Topological and Energy Analysis of *K*– Connected MANETs: A Semi-Analytical Approach

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Summary

Mobile Ad-hoc Networks (MANETs) are highly decentralized, independent and self-organizing networks, and these tend to be highly unstable with respect to packet delivery, connectivity between the nodes and routing between the nodes. It is important to study the topological parameters including energy of the network to optimize the routing process by means of cross layer interaction across the layers of the network. This paper employs a semi-analytical approach to analyze topological and energy related properties of *K*-connected MANETs.

Key words:

K-connectivity, graph energy, network energy, routing, connectivity index.

1. Introduction

Ad-hoc networks are decentralized, self-organizing, short-lived networks capable of forming a communication network without relying on any fixed infrastructure. Each node in an ad-hoc network is equipped with a radio transmitter and receiver that allow it to communicate with other nodes over wireless channels. All nodes can function, if needed, as relay stations for data packets to be routed to their final destination. In other words, ad-hoc networks allow for multi-hop transmission of data between nodes outside the direct radio reach of each other.

A lot of research is done in MANETs related to the fundamental properties of the networks connectivity, routing and security. Mobility of the nodes, communication among the nodes through wireless mode, and varying transmissions and receiving ranges of the nodes introduce extensive dynamicity related to connectivity, routing, packet delivery and quality of the packets delivered to the nodes in MANETs. Hence there is a need to study the stability of the network in terms of qualities of service (QoS) related issues like packet delivery rate, packet delivery delay, energy of the network, reliability and signal interferences impact on quality of packets. This paper particularly focuses on K-connected MANET topologies. A K-connected topology is one, in which, between any two nodes of the network, there are K independent routes, so that a very high rate of successful packet delivery can be made [25, 26].

A lot of research has been done related to node density, critical transmission power and critical receiving power required for minimal connectivity of the MANETs [1-20]. To study the network stability, the basic properties such as link formation between the nodes, transmission and receiving ranges of the nodes, signal interferences are required in advance. Coming to routing, there exist works related to efficient routing protocols optimizing the routing delays with minimum energy utilization. However, the issue of stability due to the mobility of the nodes, which in turn affect the routing algorithms, needs to be studied. The parameters that need to be evaluated for stability include packet delays, total energy utilized to deliver packet from source to destination, frequency of determining routes between the nodes (which affect energy utilized), signal interferences and many more.

2. Related Work

Network connectivity is one of the most fundamental requirements for a successful MANET. There are several factors that affect the network connectivity:

1. Minimum number of nodes required for maintaining connectivity (Node density)[4].
2. Minimum number of links in the network so that a node can reach any node that it desires. This is dependent on the actual positioning of the nodes.
3. Minimum Degree of a Graph $\delta(G)$: Among all the nodes of a graph, it is the minimum number of neighbors, a node has.
4. *K-connectivity* of a network. It denotes the number of disjoint paths that exist between every pair of nodes.

The fundamental aspects, which describe the above topological attributes of a network, are spatial distribution

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of the nodes and their transmission range [2-10]. The geometry coverage of transmission range of any node is assumed to be a disk (circular) with a constant radius. Several studies assume that the transmission range of every node is uniform and circular. The minimum range *r* required to have a K-connected network for a geometric random graph, where r is the Euclidean distance between the two nodes such that they can communicate each other, is given in [25]. Similarly, the minimum number of neighbors should each node be connected to in order that the overall network is connected in a multi-hop mode is dealt in [26-30].

In this paper we are utilizing the K-connectivity concept to study the stability of the network. The study of K-connected network topology is of significant importance, since it ensures the connectivity of the network and also identifies multiple or redundant paths over which routing can be done.

One can examine K-Connected MANET using a simulation methodology, in which, a special node is designated to compute whether the network is K-connected or not. From all the nodes, this special node receives the number of neighbors' information and computes the connectivity. This information can be sent to all other nodes. From a randomly selected node, flooding can be initiated to study various QoS-related parameters. Instead of carrying out this large-scale simulation, a semi-analytic approach is adopted in this paper to study some key issues relevant to K-Connected MANETs.

The rest of the paper is organized as follows: In Part 3, few basic definitions are captured. Part 4 brings out several important properties related to K-connected ad-hoc networks through an analytical study. Part 5 focuses on simple simulations based on the results derived in Part 4. Finally, conclusions are given in Part 6.

3. Some Basic Definitions

Since, the analytical examination carried out in the paper uses Graph-Theoretic framework, we start with the definition of a Graph. A graph *G* is a triplet consists of vertex set $V(G)$, edge set $E(G)$ and a relation that associates with each edge, two vertices. An edge between two nodes (vertices) *i* and *j* is represented as (i, j) and $E(G) \subseteq \{(i, j) \mid \forall\, i, j \in V \text{ and } (i, j) = (j, i)\}$. Graph *G* is denoted by $G(V, E)$. Two vertices are said to be *adjacent* to each other, if there exist an edge between them. The number of edges associated with the vertex is called degree of a vertex denote by $d_G(V)$ *or* $d(V)$. A graph *G* is said to be *connected*, if for every pair of vertices *u, v* belongs to *G*, there exist a path (otherwise the graph is *disconnected*). A disconnected graph has a number of components, with each component being a connected graph.

***K*-connected Graph**[31]: A graph *G* is said to be K-connected, if on removal of any *K* nodes, the graph will become disconnected. The important property of K-connected graph is that there exist K disjoint paths between any two nodes of *G*. Figure 1 describes the various *K-connected* networks for *K*=1, 2 and 3.

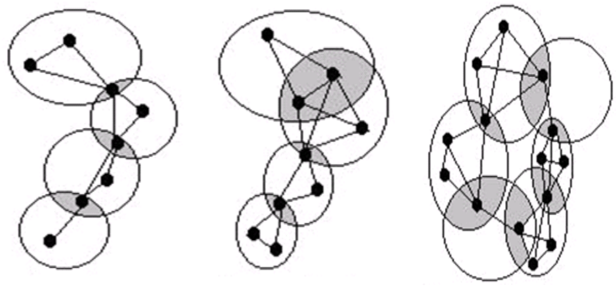

Figure 1: *K*-Connected Networks (*K* =1,2,3)

Energy of a Graph: Let A be the adjacency matrix [31] of a graph *G*. Let $\sigma(A) = \{\lambda_1, \lambda_2, ...\lambda_n\}$ be the set of ordered eigenvalues of *A*. Then the energy E_π of the graph is defined as sum of absolute values of all the eigenvalues of A, that is, $E_\pi = \sum_{i=1}^{n} |\lambda_i|$.

Energy of a Network $E_N(t)$: The energy of the network at any instant of time t is the sum of product of packets transmitted by each of the nodes and of transmission energies required by each node to transmit the packets to neighbor node. Compactly, $E_N(t) = \sum_{i=1}^{N} N_t(i) T_E$, where $N_t(i)$ is the number of packets generated by node *i* at time *t* and T_E is the transmission energy required to transmit a packet.

Connectivity Index $\chi(G)$: Connectivity Index or Randić index was proposed by Randić in 1975. $\chi(G)$ of graph *G* is defined as $\sum_{uv \in E(G)} \frac{1}{\sqrt{d_G(u) d_G(v)}}$ of vertices $u, v \in V$

where $d_G(x)$ denotes the degree of vertex $x \in V$ [32] (see also our previous work [1]).

Gauss value of x: denoted by $\lfloor x \rfloor$ is the largest integer not exceeding x, where x is a real number (that is, $\lfloor\ \rfloor$ is the usual "floor function")

Combination $\binom{n}{r}$: is the number of ways of selecting r objects from *n* objects.

4. Study of *K*-connected Ad-hoc Networks:

As mentioned earlier, the stability of any Ad-hoc network is an important aspect and needs careful study. Since, stability is tightly coupled with topology in the following we consider K-connected Erdo˝s and Re´nyi random graph models. A random graph is consists of *N* labeled nodes connected by *n* edges, which are chosen randomly from the $\frac{N(N-1)}{2}$ possible edges [31]. In total there are $\binom{N(N-1)}{n}$ graphs with *N* nodes and *n* edges, forming a probability space in which every realization is equiprobable. The probability of forming an edge between any two nodes is p .

Before studying the parameters related to stability such as energy of graph, energy of network, connectivity index are evaluated for *K*-connected network in the next Part, six lemmas are given in the following. These are useful to construct *K*-connected graphs, with *K* varying from 1 to $N-1$. As far as we are aware, the Lemmas 2,3,4, and 5 proved in this Part are novel. It is worth looking at Figure 1 at this juncture, which describes some of the various *K*-connected networks.

Lemma 1: Minimum number of edges required for *K*-connected graph is [ ]

$$\begin{cases} \left\lfloor \frac{KN}{2} \right\rfloor & \text{for } K>1 \\ N-1 & \text{for } K=1 \end{cases} \quad (1)$$

Lemma 2: Minimum number of edges that needs to be added to construct a *K+1* connected graph G from *K*-connected graph G is

$$\left\lfloor \frac{N}{2} \right\rfloor \quad (2)$$

Proof: From lemma 1, the minimum number of edges required to construct *K*-connected graph G is greater than or equal to $\left\lfloor \frac{KN}{2} \right\rfloor$.

For K+1 connected graph G', the number of edges required is at least

$$\left\lfloor \frac{(K+1)N}{2} \right\rfloor \quad (3)$$

Subtracting (3) from (2), we get, least number of edges required to construct *K+1* connected graph from *K*-connected graph G. Therefore, we get

$$\left\lfloor \frac{(K+1)N}{2} \right\rfloor - \left\lfloor \frac{KN}{2} \right\rfloor \le \left\lfloor \frac{(K+1)N-KN}{2} \right\rfloor \quad (4)$$

$$\left\lfloor \frac{(K+1)N}{2} \right\rfloor - \left\lfloor \frac{KN}{2} \right\rfloor \le \left\lfloor \frac{N}{2} \right\rfloor \quad (5)$$

Hence the proof.

Lemma 3: The number of possible *K*-connected graphs with minimum number of $\left\lfloor \frac{KN}{2} \right\rfloor$ edges is less than or equal to

$$\begin{cases} \binom{N(N-1)}{N-1} & \text{For } K=1 \\ \binom{N(N-1)}{\left\lfloor \frac{KN}{2} \right\rfloor} & \text{For } K>1 \end{cases} \quad (6)$$

Proof: We know that, for any graph G, edges can be selected randomly from $\frac{N(N-1)}{2}$ edges. For *K=1*, the graph should be at least minimally connected. We know that any minimally connected graph is a tree. Hence a graph with *N* nodes is said to be minimally connected, when number of edges in G should be *N-1*. Number of 1-connected graphs with at least N-1 edges is $\binom{N(N-1)}{N-1}$.

For K>1, we know that, there are $\binom{N(N-1)}{n}$ possible graphs with N nodes and n edges. So to construct a K-connected graph we require at least $\left\lfloor \frac{KN}{2} \right\rfloor$ edges. Among these, there are graphs which are not connected and also not K-connected. (Refer to Figure 1 for example.) Hence total number of labeled K-connected graphs is less than or equal to $\binom{N(N-1)}{\left\lfloor \frac{KN}{2} \right\rfloor}$.

Lemma 4: The probability of constructing random K-connected graph ($K > 1$) is less than or equal to

$$\frac{\binom{\frac{N(N-1)}{2}}{\left\lfloor \frac{KN}{2} \right\rfloor}}{\sum_{n=1}^{\frac{N(N-1)}{2}} \binom{\frac{N(N-1)}{2}}{n}} \tag{7}$$

Proof: We know that probability of an event occurring is the ratio of number of desired outcomes to total number of possible outcomes. That is the number of desired outcomes (K-connected graphs) is less than or equal to

$$\binom{\frac{N(N-1)}{2}}{\left\lfloor \frac{KN}{2} \right\rfloor}. \tag{8}$$

This is probability of selecting $\frac{KN}{2}$ edges from $\frac{N(N-1)}{2}$ edges. The total number of possible outcomes (possible networks) is the summation of number of ways of selecting one edge, 2 edges and so on till $\frac{N(N-1)}{2}$ (9)

$$\sum_{n=1}^{\frac{N(N-1)}{2}} \binom{\frac{N(N-1)}{2}}{n}$$

Hence, the result.

Lemma 5: The maximum number of packets transmitted from the nodes in order to send a packet from one node to another node in an *N-1* connected network through flooding is

$$(N-1)(N-2)+1 \tag{10}$$

Proof: Flooding is a routing mechanism in which the start node broadcasts the packets to all its neighbor nodes. On receiving a packet, each neighbor node transmits again to its' neighbor nodes except to the source node. Every $N-1$ connected graph G is complete, where each node of G has an association with $N-1$ other nodes. From source node, $N-1$ packets are routed to all the $N-1$ nodes of the network.

Upon receiving the packet from the source node, except destination node, remaining $N-2$ nodes will transmit the packets to remaining $N-3+1$ nodes (including destination node).

So totally $(N-1)+(N-2)(N-2)$ packets are transmitted.

$$\text{This is equal to } (N-1)(N-2)+1 \tag{11}$$

Lemma 6: Let G be a graph with vertices $x_1, x_2, x_3 \ldots\ldots x_N$, and $d(x_1) \le d(x_2) \le \ldots.. \le d(x_N)$. Suppose for some K, $0 \le K \le N$, such that $d(x_j) \ge j+K-1$, $for\ j = 1 \ldots N-1-d(x_{N-K+1})$, then G is K-connected.

This lemma was proved by Bondy in 1969 [31].

In the next section, the simulation of a K-Connected network and analysis based on these lemmas is presented.

5. Simulation and Analysis of *K*-connected Ad-hoc Networks:

In order to study some properties mentioned earlier, we have simulated the relevant aspects of K-connected ad-hoc network, based on results of previous lemmas using MATLAB. The simulation process starts with a minimal 1-connected network with N (which is fixed for each simulation) number of nodes. Then progressively, K-connected network is built. The methodology adopted is:

1 Choose two nodes randomly and add the link between them.

1. Compute energy of a graph, energy of the network and connectivity index.

2. Compute the connectivity of the network (using the Algorithm given in 5.1).
3. If the resultant topology is *K+1* connected and the network topology is not fully connected, then goto step 1.
4. Plot the graphs.

5.1 Algorithm to compute the K-connectivity of the given network (Based on Lemma 6)

Input: Adjacency matrix of the given network.

1. The $N \times N$ adjacency matrix $A = (a_{i,j})_{NXN.}$ of a given network is with $a_{i,j} = 1$, whenever two nodes *i* and *j* are connected by a link and 0 otherwise.
2. Compute the degree of the each node of the network by taking the row sums of A. Row R_i sum gives the degree of node *i* denoted by d_i.
3. Arrange the degrees of the node in ascending order.
4. Check for each node, whether $d(x_j) \geq j + K - 1, \; for \; j = 1 \ldots N - 1 - d(x_{N-K+1})$

If all the nodes satisfy this condition, then the network is *K*-connected.

Some simulations have been carried out for various sizes of the network from 30 nodes to 100 nodes. As links are added randomly and whenever the network reaches higher connectivity various parameter like connectivity index, energy of graph, number of links are computed and stored. Figure 2 shows the scheme of simulations. Figure-3 demonstrates the effect of connectivity versus links, graph-energy and connectivity index respectively. It is observed that as connectivity (K value) increases, the number of links and connectivity index also increases. The graph energy remains almost constant and starts decreasing once connectivity reaches peak value. The characteristics of these graphs may be used effectively to control the topology of the network and can also be utilized to get information on parameters of the wireless network such as packet delivery ratio, signal interference, noise level of wireless channels, routing efficiency and fault tolerance capability of the network. The work in that direction is undergoing.

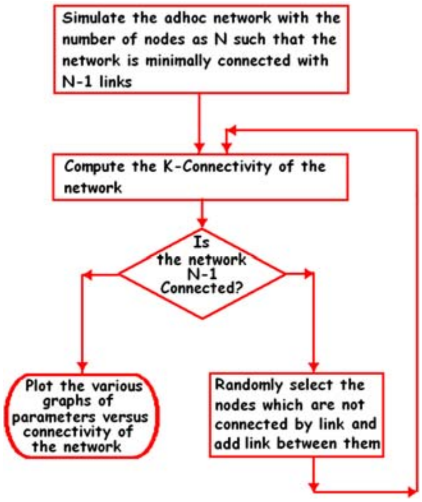

Figure 2: Simulation of K-connected Network

Figure-4 demonstrates similar graphs with links are plotted in X axis and other parameters as Y-axis. The behavior is similar to the previous graphs.

Figure-5 demonstrates the bar chart taking into account the effect of connectivity with respect to links and graph energy. From the graph it is clear that variations are uniformly progressive, except for the graph energy which decreases as connectivity reaches maximum.

Figure-6 demonstrates all the similar eight graphs for the case of 100 nodes in the network. The behavior is very similar to the graphs obtained for 30 nodes network. These observations can be very useful inputs to the topology control process and optimizing routing protocols. These are the two key areas of research in MANETs.

6. Conclusion

The analysis of various topological parameters of adhoc network along with energy is an important input to the topology control, and also for analyzing various QoS parameters with respect to routing and fault tolerance. The study presented in this paper provides a good platform for the examination of the said issues.

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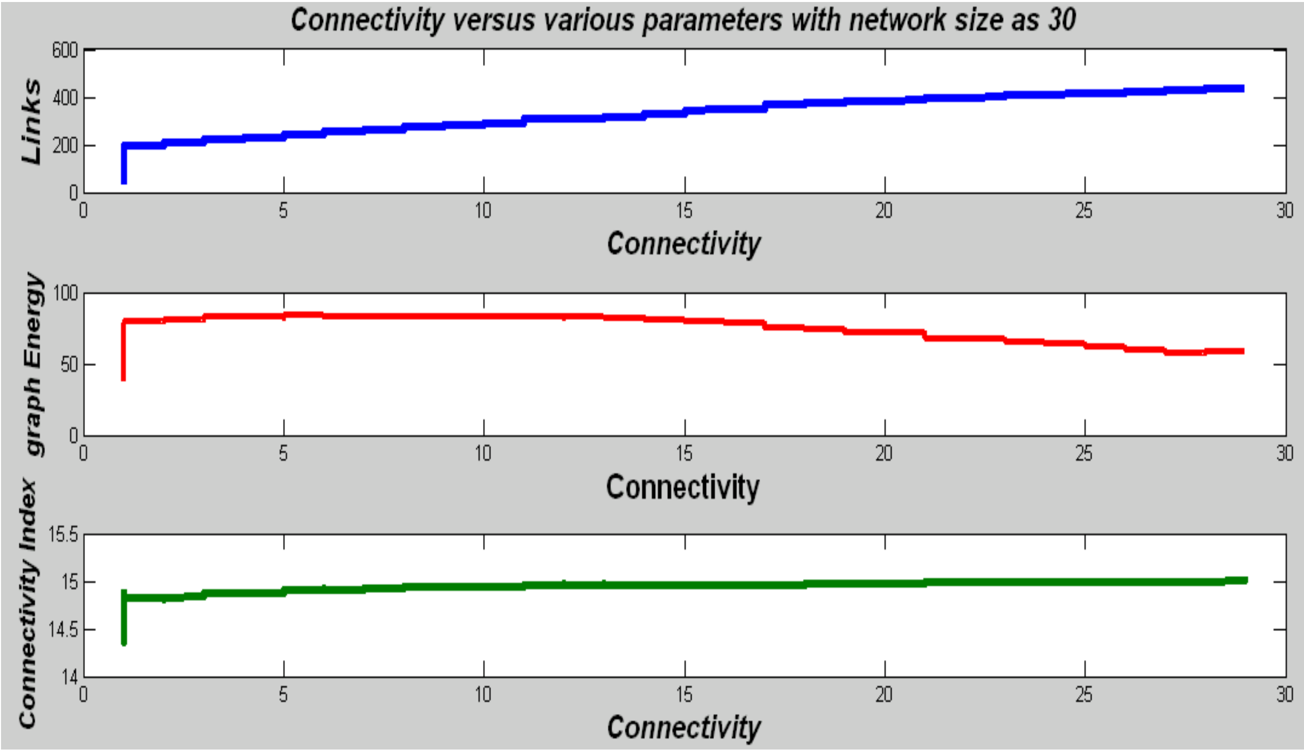

Figure 3: Connectivity Vs Various Parameters With Number Of Nodes Is 30.

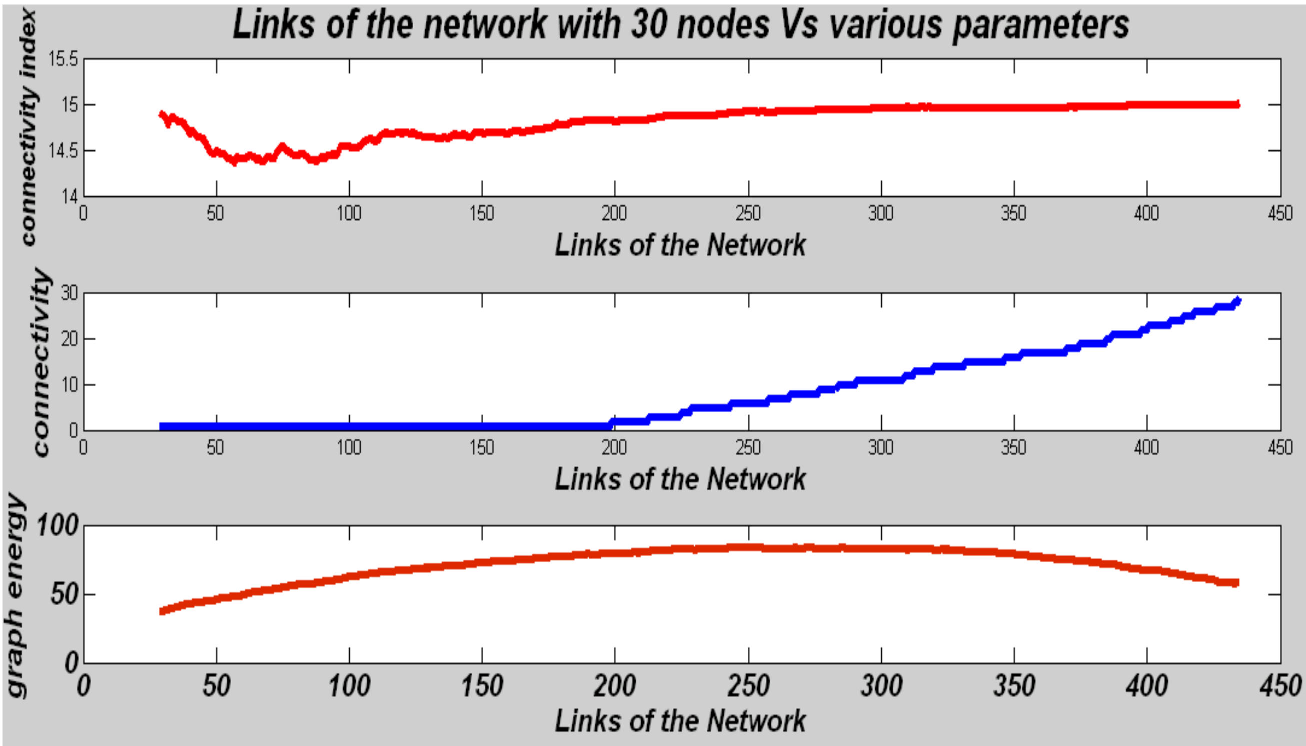

Figure 4: Graphs Demonstrating Link Vs Various Parameters With Number Of Nodes Is 30.

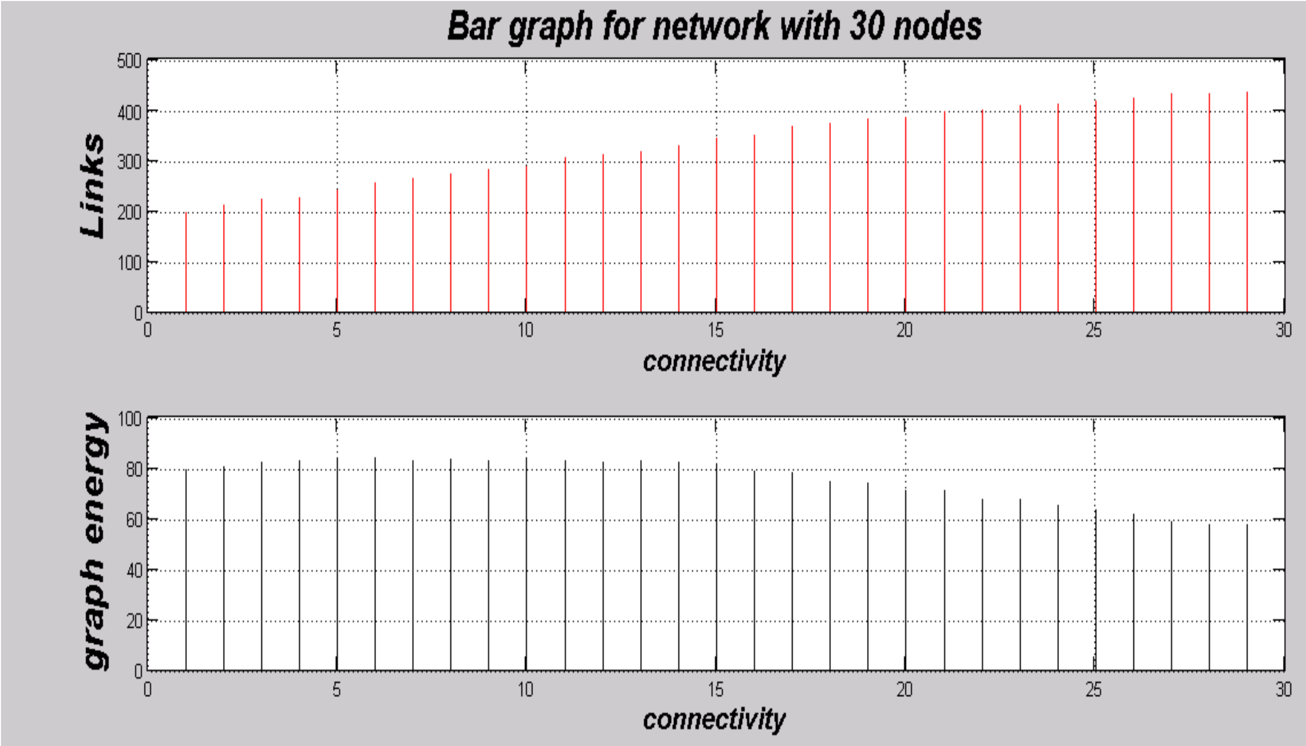

Figure 5: Bar Graphs Demonstrating Connectivity versus Links and Graph Energy Parameters.

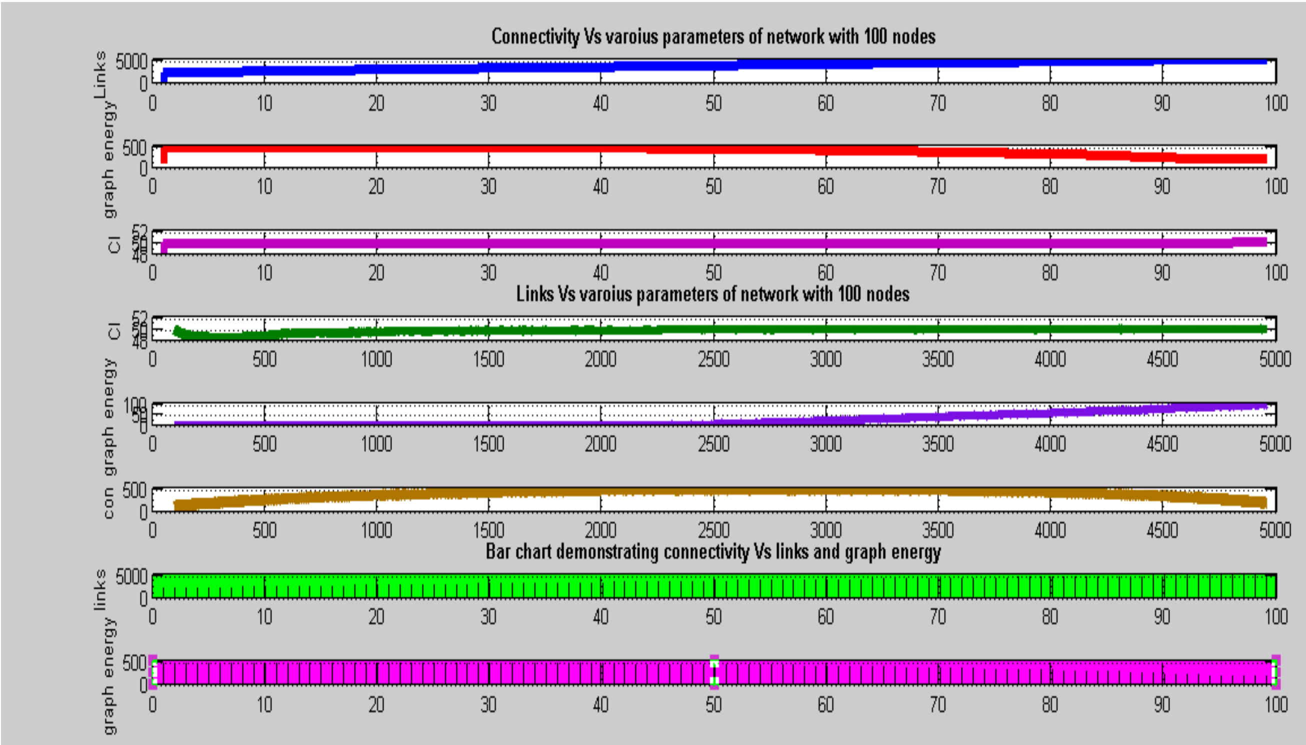

Figure 6: Simulation Results for Network with 100 Nodes.