Abstract

The paper presents a simulation-based study of topological characteristics of a mobile wireless ad-hoc network, namely, connectivity, coverage and diameter. Knowing these characteristics of the network aids in design of new distributed protocols as well as in predicting the performance and robustness of distributed protocols running on the network. The nodes exhibit intelligent mobility pattern which aims to achieve required levels of the output parameter values. The nodes also have constraints on their transmission ranges and exhibit both transient and permanent failures. The first part of the study shows the behavior of the output measures with increasing number of nodes in the topology without regard to the traffic. Next, a distributed location determination algorithm is simulated on the network with a mix of mobile nodes and anchor nodes that have location information. Measures of one-hop neighbor connectivity and anchor connectivity relevant to the application are calculated with respect to the duration the protocol is allowed to execute. The study shows that with the given node transmission range and 20% anchor nodes, at least 28 nodes are required so that the average error in location information is less than 10%.

Keywords: ad-hoc mobile wireless network, simulation-based study, node failures, distributed locationing algorithm, connectivity, coverage and diameter.

Approximate Word Count: 5000 words.

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1. Introduction

A mobile ad hoc network is an autonomous system of mobile hosts connected by wireless RF links. There is no static infrastructure such as base stations. If two hosts are not within radio range, all message communication between them must pass through intermediate hosts which double as routers. The hosts are free to move around randomly thus dynamically changing the network topology.

Sensor networks are a particular class of wireless ad hoc networks in which the nodes have micro-electro-mechanical (MEMS) components, including sensors, actuators and RF communication components. Sensor nodes are randomly dispersed over the area of interest and are capable of RF communication and contain signal processing engines to manage the communication protocols and for data processing. The individual nodes have a limited capacity, but are capable of achieving a big task through the coordinated effort in a network that can include hundreds or even thousands of nodes. Sensor nodes are typically battery-powered and since replacing or recharging batteries is often very difficult, reducing energy consumption is an important design consideration for sensor networks. Since the transmission range of a node is proportional to the square root of the transmitting power, the range of a sensor node is constrained in most deployments.

In many applications of wireless ad hoc networks, the hosts are mobile which complicates analysis of network characteristics because the network topology constantly changes. Also, the failure rates of the nodes can be quite high with sensor nodes failing because of failure of the battery. Since the battery typically has to be replaced manually, the recovery time tends to be high (of the order of hours). Both these factors make analysis of the network characteristics challenging and a function of time.

To harness the power of the massive numbers of sensor nodes for useful applications requires a middleware architecture that provides higher level primitives, such as querying, clustering, and monitoring. There have been attempts to provide such architectures – Sensor Information Networking Architecture (SINA) [1] and directed diffusion [2,3] have been proposed for ad-hoc sensor networks coordinating to achieve a higher-level task. Higher-level distributed protocols are executed to provide the middleware functionality. The protocols are of two basic types – the aggregation type where the nodes send information to an elected leader, which performs data aggregation and processing; the homogeneous kind where each node plays an identical role, such as in clustering of sensor nodes based on proximity. The safety, liveness and performance of these protocols are dependent on the network characteristics of the underlying network. There have been theoretical studies that have looked at a single parameter.
(connectivity in [14]) or two parameters (connectivity and degree in [15]) in a static wireless environment. However, these studies have not considered the effect of mobility (or done so for asymptotic cases of number of nodes), and transient and permanent failures on the network characteristics. Also, we consider intelligent mobility patterns that can be employed to improve the network characteristics.

There exists a volume of work on the low-level routing protocols in ad-hoc wireless networks. The fundamental premise of the routing protocols, such as OSPF [4] and RIP [5], is to find the shortest distance between any pair of nodes. However, characteristics of ad-hoc wireless networks (dynamic, low processing overhead tolerable for route calculation) have motivated new routing protocols, such as DSDV [6] and TORA [7]. DSDV uses a freshness index to filter out stale routes. TORA maintains multiple routes and new route computation is done only when all the routes become unusable because of node movements or failures. Energy-aware routing to minimize the energy consumption in the sensor nodes has been an active area of study [8, 9]. More recent work has proposed that minimizing energy in routing protocols may not be optimal for network lifetime or long-term connectivity of the network [10]. In our work, we are not concerned with the routing protocol in use. We assume that the system has the most appropriate routing protocol in place.

In this study, we present an analysis of three network characteristics – connectivity, coverage and diameter – as the network characteristics change because of mobility or failures. We present extensive simulation results that show how many nodes are required to satisfy given constraints on the parameters of interest. The effect of the network characteristics on a higher-level protocol for location determination is studied. A previous study had looked at network connectivity with mobility in a two-dimensional ad-hoc wireless network [11]. However, connectivity does not capture all the performance impact on the higher-level protocol. For that, it is important to know the number of hops between a source and a destination pair. For this measure, we propose to use the diameter of the network. A second measure that is investigated is the coverage of as a fraction of the total area in which the nodes are located. We believe this is the first study to evaluate a combination of network characteristics and investigate the effect of host failures on the network characteristics in an ad-hoc wireless network. We propose an intelligent mobility pattern for the nodes that can be used to optimize the combination of these network characteristics given by a user specification.

Another contribution of the study is to explore the effect of the low-level network characteristics on a higher-level middleware protocol. The protocol studied is a location determination protocol called Hop Terrain and Refinement. A one-hop connectivity measure of
relevance to this application is studied as a function of the time that the protocol is allowed to execute in a network with characteristics derived from the first part of this work.

The rest of the paper is organized as follows. Section 2 gives the system model for the ad hoc wireless network. Section 3 presents the measures of interest in the study, the intelligent mobility pattern, the failure scenarios and the location determination protocol. Section 4 presents the problem statement for the simulation work, together with the assumptions, and details of the simulation model. Section 5 provides results from the simulation and our conclusions from them. Section 6 concludes the paper.

2. System Model for Ad-Hoc Wireless Network

We consider a sensor network model for the ad-hoc network. Each node has a limited transmission range which is constant for the node when it is functional. There are two types of nodes – ordinary nodes and anchor nodes. The ordinary nodes have capability of motion in any direction in the two-dimensional space. There are constraints on the maximum speed of motion of the mobile nodes. The anchor nodes have knowledge of their position in a global coordinate system and are also mobile. Such knowledge is possible through specialized hardware, such as a GPS receiver. The mobile nodes have limited computation power on them while the anchor nodes are more powerful computation platforms. The number of anchor nodes is much smaller (about 20%) of the total number of nodes in the network.

Each sensor node has the following hardware components – CPU, wireless RF communication equipment, memory, sensor, actuator (such as, mobility device) and battery. It also has operating system and application level software, which in this study is executing a location determination protocol combining two protocols - Hop-Terrain and Refinement [12]. The sensor node can have permanent failures due to draining out of its power source, or transient failures which may arise due to temporary blocking of communication paths to the node, or transient hardware errors in the node. The node can respond to control messages dictating direction and velocity of motion. This allows the system to perform intelligent motion of the sensor nodes which is used in the study to achieve desired levels of measures of the output parameters. A unifying feature of all the components is that they are all power-aware since battery life is a critical factor in extending the lifetime of the sensor nodes. A logical view of a sensor node is given in Figure 1.
Figure 1. Logical view of a sensor node

The sensor nodes are combined into a sensor network where each node is responsible for performing local sensing and computation, as well as routing function. Since the transmission range of each node is limited, communication between two nodes in the network may have to go through multiple hops. In such a situation, the intermediate nodes act as routers, running a power-aware network level routing protocol (DSR for this study). The sensor nodes transmit in omni-directional mode and therefore the graph representing the network is undirected with an edge denoting the two nodes have a distance less than their transmission range. The network considered here is two dimensional and is organized as a grid with nodes placed only at the grid points.

3. Design of Study: Protocols & Parameters

We are interested in an intelligent motion of the sensor nodes so that some desired topological properties of the network are met. We simulate a physical situation where the nodes are deployed quickly in response to an emergency situation and are then moved to the requisite positions. First, we introduce the parameters that are being studied and explain why they are important. Next, we provide the algorithm used for the motion. Then we introduce the failure model for the nodes. Finally, we introduce the rationale for the application oriented study and give a sketch of the location determination algorithm being used.

3.1 Parameters for Network Characteristics

The most obvious and well-studied network property of relevance to a networked application is connectivity. Consider the construction of an undirected communication graph representing the sensor network. The \( n \) sensor nodes are the nodes in the graph and there is an edge between node \( i \) and node \( j \) if the inter-node distance \( d_{ij} \) is less than the transmission range \( r \), i.e., \( d_{ij} < r \), implying direct communication between \( i \) and \( j \). A desired network characteristic is that the communication graph be strongly connected, i.e., for every pair of nodes there exists a path between them. A quantified measure for the connectivity needs to be defined for analyzing the network characteristics. We define the connectivity of the network as follows. Consider that the graph has several strongly connected components, a strongly connected component being defined as a sub-graph of the original graph that is strongly connected. Let the strongly connected components of the graph be ordered in decreasing order of the number of nodes in each component. The ordered list is \( C_1, C_2, \ldots \).
The first definition of connectivity we use is

\[ \text{CONNECTIVITY} = \frac{G_1}{n} \quad \ldots \text{(I)} \]

By this definition, only the largest connected component is relevant to the network. However, with application specific knowledge, it is possible to consider that useful work may be done in multiple components, the requirement being that the component have greater than a certain threshold number of nodes. A practical example of such a scenario is a fault-tolerant database application requiring a quorum for reads and a quorum for writes. If the number of nodes in a connected component is greater than the quorum, the application can be executed on the cluster. Let the threshold number of nodes required in a cluster be \( G_{\text{min}} \). Then the definition of connectivity is

\[ \text{CONNECTIVITY} = \frac{|\{C_i: G_i \geq G_{\text{min}}\}|}{k} \quad \ldots \text{(II)} \]

The application that we study here does not have a well-defined threshold \( G_{\text{min}} \) and therefore, we use the first definition of connectivity in this paper.

We believe that for the sensor network to be usable to an application, it is required to know several other properties of the network. Degree of a node is a property that has been studied in the context of a static network [15] since it is a measure of the resilience of the node to link failures. However, the dominant failure model in the sensor network model studied here is not individual link failures but node failures which implies failure of all the links. Link failure rates are a function of the relative motion of the neighboring nodes [16,17] and if the speeds are small and the transmission is omni-directional, as here, we don’t expect them to be a major concern.

We focus instead on the diameter of the network, which is the diameter of the communication graph and is given by the length of the longest path between any two nodes in the graph. Considering the communication delay between node neighbors to be constant, the delay between any two nodes in the network is given by the per-hop delay * number of hops. Thus, knowing the diameter of the network, allows us to place an upper bound on the communication delay in the network. This is likely to be a parameter of interest to applications which have real-time requirements. The diameter is meaningful only for nodes which are in the same connected component and therefore, reachable from each other.

The third parameter that we focus on is the coverage which is defined as the percentage of the total sensor field that is covered by at least one node. A point being covered implies the point is in the transmission range of at least one node in the system. Coverage is an important metric for several application scenarios of sensor networks. Consider the sensor field is a surveillance region and the network is deployed for target location. A higher coverage in the network increases the likelihood of successful detection. We calculate a lower bound on the coverage since the exact analysis with a
rectangular field and circular transmission region is computationally expensive for arbitrary placement of nodes and not suitable for use in multiple iterative steps of a simulation. Consider the circle of radius $r$, that represents the transmission region of a node. A square that is inscribed in the circle is completely covered by the code. Such a square, shown in Figure 2(a) has sides of length $\sqrt{2}r$ and is called the square_tx_range(STR) for the node. To estimate coverage of the sensor field, it is divided into square cells of side $\sqrt{2}r/4$ each (Figure 2 (b)). Any such cell is covered if there is a node in either that cell or in any of the 8 neighboring cells. To understand the logic consider a node placed at the grid point shown in (c). It completely covers a square region of side $\sqrt{2}r/2$ which is one quadrant of its square transmission region from (a). Therefore the entire cell $(i,j)$ is covered by this node. The coverage of the network is given by the fraction of cells covered by the total number of cells which is $L^2/STR^2$.

3.2 Intelligent Motion Algorithm

The algorithm for motion has the objective of meeting the requirements of coverage, connectivity and diameter simultaneously. The connectivity and coverage requirements bound the allowable values from below (e.g., connectivity must be greater than 90%), while the diameter requirement bounds it from above (e.g., the network diameter should not exceed 10). The algorithm runs iteratively and at each step, it chooses one of two possible mobility models depending upon which metric has been satisfied and which needs to be improved.
preserves coverage. Instead of moving a node to the centroid, it is moved a fraction of the distance and then the move is evaluated using an evaluation function. The evaluation function, henceforth called a local evaluation function (LEF) is given by:

\[ LEF = w_1 \times \text{sum of distances from its } k\text{-and-less neighbors} - w_2 \times \text{distance from centroid} \]  

(III)

If the LEF gives a negative value, the node is not moved. Intuitively, for high coverage, the nodes should be spread out and the first term should be higher. For low diameter, the second term should be smaller. Depending on which of the parameters has already been satisfied, the values of \( w_1 \) and \( w_2 \) can be adjusted. For normalization, instead of absolute values, relative changes are considered from the previous value.

The second mobility model is meant to increase connectivity and coverage and is called \( A3 \). The algorithm can be thought of as sweeping through the sensor field, once from left to right starting at the top and next from right to left starting at the bottom pushing the nodes away from each other without disconnecting two immediate neighbors. In the sweep from left to right, when a node \( i \) is considered, all the nodes in the fourth quadrant of its square_tx_range (STR) are pushed away from the center of node \( i \). A neighbor can be pushed a maximum of \( r \) distance away without disconnection. However, to avoid the situation of many nodes squished at the bottom of the field, the push is a fraction \( f \) of \( r \). The fraction \( f \) is a decreasing function of the number of nodes. The working of the algorithm is shown schematically for two nodes \( i \) and \( j \) in Figure 3. Node \( i \) is the current node in the algorithm and node \( j \) is the neighbor that is to be pushed away. A similar process is followed when the sweep is done from the right to the left starting at the bottom.

![Figure 3. Node motion by algorithm A3 designed to increase coverage and connectivity](image)

The intelligent motion algorithm executes either \( A2 \) followed by \( A3 \), or just \( A3 \) depending on whether diameter constraints have been satisfied or not. After the execution, a global evaluation function (GEF) is evaluated to decide whether to preserve the motion or roll it back. GEF incorporates all three parameters and is higher for better topologies. It is given by:

\[ GEF = W_1 \times \text{Connectivity} + W_2 \times \text{Coverage} - W_3 \times \text{Diameter} \]  

(IV)

The parameter values are normalized with respect to the desired values. Also, if a desired value for a parameter has been reached, its impact is deemphasized by setting the weight for that parameter to zero.

If a move is rolled back, a random perturbation of the nodes is employed followed
by A2-A3 or A3 singly. If the desired parameter values are not obtained after a move, the process is repeated a fixed number of times. At that point, an extra node is introduced and the process iterates with one greater number of nodes. The new node is added intelligently to a region which is sparsely populated with other nodes. The algorithm followed is to place it randomly in one of the cells which were found not to be covered in the coverage calculation phase. This will increase the coverage and sometimes the connectivity.

3.3 Node Failure Model

Sensor nodes are likely to be far more prone to failures than the average wired computational node in today’s networks. The higher failure rates can be attributed to several reasons: extreme miniaturization, low cost requirement, power exhaustion, deployment in hostile environments, and interference from large numbers of similar devices in the vicinity. The failure modes considered in the study are permanent failures (e.g., a node failing due to physical damage or battery exhaustion) and transient failures (e.g., a node unable to communicate because of temporary unavailability of line-of-sight communication channels). An exponential mean time to failure is assumed with a certain fraction of the total failures being permanent. For the transient failures, an exponential mean time to recover is assumed. Failures of individual links to a node are not considered.

3.4 Workload driven Study

In the previous sections, the network was analyzed purely from a topological standpoint. In the next part of the study, we analyze the network characteristics from the point of view of workload in the network. This study gives us the suitability of executing the workload in the network, given certain topological properties of the network. It answers the question that given a configuration which meets the topological requirements of connectivity, coverage and diameter, what level of QoS is achieved by the application. Observe that high topological QoS does not guarantee a high application QoS and vice-versa. A network that has a majority of nodes in the central part of the field and connected, and a few outliers towards the boundaries will have a high connectivity value. But if the nodes around the boundary are critical for the application (such as, anchor nodes in a location determination protocol), then the application QoS will be poor.

The workload selected for the study is the implementation of a robust positioning algorithm for wireless sensor networks. The algorithm is a two-step one consisting of the Hop-TERRAIN algorithm that runs in the startup phase and an iterative Refinement algorithm that runs after the startup. The Hop-TERRAIN algorithm is by Savarese and Rabaey from the Berkeley Wireless Research Center [12] and the Refinement algorithm is from Beutel of ETH Zurich [13]. In the network, a few of the nodes, called anchor nodes, have
location information, through special hardware at the node, such as a GSM receiver. This information is diffused to other nodes through multiple transmissions. On termination of the algorithm, each node has an estimate of its position with respect to a global coordinate scheme, such as latitude and longitude. Location determination of wireless nodes is an important problem for several reasons. The information gathered by a node often needs to be interpreted based on the location of the node. The problem becomes challenging when only a fraction of the nodes can act as anchor nodes. Also, the range estimation between neighbor nodes is subject to errors because of errors in physical measurements, such as the received signal strength, and also due to the mapping of the physical measurements to the range estimation not being exact. The protocol being considered here is robust with respect to both these constraints – few anchor nodes and errors in range estimation between neighboring nodes. The error in the final position estimate made by the non-anchor nodes is the QoS metric of the protocol and is a function of the number of one-hop neighbors that have received the diffusion, called neighbor connectivity, and the number of anchor nodes from which the diffusion has been received, called anchor connectivity. The error in the position estimate is a function of how long the protocol is allowed to execute. We consider the values at various time points including the asymptotic case where the protocol executes forever.

4. Simulation Model

4.1 Topological Simulation

The network simulator ns-2 is used as the simulation environment. The sensor field is represented by a two-dimensional grid with resolution $res$. The value for $res$ as well as all the other simulation parameters are given in Table 1. The nodes are placed on the grid points and move in discrete steps from one grid point to another according to the intelligent motion algorithm described in Section 0. The higher the resolution the more controlled the movement can be, but the simulation is also more time consuming. The movement of the nodes is in epochs, which denotes the time period of uninterrupted motion in one direction with a constant velocity. The epoch follows an exponential distribution with a given mean. The computation of the network characteristics is meaningful when the nodes are relatively stationary. This is simulated by having the nodes pause after their epochs and the analysis of network characteristics is performed when all nodes are paused after which the nodes can exhibit the next round of motion.

The initial placement of the nodes is not uniform random contrary to most simulation studies. We simulate a practical scenario where the nodes are deployed quickly in dense clusters and then diffuse to different regions of the sensor field for their operation. Consider sensor nodes being carried by soldiers and the soldiers being air-dropped at a fixed number of locations,
or sensor nodes being used to monitor the chemical composition of the air in a building in an emergency situation and deployed initially close to the entrances. In the study, the initial placement of the sensor nodes is in two clusters at the top and at the bottom of the field. We assume a time-invariant homogeneous transmission range $r$ for each node. A more realistic scenario will be a temporal monotonically decreasing function for $r$, but is not attempted to keep the simulation tractable.

The simulation is started with user inputs of the desired values for connectivity, coverage and diameter. Initially, a low number of nodes (5) are placed in the field. The simulation is run a fixed number of times (40) with the given number of nodes. If the constraints are met within these runs, then the simulation is terminated, otherwise an additional node is inserted. It is possible that some configuration can be found without increasing the number of nodes to satisfy the constraints. However, since an exhaustive placement is not possible, the number of trials is used as a heuristic to conclude the impossibility of satisfying the constraints.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor field grid dimensions</td>
<td>500 m X 500 m</td>
</tr>
<tr>
<td>Grid resolution</td>
<td>1 m</td>
</tr>
<tr>
<td>Initial placement regions</td>
<td>Two bands: (0,0) – (70,70), (430,430) – (500,500).</td>
</tr>
<tr>
<td>Node transmission range</td>
<td>125 m</td>
</tr>
<tr>
<td>Percent of anchor nodes</td>
<td>20%</td>
</tr>
<tr>
<td>Mean epoch</td>
<td>200 ms</td>
</tr>
</tbody>
</table>

4.2 Workload Driven Network Analysis

In the second part of the study, we consider a workload running on the wireless network. The output metrics are computed based on the communication traffic generated by the workload. This means that if no traffic is generated between two nodes in the network, the connectivity of these two nodes is considered immaterial. In computing the diameter of the network, only the maximum distance among communicating nodes is considered. Also for degree computation of the nodes, a link is considered only if some communication happens on the link.

5. Result

In the first experiment, we consider the number of nodes needed to satisfy different connectivity requirements for a given coverage and diameter. The runs are for the error-free case. The result is plotted in Error! Reference source not found.(a). Three different coverage levels are used. It is found that the results are not sensitive to the diameter and that is kept fixed at 10. The plot shows some oscillation with increasing number of nodes, but the trend is a horizontal curve. The number of nodes is most significantly influenced by the coverage level. This indicates that for the given initial placement
and transmission ranges, the number of nodes required is insensitive to the connectivity desired and it is coverage that dictates the number of nodes that should be deployed. The oscillation can be explained by the random nature of additional node placements. For the range of nodes considered, there are enough cells that are not covered and since the new node is placed randomly among these cells, it is possible that addition of a remote node decreases the connectivity.

The second experiment is similar in nature to the first and here we plot the number of nodes required to satisfy a given coverage requirement. The experiment is conducted for three different connectivity requirements and it is observed that the number of nodes does not vary significantly with the connectivity requirement confirming our conclusion from the first experiment. The node requirement increases substantially with the coverage requirement and shows an exponential trend. In fact, with the given parameters, a coverage of 90% cannot be achieved for the simulation range of up to 50 nodes.

In the third experiment, we investigate the requirement for number of nodes for three different QoS levels for the combined network characteristics. This is an approximation of a practical situation where the number of nodes to be deployed is to be decided based on several possible discrete levels of performance available. The result plotted in Figure 5(a) shows an expected increasing trend. Investigation of the experimental data reveals that it is again the coverage that is the gating factor that increases the node requirement. For example, for the medium QoS, only 7 nodes are enough to satisfy the connectivity and diameter requirements, while 12 are required when coverage is added. It is also observed that the diameter tends to stay within a bound of 6 for the entire range of number of nodes explored. We believe that the level of sensitivity to the different parameters is dependent on the initial
configuration. For our starting position, the connectivity is approximately 50% and the diameter is close to 1, while the coverage is very low. The first iteration of algorithm A3 increases the connectivity substantially and the coverage more gradually.

The next set of experiments deals with the application driven network characterization. In the first experiment, we ask the question – What is the error rate in location estimation with the configurations provided by the topological analysis. We pick the three topologies that satisfy the three different QoS levels and analyze them with respect to the neighbor and anchor connectivity. The plot of neighbor connectivity with the execution time of the protocol is shown in Figure 5(b). The derivation of the error from the connectivity information uses the analysis from [18]. The connectivity is a function of time and gives an indication to a system designer how long to run the combined Hop-TERRAIN and Refinement algorithms for a desired error level. The experiment is run till it is seen that the connectivity saturates with time. For the best topological QoS, the neighbor connectivity saturates at 3.28 which corresponds to a high 25% error level. The connectivities for the two other QoS levels are lower giving rise to even higher errors in location estimation. This shows that even though 20 nodes can achieve the required topological QoS requirements, a higher number would be required from the application standpoint.

In the second experiment, we answer the question – How many nodes are required to satisfy the application QoS measured by error level in location estimation. This is a counterpart of the question we answered in the topological case. This analysis is done for both failure-free and failure-prone cases. We know from the results in [18] that a minimum neighbor connectivity of 12 and anchor connectivity of 3 is required with 20% anchor population for an average error level of less than 10%. The anchor connectivity requirement is satisfied for the entire range of number of nodes considered. Therefore, from Figure 6 (and the underlying
data), we can conclude that if the protocol for location determination was run for 200 ms, at least 67 nodes in the failure-free case and 72 nodes in the failure-prone case will be required. If the protocol could be run for a longer period, asymptotically till infinite time, respectively 67 and 70 nodes will be required. This indicates that for the network 200 ms is a close approximation of the asymptotic behavior and may be used as a system designer to bound the execution time of the protocol.

6. Conclusions

The paper presented a simulation based study of network characteristics of a mobile sensor network. The study looked at the topological characteristics of the network as well as characteristics from an application point of view. The study investigated the individual and combined effects of connectivity, coverage and diameter on the number of sensor nodes that need to be deployed and concluded that it is coverage that dictates the requirement for the network under study. Next, the study investigated the effect of the topological characteristics on a location determination application that is relevant to a sensor network and showed that the configurations which achieved high topological QoS still gave a high 25% error level in location estimation. A simulation with and without node errors showed the minimum number of nodes that would be required to reduce the error level to below 10%.

For future work, the effect of the variation of transmission range on the parameters, and time varying and heterogeneous transmission ranges need to be investigated. It would be interesting to study the sensitivity of the parameters of interest to failures in the nodes. An investigation of what network characteristics are required for supporting other classes of applications (soft real-time, bursty traffic, etc.) would make an important contribution to the adoption of sensor networks.

References