensor and relay nodes are location aware. Thus sensor nodes can compute their distance to the prompting relay nodes and adjust their transmission power accordingly. In a similar manner relay nodes know their distance to the sink and adjust their transmission power.

Table 4.3.8: Pseudocode for Hierarchical Topology Simulation with Location Aware Relay and Sensor Nodes

```
Initialize time and energy
FOR all nodes
      Set the node at its initial location
      Assign a destination at random
      Compute distance and direction to be covered at each time step
END LOOP
WHILE data sink has not received data from all target point at least once
      IF the remainder of time divided by sensing interval equals zero
            Find sensor nodes that are within the beacon range of relay nodes
            IF there is any found sensor node
                  FOR all found sensor nodes
                        Find target points within sensor node's sensing range
                        IF there is any found target point
                              IF the found target point is not flagged
                                    Compute sensor node's distance to the
                                    corresponding relay node
```

Table 4.3.8 (cont'd)

```
                        Transmit target point data to the corresponding
                        relay node
                        Flag the target point
                        energy = energy + (sensor node's distance to
                        corresponding relay node)^2
                    END IF
                END IF
            END LOOP
            FOR all relay nodes that received target point data
                IF the found target point is not flagged
                    Compute relay node's distance to the sink
                    Transmit target point data to the sink
                    Flag the target point
                    energy= energy + (relay distance to the sink)^2
                END IF
            END LOOP
        END IF
    FOR all nodes
        IF destination not reached
            Move the node towards its destination
        ELSE
            Assign a destination at random
            Compute distance and direction to be covered at each time step
            Move the node towards its destination
        END IF
        Increment time
    END LOOP
END LOOP
```

CHAPTER 5

SIMULATION RESULTS

In this chapter we give the results of the simulations conducted under different network configurations and parameters.

5.1 Total Coverage Time in Extreme Sensor Node Transmission / Beacon Broadcast Power

For the case of hierarchical topology, one can intuitively see that increasing beacon / sensor node transmission power does not continuously improve coverage characteristics of the network and there should be a threshold after which any increase in transmission powers has no effect on the total coverage time. Since the target points are distributed within a 20m x 20m area and data sink is located at the center of this square, the farthest point to the data sink from which a sensor node can sense a target point is $9\sqrt{2} + r^s$ (where r^s is the sensing range) away from the data sink, see figure 5.1.1.

In the Figure 5.1.1 the filled circle denotes the sensor node, the filled square denotes the data sink and the crosses spread with in the 20m x 20m area denote the target points.

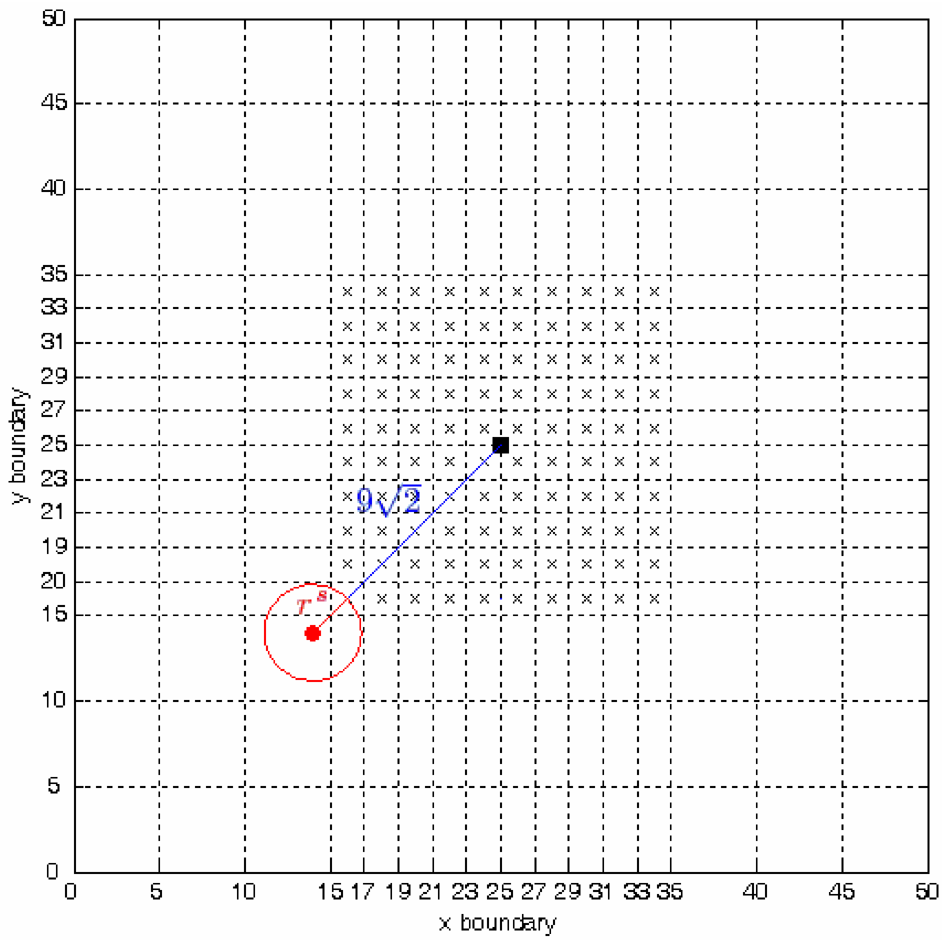

Figure 5.1.1: Largest Distance Between Sensor Node and Data Sink

In the simulation setting the farthest nodes to the sink are located on the coordinates (16,16), (16,34), (34,16), and (34,34). The data sink is at the center of the simulation area, (25,25). The distance between data sink and these farthest target points are $9\sqrt{2}$. A sensor can sense a target point when it is r^s away from the target point. Thus the farthest sensor node which senses a target point is $9\sqrt{2}+r^s$ away from the data sink, as shown in Figure 5.1.1.

We assume that P is the corresponding power level to provide a transmission range of $9\sqrt{2}+r^{s}$. As a consequence, in a flat topology if sensors utilize a transmission power of P it is guaranteed that all the sensors can communicate data to the sink when they sense a target point. We use power level P as a base unit for investigating how total coverage time varies as the beacon transmission power of relay nodes change in the hierarchical topology.

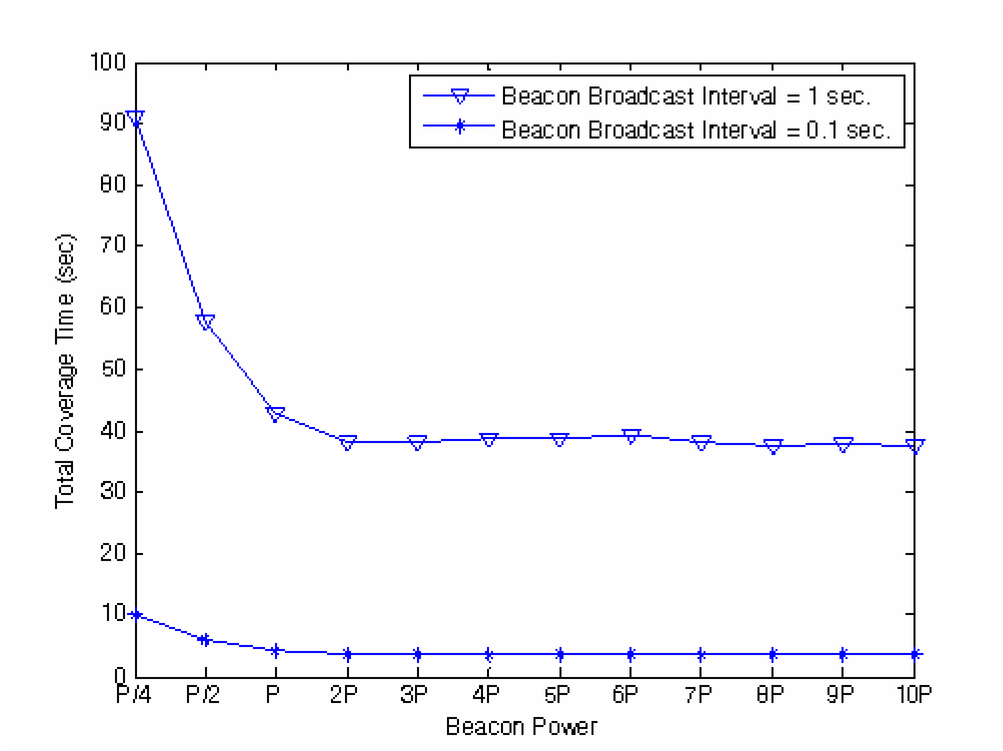

Figure 5.1.2: Total Coverage Time vs Beacon Broadcast Power

Figure 5.1.2 shows the effect of beacon transmission power on total coverage time when beacon broadcast interval of relay nodes are 0.1 and 1 seconds. The number of sensor nodes and the number of relay nodes are 55 and 5 respectively in both simulations and the results are an average of 500 distinct simulation runs.

Form the geometrical properties of the simulation area we can theoretically deduce that when beacon / sensor node transmission power reaches the level of 3.58 P (for $34\sqrt{2}+r^{s}$ m and r^{s} = 1m) any sensor node, which is in a location where it can sense a target point, can hear the beacon and respond, see Figure 5.1.3.

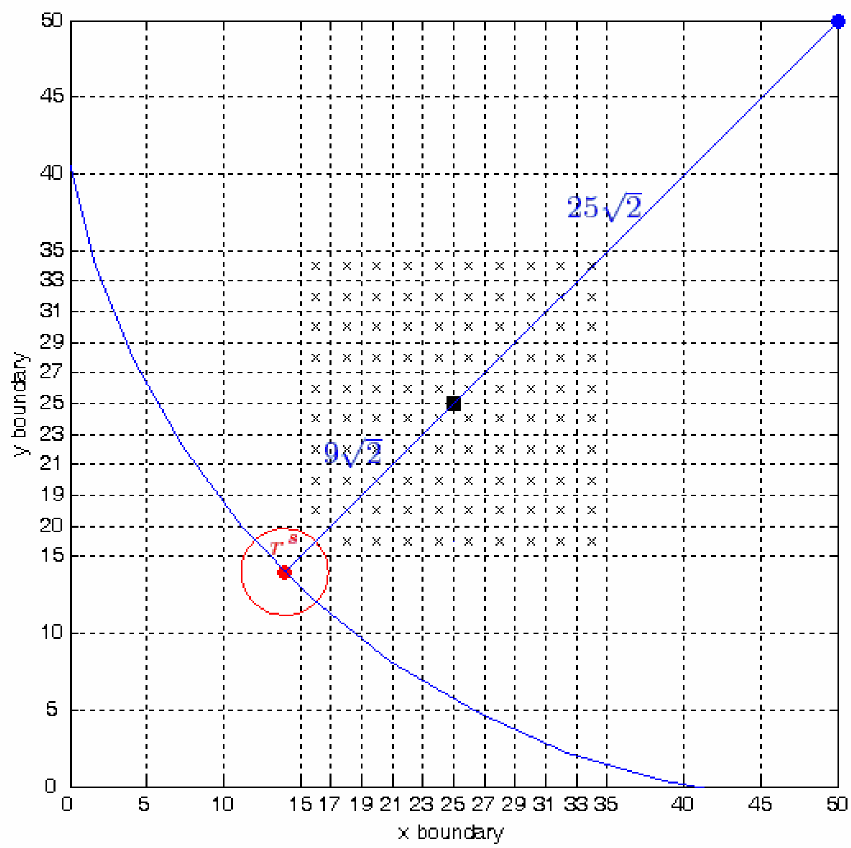

Figure 5.1.3: Largest Distance Between Sensor Node and Relay Node

In Figure 5.1.3 the filled circle at the upper right corner of simulation area denotes a relay node, the filled square denotes the data sink, the filled circle to the lower left of data sink denotes a sensor node and the crosses spread within the 20m x 20m area denote the target points. The relay node is located at (50,50) and the data sink at (25,25) therefore the distance between the sink and relay node is $25\sqrt{2}$ m. Thus in the worst case the distance between relay node and sensor node is $34\sqrt{2}+r^{s}$ m.

After 3.58 P (corresponding to beacon range of 49.09m when the sensing range is 1m) increasing beacon / sensor node transmission power any further does not contribute to coverage. Simulation results as shown in the Figure 5.1.2 indicate that the total coverage time levels off after power level of 2P which corresponds to the beacon range of 27.46m when sensing range is 1 m.

5.2 Total Coverage Time vs Beacon Broadcast Interval / Sensing Interval

In order to determine relationships between the total coverage time and the network parameters (sensing / beacon broadcast interval, beacon range) we ran a series of simulations, results of which are displayed in the following pages. The results are an average of 100 distinct simulation runs.

We ran the hierarchical topology simulations using 55 sensor nodes 5 relay nodes, and we chose beacon / sensor node transmission range as 6.86m, and 2.75m (corresponding to power levels of P/4, and P/25 respectively). The beacon broadcast interval of relay nodes ranges from 0.1 second to 1 second.

The most distant point to the data sink where a relay node can receive data of a target point is $9\sqrt{2}+r^s+r^c$ away from the data sink (where r^s and r^c are sensing and communication range of sensor nodes respectively), see Figure 5.2.1. In hierarchical topology simulations, the communication range of sensor nodes is equal to the beacon transmission range of relay nodes.

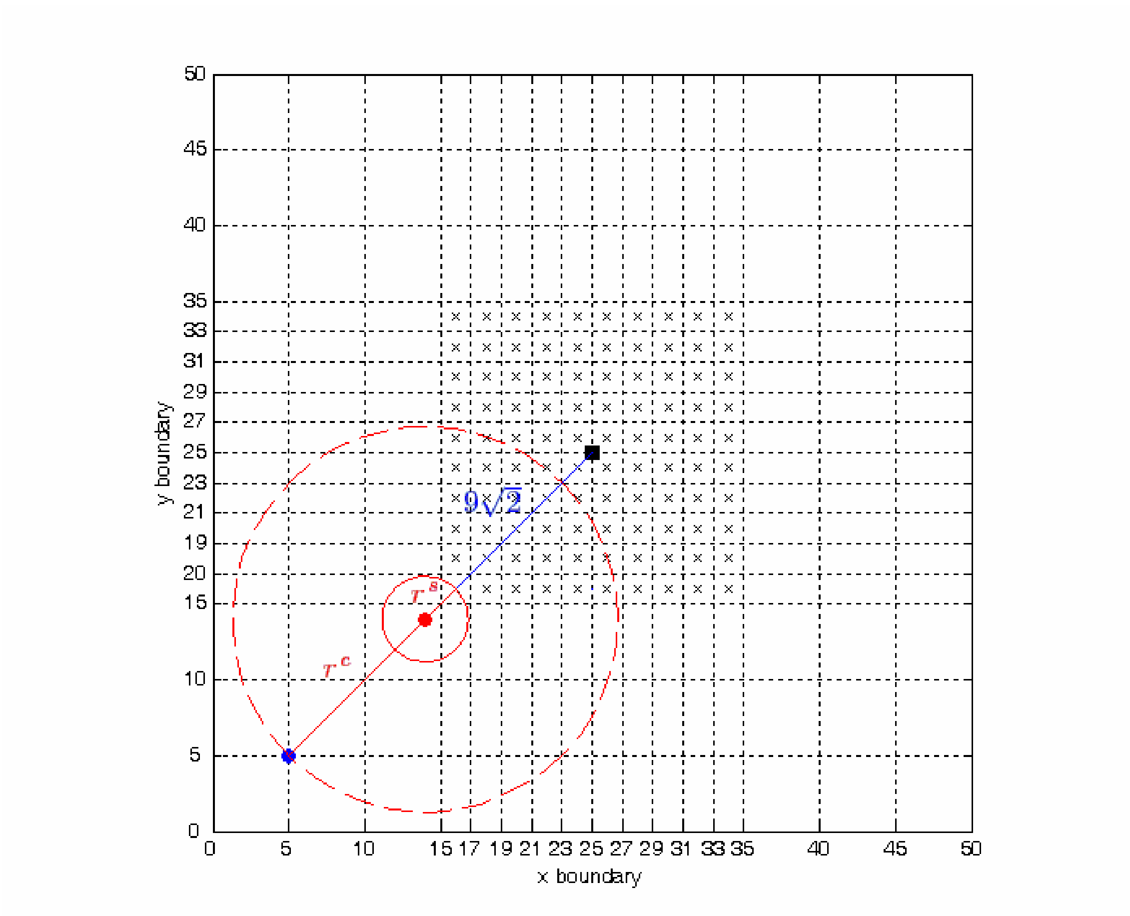

Figure 5.2.1: Distance Between Relay Node and Data Sink

Therefore to cover the worst case simulations $9\sqrt{2}+r^s+r^c$m is used as the communication range of relay nodes. It follows that, when sensor nodes have a transmission power level of P/4, and P/25 the corresponding relay node communication powers are 5P/4 and 26P/25 respectively.

In flat topology simulations there is no beacon broadcast thus beacon transmission power does not exist. Likewise sensing interval takes the place of beacon broadcast interval of hierarchical topology. We ran hierarchical topology simulations with 60 nodes and when the sensing interval ranges from 0.1 to 1 second. All nodes have a communication range of $9\sqrt{2}+r^{s}$ to ensure connectivity to the sink.

The Figure 5.2.2 shows the relation of total coverage time to the beacon broadcast interval in hierarchical topology and the sensing interval in flat topology. It can be observed that beacon broadcast frequency shortens total coverage time almost linearly.

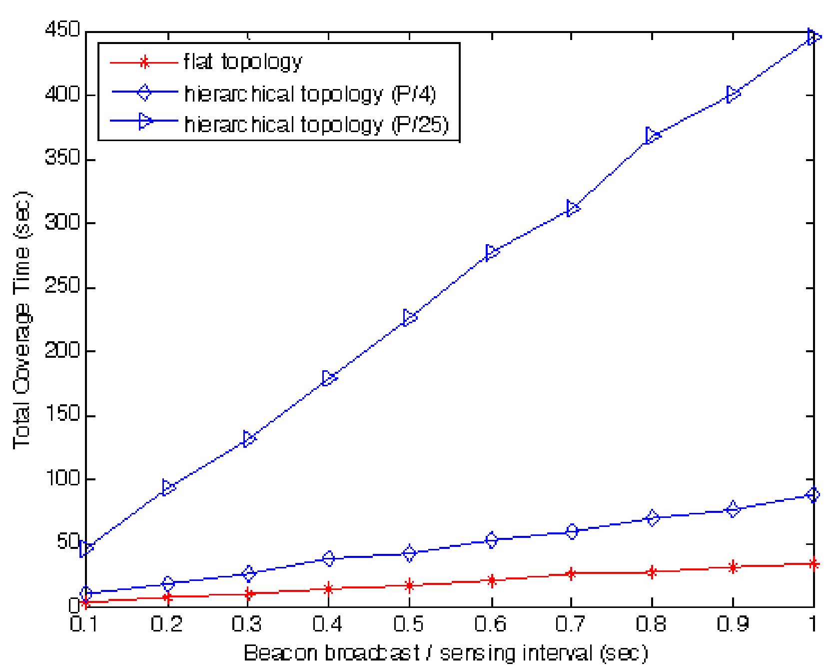

Figure 5.2.2: Total Coverage Time vs Sensing / Beacon Broadcast Interval

5.3 Energy Consumption vs Beacon Broadcast Interval / Sensing Interval

To analyze relationship between energy consumption and beacon broadcast interval (in hierarchical topology) and sensing interval (in flat topology) we performed the following simulations. The results are average of 100 distinct simulation runs.

In the hierarchical architecture we ran simulations using 55 sensor nodes and 5 relay nodes, and we chose beacon / sensor node transmission range as 6.86m, and 2.75m (corresponding to power levels of P/4, and P/25 respectively). Thus the corresponding communication powers of relay nodes are taken as 5P/4 and 26P/25. The beacon broadcast interval of relay nodes ranges from 0.1 second to 1 second.

As described in the previous section, there is no beacon transmission power for the case of flat topology simulations and sensing interval takes place of beacon broadcast interval. We ran the flat topology simulations using 60 nodes and the sensing interval ranges from 0.1 to 1 second. All nodes have a communication range of $9\sqrt{2} + r^s$ m, corresponding to a power level of P.

The power and energy consumption of the network is proportional to the square of transmission ranges, so in energy consumption calculations transmission of a packet when range is 1m is taken as 1 unit, when range is 2m it is taken as 4 units and so on.

Figure 5.3.1 shows the relationship between energy consumption and sensing / beacon broadcast interval. From Figure 5.3.1 it is seen that in hierarchical topology as beacon power decrease so does the energy consumption of the network. On the other hand Figure 5.3.1 also shows that within the scope of these parameters, sensing / beacon broadcast frequency seems to have no effect on the energy consumption.

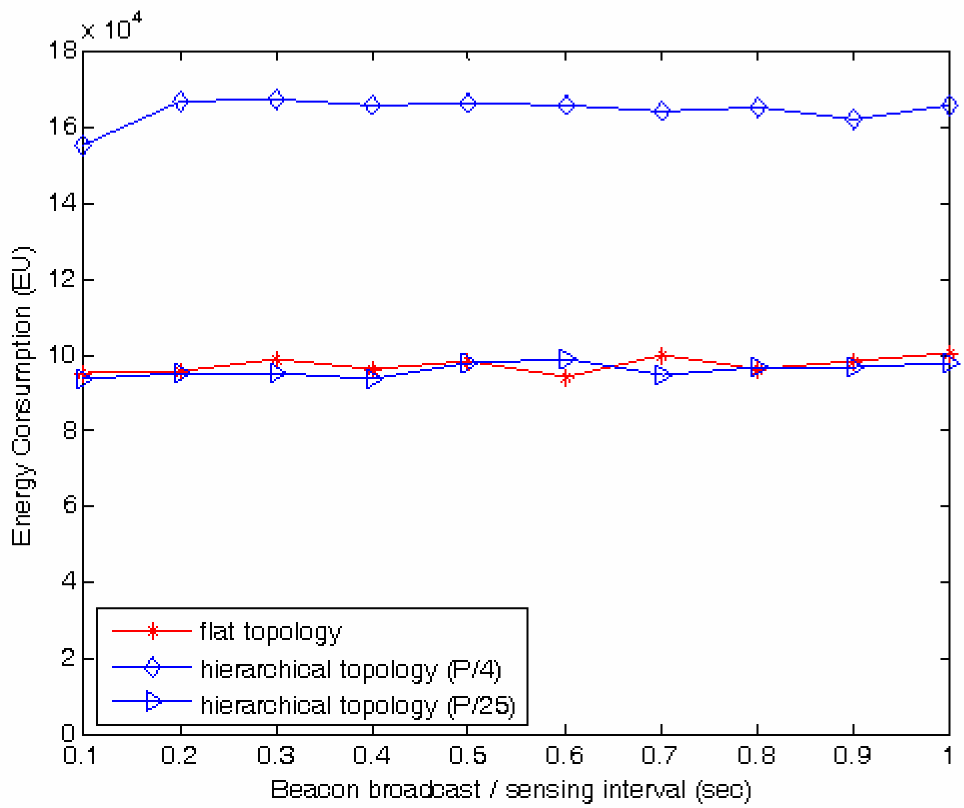

Figure 5.3.1: Energy Consumption vs Sensing / Beacon Broadcast Interval

Figure 5.2.2 and Figure 5.3.1 indicate that the behavior of energy consumption and total coverage time with varying sensing interval in the flat topology is very close to the behavior of energy consumption and total coverage time with varying beacon broadcast interval in the hierarchical topology. Increase in the sensing interval causes a linear increase in the total coverage time, meanwhile sensing interval seems to have no effect on the energy consumption of the network.

5.4 Energy Consumption in Extreme Beacon Broadcast Interval / Sensing Interval

In order to further analyze the effect of beacon broadcast and sensing frequencies on energy consumption, we performed additional simulations both in flat and hierarchical topologies. The results are average of 100 rounds of simulations.

In the hierarchical topology we have 55 sensor nodes and 5 relay nodes. The beacon power ranges from P/4 to P/25 and relay communication power ranges from 5P/4 to 26P/25. The beacon broadcast interval on the other hand varies between 0.005 seconds to 0.1 seconds. Similarly, in flat topology the number of nodes is 60 and the sensing interval varies between 0.005 seconds and 0.1 second. All nodes have a transmission power of P in the flat topology.

Figure 5.4.1 shows energy consumption against beacon broadcast / sensing frequency. It can be seen that in hierarchical topology the energy consumption increases as beacon broadcast interval gets smaller than 0.03 seconds. Whereas in the flat topology, energy consumption does not seem to be effected by the sensing frequency and displays a flat pattern.

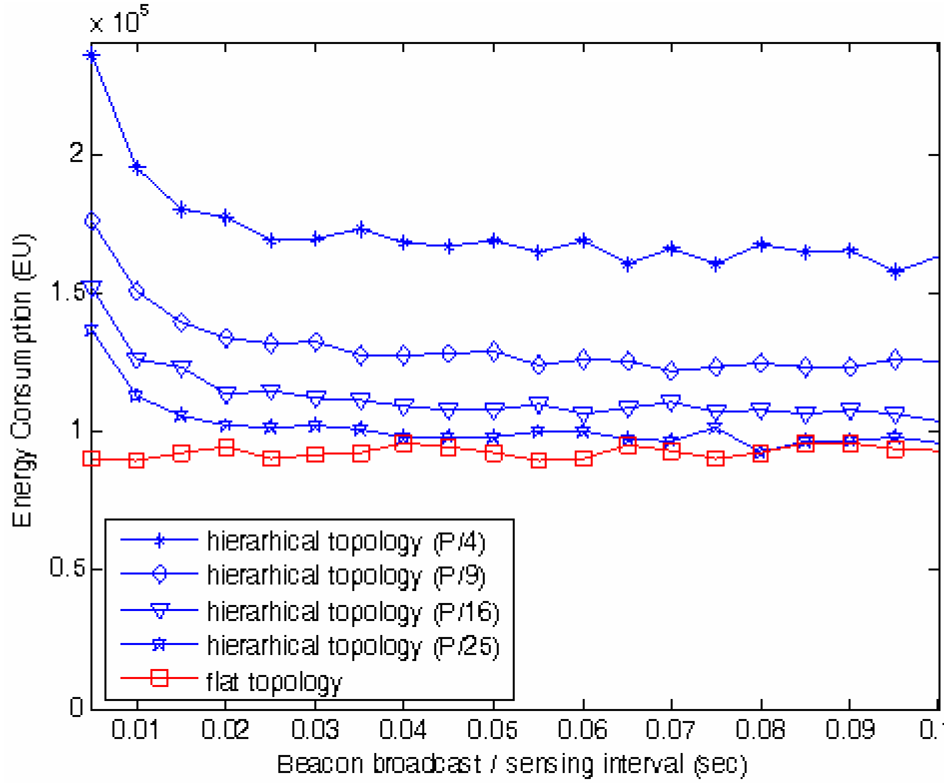

Figure 5.4.1: Energy Consumption vs Sensing / Beacon Broadcast Interval

To find out whether relationship between energy consumption and beacon broadcast / sensing interval dependents on node velocities or not, we repeated the same set of simulations only changing the node speed from 20 m/s to 40 m/s.

Figure 5.4.2 shows the energy consumption against beacon broadcast / sensing frequency when nodes have a speed of 40 m/s. Figure 5.42 closely resembles Figure 5.4.1 but the increase in node speed seems to smoothen the energy consumption graph and especially at lower beacon transmission powers the energy consumption levels around 0.02 seconds. The energy consumption in flat topology appears not to be effected by the changes in sensing interval. From Figures 5.4.1 and 5.4.2 we can see that increasing node speed decreases the energy consumption in hierarchical topology. But in flat topology the effect of node speed is less significant.

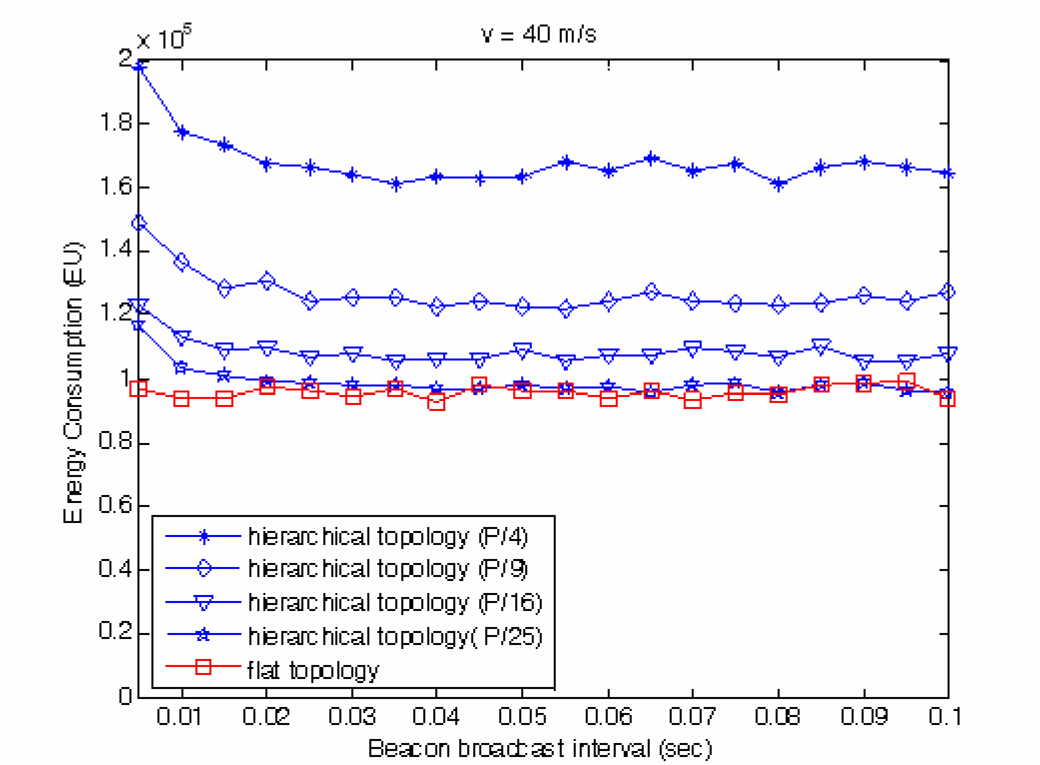

Figure 5.4.2: Energy Consumption vs Sensing / Beacon Broadcast Interval (v = 40m/s)

5.5 Total Coverage Time in Extreme Beacon Broadcast Interval / Sensing Interval

To see the effect of beacon broadcast / sensing frequency on total coverage time, we conducted simulations with the same parameter sets as in Section 5.5. And the results are the average of 100 distinct simulations.

Figure 5.5.1 shows how total coverage time changes with varying beacon broadcast / sensing interval. The total coverage time tends to slightly decrease as beacon broadcast frequency increases in hierarchical topology. The decrease becomes more apparent as the transmission power of sensor nodes increases. In the flat topology, on the other hand, the total coverage time is not effected by the sensing frequency. The non-smoothness in the graph is due to the fact that 100 rounds of simulation runs were not sufficient to obtain a stationary average.

Figure 5.5.2 displays the behavior of total coverage time against varying beacon broadcast / sensing interval when node speed is 40 m/s. Total coverage time when node speed is 40 m/s has a similar pattern as when node speed is 20 m/s.

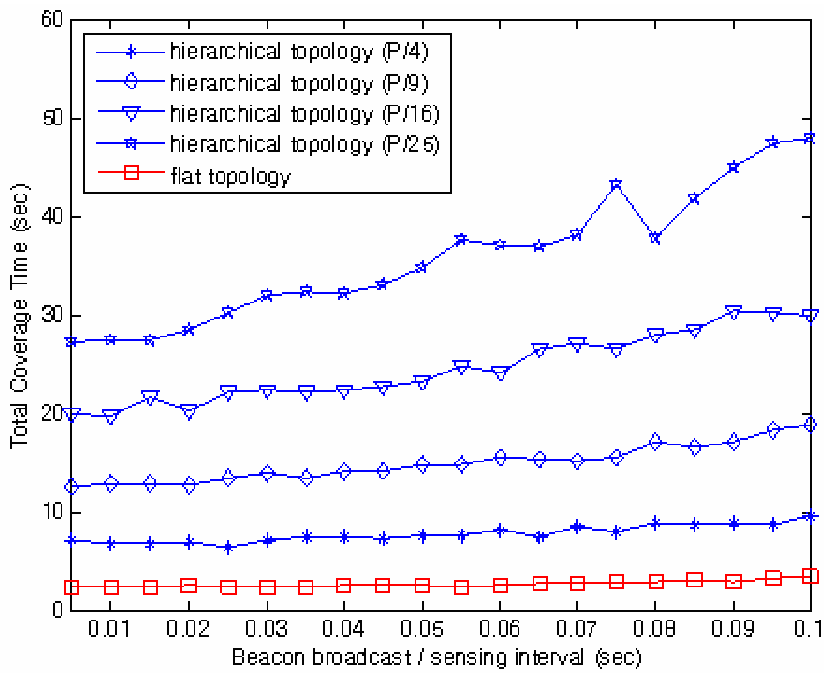

Figure 5.5.1: Total Coverage Time vs Sensing / Beacon Broadcast Interval

However Figure 5.5.2 shows that at node speed of 40 m/s the decrease of total coverage time in hierarchical topology with decreasing beacon broadcast interval is more significant than it is in Figure 5.5.1. In addition, Figure 5.5.2 indicates that total coverage time in flat topology slightly decrease with decreasing sensing interval.

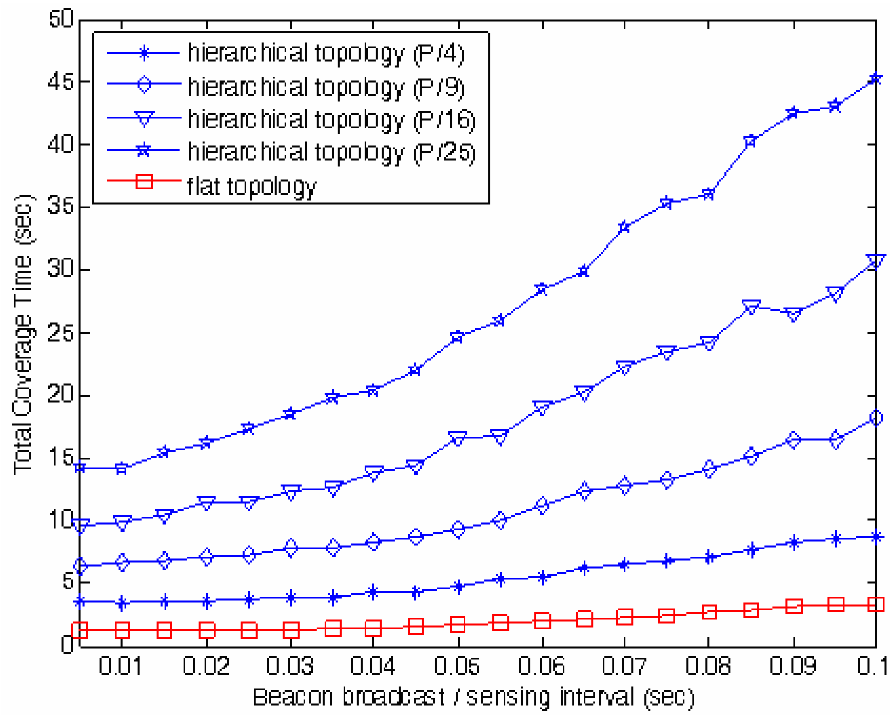

Figure 5.5.2: Total Coverage Time vs Sensing / Beacon Broadcast Interval (v = 40 m/s)

5.6 Total Coverage Time vs Sensor Node Transmission / Beacon Broadcast Power

The results presented in the Section 5.4 and 5.5 reveal that, for the case of hierarchical topology, there exists an optimum probing frequency. Figures 5.5.1 and 5.5.2 show that decreasing beacon broadcast interval has a desirable effect and decreases total coverage time. However, Figure 5.4.1 and 5.4.2 show that after a threshold, decreasing beacon broadcast interval negatively effects the energy consumption. Thus the threshold after which energy consumption levels out can be said to be the optimum beacon broadcast interval.

Based on these findings we take beacon broadcast / sensing interval as 0.03 seconds for the subsequent simulations (where node speed is 20 m/s).

For the case of hierarchical topology, in order to be able to analyze the effect of sensor node transmission / beacon transmission power on the total coverage time we performed another set of simulations. The results are average of 100 distinct simulations.

In hierarchical topology simulations, the network is composed of 55 sensor nodes and 5 relay nodes. The sensor node / beacon transmission power varies between P/4 (a beacon range of 6.86m) and P/100 (a beacon range of 1.37m). Correspondingly communication powers of relay nodes varies between 5P/4 and 101P/100 (for ranges of 20.59m and 15.10m respectively). In the flat topology simulations, on the other hand, network is comprised of 60 nodes and transmission power of the nodes is P (corresponding to a range of 13.73).

Figure 5.6.1 shows how the total coverage time changes with beacon power in the hierarchical architecture. Total coverage time of the flat architecture is shown as a straight line since there is no beacon power in this topology. From Figure 5.6.1 it is seen that increasing sensor transmission / beacon broadcast power significantly decreases the total coverage time. Flat topology performs better than hierarchical topology within the beacon power range of P/4 to P/100.

These results indicate that introduction of hierarchy, in general, increases the total coverage time. When beacon range is 6.86m (when beacon power is P/4) total coverage time is 6.85 seconds, whereas in the flat mobile WSN total coverage is attained in 2.35 seconds. At a beacon range of 1.37m (when corresponding power is P/100) total coverage time for the hierarchical topology becomes 94.53 seconds. Thus it is clear that hierarchy sacrifices coverage time.

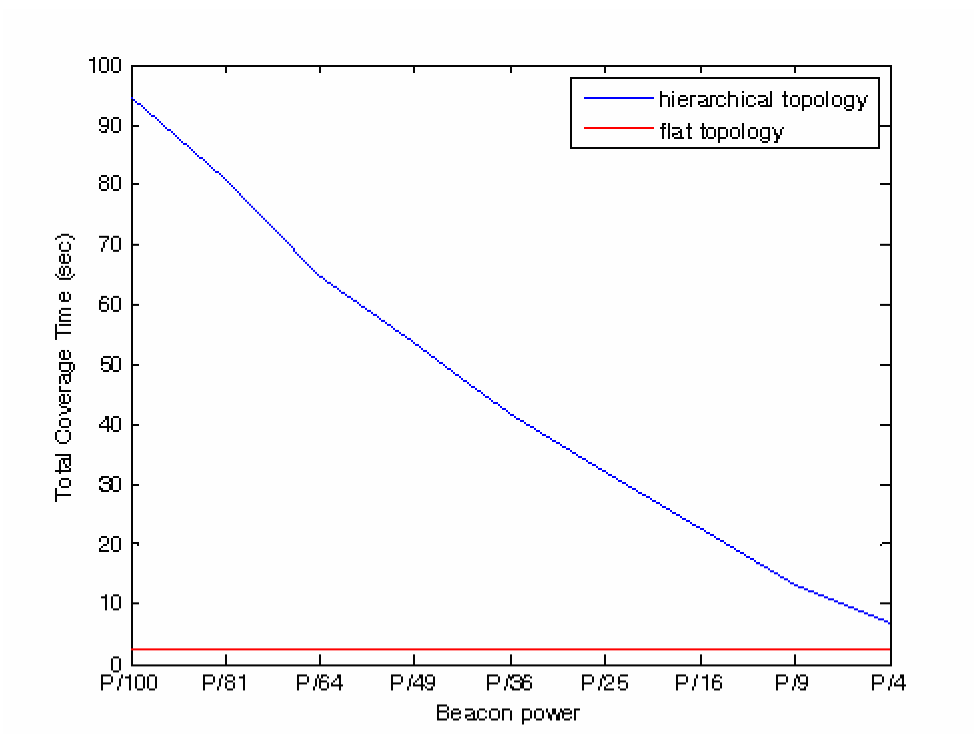

Figure 5.6.1: Total Coverage Time vs Beacon Broadcast Power

5.7 Energy Consumption vs Sensor Node Transmission / Beacon Broadcast Power

With the same parameter sets described in Section 5.6, we performed further simulations to observe the effect of sensor node transmission / beacon broadcast power on energy consumption of the mobile WSN. The results are the averages of 100 distinct simulations.

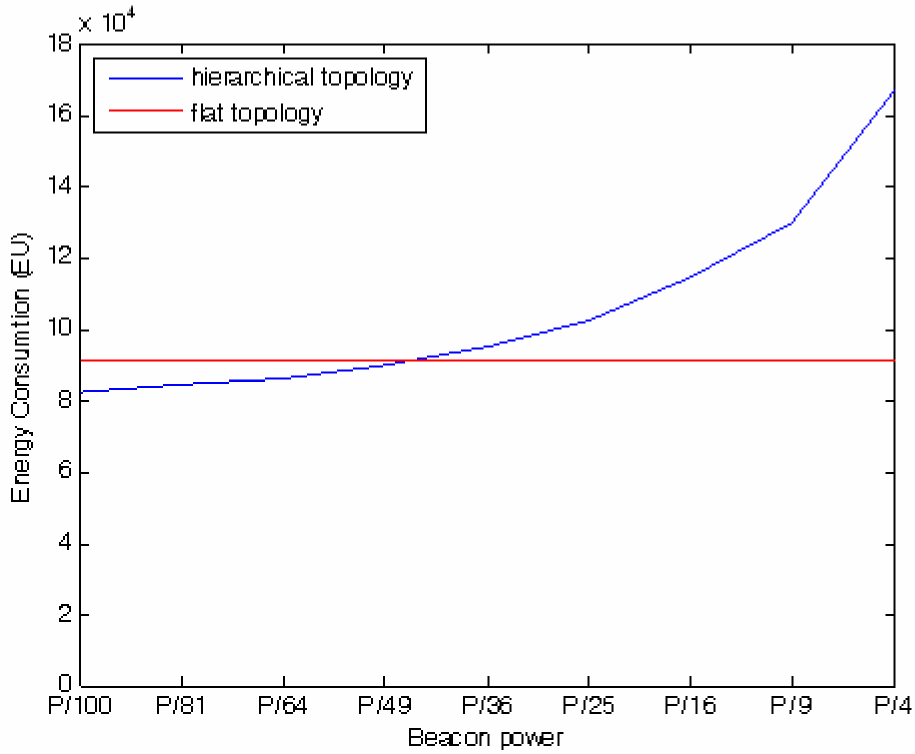

Figure 5.7.1: Energy Consumption vs Beacon Broadcast Power

Figure 5.7.1 displays energy consumption versus beacon power. Figure 5.7.1 shows that, hierarchical mobile WSN performs better in terms of energy consumption when beacon range is smaller than 2m. When beacon range is 6.86m (P/4), 1.96m (P/49), and 1.37m (P/100) energy consumption of the hierarchical mobile WSN is 167.271, 89.910, and

82.165 units respectively, the flat mobile WSN on the other hand has an energy consumption of 91.467 units.

To summarize, introducing hierarchy to the proposed mobile WSN brings a trade off between quality of service (through coverage sensitivity) and longevity (through energy consumption). The sacrifice in coverage seems to be more than the benefits gained in energy consumption (see Figure 5.7.1). However the energy consumption of the hierarchical mobile WSN is mainly due to the relay nodes which have rich energy resources: when beacon range is 6.86m (P/4), 1.96m (P/49), and 1.37m (P/100) relay nodes' energy consumptions constitute to 82.25%, 97.32%, 98.61% of the total energy consumption respectively (see Table 5.7.1).

Table 5.7.1: Energy Consumption Table for Hierarchical Topology

	P/100		*P/81*		*P/64*		*P/49*	
	EU	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*
Relay Nodes	81.023	98,6%	83.134	98,3%	84.302	97,9%	87.501	97,3%
Sensor Nodes	1.142	1,4%	1.427	1,7%	1.780	2,1%	2.409	2,7%
TOTAL	**82.165**	**100%**	**84.561**	**100%**	**86.082**	**100%**	**89.910**	**100%**

	P/36		*P/25*		*P/16*		*P/9*		*P/4*	
	EU	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*
Relay Nodes	91.498	96,5%	97.462	95,2%	106.506	93,0%	116.106	89,6%	137.585	82,3%
Sensor Nodes	3.297	3,5%	4.948	4,8%	8.038	7,0%	13.492	10,4%	29.687	17,7%
TOTAL	**94.795**	**100%**	**102.410**	**100%**	**114.543**	**100%**	**129.598**	**100%**	**167.271**	**100%**

5.8 Node Density

To examine the variation of coverage and energy consumption of the proposed mobile WSNs with increasing node number we ran another set of simulations. In the hierarchical architecture, number of relay nodes is 5 and the number of sensor nodes ranges from 20 to 100, beacon broadcast interval is taken as 0.03 seconds and beacon power ranges between P/4 and P/25. In the flat topology number of nodes varies between 20 and 100 and sensing interval is 0.03 seconds as in hierarchical topology.

Figure 5.8.1 shows how the number of nodes effects total coverage time in flat and hierarchical architectures, likewise Figure 5.8.2 displays the relationship between the number of nodes and energy consumption of both flat and hierarchical networks.

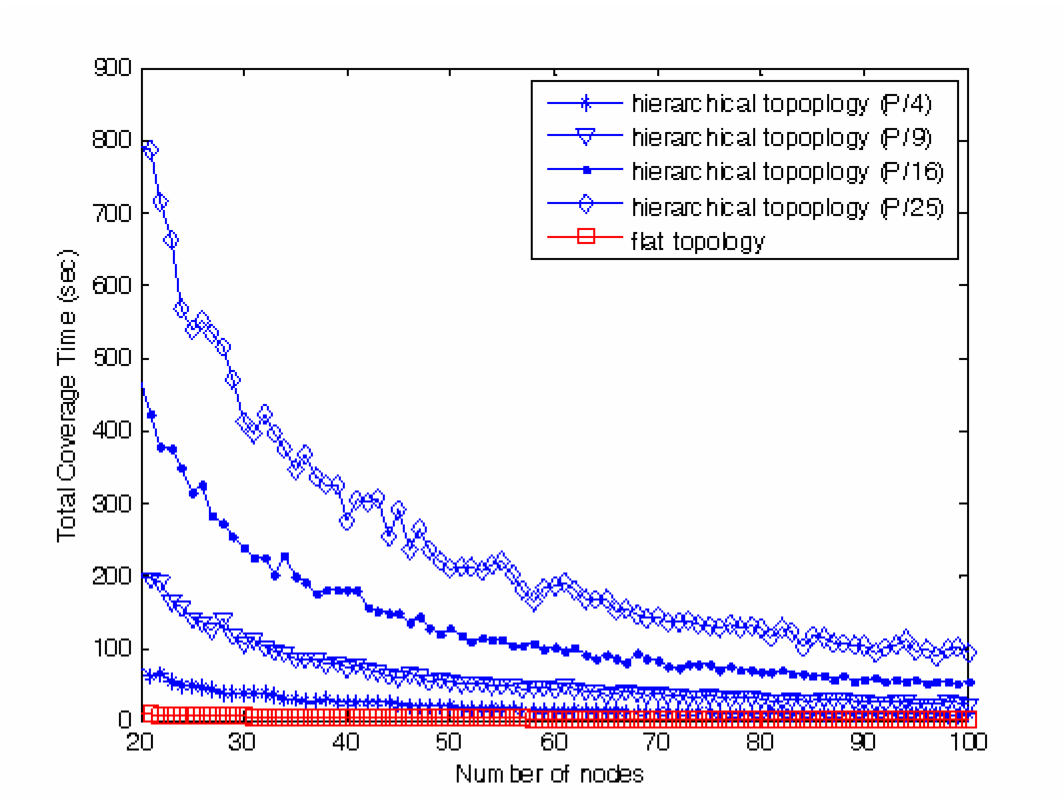

Figure 5.8.1: Total Coverage Time vs Number of Nodes

Figure 5.8.1 and Figure 5.8.2 show that increasing node number in the network decreases total coverage time in both flat and hierarchical topologies. However, energy consumption of the hierarchical topology WSN does not seem to be effected by node number. Increasing number of nodes in the flat topology, on the other hand, seem to cause a very slight increase in the energy consumption.

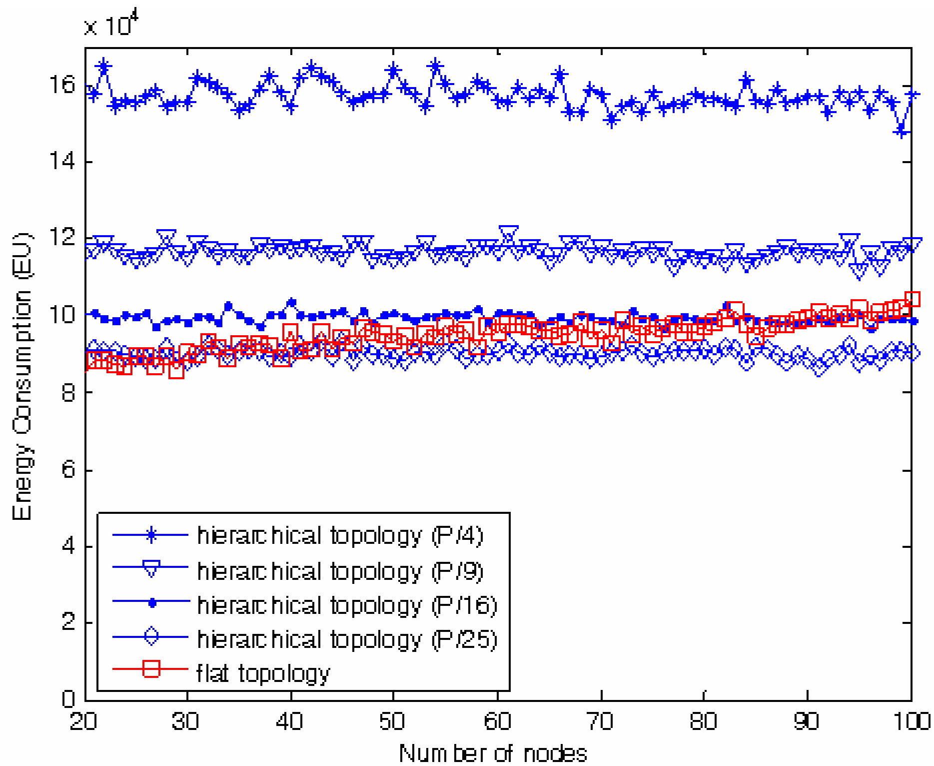

Figure 5.8.2: Energy Consumption vs Number of Nodes

5.9 Location Awareness

So far in all simulations the transmission power of the nodes (be it relay or sensor) were predetermined. To investigate how location awareness effects the QoS of proposed network we conducted another set of simulations in which nodes know their distance to the data sink (via GPS) and adjust their transmission power accordingly.

In the hierarchical architecture the number of sensor and relay nodes are 55 and 5 respectively, and beacon broadcast interval is 0.03 seconds and beacon power varies between P/4 (for 6.86m) and P/100 (for 1.37m). In the first simulation setup relay nodes are assumed to have GPS and when they receive data from sensor nodes they arrange the transmission power so that transmission range is just enough to reach the data sink. In the second simulation setup relay nodes are again assumed to have GPS as in the first case, and sensor nodes are assumed to have adequate computing capacity that they can calculate the distance to the corresponding relay node then they hear a beacon packet and adjust transmission power accordingly. In the flat topology all nodes are assumed to have GPS thus they know their distance to the data sink, and they use a transmission power that is just enough to reach the data sink. All displayed results are the averages of 100 separate rounds of simulations.

The figures 5.9.1 and 5.9.2 show how total coverage time and energy consumption changes with varying beacon power under flat and hierarchical topologies with and without location awareness. The graphs of flat topologies are straight lines because in the flat network there is no beacon transmission at all. The non-smoothness in the graphs is due to the fact that 100 rounds of simulation runs were not sufficient to obtain a stationary average.

From the Figure 5.9.1 it can be observed that neither in flat nor in hierarchical topology does introduction of location awareness have any significant effect in terms of total coverage time.

However in Figure 5.9.2 it can be seen that introduction of location awareness significantly reduces energy consumption. Additionally the introduction of location awareness seems to decrease the influence of beacon power on energy consumption. Although energy consumption tends to decline with decreasing beacon power, digressions are noticeable and graph is not strictly decreasing. When flat and hierarchical topologies are compared under location awareness we notice that hierarchical network is more energy efficient when beacon range is less than 2.75m (P/25).

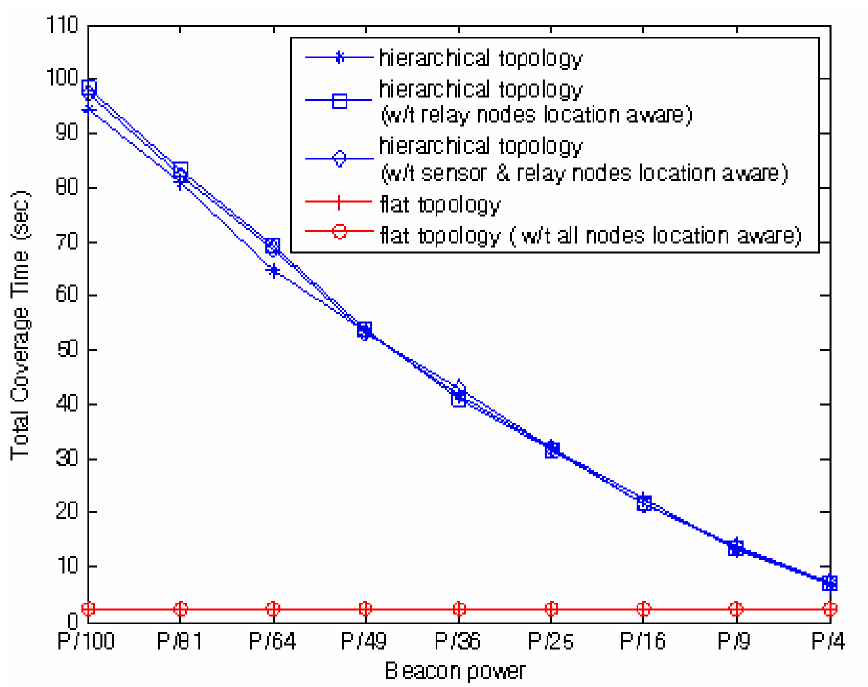

Figure 5.9.1: Total Coverage Time vs Beacon Broadcast Power

In location aware hierarchical architecture the energy consumption of the network is mainly due to relay nodes as when there is no location awareness. However in this case sensor nodes' share in energy consumption is a little higher, especially when they do not know their distance to relay nodes (see Tables 5.9.1 and 5.9.2).

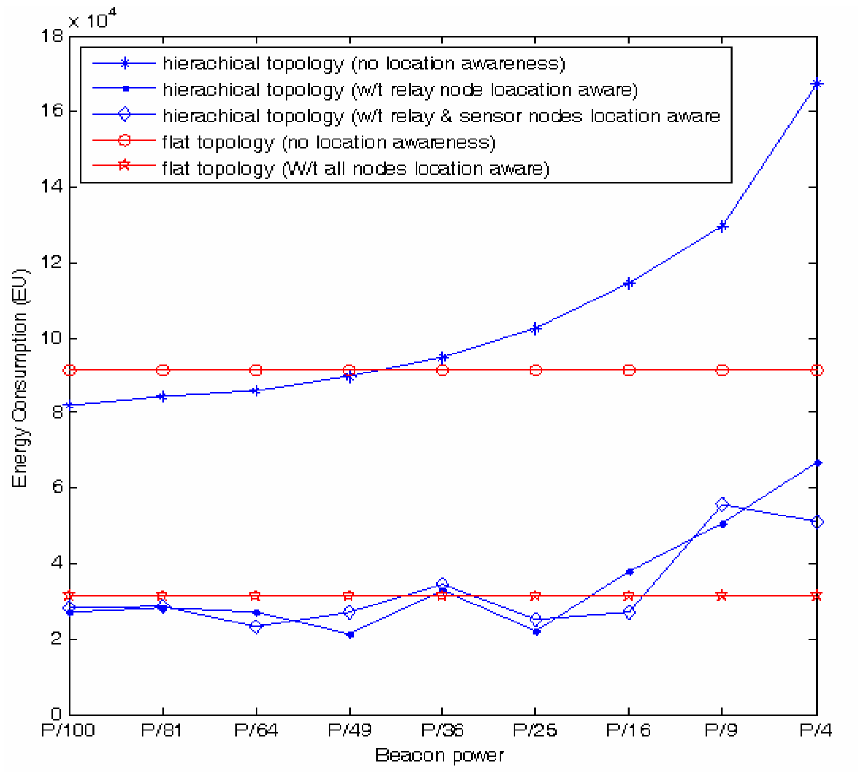

Figure 5.9.2: Energy Consumption vs Beacon Broadcast Power

Table 5.9.1: Energy Consumption Table for Hierarchical Topology (relay nodes are location aware)

	P/100		*P/81*		*P/64*		*P/49*	
	EU	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*
Relay Nodes	26.020	95,79%	26.922	95,12%	25.401	93,90%	19.796	92,35%
Sensor Nodes	1.144	4,21%	1.380	4,88%	1.650	6,10%	1.641	7,65%
TOTAL	**27.164**	**100%**	**28.302**	**100%**	**27.051**	**100%**	**21.437**	**100%**

	P/36		*P/25*		*P/16*		*P/9*		*P/4*	
	EU	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*
Relay Nodes	29.630	89,69%	18.994	86,08%	30.241	79,57%	36.138	71,29%	38.156	57,07%
Sensor Nodes	3.406	10,31%	3.072	13,92%	7.763	20,43%	14.556	28,71%	28.700	42,93%
TOTAL	**33.036**	**100%**	**22.066**	**100%**	**38.004**	**100%**	**50.694**	**100%**	**66.856**	**100%**

Table 5.9.2: Energy Consumption Table for Hierarchical Topology (relay and sensor nodes are location aware)

	P/100		*P/81*		*P/64*		*P/49*	
	EU	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*
Relay Nodes	27.627	97,56%	27.783	97,07%	22.531	96,85%	26.090	95,46%
Sensor Nodes	692	2,44%	840	2,93%	732	3,15%	1.240	4,54%
TOTAL	**28.320**	**100%**	**28.623**	**100%**	**23.263**	**100%**	**27.330**	**100%**

	P/36		*P/25*		*P/16*		*P/9*		*P/4*	
	EU	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*	*EU*	*%*
Relay Nodes	32.439	93,72%	23.292	91,45%	24.283	88,84%	46.005	82,42%	35.946	70,44%
Sensor Nodes	2.173	6,28%	2.178	8,55%	3.049	11,16%	9.815	17,58%	15.083	29,56%
TOTAL	**34.611**	**100%**	**25.470**	**100%**	**27.332**	**100%**	**55.820**	**100%**	**51.029**	**100%**

CHAPTER 6

CONCLUSION AND FUTURE WORK

Coverage in WSN and hierarchical architectures in WSNs are active and interesting research topics. In this thesis we analyzed how introduction of hierarchy effects provision of coverage in mobile WSNs.

We defined and then analyzed two mobile WSN architectures; one with flat and the other with 2-level hierarchical topology. We implemented the test-bed in MATLAB platform and ran the crucial parts of the simulations in animation mode with a pace at which a human observer can notice anomalies. Thereby, we validated that communication and mobility models in the implementation truly represent the design.

We utilized total coverage time as a QoS metric that provides a measure regarding coverage properties of the mobile WSN. Similarly, for the evaluation of the energy efficiency of the mobile WSN we investigated total energy consumed until a certain level of coverage is provided. We analyzed the effects of some network parameters on the energy consumption and the total coverage time. These parameters are probing / sensing frequency, packet transmission power, node density, and location awareness.

Within our scope, the simulation results showed that in the hierarchical architecture, after a threshold, increasing sensor node transmission / beacon broadcast power have no contribution to coverage. Increasing probing frequency, on the other hand, positively effects coverage. However it does not effect energy consumption of the network up to a threshold which depends on node speed. After the threshold, further increase in probing frequency increases energy consumption. In the flat topology sensing frequency has a positive effect on the coverage time of the network, as in the hierarchical topology. But, it has no effect on energy consumption.

At the first glance, introducing hierarchy, when beacon ranges are relatively high, seem to be disadvantageous for both coverage and energy consumption. However one should note that large portion of energy consumption is attributed to resource rich nodes and, in fact, burden on low resource nodes is reduced. As beacon ranges decline, hierarchical architecture performs better than flat topology in terms of energy consumption. However the coverage time of flat architecture outperforms that of hierarchical architecture. With large beacon ranges around 82% of the energy consumption is undertaken by the relay nodes. Moreover, as beacon ranges decline the share of relay nodes in total energy consumption of the mobile WSN mounts up to more than 98% of the total energy consumption. If nodes with high durable energy units are utilized for relay nodes hierarchy may prolong the network lifetime due to energy savings of sensor nodes.

When nodes are aware of their distance to each other or to the data sink, coverage time does not change compared to the case with no location awareness, however the total energy consumptions for both flat and hierarchical networks significantly drop. Thus the introduction of location awareness may be beneficial if energy savings compensate the cost of expensive hardware.

In brief, although causing a sacrifice in coverage sensitivity, the introduction of hierarchy can be desirable due to the energy savings which in turn prolongs network operation time. Similarly providing location awareness may induce a considerable initial deployment cost but this can be offset by the energy efficiency and longer network life time. However, one should note that these results pertain to a specific mobile WSN setting where communication to the data sink is one hop. The effects of hierarchy may be different for other network configurations with different assumptions.

This thesis is an initial attempt to determine the relationship between mobile WSN coverage and hierarchical mobile WSN architectures and there is plenty of room for further research in this area. With minimal modifications to the simulation test-bed, additional simulations can be performed with more complicated communication properties (with lossy medium, obstacles) and network structure (multihop routing, n layered hierarchy), and different mobility models. The test-bed we utilized performs continuous time simulations thus some of the simulations took more than a day to complete because of small time steps. With SimEvents, the recently released DES toolbox of MATLAB, the test-bed can be modified to perform discrete event simulations in order to speed up the simulations.

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