Using Complex Network in Wireless Sensor Networks

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***Abstract*—**In multihop wireless sensor network (WSN) each packet will traverse through multiple hops before it reaches the base station. The amount of energy required to transmit a packet is directly proportional to the number of hops. The lifetime of the WSN will be increased if the energy consumption for transmitting the packets is reduced. In order to reduce the energy consumption, we need to reduce the number of hops i.e. the path length. This paper focuses on increasing the lifetime of WSN by using small world networks characteristics such as small characteristic path length and high clustering coefficient.

Keywords: Wireless sensor networks, Complex networks, Small world network, Clustering coefficient, Path length

1. Introduction

In wireless sensor network, hundreds or thousands of sensor nodes are randomly deployed over a certain area of interest. The job of all the sensor nodes is to sense the physical phenomenon, process it and send the data to the base station. The base station acts as a gateway network to an external network such as Internet. The sensor nodes are equipped with limited power source and in some cases replenishment of power sources may not be feasible. In WSN, the energy consumption can be categorized based on sensing, communication and data processing. The amount of energy required in communication is quite high in comparison to the energy required for processing as well as sensing the information. The data communication in WSN is different than in other type of networks. In other type of networks, the data communication takes place between arbitrary communicating entities but in WSN all the data communication is usually routed towards a base station. In other words, the traffic in WSN is many to one type rather than any to any type. Further, the WSNs need to be designed with an approach to efficiently utilize the nodes' energy.

In WSN, death of first sensor node (i.e. exhaustion of its battery), decides the lifetime of the network. The term lifetime can be defined as the tenure over which the base station is successfully receiving the information from the nodes deployed in the network before formation of any coverage hole in the sensing field. The coverage hole is generated if the nodes in any particular part of the network die out, due to which the information pertaining to that area can not reach the base station.

The flow of data from the nodes to base station can either be done in a single hop or it can take multiple hops. The data forwarded in multi-hop fashion to the base station is often more energy-efficient than transmitting the data directly to the base station. In WSN the amount of energy required to transmit a packet is directly proportional to the square of distance between them. In multi-hop WSN, each intermediate node acts as a router for other node's packet and originator for its own packet. The lifetime of the network is inversely proportional to the number of hops (i.e. the path length). We are assuming that each node will transmit to fixed length in each hop. So, in order to increase the lifetime of WSNs the path length (or number of hops) should be kept as small as possible. This motivates us to see if the WSN topologies can be modeled as small world network. The small world network (i.e. a class of complex networks) is characterized by small characteristic path length, and high clustering coefficient [2]. In this paper, we will explore the possibilities of using complex network as a tool for increasing the lifetime of WSN.

Complex networks is a term widely used for modelling of complex systems. The two important classes of complex networks are scale free network and small world network. A network is said to be scale free if its degree distribution follows power law, atleast asymptotically. This means that a fraction P(*k*) of nodes in the network having *k* connections to other nodes, for large values of *k*, is

$$P(k) = k^{-\gamma}$$

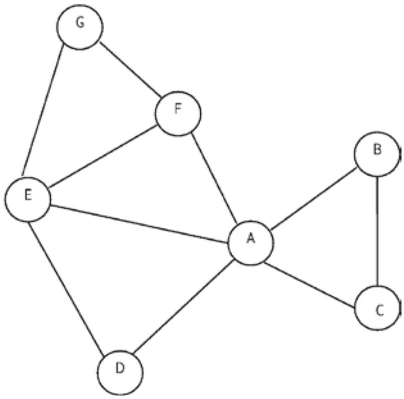
Here, γ is a degree exponent whose value lies in the range $2 < \gamma < 3$. The scale free property implies a non-zero probability that there exist nodes connecting to most of the nodes in the network. The nodes having larger degree are called hub nodes. These type of networks are constructed by incremental growth and preferential attachment. The term preferential attachment means that it is more likely that a new link will associate with a node having higher degree. The robustness of the network against node failures increases with the scale free property.

The small world concept was first introduced by Watts and Strogatz [10], where two randomly selected nodes are somehow connected by a chain of nodes. The Small-world phenomenon is also known as the six degrees of separation. The small-world phenomenon says that an arbitrary person is connected to another arbitrary person anywhere in the world with the help of chain of acquaintances and average number of hops between any two person is quite small. In 1967, Stanley Milgram tested experimentally this hypothesis, which led to the famous phrase “six degrees of separation”.

One can construct a random graph from a regular graph by moving one end point of each edge with a certain probability P_r. Watts and Strogatz [9] proved that if we increase P_r, then characteristic path length as well as clustering coefficient both decrease. The rate at which characteristic path length decreases is very fast as compared to that of the clustering coefficient. The term clustering coefficient is a measure of degree by which nodes in a graph tend to cluster together. It can be calculated locally as the ratio of number of links that exist in the neighborhood of a node to the maximum possible links between the neighborhood [1]. The clustering coefficient of the overall network as given by Watts and Strogatz [10] is calculated as the average of all the local clustering coefficients for all the vertices in *N*.

$$\overline{C} = \frac{1}{n} \sum_{i \in N} C_i$$

Here ,n is the number of nodes in N. Consider the following connected network consisting of 7 nodes and 10 links. The clustering coefficient of node A can be calculated as follows:



Total number of neighbors of node A = 5 (i.e. nodes B, C, D, E, F), maximum possible links between A's neighbor= ${}^5C_2$=10, number of links that are present between A's neighbors= 3 (i.e. links BC, DE, EF). Thus, the clustering coefficient of node A = 3/10 =0.3. Similarly we can calculate the local clustering coefficient for nodes B, C, D, E, F and G as 1, 1, 1, 0.5, 0.67, 1. The clustering coefficient of the overall network is the average of all local clustering coefficients i.e. (0.3 + 1 + 1 + 1 + 0.5 + 0.67 + 1) / 7 = 0.7814.

2. Related Work

Wireless sensor networks are considered as spatial graphs where the link between the nodes exists only if they come in radio range of one another. These graphs have much higher path length in comparison to the random graphs and also they tend to be much more clustered. In WSN, the minimum amount of energy required to send a packet is directly proportional to R^{α}, where R is the communication radius of a node and α is the path loss exponent such that $2 \leq \alpha \leq 4$ [8].

By Rewiring a few random links in regular graphs, the average path length reduces drastically and it also results in lower clustering. The rate at which clustering coefficient reduces is far less than the rate at which average path length reduces. These graphs are called small world graphs. This small world graph lies in between the regular graphs and the random graphs. In regular network such as square grid networks, all the nodes have many mutual neighbors which results in high clustering coefficient but these networks also have high characteristic path length. In random graphs, we have a small characteristic path length but it exhibits smaller clustering coefficient.

Helmy [5] first introduced the concept of small world phenomenon in wireless networks. He established a relationship between small world graphs and wireless networks. He proved that it is possible to reduce the path length in wireless networks by adding a few shortcut links. He showed that these random links may be confined to a small fraction of network diameter. Sharma and Mazumdar [7] improved the energy efficiency of wireless sensor networks with the use of limited infrastructure in the form of wires. The resulting structure is named as Hybrid sensor network. The wires were used to provide shortcuts to bring down the average hop count of the network. This resulted in reduced energy dissipation per node.

Hawick and James [4] proved that adding a small number of random links between the sensor node, results in drastic reduction of all the pair length when the network is fully connected. The authors also proved that the addition of random links also results in the formation of number of isolated clusters, when network is not fully connected. Here, the author placed sensor agents at random locations within the space and studied the effect of additional edges in the network. An additional edge was termed as “worm-hole”, that allows unconnected objects to communicate directly. Thus, worm-holes conceptually make the neighbours of the objects that are possibly physically far apart. This typically serves the reduction of the effective path length of the network.

Chitradurga [3] investigated the use of wired shortcuts in large scale location aware sensor networks. He used the wired shortcuts to reduce the average path lengths of the network. His results proved that by selecting an optimum wire length the path length reduces to its minimum, beyond which it increases.

3. Complex Networks in WSN

3.1Homogeneous Networks

The homogeneous networks is a class of complex network in which most of the nodes in the network have similar degrees i.e. there exist little fluctuations in the degree distribution of the nodes. The small world network belongs to the category of homogeneous network. Here, in this section we will model wireless sensor network as a homogeneous network, by connecting each node with almost equal number of neighbors say *K*. The main idea is to generate a homogeneous network by connecting each node with smallest necessary set of neighbors that are sufficient to maintain the network connectivity. If nodes are either Poisson or uniformly distributed, then with high probability a connected network topology would be created if each node is associated with minimum appropriate size of neighborhood. In order to obtain homogeneous network in WSN, we can use the concept of *K*-neighbor graph. A *K*-neighbor graph is formally defined as:

$$G_K = (N, E_K)$$

$$where$$

$$E_K = \{(u,v) \in E; u,v \in V \ s.t. \ d(u,v) \le d_K(u)\}$$

Here, $d_K(u)$ is the distance from the K^{th} closest neighbor of u and $d(u,v)$ is the distance from node u to v.

Each node will adapt its transmission range in order to have a direct link to its *K* closest neighbors. The value of *K* cannot be choosen at random as it may break the connectivity of the overall network. The selection of optimum value of *K* allows the base station to receive information from all the nodes in the network. Kleinrock [6] has given a magic number of 6 for *K*, i.e. if each node is connected to six neighbors then it will preserve the network connectivity.

Once a homogeneous WSN is constructed, we can rewire some of the edges at random with probability P_r. Now, in order to introduce small world characteristic in wireless sensor networks, we need to create shortcuts by using unicast transmission. This can be done either using wired link, or using certain nodes with larger transmit power so that they can communicate with nodes separated by much larger distance. The goal of these shortcuts is to optimize the communication between pairs of nodes. In WSN, the energy of the sensor nodes is limited, so we need to decide where these shortcuts need to be created. In order to optimize the routing of messages, the sink should be one of the end point of all the added shortcuts.

Heterogeneous Networks

The heterogeneous network is a kind of network in which there exists large number of fluctuations in degree distributions. The scale free network belongs to the category of heterogeneous network.

The large scale WSN contains thousands or even millions of nodes. In these type of networks, we divide the entire network into multiple clusters and each cluster is associated with a cluster head. Each cluster contains different number of nodes. All the nodes in the cluster are required to send their information pertaining to an event to their respective cluster heads. The cluster head will collect the data from all the nodes in its cluster, aggregate it and then forward it to the base station. The cluster heads acts like hub nodes of scale free network i.e. these nodes are having very high degree whereas all the non cluster head nodes are low degree nodes. This network topology can be modeled as scale free network.

4. Simulation and Results

This section is categorized in two parts. In first part, the simulation results for homogeneous wireless sensor network are presented. These include average path length variation with different number of nodes (*N*), rewiring probability (P_r) and average nodal degree (*K*). In later part, the simulation results for heterogeneous wireless sensor networks are presented. These include the variation of clustering coefficient (*C*), average nodal degree (*K*), average path length ($\bar{L}$) and maximum nodal degree as a function of degree exponent.

4.1 Homogeneous WSN

The small world network model for WSN is simulated for different number of nodes. Here we assume that each hop distance is same. In Fig. 1, average path length is plotted against rewiring probability P_r. The average nodal degree is maintained as six. This figure tells that as the rewiring probability (P_r) increases, the average path length decreases drastically.

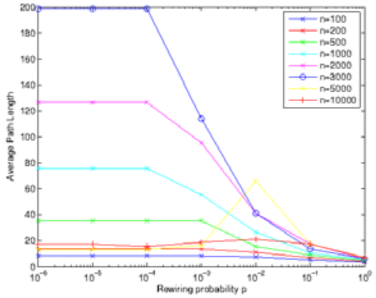


Fig 1

The Fig. 2 shows the plot of average path length ($\bar{L}$) against rewiring probability (P_r) but with different average nodal degrees in a 100 node WSN. As expected, the average path length decreases with the increase in neighbor degree. The average path length will keep on decreasing further with increase in rewiring probability.

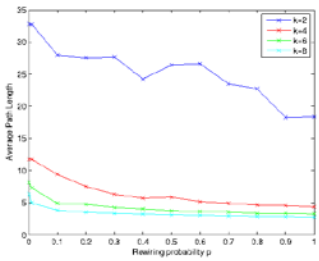


Fig 2

Fig. 3, shows the variation of average path length with different number of nodes for different average nodal degrees. The average path length will decrease if we increase the average nodal degree. This simulation is performed for fixed rewiring probability of 0.5.

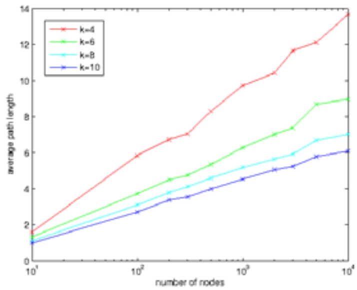


Fig 3

In Fig. 4, the average clustering coefficient of the overall network is calculated for different rewiring probabilities P_r. The clustering coefficient of the network reduces with increase in the rewiring probability.

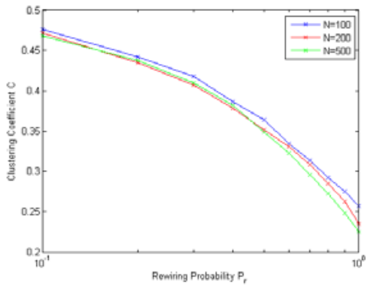


Fig. 4

In Fig. 5, average hop distance w.r.t. rewiring probability is plotted for different average nodal degrees. The graph shows that average hop distance decreases sharply when we increase the rewiring probability. If the average nodal degree is kept at 6 then with small rewiring probability of 0.1 the average hop distance reduces by 54.47%.

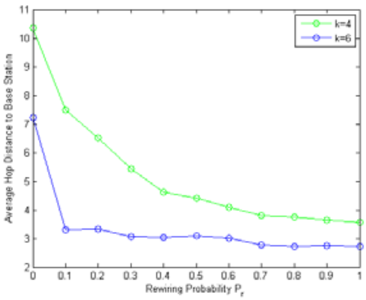


Fig 5

The Fig. 6, shows the variation of average path length as a function of average nodal degree for different density of nodes.

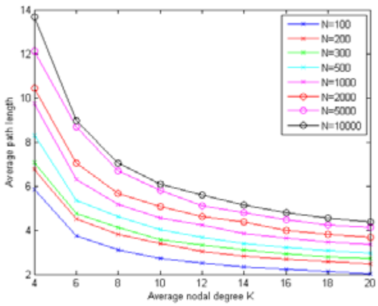


Fig 6

In this simulation, the rewiring probability P_r is set to 0.5. The average path length ($\bar{L}$) decreases rapidly for higher density nodes in comparison to the lower density nodes. The plot also tells that after attaining a certain average nodal degree, the average path length almost saturates i.e. after certain K, the average path length almost remains constant.

Thus we need to select an optimum value of P_r so that the average hop distance should be minimum and also the clustering coefficient should be maximum. The results show that if we select the rewiring probability of 0.1 for each of the node in wireless sensor network then it will result in clustering coefficient of .475 and also the average path length reduction of 54.47%.

4.2 Heterogeneous WSN

The Fig. 7 shows the variation of average path length with degree exponent for different K_{min}. As expected, the average path length increases with the increase in degree exponent for each value of K_{min} in wireless sensor network.

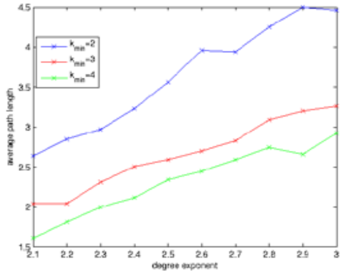


Fig 7

In Fig. 8, the average clustering coefficient in the WSN is calculated for different degree exponents. The clustering coefficient decreases with increase in degree exponent but it increases with the increase in minimum number of neighbors i.e. K_{min}.

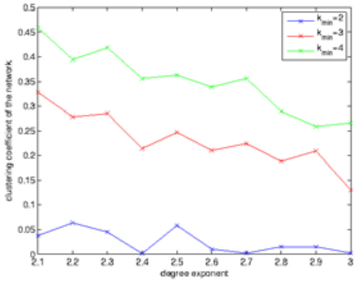


Fig 8

5. Conclusions

In this work, we have presented the advantages of using small world and scale free network in the wireless sensor networks. The results verified that the lifetime of wireless sensor network can be increased by using small rewiring probability of 0.1. This rewiring probability not only reduces the average path length but it also results in good clustering coefficient for the wireless sensor networks.

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