Optimization of Wireless Sensor Network Lifetime by Deploying Relay Sensors

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Abstract
Topology control in wireless sensor networks helps to lower node energy consumption by reducing transmission power and by confining interference, collisions and consequently retransmissions. Decrease in node energy consumption implies probability of increasing network lifetime. In this paper, first we analyze popular topology control algorithms used for optimizing the power consumption in the wireless sensor network and later propose a novel technique wherein power consumption is traded with additional relay nodes. We introduce relay nodes to make the network connected without increasing the transmit power. The relay node decreases the transmit power required while it may increase end-to-end delay. We design and analyze an algorithm that place an almost minimum number of relay nodes required to make network connected. We have implemented greedy version of this algorithm and demonstrated in simulation that it produces a high quality link. We use *InterAvg, InterMax* (no of nodes that can offer interference) *MinMax*, and *MinTotal* as metrics to analyze and compare various algorithms. Matlab and NS-2 are used for simulation purpose.
Keywords: Energy saving, sensor networks, Interference, network connectivity, topology control

I. INTRODUCTION

Sensor network applications became popular due to their easy and rapid deployment processes. They can be deployed even into hazardous environments. These networks monitor outdoor environments and provide crucial data for emergency situations. Hence network connectivity is utmost important. They also work under extreme conditions such as noise and hostile atmosphere. They must work with minimum energy so that they work longer periods and offer minimal interference. Topology control can play major role in reducing node power consumption and extend network life time. In order to conserve the energy, the nodes are preferably configured at low transmit power. When the sensors are deployed at random locations, each node is to be configured at different transmit power levels making the network heterogeneous. However, it is possible to make the network homogenous by adding additional relays nodes at certain places which also conserve the network energy.

We describe an efficient and energy conservation multi-hop wireless sensor network. If the node are deployed at random places and all nodes are configured uniformly with low transmit power, obviously, there is high probability of forming an unconnected network as shown in fig1. Such unconnected network can be converted into connected network by i) adjusting transmit power of each node to appropriate level as shown in fig2 ii) deploying relay nodes without changing transmit power.

In the later case, we observe two types of nodes; i) original nodes which comprises of sensor and wireless transceiver ii) relay node which comprises of only wireless transceiver as shown in fig3.

We can divide wireless communication link into multiple segments; and the segments can be connected through relay node; from following mathematical equations, we can understand that transmit power required is less when the link is split into multiple segments. For simplicity, we assume free space communication. T is transmitting sensor node. R is receiving sensor node. Y is relay node. D is distance between T & R. After adding relay node Y, revised distance between T & Y and Y & R is *d/2*. From the following equations, we can see that transmit power of fig4a is more than transmit power of fig4b.

$P_t = P_r\,[(4\pi d)^2 L]/[G_t\, G_r\, \lambda^2]$ 1.1

$P'_t = P_{ry}\,[(4\pi d/2)^2 L]/[G_t\, G_r\, \lambda^2]$ 1.2

$P_{ty} = P'_r[(4\pi d/2)^2 L]/[G_t\, G_r\, \lambda^2]$ 1.3

If $P_r = P_{ry} = P'_r$ then $P_{tr} = P'_t + P_{ty}$

$P_t > P_{tr}$ and $P_t = (n+1)*P_{tr}$ where *n* is number of relay nodes.

P_t = Transmit power without relay node; P_{tr} = Total transmit power with relay node; P'_t = Transmit power of first segment; P_{ty} = Transmit power of second segment; $P_r = P_{ry} = P'_r$ = receive power. All other parameters are assumed to be same.

Further, we also optimize, ***N*** the number of relay nodes, which can lead to minimize energy consumption. Hence energy saving can lead to larger number of nodes/edges in the network compared to original network. This is in contrast to general topology control algorithms which mainly focus on reducing number of edges in order optimize energy consumption. However, the resulting super-graph must preserve connectivity of original nodes. The resulting topology can for instance be required; i) to maintain connectivity of the given nodes, ii) to be spanner of the underlying graph (the shortest path connecting a pair of nodes u, v on the resulting topology is longer by a constant factor only than the shortest path between u and v on the given network), iii) to be plannar (no two edges in the resulting graph intersect). The objective must be to find a topology which meets one or a combination of such requirements.

In this paper, we focus on the optimal transmission power of nodes by installing relay nodes to maintain the network connectivity. The goal of our research is to maximize the network lifetime by reducing transmit power at each node. In our work, first we present a scheme of computing relay nodes required and their locations for a given transmission power, and the scheme must ensure the connectivity of network. Then, we propose to eliminate redundant edges to minimize interference. We also compare the algorithm with other popular algorithms in respect of MinMax and MinTotal. We propose to call this algorithm as Power-Sensor (PS) algorithm. As shown in experiment results, the Power-sensor algorithm has good stability of network and promotes the energy-efficiency.

The remainder of this paper is organized as follows: In Section II, we present related work with a focus on topology control and transmission power control in Wireless ad-hoc or sensor networks. In Section III, we present a scheme for calculating the additional nodes and their locations for a given transmission power of nodes to sustain connectivity. The analysis and experimental results of the proposed algorithm are given in Section IV. Finally, we conclude this paper in Section V with a summary of the work done and an outlook on future work.

Definition 1: ***MinMax***: Maximum power that needs to be transmitted by any node to make network connected.*Definition 2*: ***MinTotal***: Minimum of total power transmitted by all nodes together in optimized connected network.

Definition 3:***InterAvg***: Average number of nodes that interfere per edge in the connected network.

Definition 4:***InterMax***: Maximum number nodes that can interfere to any edges in the connected network.

Definition 5: ***Network life time***: Time elapsed before any node discharges its battery energy to a level which is not sufficient to transmit to its first-hop neighbor.

II. RELATED WORK

Many previous studies focused on solving topology control problems. Primarily, the algorithms focused on reducing number of edges to reduce energy consumption. Relative Neighborhood Graph (RNG) used to reduce the number of links between a node and its neighbors [1]. An edge belongs to the RNG only if it is not the longest leg of any triangle it may form in the original graph. N.Li [2] proposed a minimum Spanning Tree based algorithm for topology control. LMST is a localized algorithm to construct MST based topology in ad-hoc networks by using only information of nodes which are one hop away.

In recent years some new approaches have been proposed. In [3] the authors modeled the interaction among nodes as a game and analyzed the problem as non-cooperative game. In [4] authors proposed an algorithm to optimize the traditional topology control scheme. In this algorithm, each node iteratively increases its transmit power. In [5] Kenji proposed LTRT (Local Tree based Reliable Topology) which is motivated by LMST and TRT (Tree based Reliable Topology). LTRT can achieve nearly optimal performance at lower computational cost. Renato [6] presented three missed integer programming formulations for the k-connected minimum consumption problem. Rajan [7] presented a semi-analytical approach to analyze topological and energy related properties of K-connected MANETs. In [8] authors have analyzed the optimal transmission power of nodes according the optimal number of neighbors, and proposed the optimal topology control algorithm based on virtual clustering scheme. Authors in [9] analyzed the different approaches, constraints, and methods used for topology control algorithms.

Chen Wei et al [10] described an energy conservative unicast routing technique for multihop wireless sensor networks over Rayleigh fading channels. In Chen Wei model the *assistant nodes* transmissions can cause multiple packet reception at the receiving end and there by reordering requirement. In our model all the relay nodes are in-line so that they relay the same packet. So packets reach the destination in the same order. Jonathan et, al [11] focused on identifying the additional sensor placement for repairing and ensuring the fault-tolerance with *k*-connectivity. Our model is focusing more on reducing transmit power and thereby improving network life time while retaining connectivity. Martin [12] had presented a model identifying potential interference sources computing minimal interference path. To the best of our knowledge, all currently known topology control algorithms constructing only symmetric connections have in common that every node establishes a symmetric connection to at least its nearest neighbor. In other words all these topologies contain the *nearest neighbor Forest* [12] constructed on the given network. The symmetric connectivity is made with configuring the neighbors to appropriate transmit power level. In other words to preserve the connectivity, transmit power of the neighbors are adjusted to optimal level. However, in our model, we kept the transmit power of all nodes at lowest level possible and connectivity is preserved with adding relay nodes to compensate transmission distance. With this we show that inspite of increased number of nodes, transmit power on each edge is optimized.

III. NETWORK MODEL

We consider multi-hop wireless network, and assume that each node able to gather its own location information via GPS or several localization techniques for wireless networks [13][14].We represent a network as an undirected graph ***G = (V,E)*** where $V = \{v_1, v_2, .., v_n\}$ is a set of nodes randomly deployed in a two-dimensional plane. Each node $v \in V$ has a unique id, $(v_i) = i$ where $1 \leq i \leq n$ and is specified by its location. ***E*** is set of edges. Let $P_i = [p_i^1, p_i^2, \ldots, p_i^m]$ be a finite list of increasing power levels that can be assigned to node $i \in V$. We denote p_i^1 the minimum power p_i such that transmission from node i reach at least one node in $V \backslash \{i\}$. Further, $p_i^{l+1} > p_i^l$ for any l = 1,..,m-1. We define S_i^l as the set of nodes reachable from node i with the power assignment $p_i = p_i^l$ for any l=1,..m. We remark that $\bigcup_{l=1}^{l=m} S_i = V \setminus \{i\}$. For ease of notation, we define $S_0 = \phi$. Initially all the nodes are transmitting with maximum power and are equipped with Omni directional antenna. We assume each node can control the power of transmission to save energy consumption. Let $p(v_i, v_j)$ be the power needed to support communication from node v_i to v_j, and we call it symmetric if $p(v_i, v_j) = p(v_j, v_i)$. The power requirement is called Euclidean if it depends on the Euclidean distance $d(v_i, v_j)$ [15]. Assuming unit disk model (UDG) maximum power a node can transmit is equal to the longest Euclidean distance among all pairs of nodes. For simplicity purpose we normalize the Euclidean distance of every pair of node with longest Euclidean distance. By topology control we have sub graph ***G'=(V,E')*** of ***G***, in ***G'*** the node has shorter and fewer numbers of edges as compare to ***G***. Power consumed by $G' \leq G$ is implied. To compute the subgraph, we start with configuring all the nodes at lowest transmit power level. With that we compute the edges that are within communication distance. In addition, we also validate the edge as per the algorithms given below. Then we verify if the subgraph is a connected network. Incase the subgraph is not connected network, we raise the transmit power of the nodes that are not connected to next level. We repeat the process till the subgraph is a connected network. Here with this model, we compute subgraph using different popular algorithms like GG, RNG, LMST, OTC, OTTC, XTC, and FLSS. For the subgraphs produced by each algorithm, we compute MinMax, MinTotal, number of edges, average interference of all edges (Intavg), Maximum interference on any edge (Intmax), and Average number of hops between two nodes.

Later, in our proposed algorithm, we assume the nodes are configured initially at the lowest transmit power level possible p_i^1, i=1...N. At this power level we identify the edges that are within communication distance. Then in order to make the network connected, we identify the unconnected edges and sort them in ascending order. We pick up each edge from sorted list and then compute number of relay nodes required to be installed between them and their locations so that the two nodes connected. Further, we also check if the subgraph produced after adding relay nodes can give a connected network of original nodes. In case of not producing connected network, we go to next edge from the list and repeat the process till a connected subgraph is produced.

Now we turn our attention to identify redundant nodes among the newly added relay nodes and remove them. For this purpose, we follow the greedy approach wherein we select one node at a time and remove it. If the subgraph is still a connected network of original nodes, the edge is declared redundant and removed; otherwise it will be added back. We continue this for all newly added relay nodes and there by producing a connected subgraph with optimal number of additional nodes. Interference for an edge is defined [12] as ***Cov(e)=|{w∈ V| w is covered by d(u,|u,v|)}*** $\bigcup$ ***{w∈ V| w is covered by d(v,|v,u|)}|***

InterMax = max Cov(e)∈ E and

$$InterAvgx = \sum_{n=1}^{E} Cov(e)/E$$

Theorem1: Any pair of unconnected wireless sensors can get connected by adding sufficient number of relays between the nodes at regular intervals without changing transmit power

Proof of this is given through Lemma1 and Lemma2 below.

Lemma1: Pair of nodes can be connected by adding $\frac{d(u,v)}{p_u}$ relays between the nodes.

Proof: Assuming omni-directional radio, power p_u can communicate d. If $d(u,v)$ is more than d, $u \,\&\, v$ will not be able to communicate. However, by installing relay with p_u at a distance d from u in the direction of v, we can extend the communication distance to $2d$ distance. Thus by adding $\frac{d(u,v)}{p_u}$ we extend the communication distance upto v.

Lemma2: Additional relay do not disturb the existing connectivity.

Proof: if $(w,v)\,|\,w \in V \leq p_u$ then if w is in the direction (u,v) then $d(u,w)+d(w,v)=d(u,v)$

Theorem2: Transmit power P_t can be reduced by a factor of $n+1$ with n relay nodes where $n > 0$ to cover the communication distance.

Proof of this is given through Lemma3 and Lemma4 below.

Lemma3: for free space communication, if distance d between transmitter and receiver is reduced to $\frac{d}{k}$ then P_t is reduced by P_t/k^2

Proof: Let us start with the familiar free space communication equation $P_r = [P_t\, G_t\, G_r\, \lambda^2]/[(4\pi d)^2 L]$ where P_r is receive power, P_t is transmit power and d is distance between transmitter and receiver. And we can observe that P_t is directly proportional to d^2. Hence by reducing the d by k times, required Pt gets reduced by k^2.

Lemma4: In free space communication total transmit power required by k segments of equal distance is $k*P_t$.

Proof: Let us assume distance d is divided in to k equal segments. Relay node is placed at each segment. Transmit power required for each segment is P_t/k^2. Total transmit power required by k segments is P_t/k .

IV. SIMULATION

In order to demonstrate the effectiveness of our proposed algorithm, we evaluated the Power-sensor algorithm via extensive simulations and compared with other existing algorithms. Computational experiments have been carried out on a set of moderately sized network (20, 40, 80, 100, 150,200 nodes) with symmetric links MATLAB software as well as NS-2 simulator.

In the first experiment was done with 20 nodes distributed in 1000x1000 grid.

netXloc = 950.1293 231.1385 606.8426 485.9825 891.2990 762.0968 456.4677 18.5036 821.4072 444.7034 615.4323 791.9370 921.8130 738.2072 176.2661 405.7062 935.4697 916.9044 410.2702 893.6495

netYloc = 57.8913 352.8681 813.1665 9.8613 138.8909 202.7652 198.7217 603.7925 272.1879 198.8143 15.2739 746.7857 445.0964 931.8146 465.9943 418.6495 846.2214 525.1525 202.6474 672.1375

A connected network of the above nodes was generated using PS, RNG, GG, LMST, OTC, OTTC, XTC, and FLSS. The algorithms have been studied w.r.t *MinToal, MinMax, InterAvg, and InterMax* and results are plotted. Better performance of the proposed algorithm (PS) with respect to other algorithms is shown in fig6, fig7, fig8, fig9.

We also extended the study using NS-2 simulator. We have activated the energy model in NS-2 to capture the energy consumed by each node. Energy model computes energy consumed by each packet transmission and stores the residual energy at each node. We can run the simulation till any of the node residual energy becomes zero. This gives the network life time. We simulated various sizes of the network with and without relay nodes. For RNG and GG algorithms, each node are configured to appropriate transmit power P_t. For PS algorithm, all nodes are configured at uniform P_t. We compared RNG and GG algorithms with PS algorithm. The consumed power includes energy consumed in transmitting the packet, receiving the packet, sensing power and idle power. We used AODV as under lying routing protocol. The power consumed includes the impact of AODV overhead. For simplicity, we assumed power consumption for receiving packet, sensing power and idle power to be zero. Comparison of the network life time is plotted at fig13 which indicates increased life time for PS algorithm. MinMax is directly related to Network Life Time. We can observe that number of relay nodes required decreases with increased density. So the gain in MinMax becomes negligible as the density increases as can be seen in fig7. This is obvious because the original nodes are so close that they can communicate with $P_t = p_i^1$, i=1...N without relay nodes. Gain in MinMax or relay nodes impact is significant for sparsely deployed nodes. We have also computed the throughput and end-to-end delay for both cases and plotted the graphs at fig.11 & fig.12. Increase in end-to-end delay and decrease in throughput is implied due to increased hops in the communication. Since the objective is to reduce power consumption and increase in network life time, the variations in throughput and end-to-end delay are acceptable.

V. CONCLSION

As shown explained in the previous section, the proposed PS algorithm has clearly established improvement in MinMax, MinToatl, InterAvg and InterMax terms. However, cost of the relay nodes and increased end-to-end delay to be traded with the saving obtained in the above specified aspects. In the present study, we placed the additional nodes on Euclidean line to connect the unconnected nodes. However, further optimizations are also possible by position the additional nodes at optimal places.

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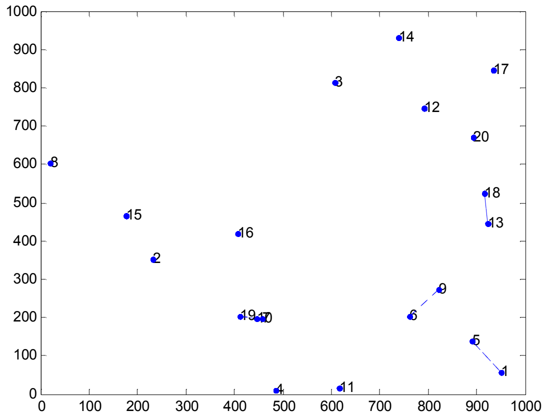

Fig.1 20-node unconnected network with uniform P_t =0.1

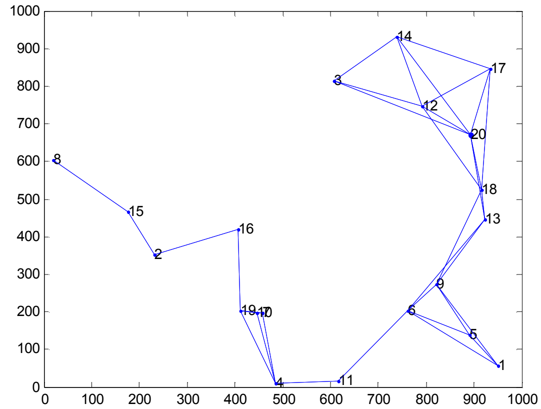

Fig2. 20-node connected network using non-uniform P_t

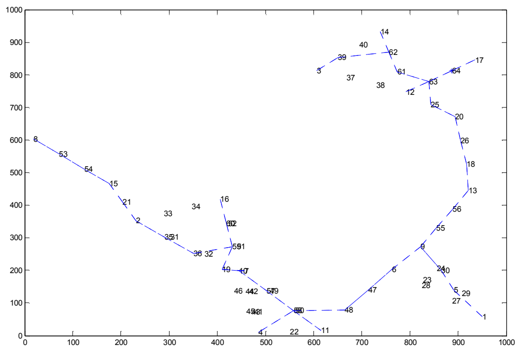

Fig.3 20-node connected network with P_t =0.1after adding relay nodes

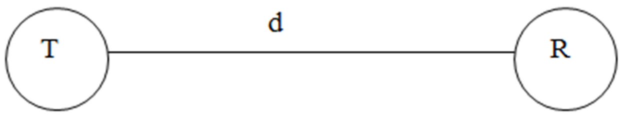

Fig.4a. Link connecting two nodes without relay nodes.

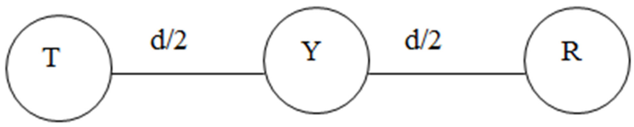

Fig.4b. Link connecting two nodes with a relay node

PS_Algorithm

Input: Set of V nodes each $v \in V$ and each node is powered with lowest normalized power p

$G = (V, E)$ with all nodes configured with lowest normalized power p. G is not connected graph

$G_{ps} = (V_{ps}, E_{ps})$ is a connected graph with lowest normalized power p

$G = (V, E)$

$V_{ps} = \phi$

$E_{ps} = \phi$

$G_{ps} = (V_{ps}, E_{ps})$

for all $v \in V$ **do**

$V_{ps} = V_{ps} \bigcup v$

end for

for all $e = (u, v) \in E$ **do**

if $v \neq u$ and $|(u, v)| \leq p$ and $|(v, u)| \leq p$ **then**

$E_{ps} = E_{ps} \bigcup \{e\}$

$E = E \setminus \{e\}$

end if

end for

While G_{ps} is not a connected graph **do**

$e = \min\{(u, v) \in E, | u, v |> p\}$

$N = \{(| u, v | -1) / p\} + 1$

$\Delta N = |u, v| / N$

for $i = 1$ to N

$u_i =$ location $u + \Delta N$ in $|u, v|$ direction

$Vps \longleftarrow u_i$

$e = (u, u_1)$ or (u_i, u_{i+1}) or (u_N, v) as case may be

$E_{ps} = E_{ps} \bigcup \{e\}$

$G_{ps} = (V_{ps}, E_{ps})$

end for

$E = E \setminus \{e\}$

end while

while unprocessed $e = (u, v)$ where $(u \in V_{ps}$ and $u \notin V)$ or $(v \in V_{ps}$ and $v \notin V)$ or $(u, v \notin V)$ **do**

$G'_{ps} = G_{ps} \setminus \{e\}$

if $G'_{ps} \longrightarrow$ connected $G = (V, E)$ **then**

32. $G_{ps} = G'_{ps}$

33. end if

34. end while

Output: G_{ps} connected graph of G

Fig-5 PS-Algorithm

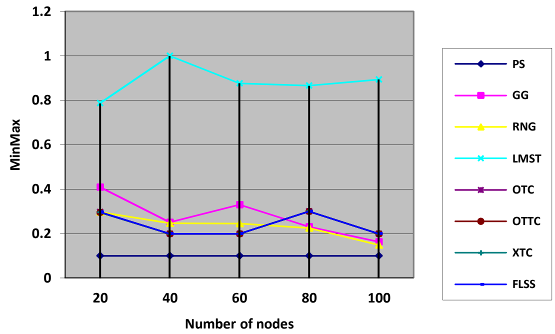

Fig.6a Comparison of MinMax for different algorithms

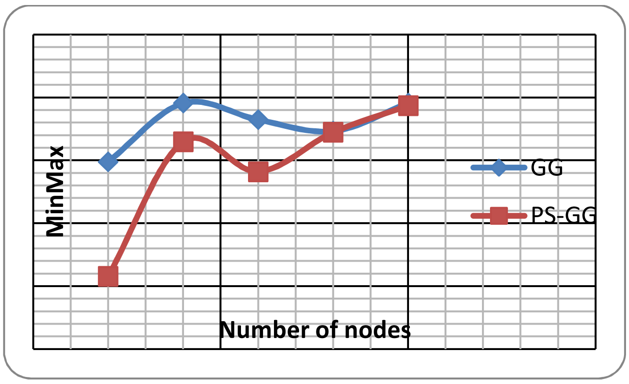

Fig 6b. Comparison of MinMax with and without relay nodes

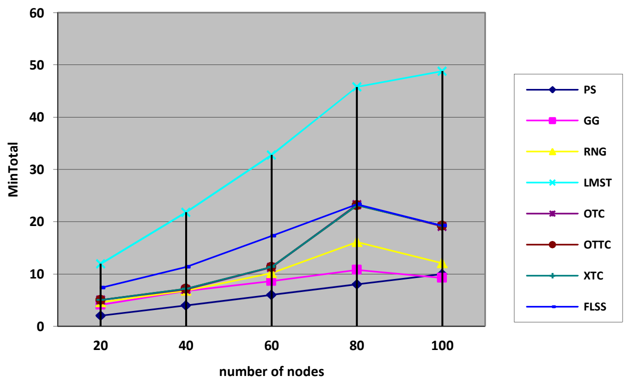

Fig7. Comparison of MinTotal for different algorithms

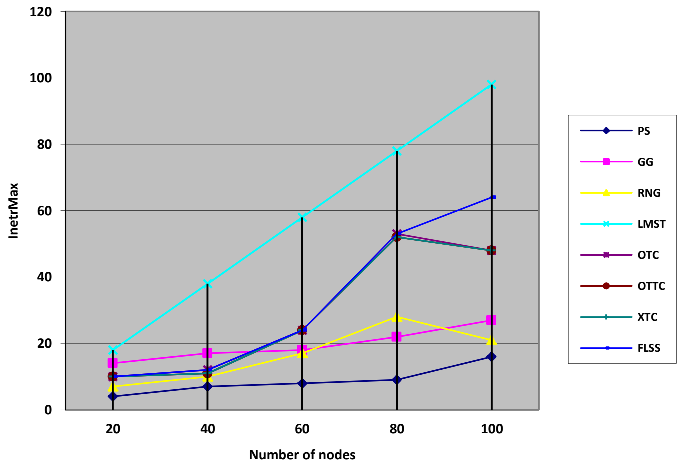

Fig.8 Comparison of InterMax for different algorithms

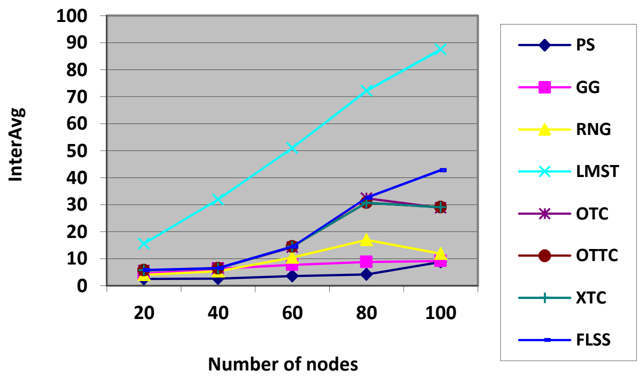

Fig9. Comparison of InterAvg for different algorithms

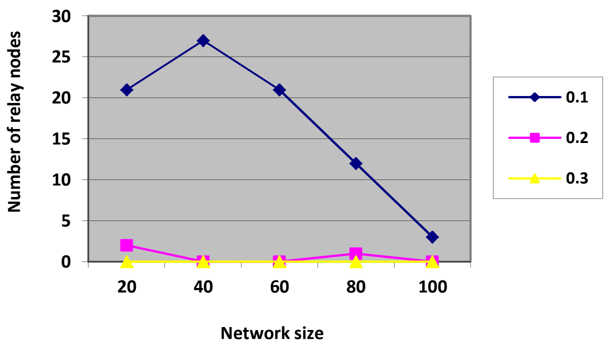

Fig 10. Number of relay nodes with different transmit power levels

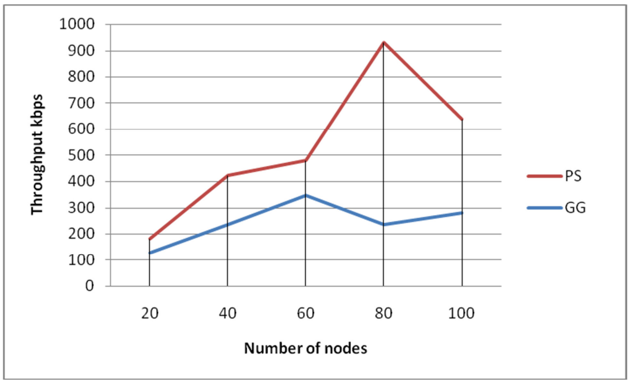

Fig 11. Comparison of throughput with and without relay nodes

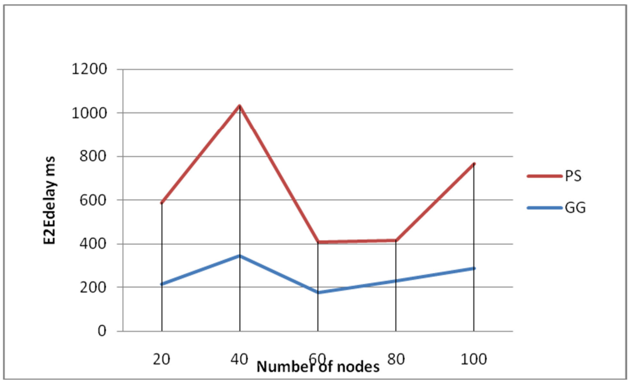

Fig12. Comparison of end-2-end delay with and without relay nodes

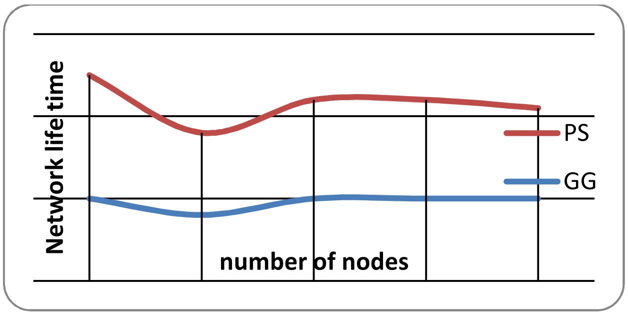

Fig13 Network life time comparison with and without relay nodes