Wireless Network Connectivity Measure

Master's Thesis in Embedded and Intelligent Systems

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Preface

We are grateful to our parents for their love and affection, without them we would not have achieved greatness in our lives and we sincerely thank Professor Tony Larsson for his valuable suggestions and ideas towards this thesis work.

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Abstract

The efficiency to which a wireless multi node network is connected is generally measured by the probability that all the nodes are connected to a master node or connected to a master node via other connected node. The grade of connectivity measures how easily and reliably a packet sent by a node can reach another node. Our thesis work is aimed to find connectivity measurement between the nodes in a wireless multi node network. The result is investigated by randomly placing all the nodes in a given area of 38*38 meters and by estimating the connectivity of the whole network. The sub goals of the thesis are

- To Design a link metric
- To Find a Routing algorithm which provides information about neighboring nodes

Achieving the expected results from this thesis work, it can be a contribution to the research in the measure of connectivity for a wireless multi-node network. By using the available routing algorithm and by setting up appropriate threshold for (i) Good connectivity (ii) Average connectivity (iii) bad connectivity, the status (connectivity measure) is informed to the master node (teacher node) in the network, so that the life time of the whole network is enhanced. Various results and solutions are provided and discussed for the above stated problem from the practical experiments.
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1. Introduction

Wireless technologies are among the fastest developing technology sectors. Wireless networking can theoretically improve our capabilities to solve real life challenges. A mobile radio network is a self-organizing and can be a randomly distributed network in which neither a wired backbone nor centralized control exist. The network nodes communicate with one another over scarce wireless channels in a multi-hop fashion. A wireless network is a random collection of devices with radio transceivers that go along with each other without any prior infrastructure in a provisional manner to collectively finish a task. The devices or the nodes can be immobile, mobile, or both and they can join or leave the network as they want.

The range of communication that a wireless multi-node network can support is a matter of interest for designers and users of the network. The vital limiting factor is the absence or presence of possible links and routes between the nodes. A major challenge aroused by the absence of fixed infrastructure in wireless networks is the incapability of the participating nodes to communicate with the other nodes which are in or out of their radio range. Since it is a necessary characteristic of a wireless network that all of the participating nodes are able to communicate with each other, a wireless network requires additional mechanisms to establish multi-hop connectivity. To achieve a connected network, a wireless multi-hop path must exist from each node to each other node. Each single node contributes to the connectivity of the entire network; if a node fails the connectivity might be destroyed. The probability for a network to be fully connected depends on the density and physical distribution of nodes and their transmission ranges.

In general the links and routes between the nodes can be determined by the graph, but it is always interesting to understand and know how effectively the nodes are connected and this determines the reliability of communication between the nodes within the whole network. The estimation of the connectivity is performed by the information obtained by each and every node during each and every communication event.

1.1 Motivation

The (i) reliability (ii) efficiency and (iii) connectivity, of wireless sensor networks has been the main focus in many researches and development in recent times. Various applications in the field of wireless networks are developed, in which monitoring the wireless network becomes very important. Hence the need or demand for more reliable network is always expected. In such an environment the information or the knowledge about the connectivity measure is very important. In most cases with respect to wireless networks when the degree of connectivity is high then, naturally the reliability of the network is also high, which ultimately will result in better connectivity between the nodes.

In many applications, there is a fair chance that a node in the network can be lost; and in certain cases the whole network can be dead or completely lost. Among all the above mentioned parameters like (i) reliability (ii) efficiency and (iii) connectivity, to measure and improve the connectivity within a network is a challenging and motivating factor for us to suggest a solution for (i) measuring the connectivity of the network by measuring connectivity between the individual nodes and the whole network (ii) reducing the connectivity loss between the nodes within a network. The reason for this measure is because all the nodes in the network within the specified range is connected with each other, the measure of the connectivity will provide the
users in the application with the specified range or exact measure of the overall connectivity. The parameters which are considered in formulating this design are:

(i) Link metric
(ii) Routing algorithm

By achieving the desired results, measure of connectivity for a network is known.

1.2 Chosen application

![Diagram of students and teacher nodes]  

**Figure 1 - Application**

We are considering an application where there is group of (i) students and (ii) teacher. Each member in the group is provided with a wireless node. Connectivity measure between individual nodes (teacher is also included) and connectivity measure for network as a whole is measured and strategies to improve the connectivity of the whole network is also designed, in such way that no node is lost communication with other nodes in the network or connectivity of the network is lost. In this application we are considering that all the nodes in the network is placed within a square formed room of 38*38 m. Here the students and teacher are placed in the room, under various scenarios.

**Scenarios:**

We have performed 100 different experiments for the connectivity measure. A scenario is nothing but placing all the nodes randomly within the square 38*38m and measuring the corresponding connectivity measure. Given below are some of the scenarios that was performed

1. Consider a scenario where a student node is far away from the teacher and all other nodes in the network.
2. Consider another scenario where the teacher or the master node is far away from the rest of members in the group.
The corresponding connectivity measure between the individual nodes and connectivity measure of the whole network is also measured, when any node in the network is about to loss connectivity with other nodes the status of the corresponding node is intimated to the teacher node. Likewise we have carried out measurements in 100 different scenarios and their corresponding measurement values are tabulated and the graph is also plotted which will be discussed in the coming chapter [4].
1.3 Problem statement

The purpose of the current research work is to provide a solution for measuring connectivity between the nodes and connectivity of a whole network within a wireless network. In real time monitoring and data transfer applications based on wireless networks, connectivity requirement plays vital role.

In the process of providing a solution for the connectivity measure in a wireless network by placing the wireless nodes are placed randomly in the network for each test case or for each test scenario within a square of 38*38m and the approach followed to solve this problem is by using appropriate routing protocol , utilizing the parameters that can be retrieved upon by any node in the network upon receiving any communication event, and appropriately forming a link metric using these parameters in order to find measure of the connectivity between any nodes and the whole network. Since the nodes are placed randomly at different instance of time for every test set that is performed, so we cannot have a standard fixed topology.

1.4 Goal

The main goal of this thesis work is to suggest a solution for measuring the connectivity between the individual nodes (master node is also included) and connectivity measure for a whole network. To avoid network failure, the status of the corresponding nodes is informed periodically to the master node; by this the connectivity loss between any nodes in the network is reduced, this can be specified as the sub goal of the thesis work.

With reference to the application of this thesis work, the connectivity measure between the student nodes, teacher node and the other measure is connectivity for the whole network is the main goal, by setting up appropriate threshold for badly connected nodes in the network, the status of the corresponding node (teacher or student) which is about to lose contact with other nodes in the network is informed to the teacher node so that the node doesn’t get lost once for all from the network. For calculating connectivity an appropriate link metric is formulated.

1.5 Approach

First step in the approach is understand the characteristics and the use case of the parameters that are being used in the network connectivity estimation or measure, the network connectivity estimation process is carried out by the information or the parameters obtained by each and every node during the during each and every communication event. The second step is to formulate a link metric, in which parameters such as RSSI and LQI (mention chapter name in which it is discussed) are being used as the integral part of the metric formulated, which in turn will give the exact measure of the connectivity between the nodes and the network as a whole.

If a node in the network is likely to lose all its connectivity with rest of the nodes then the base station may intimate the corresponding node about its connectivity measure. This is can be achieved since all the connectivity measure is reported to the base station. The other parameters which were also taken into consideration such as a) protocol for communication between the nodes b) system reliability and c) mathematical analysis.
2. Background

The recent developments in wireless networks have been tremendous. There are many applications which are being deployed based on this Technology. There is obviously scope for improvements in the technology that is being deployed in the current applications. The range in which the wireless network being used is very large ranging from military applications to forest temperature monitoring, humidity measurements, animals (certain group) movements or behavior monitoring within a certain area, so the range of applications is very large. The areas of development in wireless networks that this thesis focuses on are (i) energy used in the nodes (ii) connectivity between the nodes within the network, and (iii) reliability in the network.

There are many approaches that are followed to estimate the connectivity measure which depends upon the specification and need of the application. In our effort to estimate the connectivity measure, the emphasis was given in link metric, understanding the qualities possessed by the parameters forming the link metric and the communication protocol used for communication and finally the reliability theory. Each of these parameters is discussed in the detail.

Forming the link metric involves using the values from the motes (TelosB motes) such as (i) rssi (ii) lqi. Rssi stands for received signal strength indication and lqi stands for link quality indication. Both are the measures taken from each communication event, and can be obtained from any node in the network. Link quality indication represents the error rate of the signal received by the mote and rssi represents the strength in the received signal. The parameters (i) rssi and (ii) lqi will vary in accordance with the distance and atmospheric conditions [19].

The connectivity measure is always taken for each and every communication event. Their corresponding measures are compared with the threshold, with respect to that comparison the nodes which are about to lose its connectivity completely or which are badly connected is informed by the master node (teacher node) so that the corresponding measure of connectivity is improved. There are various routing protocols which can be implemented in wireless networks; each predefined routing such as (i) broadcast (ii) unicast (iii) anycast (iv) Multi cast according to the requirement of the specific application of the wireless network where it is implemented. Many routing algorithms are also developed according to the requirements of the application, in a case where there is hybrid anycast routing protocol developed for a specific application [20].

2.1 State of the Art

A problem is the mobility of the nodes in some specific applications. Because of their mobile nature, many nodes in the network fail to be connected all the time and, due to this reliability the whole system goes down. There are many strategies which are developed to date to improve this with regard to wireless networks.

(i) Making the network multi-hop rather than a single hop. The advantages of using multi hop in a network in real environment [9].
(ii) Designing a better link metric to understand the connectivity of the nodes.
(iii) Making reliability theory an integral part of connectivity measures and coverage area of the wireless network [21].
(iv) Calculating connectivity in terms of reachability, based upon the graph theory.
(v) Increasing the connectivity in wireless networks by using cooperative transmissions, in which all the nodes are in a sparse network, where a group of nodes can combine its emission power and achieve a higher emission power as a whole [4].

(vi) Fault tolerant relay nodes are placed in heterogeneous wireless networks, in a measure to increase the connectivity of the network. Where it provides better fault tolerance and enhances the network connectivity [10].

2.2 Related work

The most important factor in many wireless networks is having a reliable network. That is all the nodes in the network should stay connected with rest of the other nodes in the network (at least possibly one other node) in the network. To achieve this task a suitable approach has to be implemented where one can have a measure of connectivity between all the nodes in the network and also a measure for the whole network connectivity. Once we manage to achieve the measure of connectivity, various other measures which can improve the connectivity in the network can be implemented.

There is work in which, the group of nodes form a network under clustering based technique, where there are \( n \) number of cluster head’s according to the number of nodes and all the cluster head’s will report the identity of the ordinary nodes under them. The corresponding measure of connectivity with respect to the cluster head is passed on to the master node of the whole network: The problem with this approach is that the cluster head and the master node is selected in accordance with the remaining battery in any of the node within the network.

The problem with the hierarchical approach is that the master node or the cluster head tends to lose out all its remaining battery for communication related protocols, and in turn the battery will be dead or the corresponding node will be dead much faster with respect to the ordinary nodes in the network. In mobile node applications one cannot expect always to form a clustering network topology because is the nodes are ever changing[22].

Another measure to increase the connectivity in wireless network is done, where the connectivity is increased by means of cooperative transmission, this approach has some members in the network that tends to form a group, and these nodes within the group will use high energy to communicate with rest of the other nodes in the network.

By doing this the connectivity range for the corresponding node is increased and the network is more reliable. The disadvantage of using this approach is that the nodes which are in group of emitting high power will lose its battery life, in turn the corresponding node will be completely lost from the network [4].

2.3 Methods to find a better solution

There are many advantages with small battery driven wireless nodes, however their memory, processing ability and energy are among their various drawbacks. Considering all these factors, we have to come with a solution that will provide the necessary information to fill in the routing table dynamically, get updated and avoid any retransmissions during its communication due to its energy constraints. The information that is passed on the dynamic routing table is the current nodes neighboring node id and the corresponding link metric values. With respect to the routing table, the reliability and connectivity of the network can calculated.

2.4 Software Tools
2.4.1 *NesC*

In general, *NesC* (network embedded systems C) is an extension of *C* programming language [23]. *NesC* is a component-based programming language used to develop applications for TinyOS platform. TinyOS is an event-driven operating environment for sensor network nodes with limited resources. This *nesC* is developed for programming wireless sensor nodes which enables all the sensors, interrupts and etc., to be used by the programmer. In simple words, *NesC* is an event driven and component based programming language. In a structured manner, this programming language (*nesC*) is divided into order of structures and *nesC* allows the programmer to use a concurrency (threads) in form of either a task or hardware event handlers [23]. *NesC* applications are made out of components with bidirectional interfaces.

2.4.1.1 *Components*

Components are assembled together to form a whole application. A component either uses an Interface or it provides an interface. In *nesC* components are categorized into sections namely modules and configurations.

Modules are the section where the programmer is allowed to implement an interfaces it provides and event of interfaces it uses and it is the section where the application code is provided [23]. By default in *nesC* modules are singletons: we can’t instantiate them. It skins whether a component is hardware or software. Configurations are the section where all components are joined together. There is a special element called “wiring” in *NesC* that is for connecting other components together.

Modules provide implementation code and Configurations wire one or more components together to make whole program [23].

2.4.1.2 *Interfaces*

Interfaces are the collections of related methods (Functions) and it is bidirectional. Interfaces specify a multifunction communication channel between the provider and user [24]. The interface specifies two functions called commands and events. Commands are functions to be implemented by the interface provider which are already declared by an interface. Events are the set of functions that is already declared by the interface, but the implementation part has to be done by the programmer or the user of the corresponding interface.

- **Commands** - Implemented by the interface’s provider, one component demanding service from another Component [25].
- **Events** - implemented by the interface’s user, indicating completion of service by a component [25]. Event is invoked by interrupt or module and event may preempt task.

2.4.2 *TOSSIM*

*TOSSIM* is known as TinyOS simulator, it compiles directly from TinyOS source code and *TOSSIM* runs natively on a laptop or desktop [15]. Implementation of a wireless network becomes a very difficult task practically in a real-time environment. Tinyos is supported by TinyOS Simulator designed for simulating wireless networks. *TOSSIM* simultaneously simulate thousands of nodes. Each and every mote in a simulation runs the same TinyOS program. *TOSSIM* offers run-time configurable debugging output, permitting a user to inspect the
execution of an application from different perspectives without recompiling the program [15]. TinyViz is a Java-based GUI it permits user to visualize and control the simulation as it runs [15]. This makes it easier for the users to experience the real time environment within a simulator. TOSSIM works for mica2motes, TelosB motes and Iris motes. This can also return values like LQI and RSSI between the links and paths. All the protocols from the NesC programming language are supported by TOSSIM.

2.5 Available Communication protocols

Important protocols available with the nesc, tinyos is that it supports unicast, anycast, and broadcast communication protocols between the nodes. With the requirement of the application each of the communication protocols can be used upon, we have used collection tree protocol in our application, where in which it collects data from the neighboring node and sends the corresponding information to the root node of the application.
3. Methodology

Designing a link metric will define our solution to the problem, and understanding the importance of using the proper communication protocol because the routing protocol will play a vital role in designing our application, and in our application all the nodes are to be placed in different locations for different test scenario’s, so by designing a methodology for a standard or static topology will not solve our requirement towards our application, the link metric will have to support different topology that may be formed during the test scenario of our application, the problem which was defined earlier that is to measure the connectivity from the master to an individual node in the network and another for the network as a whole. So for designing a solution for calculating the connectivity and reliability of the network most importantly depends upon having a clear idea about link metric, and how the link metric is designed.

The important elements in designing the link metric are the received signal strength indicator (RSSI) and link quality indicator (LQI). We chose to use addition as a mathematical operator to make into a single expression, but the link metric will go in for further changes mathematically that will be discussed in the coming chapters, the other important factor in designing is deciding upon our topology, we have to make sure that there is not much dependency within the network, avoid any hierarchical approach within the network make sure that a node can communicate with any node possibly within its range in the network.

So we have chosen to use a fully connected network where it fulfills all our requirements in an ideal situation where in which all the nodes are placed very near to each other or it can be a situation where in which all nodes are possibly in direct or indirect contact with each other within the network, our application is designed not only to support single hop communication but also multi hop communication. The various advantages of making this is a multi-hop application the connectivity or the communication is much higher than the single hop application because a node can be reached in more than one way because it is a fully connected network and it is a multi-hop supported application. The above mentioned are the methodologies that are implemented regarding this application.

3.1 Link Estimator

The emphasis on link estimation is high in recent research works in wireless networks domain. Spatial correlation for link quality estimation is a technique which is widely implemented to improve the quality of the packet sent and received within the network [1], and Four bit wireless link estimation is another method which vastly increases the quality of the packet propagated throughout the network [5].

In wireless networks, a good solution to manage neighbor nodes is using link estimator due to the consumption of less energy and need of few resources. By using link estimator it is possible to find suitable mechanism for the propagation of messages among all mobile nodes which causes network to be more reliable. Since most of the applications use (i) ad-hoc network and (ii) multi hop connection between the nodes. So the need for a link estimator is very important aspect in a network (i) to manage and (ii) support routing protocols.

There are number of ways to develop Link Estimation. One is developing link estimation by using Signal Strength which provides a good estimation. The good link estimator must be stable and fit in a limited storage, needs less memory and react quickly according to changes of link quality. In addition to reduce the energy cost, it should use simple computing process.
Wireless network link estimators use different combinations of information which consists of the condition of the network, quality, availability and reliability of the link, specific properties of nodes like radio transmission, storage capacity and processor power, environmental conditions to form a metric for the network. Link estimators have to react quickly according to changes in the network. It also needs processing energy and small memory resources.

3.2 System Reliability

The collection of components and subsystems for a specific design to perform desired tasks and their corresponding performance is called a system, in which system reliability plays an important role with respect to system performance and stability. The system reliability comprises of:

1. System components
2. System quality and
3. Type of arranging components within the system.

Reliability block diagrams are used to define the system and explain the relation between components. They are related directly to derive mathematical description which is a key to determine system reliability (in terms of component reliability).

Consideration of the reliabilities of all components which makes the entire system useful for system reliability prediction. The components reliability configuration has to be determined to construct the reliability block diagram. The configuration will be simple like series and parallel configurations. There can also be complex systems which cannot convert to series or parallel configurations.

The configuration types are:

1. Series configuration
2. Parallel configuration
3. Series and Parallel (combined) configuration.

3.2.1 Series configuration:

In series configuration, the components will be arranged in reliability wise at the subsystem level. In this configuration, the failure between any of two nodes causes failure of the entire system. Hence all the components have to be succeeded to the success of the entire system.

![Figure 4 - serial connection (a)](image-url)
Here, the system reliability will be the probability that component $n_1$ success, component $n_2$ success and so on. Hence the reliability of the system will be

$$R = P(X_{n1} \cap X_{n2} \cap \ldots \cap X_n)$$

$$= P(X_{n1}) P(X_{n2}/X_{n1}) P(X_{n3}/X_{n1}X_{n2}) \ldots P(X_n/X_{n1}X_{n2}\ldots X_{n-1})$$

Where, $R$ = System Reliability and $X_{ni}$ = unit $i$ event

Independent components reliability will be

$$R = P(X_{n1}) \cdot P(X_{n2}) \ldots P(X_n)$$

Hence, in series systems reliability of a system will be the product of component reliabilities.

Example:

![Diagram of a system with nodes $n_1$, $n_2$, and $n_3$.]

**Figure 6 - system reliability for series connection**

<table>
<thead>
<tr>
<th>Node1</th>
<th>Node2</th>
<th>Node3</th>
<th>System Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.336</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>0.392</td>
</tr>
<tr>
<td>0.6</td>
<td>0.8</td>
<td>0.8</td>
<td>0.384</td>
</tr>
<tr>
<td>0.6</td>
<td>0.7</td>
<td>0.9</td>
<td>0.378</td>
</tr>
</tbody>
</table>

**Table 1 - Table for system reliability for series connection**

In the above mentioned figure [6], suppose $n_1$ is connected $n_2$ with a reliability of 60%, $n_2$ is connected with $n_3$ with a reliability of 70%, $n_3$ is connected with $n_4$ with a reliability of 80%. From Table [1], the system reliability will be the product of each node’s reliability. We can conclude that if there is an increment in the lowest node reliability ($n_1$), there will be highest increment in system reliability (0.392). When the number of components is increased in the series configuration, the system reliability decreases.
3.2.2 Parallel configuration:

In Parallel configuration, success of entire system depends on at success of one node. The nodes in parallel configuration are called as redundant nodes. Hence all nodes have to be failed for the failure of entire system.

\[
R = 1 - Q
\]

Where, \( Q \) = Unreliability of the system, from the above mentioned figure 15, the Unreliability of the system will be,

\[
Q = P[X_n1 \cap X_n2 \cap 2X_n3 \cdots \cap X_n4]
\]

\[
= P[X_n1]P[X_n2/X_n1]P[X_n3/X_n1 X_n2] \cdots P[X_n/X_n1 X_n2 X_n3 \cdots X_{n-1}]
\]

Where, \( Q \) = system unreliability and \( Xi \) = event of node failure

In parallel configuration reliability of the system can be given as,

\[
R = 1 - Q
\]

In series configuration, unreliability of the system is the product of unreliability of components and in series configuration, product of component reliabilities will be the entire system reliability.

Here, reliability of the entire system in parallel configuration is

\[
R = 1 - Q
\]

\[
= 1 - [Q_{n1} \cdot Q_{n2} \cdots Q_{n}]
\]

(OR)

\[
= 1 - [(1 - R_{n1}) \cdot (1 - R_{n2}) \cdots (1 - R_{n})]
\]

Example:

From the Figure [8], Let us consider that \( n_1 \) is connected \( n_2 \) with a reliability of 50%, \( n_2 \) is connected with \( n_3 \) with a reliability of 60%, and \( n_3 \) is connected with \( n_4 \) with a reliability of 70%. Now, we can examine the reliability of entire system with each node’s reliability. From Table [2], The reliabilities of \( n_1 \) is increased to 10% in second column, reliability of \( n_2 \) is increased in 3rd column and \( n_3 \) is increased in 4th column, from this observation, it was concluded that in parallel configuration, highest reliable node has high effect on system reliability where as in series
configuration lowest reliable node has high effect on system reliability. In this configuration, system reliability increases according to the increase in number of nodes. And one more important thing in parallel configuration is highest reliability node failure occurs at last.

![Figure 8 - System reliability in parallel configuration](image)

<table>
<thead>
<tr>
<th>Node1</th>
<th>Node2</th>
<th>Node3</th>
<th>System Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.86</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td>0.88</td>
</tr>
<tr>
<td>0.5</td>
<td>0.7</td>
<td>0.7</td>
<td>0.95</td>
</tr>
<tr>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
<td>0.96</td>
</tr>
</tbody>
</table>

**Table 2 - Table for systems reliability for parallel connection**

From the Figure [8], Let us consider that \( n_1 \) is connected \( n_2 \) with a reliability of 50%, \( n_2 \) is connected with \( n_3 \) with a reliability of 60%, and \( n_3 \) is connected with \( n_4 \) with a reliability of 70%. Now, we can examine the reliability of entire system with each node’s reliability. From Table [2], The reliabilities of \( n_1 \) is increased to 10% in second column, reliability of \( n_2 \) is increased in 3rd column and \( n_3 \) is increased in 4th column, from this observation, it was concluded that in parallel configuration, highest reliable node has high effect on system reliability where as in series configuration lowest reliable node has high effect on system reliability. In this configuration, system reliability increases according to the increase in number of nodes. And one more important thing in parallel configuration is highest reliability node failure occurs at last.

### 3.2.3 Combined Series and parallel Configuration

Series or parallel configurations are suitable only for smaller systems. But there may be combined series and parallel configurations involved in the case of large systems. We can analyze these systems (like combined series and parallel configurations) by calculating and combining reliabilities of each series and parallel configuration in particular manner.
In the above mentioned figure [6], node $n_1$, $n_2$ are connected in series and node $n_3$ is connected in parallel configuration.

Hence reliability of nodes $n_1$ and $n_2$ are

$$R_{n_1n_2} = R_{n_1} * R_{n_2}$$

the entire system reliability will be,

$$R = 1 - [(1-R_{n_1n_2})*(1-R_{n_3})]$$

![Diagram of Combined Series and parallel Configuration](image)

**Figure 9 - Combined Series and parallel Configuration**

From Figure [9], let us consider that node $n_1$ is connected with a reliability of 60%, $n_2$ is connected with a reliability of 70% and $n_3$ is connected with a reliability of 80%.

<table>
<thead>
<tr>
<th>Node1</th>
<th>Node2</th>
<th>Node3</th>
<th>System Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.884</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>0.898</td>
</tr>
<tr>
<td>0.6</td>
<td>0.8</td>
<td>0.8</td>
<td>0.896</td>
</tr>
<tr>
<td>0.6</td>
<td>0.7</td>
<td>0.9</td>
<td>0.942</td>
</tr>
</tbody>
</table>

**Table 3 - Table for systems reliability for Combined Series and parallel Connection**

In the above mentioned table, node1 node2 and node3 are increased to 10% from this observation, it was concluded that, in combined series and parallel configuration systems, the entire system reliability (0.942) is effected by the component which has highest reliability(like in parallel configuration).

### 3.3 Chosen Link Metric

In Wireless networks, Link metric is used to select the most efficient path between two nodes. WSN should be consider different factors (which effects the link quality) to form good link metric. And it should act quickly according to the network changes. So the connection is more guaranteed.

The Factors that make the link metric are:
1. Received signal strength

2. Received packet quality

The received signal strength is a factor which can be used for link metric. In wireless networks, the transmission of the data is done by using the power of radio transmission. The radio signal which is having low power reduces the connectivity of network due to small coverage. Since mobile nodes are part of the wireless network, node movements have great impact on the signal power and reliability of link. Hence RSSI is one of the main factors to calculate link metric. Received packet quality is another factor to calculate link metric. There are to factors that can modify the transmitted packets. They are Channel interference and environmental situations. The radio signal can be affected by propagation loss (path loss, signal fading). Path loss occurs when node moves very far (causes degradation of power density). Signal fading occurs in the signal due to various changes with the environmental conditions. Since the link quality is also very much emphasized in various research works, we have added LQI to the link metric.

\[
\text{Link metric} = \text{Received signal strength} + \text{quality of received packet}
\]

In the network, according to node role and network topology the link metric factors can be different. This will be used in connectivity measurement and network topology.

\[
\text{Hence, } \text{Connectivity} = \sqrt{K_1 \cdot (\text{RSSI})^2 + K_2 \cdot (\text{LQI})^2}
\]

Here constants \(K_1\) and \(K_2\) represent importance of relevant factor for node.

### 3.4 Wireless Network Topologies

In general nodes in a wireless networks are spread around in a distance between them, so placement of nodes should follow certain topology which fulfills the requirement of the application. There are various important actions that take between the nodes placed in the network, namely;

(i) Sending data  (ii) Receiving data.

Depending upon number of nodes in the network the desired topology has to be decided, for example; when the number of nodes is higher, then by using certain topologies in the application will result in high latency within the network and will result to high error rate, loss within the network. The various topologies are:

1. Line Topology
2. Tree Topology
3. Star Topology
4. Mesh Topology
5. Ring Topology
6. Cluster Topology
It is very important to discuss the characteristics and the corresponding advantages and disadvantages of all the above mentioned topology since we have to place all our nodes in various different positions in each and every scenario, that is the position of placing the nodes is randomly generated within the given area (38*38m). The topology should be selected based on the application requirement. Topologies such as; (i) mesh (ii) Cluster topology are much more redundant compared with other topologies. In many applications cannot tolerate latency in the network, latency occurs when there are more number of nodes in the network, that has to communicate with each other through a central hub or a system then the hub will be over loaded then there will be latency throughout the network, and certain topology will run out the battery life time of a particular node due to hierarchical approach it follows for data communication, all these factors are discussed in detail in the coming chapters.

3.4.1 Ring Topology

The term “ring” topology suggests that all the nodes in the network are connected in a circular manner. Each node is at most connected with two other nodes directly in the network that is a node is connected to its previous node and its next node in the network. When a node needs to transfer data to other nodes in the network it broadcasts the intended message to the entire network. In the broadcast message will have (i) sender node id (ii) receiver node id and (iii) message. Each and very node in the network will receive the message and it will check for the receiver node is, if it matches then the corresponding node will receive the message from the sender if not, the message will be discarded.

**Advantages using this topology:**

All the nodes have their opportunity to broadcast their message and as well as all the node can receive messages sent by other nodes in the network.

**Disadvantage of using this topology:**

When a node fails to work then all the other nodes in the network will also fail to communicate with each other.

**Figure 10 - Ring Topology**
3.4.2 **Clustering Topology**

Cluster topology is a hierarchical topology where the top node in the network is called as “cluster head”. Cluster head can have ‘n’ number of lower level hierarchical nodes, and all these lower level nodes are the cluster heads for the nodes under them. Lower level cluster heads are directly connected to the root node or the main cluster head of the whole network.

![Figure 11 - Clustering topology](image)

For example; in the above Figure [11], \( cc_1 + sc_1 \) is the Lower level cluster head 1 and it has 3 simple nodes under it, similarly \( cc_2+sc_2 \) is the Lower level cluster head 2 which again has 3 simple nodes under it and \( clc \) is the root or main cluster head for the whole network. All the simple nodes under \( cc_1 + sc_1 \) and \( cc_2 + sc_2 \) can communicate with each other through gate way nodes. All the information about the simple nodes in the network will be available with the corresponding cluster head nodes, which then will be forwarded to the main root or main cluster node for the whole network.

3.4.3 **Star topology**

Star is a simple topology to form. There can be n number of nodes in the network; they are generally simple nodes which can communicate with each other with a hub in the center of the network. The nodes in the entire can transmit and receive message when and where they intend to. All that a simple node in the network does is it forwards it’s data to the central hub with the source and destination address. All that the central hub does is that, it will receive data from all the nodes in the network and forward the data to the corresponding node in the network.

**Advantages of using this topology are**

(i) the design structure of this topology is very simple  
(ii) This topology can have any number more of nodes in the network.

**Disadvantages of using this topology are**

In case the central node (hub) fails to work then all the nodes in the network fails communicate with other nodes, and this makes the whole system unreliable. The example Star topology network is shown in the figure [12].
3.4.4 Line network

A line network is typically a series network, in which all the nodes succeed the previous node in the network. Any node in the network is allowed to transmit data and receive data which will be forwarded serially to all the nodes within the network, with help of source and destination address in the message packet the data is passed on to the corresponding node. Any number of nodes can joined in the network, when any one node fails then, the entire network is failed, and redundancy in the network is very less.

3.4.5 Tree Topology

Tree topology is a hierarchical topology where the top node in the network is the root for the whole network.
A root can have two or more lower level hierarchical nodes connected to it. All the lower hierarchical nodes will send their data to the root node for communication within the network. Root nodes in the network will consume more energy compared with other nodes in the network.

3.4.6 Mesh topology
Mesh networks have three or more wireless access nodes, works by sharing routing protocols each other. In this topology, every node has a link to other node in the network. This topology has greatest ability that if any node in the network fails, it can reconfigure the network and select the best route according to the quality of link. Even though these networks have low data transmission loss, latency of sending or receiving data occurs. There are two types of Mesh Topologies

- Partial mesh network
- Full mesh network.

There are various differences between the above mentioned two, but in general both of this topology follows the basic mesh topology

3.4.6.1 Partial mesh topology
Types of partial mesh topology are multi point to multipoint, multi-point to point, point to point. This type of network has some nodes which are fully connected and one not full connected but they will be in connection with at least one node. The advantage of using a partial mesh network is that the latency of data is minimized compared to full mesh networks. But the dis advantage of using this partial mesh topology is that, the redundancy within the network is less comparatively with that of a full mesh network topology, the reason is that because all nodes within the network are not fully connected.

3.4.6.2 Full mesh topology
All the nodes within the network will be connected to each other. A node can be reached in more than one way or route within the network. When a full mesh topology is implemented in an application, then before one must know “Reeds law”.

![Figure 15 - Full mesh topology](image)

A node is connected with all other nodes within the network except itself. That is expressed as \( n(n-1) \) in a full mesh network. For certain applications all the nodes in the network is required to
be connected with all the other nodes which in return will yield more connectivity for the whole network. All the nodes in the network will consume same amount of energy, and there is no risk of losing a node in the network because there is no hierarchical approach in this topology, since a node can be reached by more than one way throughout the network redundancy in the network is much higher, the system has very less probability for system failure. The drawback of using topology is; that it is not feasible to use this topology when there is more number of nodes in the network.

3.5 Chosen topology:
Aim of our work is to efficiently measure the connectivity, in order to achieve this; all the nodes in the network should be able to communicate with every other node in the network. A fully connected network will satisfy all the above mentioned requirements. Since a node can be reached by more than one way the redundancy in the network is increased, in an ideal situation as shown in figure [15], a fully connected network is one of the best topology which can support multi-hop connections in the network. A fully connected network is explained in detail in the above mentioned chapter [3.3.2.2], but the topology structure is ever changing because of the mobile nodes within the network.

3.6 Connectivity
Connectivity in networks can be calculated in many different ways as it was discussed in the previous chapter [2.1]. Before discussing more about, how the connectivity is calculated, it is important to discuss about graph theory [14]. Let us take a simple example; In wireless networks communication between the nodes is the important factor. All the nodes in the network will transmit and receive data periodically. In terms of networking, sending and receiving data within the network is termed as communication between the nodes. Communication can be (i) one way and (ii) two way communication between the nodes which is also known as (i) uni-directional and (ii) bi-directional communications between the nodes.

![Figure 16 - bi directional connection](image16.jpg)
![Figure 17- Uni directional connection](image17.jpg)

In figure [18] there nodes have a bi-directional connection between the nodes. That is, both the nodes (node1 and node2) can transmit and receive data between them. Since, both the nodes can communicate with each other, the network or the connection between the nodes is bi-directional. In figure [17] there are two nodes (node 1 and node 2). Where, node 1 can transmit data or communicate with node2 and node 2 cannot transmit data any of its data to node1 in the network. This type of connection is called as uni-directional communication.

As shown in figure [18.a] the network is in combination of both uni-directional and bi-directional communication between the nodes. Taking figure [18.a] as an example the concept of connected nodes can be explained, in figure [18] the network has three nodes (node1, node 2 and
node 3) where the nodes 1 and 2 communicate with each other directly. The node1 and node2 have a path between them; this makes it a connected network.

![Figure 18. multi hop connection](image)

As shown in figure [18.b] there are three nodes (node1, node2 and node3) in the network. All the three nodes are not directly connected with each other within the network. Node1 is connected directly with node 2 and node 2 is directly connected with node3, all these connections have bi-directional communications within them. If suppose node 1 intends to send a message to node 3 which is not directly connected with node1, then the message is first sent to node2 which is the intermediate node between node1 and node 3, and once when node 2 receives the message from node1 it forwards the message to node3. This kind of network is known as multi-hop network. This network is perfectly a k-connected network, where removal of any one node within the network will leave the network disconnected.

In real time applications the network can be (i) sparse and (ii) it can be ad-hoc network. The connectivity depends upon the number of nodes deployed in a specified distance. The nodes need not necessarily connect with each other in a single hop rather it can connect in a multi hop manner within the network, which increases the connectivity at large. From the motes (i) received signal strength indication and (ii) Link quality indication can be obtained. Managing two entirely different parameters and managing it is a very difficult task to form and update the routing table periodically. So we make the basic connectivity formula as

\[
Connectivity (C) = Rssi + Lqi.
\]

As mentioned in the above formula the connectivity formula does not look complete, because putting in weights or constants with the Rssi and Lqi will make the values more scalable.

\[
Connectivity (C) = K_1 * Rssi + K_2 * Lqi.
\]

Now we introduce square root of sum of squares to the above equation. This is generally used when aggregation of two values is calculated and the values are typically from two different measurements. Here in this case Rssi and Lqi are the two different measurements which are obtained. Suppose in a case, if there is an error in one of the measurements and when these two measurements are simply added then the result will be an incorrect output. In order to avoid an incorrect output, we apply square root of sum of squares is applied.

\[
Connectivity (C) = \sqrt{K_1 \cdot (Rssi)^2 + K_2 \cdot (Lqi)^2}
\]
If we notice from the output the above mentioned formula for the connectivity, we can notice that the final output value of the connectivity will be higher than that of the two measurement values. This way the incorrect output is negotiated, and better solution is taken as the final output.
4. Detailed Description of the Investigated Solution

4.1 Hardware description

TelosB mote (TPR2400) is designed by UC berkeley. TelosB has sophisticatedly designed to work in a wireless environment with all the features being embedded into a single device. The various features of the TelosB motes are

(i) It has USB programming capabilities. That is programming and the data collection for the motes is performed through the USB attached with the mote.

(ii) It has an IEE 802.15.4 radio with an integrated antenna attached with it.

(iii) The TelosB mote has an micro-controller (TI MSP430) attached with it.

(iv) It has an memory of 10kb RAM.

(v) Light, temperature and humidity are the various that are available with the TelosB mote.

![TelosB mote component description](image)

The TelosB motes are an open source platform typically designed to perform various applications or experiments on wireless communication environment. These motes can typically interact with each other which in way tailor made for wireless applications. The TelosB motes have to be powered up by the AA batteries. For data transfer or communications with the computer the TelosB motes have to use their USB and it does not need any battery backup for the USB operation. The TelosB mote runs in Tinyos 1.1.10 or higher versions and it work’s good with all the Tinyos distribution (open source).

**Advantages:**

(i) The TelosB motes give an option to the users to interface with additional devices.

(ii) Low power consumption of TelosB mote is an important advantage because, generally these motes are used in wireless networks, energy constraints in Wireless Network is a big problem because the motes are battery operated and the motes need
to stay alive as much possible to meet the requirement of the designed application by the user.

**Figure 20 - TelosB mote top view [18]**

4.2 Rssi

The Rssi stands for Received signal strength indication. In radio communication, the power present in the received signal represents the Rssi value. Generally all the motes (in this application it is TelosB) will have antenna in their hardware assembly. We use cc2420 chip which is integrated with the TelosB motes for radio communications. In some cases the power will be high or the power received will be low, it depends upon the capability of the motes that is being used for the application. But the received Rssi value is not directly used, we subtract -45db with the received Rssi value. Where -45db is the offset value for Rssi. In many cases the Rssi value has proved to give a better prr (packet reception rate) over the link [6].

4.3 Lqi

Lqi stands for link quality indication. Lqi refers to the error rate in the received signal or in other terms signal to noise ratio (snr) in a signal represents the Lqi value. For each data sent over the network the link quality indication can be calculated.

4.4 Fundamentals of our work:

The topology cannot be fixed statically or cannot be choose a topology for this application since all the nodes will be placed in different positions in each and every scenario, and in a ideal situation where the nodes are placed relatively close with each other, a is a fully connected network is implemented, where in which possibly all the nodes in the network is to be connected with each other or at least possible one of the nodes in the network, and the corresponding the metrics and connectivity measure is calculated, and it is important to know that, more the number of connected nodes in the network more is the reliability of the network. There are various nodes which has various responsibilities within the network.

In our application we have termed the master node as the teacher node and all the remaining client nodes are termed as student nodes. We used collection tree protocol which is developed by tinyos. Each node in the network is given with a unique id so that corresponding link metrics is easily identified. Initially all the nodes in the network will send their information and the neighboring nodes information to the root or the teacher in this application. The roles that are to performed by the nodes within the network are as follows
(i) All the student nodes in the network will forward about its routing table to the master node where all the data regarding the routing table is collected.

(ii) The important factor while forwarding the data is that all the information has to updated or filled, because without this routing table connectivity or reliability cannot be calculated

(iii) A student has to have connection with one node within a network in minimum case and it can be connected most number of possible nodes within its range

(iv) This application is an multi hop link between the nodes within the network so a node can possibly reach to a node directly or through a hop in between the nodes.

If all the student or slave nodes within the network has been forwarded then the major part of the slave nodes responsibility is done. All that the student nodes have to do is getting connected to as much possible number of nodes as possible.

All the information or the routing table will be finally forwarded to the teacher. The teacher node will simply forward the gathered data to the base station unit where the connectivity and reliability for the obtained routing table is calculated. In general during the application the teacher can perform the following tasks

1. A teacher or master node can connect directly to one or more student nodes directly in a single hop.
2. The corresponding routing table will also be updated and it will also forward to the base station unit.

Base Station unit is an important unit in our application where in which all the data which is forwarded from the root node or the teacher node will be used for computing the connectivity and reliability for the network or link. After understanding the fundamentals of our work it is important to understand what the term connectivity is referring to. As mentioned in the earlier chapters the connectivity can be calculated in more than one way. But when the measures are based on the available indicators both the received signal strength and reception quality measure (LQI) which are provided by the radio chip integrating these values is an important task. Here integrating is referring to using some mathematical operators to make it as one expression.

4.5 Algorithm

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
<td>Teacher node. It collects information from all the nodes (Student Node) in the network and forwards it to base station.</td>
</tr>
<tr>
<td>Node 2, 3, 4, 5</td>
<td>Student nodes. It may directly connected with teacher or in multi hop way.</td>
</tr>
<tr>
<td>Node 7</td>
<td>Base station node.</td>
</tr>
<tr>
<td>Base station unit (BSU)</td>
<td>Base station node serially connected with laptop / PC</td>
</tr>
</tbody>
</table>

| Table 4 - Node Description |
In this thesis work each node has unique ID, by using node id the teacher node knows about the nodes connection status. Student nodes periodically send data to teacher node; teacher node will forward it to BSU, Base Station Unit (BSU) will maintain a routing table with the following (i) node’s connection information and their respective connectivity will be calculated. A student can get connected all the nodes in the network expect itself; all the connections and the corresponding information parameters are accountable for connectivity measure. Our network connection establishment is shown in figure [24].

4.5.1 Connectivity calculation

![Flowchart showing network connection establishment](image)

**Figure 21 - Network connection establishment**

In this thesis work connectivity is calculated in base station unit; after network is established the BSU starts filling the corresponding node’s metric values and connections in routing table. After that it starts calculating their connectivity. First BSU checks weather particular student node is connected in parallel or serial with the teacher and it is treated in accordance with the reliability theory. It is verified with number of possible path from one student to the teacher; if the path to
the particular student node is greater than one then it is parallel connection, if the particular student node has only one path to reach teacher then the connection is serial connection. When the student node is connected in parallel with the teacher then the BSU uses parallel connectivity formula to calculate the corresponding connectivity. If the connection is series then BSU uses serial formula to calculate the connectivity. Graphical representation of network establishment is shown in the figure [21].

In this thesis work we use link metric for calculating the connectivity between nodes in the network.

\[ Connectivity (C) = \sqrt{K_1 \cdot (\text{RSSI})^2 + K_2 \cdot (\text{LQI})^2} \]

Here a constant K1 and K2 represents importance of relevant factor for node. We have selected \( K_1 = 0.2 \) and \( K_2 = 0.1 \) in this thesis work.

Figure 22 - Connectivity calculation flow diagram
Serial connectivity formula:  \( C_1 \times C_2 \times C_3 \ldots \times C_N \)

Parallel connectivity formula: \( ((P_{C_1} + P_{C_2} + P_{C_3} + \ldots + P_{C_N})/N) \)

Where,

\( C_1, C_2, C_3 \) up to \( C_N \) – Connectivity of nodes in the path of particular node.

\( P_{C_1} \) – Connectivity of path one

\( P_{C_N} \) – Connectivity of \( N^{th} \) path

\( N \) – Number of path

After getting the connectivity of a particular student node to the teacher and connectivity of the network the base station unit will check with threshold value and inform about the badly connected node in the network to the teacher and other student nodes in the network, so the student node get warning message before being lost from the network.

4.6 Functional description

The main goal of this experiment is to measure the connectivity of wireless nodes in the network, for that teacher node is responsible to collect information from the all the node in network and base station unit is responsible for monitoring and informing the connectivity of the network. If a node is connected in single hop with teacher node then the teacher node is responsible for forwarding the information parameters of the particular student node, while the node is connected with teacher in multi hop way, then each intermediate node will forward their corresponding information parameters, send it to teacher node, teacher node forward it to BSU To identify the sending, reserving and broadcasting of message we use available LED’s in TelosB mote.

<table>
<thead>
<tr>
<th>TelosB Mote LED color</th>
<th>Functional description</th>
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<tbody>
<tr>
<td>Yellow</td>
<td>It indicates that message is received.</td>
</tr>
<tr>
<td>Blue</td>
<td>It indicates that message is sent.</td>
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<tr>
<td>Red</td>
<td>In base station it indicates that message is broadcasting.</td>
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</table>

Table 5 - TelosB functional description

Example Scenario: Teacher node is far away from the network

In this scenario BSU informs teacher node that the corresponding node is far away from the network. After network connection establishment the BSU calculate the connectivity of each student node and the network connectivity. BSU checks the connectivity of the entire student node in the network with the threshold value, if the entire student node in the network has lesser
connectivity than the threshold value; BSU send message the node ID 1 is badly connected in the network to the teacher node. The graphical representation is shown in the figure [23].

**Example Scenario: When one student node far away from rest of the nodes in the network**

After network connection established the BSU will calculate the connectivity of the student node and network connectivity, then BSU compares the connectivity of each student node with the threshold value. The graphical representation is shown in the figure [24].

---

**Figure 23 - Example Scenario: Teacher node is far away from the network**
Figure 24 - Example Scenario: one student node far away from the network

4.7 Graph representation for the measure of network connectivity:

Figure 25. Teacher node is far away from the network
We have clearly explained what does a scenario mean with respect to our application in the chapter [1.2. 1], scenario in this application means placing the nodes (teacher and the students) in different random positions in a square of 38*38m room, which we named it as a “science exhibition hall” and at each and every test scenario all the nodes will be placed in different positions with in that hall, the positions of all the nodes is generated by a random generator.

![Experimental Setup](image)

**Figure 26. Experimental Setup**

From the above mentioned figure[26], there are one teacher and four students, the distance between them is known directly in some cases, purely by measuring the distance between them. The unknown distance’s between any nodes are then calculated by using pythagoras theorem, so that the exact distance between all the nodes in the 38*38m square is known. By using the parameters such as Rssi and lqi which will vary with respect to the distance between the nodes.

The plot for the network connectivity measure is done under three categories, namely, (i) Average distance, is the average distance between all the nodes in the network in a particular scenario.(ii) Minimum distance, which represents the minimum distance between any node within the network,(iii) Maximum distance, which represents the maximum distance between any node within the network.

The above picture represents a scenario where a group nodes are placed together, which represents a scenario, we have performed our tests for 100 different scenarios, where each node is placed in different positions and the corresponding connectivity measure is taken. The protocol which we used for data communication is collection tree protocol, where the protocol’s follows the “anycast datagram” communication.

### 4.8 Test results of our application:

In this test analysis we have used random generator to generate 100 scenarios for node placement; then we have calculated the connectivity of the network using our formulas. The Table 6 shows the test results (Network Connectivity) with respect to average distance, minimum
distance and maximum distance. We have plotted the above mentioned table [6] in the chapter [4.8, 4.9, and 4.10].

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Table 6 - Distance vs connectivity

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4.9 Graphs

4.9.1 Average distance graph representation for the measure of network connectivity:

The above graph represents the relationship between the network connectivity and average distance of node placement. It can be noticed from figure [27], that the network connectivity is much higher when the distance is lesser, and as the distance is increased the network connectivity gradually decreases. The average distance is calculated by making the sum of all the distances between all the connected nodes in the network and dividing the sum by the total
number of connected nodes, the unknown distance between two or more nodes with in the network is calculated by pythagoras theorem.

From our test results we set that if connectivity is above 38 it is good connectivity, if connectivity is between 38 to 17 is Average connectivity and if it lesser than 17 it is bad connectivity. Then we have categorized our test results in the following way.

i. First we categorized our test by average distance, then we take 3 set of scenarios for average distance. For first set we took 3, 11,13,25,53 and81th scenarios from our test result which has average distance of 11 meters, the graph for that with standard derivation is shown in figure [28]:shows the Average distance 11 VS connectivity with Standard derivation.

![Average Distance VS Connectivity](image)

**Figure 28 - Average distance VS connectivity (a)**

![Average Distance VS Connectivity](image)

**Figure 29 - Average distance VS connectivity (b)**
ii. Then for second set we take 10, 43, 52, 69, 90 and 95th scenarios from our test result which has average distance of 16 meters, the graph for that with standard derivation is shown in figure [29]: Shows the Average distance 16 VS connectivity with Standard derivation.

iii. Then for third set we take 27, 33, 57, 63, 64, 65, 75 and 96th scenarios from our test result which has average distance of 21 meters, the graph for that with standard derivation is shown in figure [30]: Shows the Average distance 16 VS connectivity with Standard derivation.

4.9.2 Minimum distance graph representation for the measure of network connectivity:
It is the minimum distance between any two possible nodes with in the network. If the minimum distances between all the nodes are small then the connectivity measure is very high. The above graph represents the relationship between the network connectivity and minimum distance of node placement. Then we have categorized our test results in the following way, first we categorized our test by minimum distance, then we take 3 set of scenarios for minimum distance.
i. First set we took 6,13,37,38,39,41,44,78,82,85 and 86th scenarios from our test result which has minimum distance of 1 meters, the graph for that with standard derivation is shown in figure [32]: shows the Minimum distance 1 VS connectivity with Standard derivation.

ii. second set we take 2,17,22,24,36,47,68,75,91,93,98 and 99th scenarios from our test result which has minimum distance of 5 meters, the graph for that with standard derivation is shown in figure [33]: shows the Minimum distance 5 VS connectivity with Standard derivation.

iii. third set we take 26,31,34,51,55,57,61,62,90 and 94th scenarios from our test result which has minimum distance of 10 meters, the graph for that with standard derivation is shown in figure [34]: shows the Minimum distance 10 VS connectivity with Standard derivation.

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**Figure 32 - Minimum distance VS connectivity (a)**

**Figure 33 - Minimum distance VS connectivity (b)**
4.9.3 Maximum distance graph representation for the measure of network connectivity:

This distance represents the maximum length between any two nodes in the network. The connectivity measure depends upon the maximum distance that is, if all the nodes are placed with a very longer distance (the maximum distance is high between all the nodes) then the connectivity measure decreases which reflect that the corresponding network is not reliable. The above graph figure [35] represents the relationship between the network connectivity and maximum distance of node placement. Then we have categorized our test results in the following way, first we categorized our test by maximum distance, then we take 3 set of scenarios for maximum distance.
i. First set we took 4, 7, 10, 38, 40, 48 and 69th scenarios from our test result which has maximum distance of 20 meters, the graph for that with standard derivation is shown in figure [36]: Shows the Maximum distance 20 VS connectivity with Standard derivation.

ii. Second set we take 2, 20, 42, 45, 60, 72 and 79th scenarios from our test result which has maximum distance of 25 meters, the graph for that with standard derivation is shown in figure [37]: Shows the Maximum distance 25 VS connectivity with Standard derivation.

iii. Third set we take 27, 31, 36, 37, 43, 47, 49, 59, 61, 73th scenarios from our test result which has maximum distance of 30 meters, the graph for that with standard derivation is shown in figure [3]: Shows the Maximum distance 30 VS connectivity with Standard derivation.
From the above shown graphs with the standard deviation for (i) average distance (ii) maximum distance and (iii) minimum distance, it is clear that, for same distance’s the connectivity measure varies, for example: the scenario 3, 11,13,25,53 and 81 has the same average distance there relative connectivity measure is different this is because of the correlation between the maximum distance and minimum distance within the scenario.
5. Conclusions and Future Work

5.1 Conclusions

From the various experiments that were performed in our thesis work, it is concluded that the connectivity within the wireless network can measured. In our application all the nodes within the network are placed in various different positions in a 38*38m room for each and every scenario and the measure of connectivity is obtained (by forming an appropriate link metric design and a formula for connectivity) and the results was studied in depth, that is to understand the correlation between the maximum and minimum distance between the nodes in a scenario with respect to the corresponding effect of it, in the overall connectivity measure of the whole network, to work efficiently for different topology under various scenarios has increased the connectivity measure, we have used a fully connected network in an ideal situation figure[6].

Using appropriate mathematical operators and arithmetic expressions to form the required formula for calculating connectivity for example we have used a concept called RSS in forming our desired formula has enhanced our measure. Since it is a mobile network, the placement of the nodes with respect to number of nodes and distance, plays an important factor in measuring the connectivity. From the above work, a solution is provided for connectivity measure that can be studied and understood from the results provided by the above mentioned graphs, and so that a node does not lose its connection with the network. By this the life time of the network is enhanced.

The correlation between the maximum distance and minimum distance in a network will affect the measure of the network connectivity. The advantage of this approach is that: (i) The loss of connectivity of any node in the network is prevented because we have setup connectivity threshold for (i) good (ii) average (iii) bad connectivity, if any node in the network reaches threshold for bad connectivity then the information (status) about the corresponding node is informed to the teacher, so that connectivity loss to any node in the network is prevented. (ii) The node pattern distribution for all the nodes in a 38*38m square is completely analyzed that is how the correlation between the maximum distance and the minimum distance affect the connectivity measure in prospect with the whole network, so this measures can be taken as a scale for designing any network that is with regard to placing the nodes in the network.

5.2 Future work

From our thesis work it was evident that, the measure was little venerable to reflection’s. As most applications of wireless networks are based on mobile node applications, the atmospheric and the environmental conditions where the application is used, plays an important role in the connectivity measure. A lot more emphasis can be given in design phase of the application where the micro motes are used and the reflection, interference and obstacles does not play a major role in the connectivity measure. A better solution for connectivity formula can proposed, that is instead of taking the average for the network connectivity measure, accurate connectivity formula can be developed where the weakest link in the network is studied in detail and analyzed. Another important future work is that of designing a good network routing protocol for communication between the nodes in the network.

The routing protocol which we implemented in our thesis work will provide information about the neighboring node, that is a node will have information about the neighboring node (i) identity (ii) measure of connectivity, that is how good is the connectivity between the two nodes and that
information is passed on to the teacher node via all the intercepting nodes in the network, but instead of this designing a protocol in such a way that a node will get information about (i) it’s neighboring node and (ii) neighbor’s neighbor node information should also be gathered so that the we can have an improved and more reliable measure of connectivity for the whole network.
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