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ANALYSIS OF TOPOLOGY CONTROL ALGORITHMS IN AD HOC AND SENSOR NETWORKS

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ABSTRACT

Topology control is one of the major techniques used to enhance the network capacity at network level and adjusts the transmission power at node level. Proper adjustment of transmission power not only increases energy efficiency but also reduces the network interference. The topology control protocols minimizes the maximum power used by the nodes and at the same time preserves different network constraints like connectivity (biconnectivity), k-neighbor set etc. In this paper we critically analyze the different approaches, constraints, and methods used for topology control algorithms and discuss some of the open issue in ad hoc and sensor network environments.

INTRODUCTION

In ad hoc network [1] each node operates as a host as well as a router. The nodes in the network form the topology automatically depending upon the physical location and transmission range. As nodes are battery operated and mobiles in nature, hence it is difficult to maintain the existing topology for longer periods. In ad hoc network there exist many challenges [2] such as unpredictable mobility, restricted battery power, limited bandwidth, multi-hop routing, dynamic topology, security etc. Here we consider two such issues which motivate to study topology control techniques.

Let's start with an example, where node *u* want to communicate with node *v* which is in *d* distance from *u* and is in transmission range of *u* as shown in figure 1. Another node *w* is in region *C* circumscribed by circle of diameter *d* and is placed in d_1 distance from *u* and d_2 distance from *v*. As d_1 and d_2 is less than d, so communication from *u* to *v* can be possible through node *w*. In this scenario two paths exists to support communication from *u* to *v*, one of the path $u \rightarrow v$ is a direct path between *u* and *v*, while other path $u \rightarrow w \rightarrow v$ is a relay path from *u* to *v* through *w*. Distance between $u \rightarrow v$ is represented as $d(u \rightarrow v) = d$ and through *w* can be written as $d(u \rightarrow w \rightarrow v) = d_1 + d_2$. Among these two paths we have to find the energy efficient path, (as mobile devices are battery constrained). Calculation of energy consumption in both paths is required to find the energy efficient path. For simplicity it is assumed that radio signal propagates according to free space model [3], for which power required to propagate signal from $u \rightarrow v$ will be proportional to d^2 and power consumption through *w* will be proportional to $d_1^2 + d_2^2$. From triangle (Δuvw), we can find that:

$$d^2 = d_1^2 + d_2^2 - 2 d_1 \ d_2 \ \cos \ \alpha$$

as $w \in C$, so it implies that

$$\cos \ \alpha \ \leq 1, \text{ so } d^2 \ \geq \left(d_1^2 + d_2^2 \right)$$

Even when α is equal to 90 degree $d^2 = d_1^2 + d_2^2$. So it is better to communicate using short multi-hop path rather than direct path.

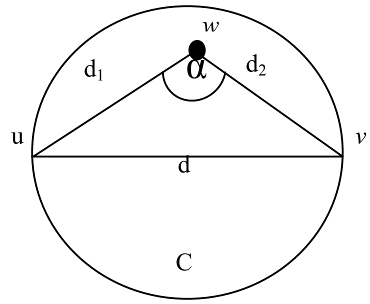

Fig. 1. Path $u \rightarrow w \rightarrow v$ is preferred in place of $u \rightarrow v$ for energy saving.

This above observation gives first argument in favor of topology control. So far energy is concerned, it is better to go through short multi hop path rather than a long direct path. In power control technique node *u* adjust its transmission power to a specific level by which it can communicate to node *v* through *w* only. If we map this observation to topology control approach it can be represent as, node *u* reduce its transmission power, such a way that it can reach *v via w* only. In other way we can say that objective of node *u* is to remove the energy inefficient link *uv* from its edge set. Minimizing the maximum power used by a node is one of the design goals of most of the topology control protocol.

The second motivation for topology control is based on network capacity enhancement by selecting an appropriate interference model. In ad hoc networking environment, increasing transmit power reduces packet drop due to far and near problem. However it increases interference in the network. So in this conflicting scenario there must be some trade-off between these two approaches. Gupta and Kumar [4] design a protocol model to derive the upper and lower bounds on the capacity of the ad hoc networks. In this model packets from node *u* to *v* can correctly received at v if,

$$d \ (vw \ ) \ \geq \ (1 \ + \ \lambda \ )(d \ (u \ , v \ ))$$

This means, distance between receiver and interference node should be more than distance between sender and receiver by a factor $(1 + \lambda)$, for any, $\lambda > 0$. Here network capacity refers the minimum value of $(1 + \lambda)$ such that it satisfies the network constraints. The above two observation motivates to study on topology control protocol [5].

PRELEMENARIES

Some of the basic concepts of topology control protocols are discussed here.

Relative Neighborhood Graph and Gabriel Graph

This is the two topology control approach based on computational geometry. In RNG (related neighborhood graph), the edge between node *u* and *v* exists if there is no node *w* such that

$$d(uw) < d(uv) \text{ and } d(vw) < d(uv)$$

Where $d \ (uv \ )$, represents the distance between node *u* and node *v*. RNG suggest that, no nodes is in the intersection area of two circles centered at node u and node v. DRNG is a distributed algorithm based on RNG.

In other hand Gabriel graph(GG), can be defined as, the edge between node u and v exists if and only if there is no any node w such that

$$d^2(uw) + d^2(vw) \le d^2(uv)$$

It suggests that there is no node inside the circle where node *u* and node *v* is the two end points of a circle. Both RNG and GG are connected graph. The figure 2 shows the RNG and GG.

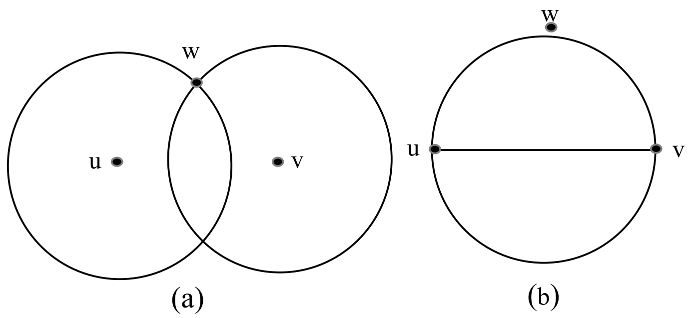

Fig 2: (a) In RNG, no node is present within the intersection area of two overlapping circle (b),In GG, no node presents inside the circle

Unit Disk Graph and Point Graph

Unit disk graphs (UDG) have been used in wireless network to model the topology in ad-hoc networks. In geometric graph theory, a UDG can be defined as the intersection graph of a family of unit circles in a Euclidean plane. That means, we can form a UDG by connecting vertex for each circle, by an edge whenever the corresponding circles cross each other. The major weakness of UDG is that, it assumes the coverage area should be perfectly regular which is difficult to achieve in real-life situations. In other hand including all the obstacles in network model will be more complex and environment dependent for this reason UDG and point graphs are mostly preferred in wireless ad hoc network. A point graph can be defined as a set of points distributed according to some probability distribution in a certain region. Points are then connected according to some rule. Most of the location based protocol relies on Euclidian distance to find the energy cost and most of the topology control protocol assumes that the topology is a unit disk graph or point graph. Figure 3 shows the example of a unit disk graph.

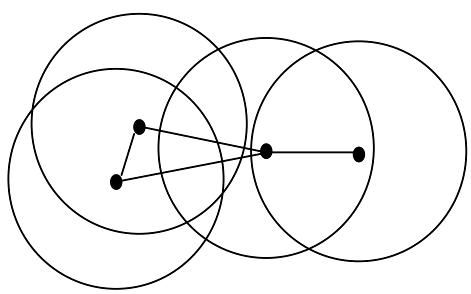

Fig. 3. Unit Disk Graph consisting of unit distance circles

Physical and Logical Topology Control

Physical topology control (PTC) satisfies the goal of topology control by adjusting transmission power; it reduces interference and energy consumptions. In other hand logical topology control (LTC) also based on the approach used by PTC along with it consider the neighbor set of a node, and restrict it to a certain number to satisfy the network connectivity. This neighbor reduction mechanism helps to reduce the routing overhead. Figure 4 (a) shows the PTC and 4(b) LTC.

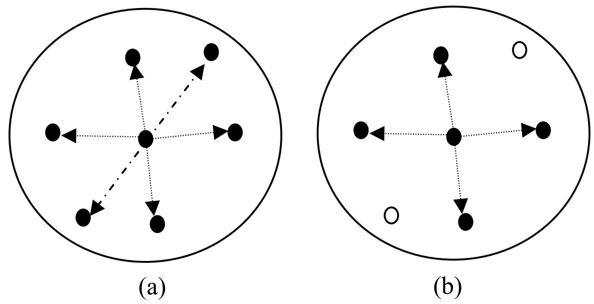

Fig. 4. (a) PTC based on the transmission power only, and (b) LTC based on transmission power and neighbor set.

PROBLEM FORMULATION

Network Model

Consider a network, which can be represented as a graph, G= (V, E), where V= {v_1, *v2,…,* v_n} a set of node randomly deployed in a two dimension plain. Each node *u* € V has a unique id, (u_i) = i, where 1 ≤ i ≤ n and is specified by its location. Initially all the nodes are transmitting with maximum power and are equipped with omni directional antenna. Let P(*uv*) be the power needed to support communication from node *u* to *v*, we called it symmetric if P(*uv*) = P(*vu*). The power requirement is called Euclidean if it depends on the Euclidean distance || *uv* || and is calculated as

$$P(uv) = c + \|uv\|^{\beta}$$

Where c is a positive constant real number, and β € [2, 5], depends upon transmission environments. 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.

Objectives and Constraints

Topology control is hereby formulated as the problem of achieving one or more *objectives* under the certain *assumptions*, subject to satisfying some *constraints*, by employing any *approaches*.

Assumption: Without topology control, all the nodes in the network are transmitting with common maximum power via omni directional antenna.

Objective: The major objective can be expressed as: (1) minimize the maximum power used by any node in the network, (referred as MinMax objective) and (2) minimize the total power used by all the nodes in the network, (MinTotal objective).

Constraints: As topology control reduces transmission power at node level, total power used by all the nodes at networks level, hence one mandatory constraint here is to maintain the connectivity. Other constraint is selecting a neighbor set (k-neighbor) to maintain link symmetric.

Approaches: PTC and LTC are the two basic approaches used, which is discussed earlier.

ANALYSIS OF DISTRUBUTED TOPOLOGY CONTROL PROTOCOL

Based on their principal frame work topology control protocols for ad hoc and sensor network, can be classified as centralize controlling and distributed controlling methods. In the former method the central entity (access point) knows the location of all the nodes and adjusts the transmission power according to the requirement. However such methods are not suitable for ad hoc network environments due to many factors. Hence must of the topology control protocol for ad hoc network are distributed in nature. Here they are categories as location based, direction based and neighbor based.

Location Based Approach

In this type of protocol it is assumed that, location information of node is somehow available by means of any of the methods such as, global positioning systems (GPS), triangulation-based positioning or any other positioning methods. In order to reduce hardware cost some of the techniques [6] assumes that a subset of the node are equipped with GPS receiver while other nodes get their node information by exchanging message with these nodes. Under location based approach we are discussing two protocols here.

In Local Minimum Spanning Tree [LMST] protocol [7], it is assumed that the nodes are homogeneous, they are transmitting with common maximum power and their links are symmetric. The protocol has three phases such as *topology construction*, *information exchange*, and *determination of transmit power*. In the information exchange phase, nodes sends beacon message to their one-hop neighbor by includeing node position and node-ID. When a node gets all beacon messages from its one-hop neighbor then it constructs the local MST by the help of Prim's algorithm. Where each edge has a weight equals to Euclidean distance between the endpoints. The specific link weight function is used to provide a unique MST. After this all the node in the network has a unique MST. The next step is to define the neighbor set in the final topology. Final topology is obtained by the intermediate neighbors of the local MST. Transmit power required to send a message to any neighbor is generated from the final topology. The node also measures the broadcast power to reach the farthest node.

Another protocol which is based on location information is R&M protocol [8]. The protocol is based on relay region and enclosure graph, and uses all-to-one communication pattern similar to WSNs. This is based on the master node concept, where other node send message to the master node. The protocol has two phases. In the first phase every node computes their neighbor set by means of local information. Every node then broadcast the beacon message same way that of LMST. All node then computes the enclosure graph based on the relay region. A relay region can be defined as

$$RR(u \rightarrow w) = \{(x, y) \in \Re^2 : P_{u \rightarrow w \rightarrow (x,y)} < P_{u \rightarrow (x,y)}\}$$

The nodes are said to be dead node when nodes are belonging relay region of other node. The protocol uses a function called *FlipAllStatesDownChain* to update the dead and alive node state. After the computation of the enclosure graph, Bellman-Ford algorithm is applied to compute the minimum-energy reverse spanning tree, rooted at the master node.

Direction Based Approach

This type protocols relies on relative direction rather than the node position. The approach is based on less accurate information as compared to location based approach, however this type of approach can able to produce good topology control protocols without any accurate location information. There are several techniques used for estimating direction for a neighbor node, we are discussing few such schemes here.

The cone based topology control (CBTC) protocol requires direction information rather than location information. Several techniques for estimating the direction has been proposed in IEEE Antenna and propagation community (IEEE 2004) [9]. In CBTC [10], each node increases its transmission power until it finds a neighbor in every cone of degree α. The generic node u tries to find the minimum power P_u such that it ensures some node is present in every cone of angel α. The protocol uses two types of messages viz. *beacon* and *acknowledgement*. The beacon message is transmitted with certain power $p \leq P_{max}$. Those nodes which are reachable through *p,* acknowledged the signal. On receiving these messages node *u* determine the directions of neighbor node by the help of angel of arrival (AoA) techniques and by multiple directional antennas. After getting messages, *u* invokes *Check Gap* procedure to find whether the condition on the angular gap is maintained or not. If the condition not satisfies it increase the transmission power and repeats the procedure until the condition is met or the transmitted power reaches its maximum value. When, $\alpha \leq (5\pi/6)$ the algorithm has been proven to preserve the network connectivity.

Distributed Relative Neighborhood Graph (DRNG) a good topology control approach based on RNG. In any good topology control protocol it is expected that the node has low degree and small transmitting power, the hop-diameter should be close to max power communication graph, and topology should support the connectivity (biconnectivity) property. Satisfying all these goals is a difficult task in protocol design point of view. Borbash and Jennings [11] performed extensive simulation on different topology such as *MST, RNG* and *minR* and found that RNG provides better results compare to other. DRNG computes the RNG in a fully distributed and localize manner. The algorithm provides neighbor coverage as RNG (RNG is discussed earlier in the preliminary) provides a good compromise between the goals discussed above. The node *u* in DRNG computes the RNG with small transmission power $p(u) \leq P_{max}$. The computing RNG continue till the covered region is equal to 2л or the current transmission power p(u) reaches maximum power P_{max}. The neighbor covered region is shown in figure 5. The coverage region of node *x* shown as shown in the figure 5 is the shaded area of cone width *byd.* The covered region of node *y* is the sum of the covered region of node *x* and *z*.

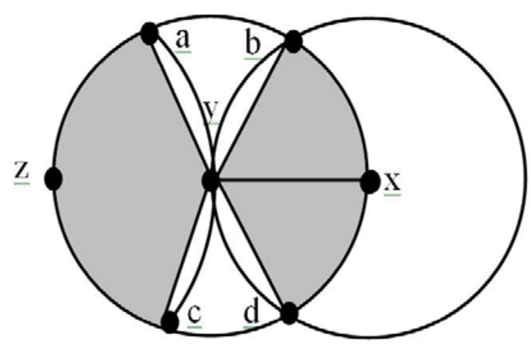

Fig. 5 coverage area of node *y* is the union of coverage area of node z and x (shown in shade)

Neighbor Based Approach

These types of topology control are based on the logical topology control approach in which every node in the network is connected to the *k* closet neighbor. Here we are discussing two neighbor based protocol called K-Neighbor and LFTC.

The k-neighbor protocol [12] is based on maintaining the number of neighbor of every node equal to or below a specific value k. It is assumed that initially all the nodes are transmitting with common maximum power P_{max} and the wireless medium are symmetric. For a generic node *u*, *k* is taken as the input parameter represented as target number. *N(u)* and *KN(u)* are neighbor set and k-closest neighbor set respectively. The final broadcasting transmit power of node *u* is represented as *p(u)*. Initially all the nodes broadcasting with maximum transmit power (P_{max}). The message includes the sender-ID. Any node on receiving the message estimates distance to that node and store these information. Then node computes its k-closest neighbor according to the estimated distance. The node *u* broadcast (u, *KN(u))* with maximum power. On receiving this message other node store this information for preparing final topology. By exchanging the neighbor set each node keeps the symmetric neighbor and removes the asymmetric neighbor. From the *KN(u)* transmit power *p(u)* is obtained which is the minimum power required to reach the farthest node in *KN(u)*.

Location free topology control [LFTC] protocol [13] is based on neighbor information to determine the topology control issue at network layer. The algorithm has two phases, *link determination* phase determine the power required to send data packet while, *interference announcement* phase handle the hidden terminal problems [14] at MAC layer. The protocol works without location information and directional information like XTC [15] protocol. In link determination phase, each node broadcast "hello" message with maximum power P_{max}., Every "hello" message contains the sender-ID and a specific data structure such as *direct communication cost, minimum communication cost*, and *link type which is known as* vicinity table. The direct communication field stores the communication cost in term of energy in the direct path. As multi hop provides better energy conservation, so when any energy efficient path is obtained its value is store in the minimum communication cost field. Link type can be direct or indirect depending on the minimum communication path cost. Initially all node find its neighbor set called direct communication set (DCS), which is obtained by transmitting with maximum power. The node *u* updates its vicinity table information when it receives any vicinity table information from other nodes. Finally node *u* prepares its DCS (u) from the updated table information. Minimum transmission power to send the data packets to the farthest neighbor in the DCS (u) is calculated from table.

COMPARISION AND ANALYSIS

We compare the different protocol discussed earlier in the following aspects: objectives, constraints, assumptions and approach. The Table 1 contains comparison results.

Table 1
COMPARISONS OF DIFFERENT TOPOLOGY CONTROL PROTOCOLS

Protocol	Assumption	Approach	Constraints	Objective
LMST	Homogeneous node	Location based	Strong-connectivity	Energy saving
R & M	Master-node & P_{max}	Location based	Strong-connectivity	Energy saving
CBTC	Direction Info. is known, P_{max}	Angel based (AoA)	Connectivity	Energy saving
DRNG	Topology is a RNG	Graph based, Angel Based	Connectivity	Energy saving
K-Neigh	No prior information of location and direction	Distance based, Neighbor based	Probabilistic connectivity	Energy saving
LFTC	No prior information of location and direction	Distance based, Neighbor based	Connectivity	Energy saving

The protocol LMST and R&M preserve connectivity in the worst case. LMST handles the unidirectional links in the final topology either by converting the unidirectional link to bidirectional link or by deleting that completely. LMST require O (n^2) message exchange to perform bidirectional links in the final topology as each node sends (n-1) message to other node. On the other hand R&M protocol has many good features to support in WSNs. Its *MinEnergyAllToOne* feature optimizes energy-efficient problem. However R&M relies explicit on radio propagation model to compute the enclosure graph. The major limitation of location based protocol (such as GPS based approach) incurs high delay in acquisition of location information. In other side direction based approach does not require accurate estimation of location information and are based on angel-of-arrival information which is relatively less accurate compare to location based information. The CBTC protocol preserves network constraints and only requires direction information. But its major limitation is its increase message overhead, as high numbers of messages are exchanged to construct the network topology by satisfying network connectivity. In DRNG the node degree are relatively low, and transmitting power of the node are less and it preserve connectivity in worst case. K-neigh protocol is a light weight protocol with low message overheads. The total message exchange in the network is restricted to 2n only. However K-neigh does not preserve network connectivity at worst case. LFTC based on vicinity table information with good energy saving feature but it require accurate distance estimation for calculating its DCS.

CONCLUSIONS

Most of the existing protocol minimizes the transmission power of the node and reduces the node degree for power saving purposes. When transmission power is reduces interference is also reduces but it increases the chance of link failure due to more hop count. So care should be taken while designing a good topology control protocol. As most of the protocols are distance based and requires an accurate estimation of signal strength through message passing. So another design aspects is to reduce the messaging over head, otherwise energy saving can be degrade.

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