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Design and Simulation of Efficient Topology Control Scheme for Wireless Sensor Network

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***Abstract* — Topology control plays an important role in the design of Wireless ad hoc and Sensor Networks; it is capable of constructing networks that have desirable characteristics such as sparser connectivity, lower transmission power, and a smaller node degree. In this research, a new distributed topology control technique is presented that enhances energy efficiency and reduces radio interference in wireless sensor networks. Each node in the network makes local decisions about its transmission power and the culmination of these local decisions produces a network topology that preserves global connectivity. Central to this topology control technique is the novel Smart Boundary Yao Gabriel Graph (SBYaoGG) and optimizations to ensure that all links in the network are symmetric and energy efficient. Simulation results are presented demonstrating the effectiveness of this new technique as compared to other approaches to topology control.**

***Keywords* — Graph Theory, Power Control, Proximity Graphs, Topology Control, Wireless Sensor Networks.**

I. INTRODUCTION

Multifunctional wireless sensor nodes are a development brought about by recent advancements in wireless communications and electronics [1]. These sensor nodes are small in size and communicate unrestrictedly over short distances. They have sensing, data processing and communication capabilities and their features have enabled, as well as provided, impetus to the idea of Wireless Sensor Networks (WSNs). WSNs are powerful in that they are amenable to support a lot of real world applications that vary considerably in terms of their requirements and characteristics.

Networks of sensors exist in many industrial applications providing the ability to monitor and control the environment in real time. Most of these networks, however, are wired and as a result are costly to install and maintain. To lower the system and infrastructure costs wireless solutions can be used [2].Wireless solutions have other benefits in industrial applications such as enhanced physical mobility, reduced danger of breaking cables, less hassle with connectors and ease of upgrading [3]

WSNs can be deployed in unpleasant, inaccessible or hazardous environments which are impractical with traditional. Wired networks such as in the bearings of motors or the inside of whirring motors [4]. In addition to this, the collaborative nature of WSNs brings about flexibility, self-organization, self-configuration, inherent, intelligent-processing capability, and enables rapid deployment.

WSNs, therefore, are an attractive option for industrial applications. They are beginning to substitute the conventional industrial wired communication systems in applications such as factory automation, distributed control systems, environment and equipment monitoring, product tracking, automotive systems and other kinds of networked embedded systems. WSNs play a crucial part in creating a highly reliable and self-healing industrial system that is highly responsive to real-time events with appropriate actions. The data collected by sensor nodes is sent wirelessly to a sink node that analyses the data from each sensor node. Notifications of any possible problems can then be sent to plant personnel or instructions can be relayed back to the senor nodes to activate on board actuators in a certain way if equipped.

In a densely deployed wireless network, a single node will have many neighboring nodes which it can communicate with directly when using sufficiently high transmission power. However, high transmission power requires a lot of energy and using many neighbors is a burden for a medium access control (MAC) protocol. Routing protocols suffer volatility in the network when nodes move around and frequently sever or form many links between one another. To provide nodes with a long period of autonomy, protocols that aim to optimize power usage are needed, so as to extend the lifetime of the nodes and the lifespan of the network as a whole.

In order to meet these challenges, topology control (TC) can be applied. Topology control is one of the most important techniques used in WSNs to reduce energy consumption and radio interference. It lends itself to the mechanisms of multi-hop communication and energy-efficient operation. Topology control aims to control the graph representing communication links between nodes, with the purpose of meeting a global property of the graph-such as connectivity, while reducing energy consumption and radio interference. additive white Gaussian noise (AWGN) channel for verifying obtained results.

II. TOPOLOGY CONTROL

A. Taxonomy

There are several different approaches to topology control and it is possible to organize them into a coherent taxonomy. The first distinction is between approaches that control transmitter power and those that impose a hierarchy in the network. Hierarchical approaches change the logical structure of the network in terms of node adjacencies and may be broken down into approaches that use clustering and those that use dominating sets.

The power control approaches act on the transmission power of nodes using several different techniques. The first distinction to make of power control approaches is between homogeneous and non-homogeneous approaches.

Homogeneous topology control is the easier of the two in which nodes are assumed to use the same transmitting power and the problem of topology control becomes in essence one of finding the value of the transmitter range that satisfies a certain network wide property.

In non-homogenous topology control nodes are allowed to select different individual transmitting powers up to a certain maximum that they can support which means that they will have different transmitting ranges. This form of topology control can be split into three different categories according to the type of information that is used to generate the topology. These three categories are location based, direction based, and neighbor based.

In location-based approaches exact node locations are known and are either used by a centralized authority to calculate a set of transmitting range assignments which optimize a certain measure or are exchanged between nodes to create an approximately optimal topology in a distributed fashion. In direction-based approaches, nodes are assumed to not know their positions but can estimate the relative direction to each of their neighbors. Finally, in neighbor-based approaches the only knowledge nodes have of their neighbors is the neighbor IDs and the IDs are ordered according to some criterion when performing topology control.

B. Quality Measures

Different approaches to topology control will produce different results. For a collection of nodes , let G denote the graph on V for which there is an edge from node u to node v only if u can directly reach to v In order to do this, some metrics and measures are required which include connectivity, energy efficiency, throughput, and robustness to mobility

1) Connectivity

If there is a multi-hop path between u and v In G then there should also be a path in T. This is a basic requirement for a topology control algorithm, that it should not disconnect a connected graph.

2) Energy Efficiency

The energy consumed for a transmission between u and v is a polynomial function of the distance between u and v. Two common notions of energy efficiency are the *energy stretch factor* and the *hop stretch factor*. The energy

Stretch factor is the worst increase in energy used to deliver a packet between any pair of nodes and along a minimum energy path between the original graph and the topology controlled graph . The hop stretch is similar except that the focus is on path length as opposed to energy consumption. Formally

$$energy\ stretch\ factor = \max_{u,v\in V} \frac{ET(u,v)}{EG(u,v)}$$

Where $EG^{(u,v)}$ is the energy consumed along the most energy efficient path in graph. Likewise

$$hop\ stretch\ factor = \max_{u,v\in V} \frac{|(u,v)T|}{(u,v)G}$$

Where (u,v)G is the shortest path in graph G and $|(u,v)G|$is its length.

3) Node Degree

In order to better evaluate the performance of the topology control technique in terms of interference, a distinction is made between the physical and the logical node degree. The physical node degree refers to the number of neighbour nodes that are within the transmitter range of a given node. The logical node degree refers to the number of neighbour nodes that a given node is linked to.

4) Simplicity and Maintainability

It is desirable for a topology T to be simple and easy to maintain and objective measures that can be used to evaluate these subjective goals are the number of edges in T and the maximum node degree (number of neighbors) of any node in T

5) Throughput

It is desirable for the network topology to have a high throughput, where it is possible to sustain a comparable amount of traffic as the original network topology. Several throughput measures can be used one of which is the *bit-meter* which is defined in terms of the bit-distance product. A network transports one bit-meter when it one bit is transported a distance of one meter. The throughput of the network is then the number of bit-meters transported per second.

6) Robustness to Mobility:

A robust topology should only require a small number of these adaptations and avoid the effects of reorganization due to local node movement affecting the entire network. A measure of robustness is the *adaptability* Which is the maximum number of nodes that need to change their topology information as a result of the movement of a node

C. Power Control

1) Non-homogeneous

a) Range Assignment

The range (R_A) assignment problem is that of assigning transmitting ranges to individual nodes in the network such that the resulting communication graph T is strongly connected and the energy cost is at a minimum. Let N = {$u_1 \ldots u_n$} be a set of points in region R=$[0,l]^d$ ford=1, 2, 3, denoting the positions of network nodes. A more formal definition of the range assignment problem is that of finding the connecting range assignment RA such that is at a minimum

$$c(RA) = \sum_{ui\in N} \big(RA(ui)\big)^{\alpha}$$

b) Minimum Energy Unicast

In minimum energy unicast the goal is to compute topologies that have energy-efficient paths between potential source-destination pairs. For a connected communication graph G obtained when all nodes transmit at maximum power, every edge (u_i,u_j) is weighted with the power $\delta^{\alpha}_{ui,uj}$ necessary to transmit between u and u_j. These edge weights are used to calculate the power stretch factor for a given path in.

Table 1 : Quality Measures Different Proximity Graph

	Distance Stretch factor	Power Stretch Factor	Node Degree
RNG	$n-1$	$n-1$	$n-1$
GG	$\sqrt{n}-1$	1	$n-1$

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RDG	$\frac{1+\sqrt{5}}{2}\pi$	$\left(\frac{1+\sqrt{5}}{2}\pi\right)^{\alpha}$	$\theta(n)$
YG	$\frac{1}{1-2\sin\frac{\pi}{e}}$	$\frac{1}{1-\left(2\sin\frac{\pi}{e}\right)^{\alpha}}$	$n-1$

The routing sub graph should ideally have the following features.

a) Constant power stretch factor, i.e., should be a power spanner. This ensures that the routes calculated on are at most a constant factor away from the energy optimal routes.

b) Linear number of edges, i.e., must be sparse. This eases the task of finding routes in and maintaining the routing graph in the presence of node mobility. It also reduces the routing overhead.

c) Node degree must be bounded. This is because nodes with a high degree have a high likelihood of being bottlenecks in the communication graph.

d) Easy computation in distributed and localized fashion where only information provided by neighbor nodes in is used. This is essential for fast and effective computation of the routing graph in a real WSN.

There are a number of geometric graphs that satisfy the above requirements and are based on sub graphs of These include the Relative Neighborhood Graph (RNG) [9], the Gabriel Graph (GG) [10], the Delaunay Graph (DG) , and the YaoGraph (YG). These graphs are called *proximity graphs*

c) Protocols

A more practical approach to the topology control problem involves designing simple, fully distributed protocols that build and maintain a fairly good topology. These protocols are called topology control protocols and may be position based such as the Local Minimum Spanning Tree (LMST), direction based such as Cone-Based Topology Control (CBTC) or neighbor based such as the -NEIGH protocol.

III. Smart Boundary YAO Gabriel Graph (SBYAOGG)

A. Objectives

There were two design objectives in developing the envisaged topology control technique for WSNs. The first objective was that it should be energy efficient and the second was that it should have low interference. Performance measures were used to determine how well these objectives were met. The relative performance of the new technique compared to other well-known approaches to topology control was also used to evaluate how well these objectives were met.

B. Requirements

To meet the set out design objectives, the routing sub graph produced by the topology control technique from the original graph had to meet certain requirements. A number of the requirements were for minimum energy unicast; these are the following.

1) Constant power stretch factor, i.e., the graph should be a power spanner

2) Linear number of edges, i.e., the graph must be sparse.

3) Easy computation in a distributed and localized way.

In addition to this, the sub graph had to be:

1) Connected with high probability if the original graph is connected.

2) Planar, meaning that no two edges in the graph cross each other. This will enable some localized routing algorithms to work with the generated topology such as Greedy Face Routing (GFR), Greedy Perimeter Stateless Routing (GPSR), Adaptive Face Routing (AFR), and Greedy Other Adaptive Face Routing (GOAFR).

C. Yao-Gabriel Graph With Smart Boundaries

In order to develop a technique that produced a network topology that met the objectives that have been set out and that adhered to the identified requirements and conformed to the choices made, it was decided to create a graph algorithm that is a hybrid of different proximity graph algorithms. This algorithm is a mixture of the Gabriel graph algorithm and the Yao graph algorithm, with the use of smart region boundaries. The algorithm is referred to as the Smart Boundary Yao Gabriel Graph (SBYaoGG). The topology is generated by first computing the Gabriel graph from the Unit Disk Graph (UDG) at maximum transmitter power and then computing the Yao graph on the reduced topology to produce the final topology. By computing the Gabriel graph from the UDG some of the requirements for the final topology are met.

- The graph produced is planar.
- The graph has a linear number of edges.

After computing the Yao graph from the Gabriel graph some other requirements for the final topology are met.

- The graph is connected. This is because both the Gabriel graph and the Yao graph are connected if the original graph is connected.
- The graph is a power spanner of the original UDG. This is because both the Yao graph and the Gabriel graph are power spanners.

1) Pruning the Edges of the Gabriel Graph:

The procedure employed to reduce interference was as follows.

- Prune the edges of the Gabriel graph using the Yao graph.
- Use large regions in computing the Yao graph.
- Select the axes of cones for each region of the Yao graph using heuristics.
- Reduce the transmitter power of each node to the lowest level so that it allows it to reach its furthest neighbor in the final topology

2) Determining the Region Boundaries of the Yao Graph:

A heuristic that was used whilst forming the reduced topology graph was to align the axis of the first cone used in the Yao graph computation to the region where nodes are most densely deployed. The

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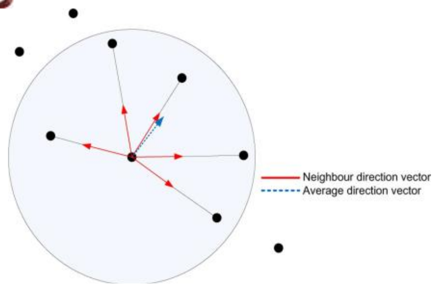

Fig.1. Neighbor direction vectors and the average direction vector

Where the neighbor direction vector and average direction vector is illustrate in Fig 1.

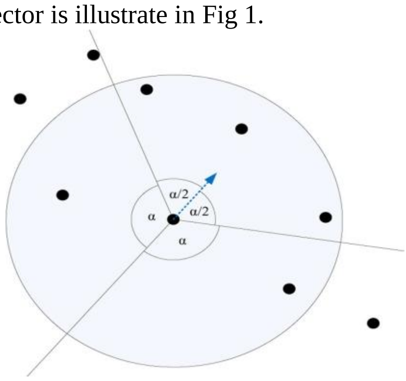

Fig.2. Yao graph boundaries using an average direction vector.

The cones of the Yao graph are as shown in Fig. 2. In the case of Figs. 4 and 5, α=120 corresponding to a Yao graph with three cones.

3) Optimizations:

Once the edges of the Gabriel graph are pruned, there will be some asymmetric edges. One optimization that was used was to make all the edges symmetric by adding the reverse edge of any asymmetric link where v € E

4) Algorithm:

The following algorithm describes how to

Construct the SBYaoGG, detailing the node in the network goes through.

Algorithm: Construction of SBYaoGG

1. The node discovers its neighbor nodes by broadcasting at maximum power.
2. The Gabriel graph is constructed locally.
3. The unit direction vectors of neighbor nodes in the Gabriel graph are computed.
4. The average direction vector is computed.
5. The axis of the cone of the first region to use in computing the Yao graph is set to correspond to the average direction vector.
6. The Yao graph is computed from the Gabriel graph, producing the reduced topology.

The final step in obtaining the SBYaoGG is to optimize the reduced topology in order to ensure low interference and good power spanner properties. Two optimizations were made.

1) All edges are made symmetric by adding the reverse edge for any asymmetric link.

2) Transmitter power levels are set to the lowest level that will allow each node to reach all the nodes with which it has an edge. After this the SBYaoGG is fully formed and can be used as input to a routing algorithm.

IV. Results

A. Simulation result

The SBYaoGG algorithm was run on several random networks in which nodes were distributed in a two-dimensional unit square region according to a uniform random point process. One-thousand samples were taken for each data point which gave results at a 95% confidence level with an accuracy of close to 3%.

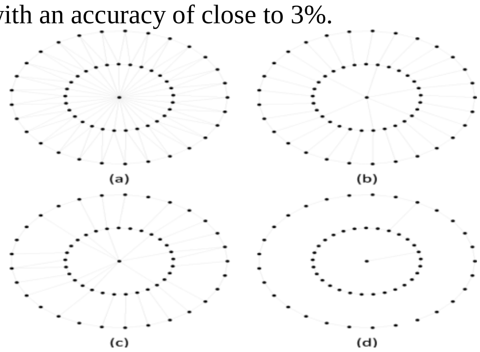

Fig.3. Topology generated from the double ring network deployment for: (a) DG, (b) $S\theta GG$ (c) SBYaoGG graph, and (d) MST

B. Predetermined network deployment

The predetermined network deployments provide a quick way of comparing the topology control algorithm with other well-known algorithms and they help in visualizing how it works. Situations in which it is well suited are also made apparent.

1) Double Ring Deployment: In the double ring deployment, the nodes are evenly distributed on the perimeters of two concentric circles with different radii, with one node located at the centre. This deployment can show topology control algorithms that are not degree-bounded and the energy efficiency of different algorithms. The topologies produced for the Delaunay graph, the , the SBYaoGG, and the MST of the double ring network with 61 nodes, are shown in Fig. 3(a)–(d), respectively, and the performance metrics are show in Fig. 4.

2) Exponential Node Chain Deployment: The exponential node deployment is a one in which the distance between nodes increases exponentially [11]. This network can be used to compare the interference of different topology control algorithms. The topologies produced for the exponential node chain network with ten nodes by the Delaunay graph, the, the SBYaoGG and the MST are shown in Fig. 5(a)–(d), respectively, and the performance metrics are shown in Fig. 6

3) Uniform Random Network Deployment: In order to characterize the performance of a topology control algorithm that encompasses all sorts of network deployments it is useful to evaluate the algorithms based on their performance in several uniform random networks. Topologies generated by different topology control algorithms, including the SBYaoGG for the same uniform random network are shown in Fig. 7

C. Comparison with Other Algorithms

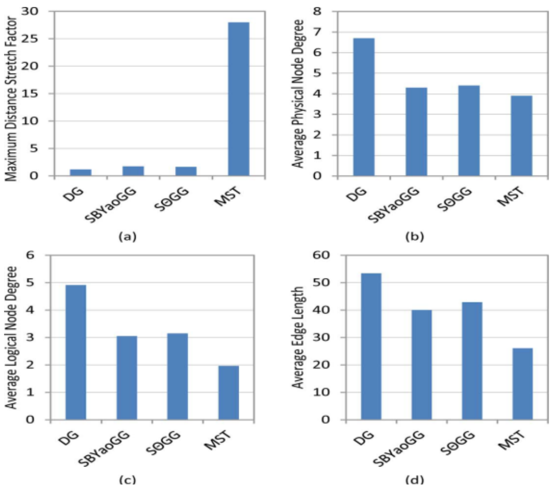

Fig.4. Performance metrics obtained from double ring network deployment.

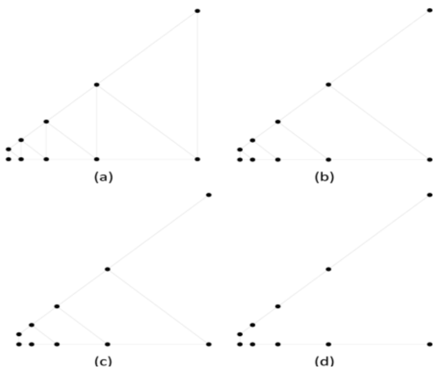

Fig.5. Topology generated from exponential node chain network deployment for: (a) DG, (b) $S\theta GG$ (c) SBYaoGG graph, and (d) MST.

1) Distance Stretch Factor:

The maximum distance stretch factor shows energy efficiency in terms of end to end multihop communication from source to sink and not from hop-to-hop, which is represented by the average edge length. The maximum distance stretch factors of the SBYaoGG compared with the Delaunay graph, the Gabriel graph and the RNG are shown in Fig 8.

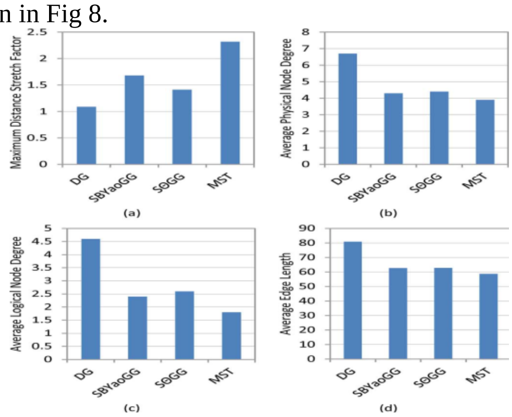

Fig.6. Performance metrics obtained from exponential node chain network

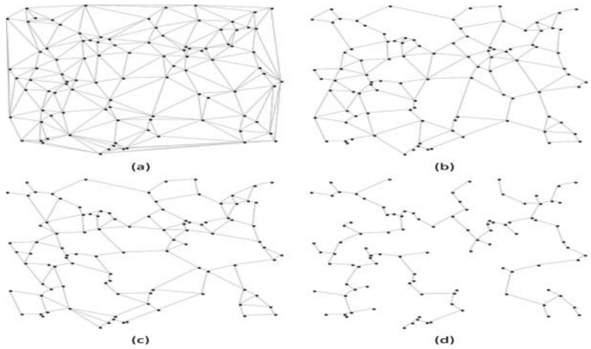

Fig.7. Topology generated from a uniform random network deployment for: (a) DG,(b)$S\theta GG$ (c) SBYaoGG graph, and (d) MST.

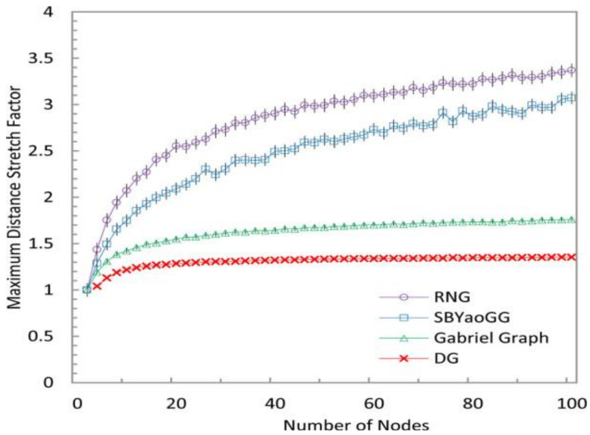

Fig.8. Maximum distance stretch factor of different graphs.

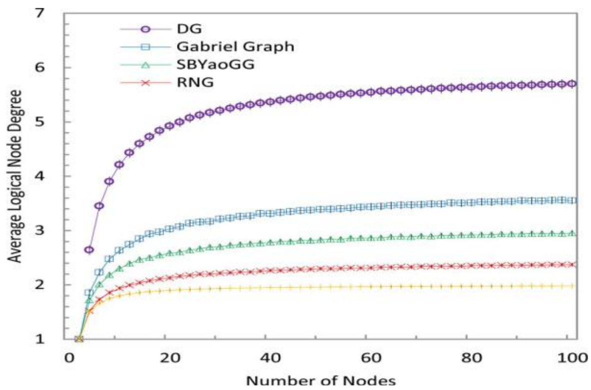

Fig.9. Average logical node degree of different graphs

2) Logical Node Degree:

The average logical node degree shoes the number of neighbors a node will have and gives an indication of how big its routing table will be. The average logical node degree of the SBYaoGG compared with the Delaunay graph, the Gabriel graph, the RNG, and the MST are shown Fig. 9. As can be expected, the MST has the lowest node degree, followed by the RNG while the Delaunay graph has the highest node degree, followed by the Gabriel graph. The SBYaoGG lies.

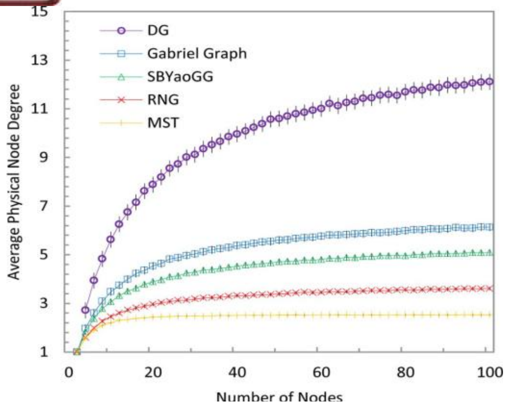

Fig.10. Average physical node degree of different graphs

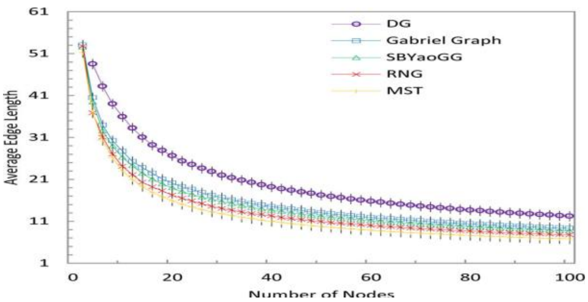

Fig.11. Average edge length of different graphs

3) Physical Node Degree:

The average physical node degree show the number of nodes affected by transmissions from a single node and is a measure of interference and spatial reuse. The average physical node degree of the SBYaoGG compared with the Delaunay graph, the Gabriel graph, the RNG and theMST are shown in Fig. 10.

4) Edge Length:

The average edge length shows energy efficiency in terms of hop to hop ommunication and is an indicator of individual node lifetime. The average edge length of the SBYaoGG, compared with the Delaunay graph, the Gabriel graph, the RNG and the MST are shown Fig. 11.

V. Conclusion

In this research, a topology control technique for energy efficient and low interference in wireless sensor networks was developed in the form of the SBYaoGG algorithm. The SBYaoGG algorithm was evaluated using a simulation program and was shown to perform favorably. The SBYaoGG algorithm is a variation of the standard Yao Gabriel graph in which the boundaries of the regions of the Yao graph depend on the distribution of neighbors around a node. The average unit direction vector of the neighbors of a node is used as the axis of the first cone of the Yao graph.

The performance of the SBYaoGG algorithm was evaluated using several performance metrics and compared with that of other topology control algorithms. The metrics that were chosen were those that measure energy efficiency, interference, and the routing efficiency that will be a result of using the topology controlled graph as input to a routing protocol.

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