

DENSITY BASED TOPOLOGY CONTROL FOR MOBILE AD HOC NETWORKS

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ABSTRACT

The design of an efficient and effective protocol for topology control in mobile ad hoc networks is a challenging task. In this paper, we present a brief review of protocols reported in the literature and propose a protocol for topology control in mobile ad hoc networks. Our protocol relies on leader election and density based clustering. A problem that may occur in cluster based topology control is usually known as alien-soldier-node problem. We discuss a framework for avoiding alien-soldier-node problem.

Keywords: Ad hoc networks, topology control, leader election, density based clustering, alien-soldier-node problem.

1 INTRODUCTION

An ad hoc network is a cooperative engagement of a collection of mobile devices without the required intervention of any centralized access point or an existing infrastructure. Applications of such a network include scenarios where either there is no infrastructure or its use is not permitted e.g. disaster recovery, search and rescue mission, battlefield communication, riot control and law enforcement, convention centers, online classrooms or conferences. In such situations, an ad hoc network may provide cheaper ways to share information.

There are many characteristics that are peculiar to an ad hoc network as compared to other wired or wireless networks. The devices used to form an ad hoc network use wireless channel. The devices used have limited transmission range. As a result, the devices need to forward packets of one another towards their ultimate destination. In other words, participating nodes need to double as routers. The transmissions of a wireless device are often received at all nodes within its vicinity, which possibly may cause signal interference at neighboring nodes. The devices are usually powered through batteries. As a result, the depletion of battery power may cause node and associated link failures. The devices often have limited memories, which in turn demand high

communication efficiency and small routing overheads. Also, the wireless devices may move about randomly or may adjust their transmission ranges during the communication. This gives rise to a dynamically varying topology of the network.

Note that each and every transmission by a device incurs a cost in terms of energy spent by the device. Since energy is a scarce resource in an ad hoc network, therefore, one should try for mechanisms to save energy. In an ad hoc network, energy can be saved, to some extent, by suitably controlling and/or organizing the topology of the network. A mechanism or a protocol that may be used to control the topology of the network is called a topology control protocol. Due to inherent characteristics of an ad hoc network, it is a challenging task to design a protocol that may be used to control the topology of the network in an effective and efficient manner.

As mentioned above, topology control is needed in an ad hoc network to conserve energy and maximizing network lifetime while maintaining network connectivity. However, other goals of a topology control protocol may also include optimizing network throughput and fault tolerance.

Recently, many researchers have focused on the topology control protocols for ad hoc networks from different perspectives. Generally, an algorithm or a protocol may either be centralized or distributed. An

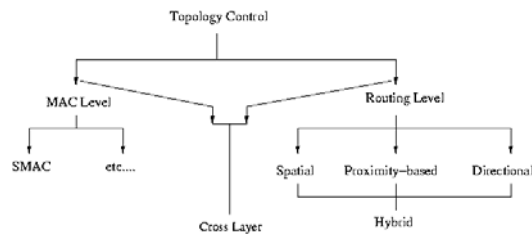


Figure 1: A classification of topology control protocols.

algorithm is said to be optimal if it either maximizes the network lifetime or minimizes the energy spent. Centralized algorithms can achieve optimality, but they are suitable for static networks due to their lack of adaptability to changes in topology. In case of an ad hoc network, one does not have the complete information about the topology of the network and the topology may change dynamically. Therefore, one would like to have an algorithm or a protocol that may work with partial information about the topology, and that may adapt to changes in topology. As a result, one would prefer a distributed algorithm as opposed to a centralized algorithm.

The rest of the paper is organized as follows. In section 2, we present a brief review of the work carried out by researchers in this field. In section 3, we propose a protocol for topology control in mobile ad hoc networks. Section 4, contains results and discussion. Finally, section 5 is for conclusions.

2 A REVIEW OF PRIOR WORK

Topology control can be provided either at the medium access control (MAC) layer or at the network layer using a routing protocol. Based on that, topology control protocols can be divided into two major categories: (i) MAC level, and (ii) routing level (see Figure 1). In what follows, we briefly review the protocols that provide topology control at the MAC layer.

2.1 MAC Level

Topology control of an ad hoc wireless network can be accomplished at the MAC level itself. Generally, the MAC layer protocols follow an approach in which the radios of nodes that are not actively transmitting or receiving packets are turned off. However, when nodes whose radios are turned off need to transmit, a significant time may be consumed to turn on their radios. In other words, the protocols that provide topology control at MAC layer may incur an overhead in terms of turn-on delays. An example of a protocol of this category is Sensor-MAC (or S-MAC) [2]. In that, the primary issue is that of energy conservation, and the issues of delays and per-node fairness are treated as secondary. As we pointed out, the main idea is to periodically turn off the radios of nodes that are idle for a certain amount of time interval. Generally, in case of the

protocols of MAC layer category, the radios of nodes are turned-off by using in-channel signaling. Note that in case of in-channel signaling the same transmission channel is used for signaling. A demerit of the protocols of this category is relatively longer delays in comparison to the protocols that provide topology control at the network layer. This is due to the fact that the MAC layer protocols have a very small view of the network.

In what follows, we present a brief review of the protocols in the second category.

2.2 Routing Level

Protocols of routing category have a provision of topology control at the network layer. Protocols of this category can be further divided into subcategories based on the type of information used by an underlying routing algorithm. An underlying algorithm may use information about position, neighbors, direction, or combination of two or more than two types of these information. We call protocols that utilize the information about the positions of participating nodes as spatial protocols. We refer the protocols that are based on the information about neighbors as proximity based protocols and the protocols that use directional information as directional protocols. In addition to that, we call a protocol to be hybrid if a combination of two or more types of information is used in the underlying algorithm.

2.2.1 Spatial Protocols

In [3], a protocol that is distributed in nature and that utilizes the position information provided by low power GPS receivers is presented. It tries to build a topology that is proved to minimize the energy required to communicate with a given master node. The master node is assumed to be a control and command station to which all nodes need to communicate. The main idea is that every node broadcasts its position and cost (of its path to master node) to nodes in its neighborhood. Upon receiving this information nodes in the neighborhood update their cost accordingly. Bellman-Ford algorithm is used to find shortest path to the master node, in terms of power as the cost function.

Although, the protocol builds a topology that is proved to minimize the energy required to communicate with the given master node, however, the same topology may not work for an all-to-all communication. In other words, the topology built by the protocol might be significantly different from energy optimal topology for the all-to-all communication scheme. The reason is that the nodes that are not direct neighbors need to communicate through the master node, even if there might be a path of less cost if the communications would have not been routed through the master node. Further, for operation of the protocol there should be some

specialized hardware (such as GPS receiver) that provides the position information. As a result, the protocol may not be applied in situations where this type of information is not available.

In what follows, we review protocols in the next subcategory.

2.2.2 Proximity Based Protocols

As pointed out earlier, we call protocols that utilize information about their neighbors other than that of their positions, as proximity based protocols. One such protocol, called MobileGrid [4], is based on an algorithm that is distributed in nature. The performance of the network is linked with a parameter known as *contention index (CI)*, which each node might estimate in a distributed manner. Therein, the *CI* is defined in terms of number of neighboring nodes and the transmission range of each node as follows. Let there be n nodes, each with a transmission range r , distributed randomly though uniformly in a region of area A . Then, contention index is given by $CI = \rho \pi r^2 = n \pi r^2 / A$. In a region with the parameter ρ is called the node density i.e. nodes per unit area. Note that the parameter, *CI*, is related to the number of nodes within the transmission range (or the interference range, if different) of a node in the network. Specifically, the average number of neighbors of a node is $CI - 1$.

In [4], the impact of *CI* on the performance of the network is presented from the point of view of network capacity and power efficiency. Therein, it is

shown that the impact of node mobility on the network performance is minimal when the value of *CI* is fairly large. In other words, there would not be a significant effect of node mobility on the performance of the network because number of neighbors of each and every node is large. However, a too large value of *CI* may result in more congestion. It is argued that the average number of neighbors of a node should be around 3-9 so that the network is fairly connected while there is a tolerable congestion. Note that a node estimates *CI* using RTS/CTS/ACK messages that it receives from unique node IDs. It is obvious that the number of unique node IDs is the number of neighbors of that node and *CI* is one more than the number of neighbors.

The MobileGrid protocol tries to keep the number of neighbors of every node within a range from a low to high threshold values. When the number of neighbors becomes less than the lower threshold value, the transmission range of nodes is increased, and vice versa. The process of adjustment of transmission range is continued until the number of neighbors fall within a given range. However, neither a characterization of the optimal value of the number of neighbors is provided nor there is any

guarantee on the connectivity of the resulting communication graph of the network. Further, in case of MobileGrid, we mentioned earlier that the number of neighbors is determined by overhearing control and data packets at different layers. This type of estimation scheme does not incur an overhead, however, the accuracy of the scheme itself depends upon the flow of control and data packets. A mobile node that is not transmitting any such packets may not be detected by any of its neighbors.

In [8], a protocol named *k-Neigh* is presented. The protocol is distributed, asynchronous, and localized. The *k-Neigh* protocol maintains the number of neighbors of every node equal to or slightly below a specific value k . Further, the protocol ensures that the resulting communication graph is symmetric. It makes the job of higher protocol fairly simple. It is also shown that, with n nodes in the network, the protocol terminates on every node after exactly flowing $2n$ messages and within a strictly bounded time. Another positive feature of *k-Neigh* is that it is based on distance estimation only, which can be implemented at reasonable cost in many realistic scenarios. It has been pointed out that the distance might be estimated based on Received Strength of Signal (RSSI) or Time of Arrival (ToA) of the signal. Therein, a special kind of graph called as *k-neighbors graph* is defined as follows. Given a parameter k , with $0 < k < n$, the *k-neighbors graph* is a network graph G_k in which every node is directly connected to its k nearest nodes.

In [8], a symmetric sub-graph, G_k^- , of the network graph G_k is constructed by deleting asymmetric edges from G_k . It is argued that a theorem proved by Xue and Kumar in [9] for symmetric super-graph G_k^+ of *k-neighbors graph*, G_k , obtained by adding k reverse edges to the asymmetric links, is also applicable to the symmetric sub-graph G_k^- . The job that remains is to set the transmission ranges of nodes. For that purpose, an optional pruning stage may be used. The optional pruning stage is based on the fact that if one can reach to a neighbor using an indirect link with less power than a direct link, then the direct link can be removed, and the transmission power can be adjusted accordingly.

Further, it is worth mentioning that *k-Neigh* may not provide significant improvement compared to MobileGrid. The difference between the two lies in the strategy in the sense that *k-Neigh* is based on distance estimation and there is an optional pruning stage, while MobileGrid is based on neighbor estimation using contention index. However, the strategy used in MobileGrid is simpler as compared

to that of k -Neigh. In what follows, we review protocols of the next subcategory.

2.2.3 Directional Protocols

Protocols in this category use directional antennas instead of omni-directional antennas. A directional antenna has the property that its peak gain is higher than that of a similar antenna with an omni-directional pattern. In addition, they enable one to reduce the unwanted interference. An ad hoc network with directional antennas can transmit in specific antenna pattern or directions so as to create a desired topology.

In [10], a distributed topology control protocol based on directional information called Cone Based Topology Control Protocol (CBTC) is proposed. The idea behind the protocol is that a node i transmits in such a fashion and with the minimum power $P_{i,\theta}$ so that in every cone of angle θ centered at i , there is at least one neighbor. The communication graph obtained so, may contain symmetric as well as asymmetric links. The graph is made symmetric by adding the reverse edge to every asymmetric link. Therein, the authors have shown that $\theta \leq (2\pi/3)$ is a sufficient condition to ensure connectivity, and if $\theta \leq (\pi/2)$, then, every node in the final communication graph shall have a degree of at most 6. Further, a set of optimizations are also presented for pruning edges that are inefficient in terms of energy and whose deletion does not cause the graph to become either asymmetric or disconnected. A drawback of the CBTC is that it neither has a bound on the number of control messages nor on the energy consumed in determining the proper transmission power.

In [11], a protocol is described which is also based on directional information. The protocol is aimed to build a Relative Neighborhood Graph (RNG) of the network in a distributed fashion. An RNG of a set of nodes V in Euclidean space is defined in [6] to be a graph $G=(V,E)$ where an edge $(v_i, v_j) \in E$ iff there is no node $v_z \in V$ such that $\|v_i - v_z\| < \|v_i - v_j\|$ and $\|v_j - v_z\| < \|v_j - v_i\|$, or equivalently, the edge between nodes v_i and v_j is valid if there does not exist any node closer to both v_i and v_j .

One of the reason for choosing RNG as the final communication graph seems that it guarantees the connectivity and it shows good performance in terms of average transmission range, node degree and hop diameter. A similar observation is also discussed in [6] while suggesting RNG as the target topology.

In [7], two protocols are described for topology control in mobile ad hoc networks. The scheme that is common between them is that both the protocols turn off the radios of redundant nodes. The first protocol is called Geographic Adaptive Fidelity

(GAF) and is based upon the location information. The second protocol is called Cluster-based Energy Conservation (CEC) and is independent of the location information. These protocols are based on the observation that when there is a significant node redundancy in an ad hoc network, multiple paths exist between nodes. Thus, one can turn off the radios of some intermediate nodes without significantly affecting the connectivity.

One may wonder that how topology control at the network layer is different than that at the MAC layer as in both cases, ultimately, radios of nodes are turned off, so why routing category protocols do not cause longer latency as that caused by MAC layer protocols. The reason is as follows. In case of a MAC layer protocol, radios of all nodes are turned off periodically, however, in case of network layer protocol, radios of only nodes that redundant (i.e. that do not lie on any routing path) are turned off. This is due to the fact that routing level protocols have access to information about the topology of the network while those at the MAC layer do not have such an access. Therefore, the routing level protocols can use routing information to ensure that the connectivity is maintained when nodes are turned off.

In what follows, we explore protocols in the next subcategory.

2.2.4 Hybrid Protocols

We call the protocols that may use information that is a combination of two or more types of information as hybrid protocols.

In [6], the problem of topology control is explored from the point of view of information dissemination in ad hoc wireless networks. It is assumed that the delay is less important than ensuring good energy-per-bit performance. The suitability of a topology is examined based on the information dissemination on that particular topology. Among the topologies examined are minimum radius graph (minR), relative neighborhood graph (RNG), and minimum spanning tree (MST). If all nodes in the network are assigned an equal transmission range, the resulting communication graph is known as minR. Although, minR has good hop diameter but it has a relatively high edge density. Through simulations it is shown that RNG has certain good graph properties, which makes it suitable for efficient information dissemination.

In [6], the topology control problem has been considered from two approaches that seem to be complementary of one another. The first approach is aimed to minimize interference by imposing a spatial constraint on the locations of the nodes while assuming that all nodes in the network are assigned an equal transmission range. However, the analysis shows that the spatial constraint has a negative effect on the dissemination of information. As the number of nodes and area are increased, the probability of

successful broadcast within a constant number of transmissions is decreased significantly because the network becomes sparser.

In the second approach a proximity graph, RNG, is considered. The RNG is examined as a viable means of achieving good performance for constructing an architecture that may be called as a *backbone communication architecture* for a set of randomly placed nodes. To guarantee connectivity, one needs at least a spanning tree. The MST is good in terms of the average maximum transmission range, edge density, and maximum node degree. However, MST is not fault-tolerant because any node or edge failure will partition the network. RNG is literally a super-graph of MST that still has some of its good graph properties.

Although, RNG is not exactly as good as minR, it is close to minR in terms of hop diameter. The hop diameter can be used as a measure for information dissemination. The minR is good in terms of hop diameter. However, among the shortcomings of minR are relatively higher transmission range, relatively higher edge density, and a node degree that increases linearly with respect to the number of nodes. This justifies the philosophy behind the RNG to be a good candidate for the target topology. A brief comparison of these topologies is given in Table 1.

Table 1: A comparison of MST, minR, and RNG topologies.

Topology	Computational Cost	Hop Diameter	Max Degree	Edge Density
MST	$O(n \log n)$	Good	Low	Low
minR	$O(n^2 \log \sqrt{A})$	Good	High	High
RNG	$O(n^2 + n \log n)$	Med.	Med.	Med.

In [5], a distributed mechanism to build a sparse power efficient network topology for non-uniform or more precisely heterogeneous mobile ad hoc networks is proposed. The proposed method can also be applied for networks where nodes are equipped with directional antennas. Therein, an ad hoc network is modeled using a *mutual inclusion graph* (MG). In an MG, there exists a link between two nodes if and only if they are within the transmission range of one another. On the other hand, there is yet another type of graph called a *unit disk graph* (UDG). In UDG, there exists a link between two nodes as long as the Euclidean distance between them is less than or equal to a threshold value. Therein, the authors are motivated to use of MG instead of UDG due to the fact that characteristics of a mobile ad hoc network can be fairly captured by an MG as

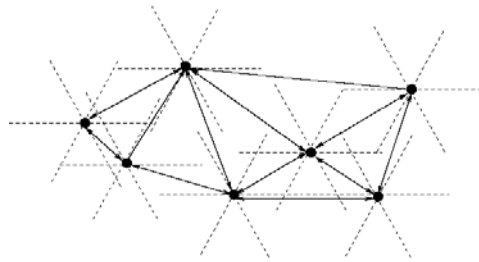


Figure 2: An example of Yao graph.

compared to an UDG. This is due to the fact that transmission ranges of devices used to form an ad hoc network may vary due to various reasons such as the device difference, the network control necessity, and the perturbation, even though initially the transmission ranges are set as the same. An UDG falls short of modeling the variations in transmission ranges as mentioned above.

In [5], the model of an ad hoc network consists of nodes that have unique node ID's and are distributed in a two-dimensional plane. Each and every node in the network is equipped with a GPS receiver so that each node is aware of its position information. Each node u can tell its location information to nodes that fall within its transmission range using a one-hop broadcast.

A peculiar feature of the method proposed in [5] is the use of an extension of a special kind of graph known as *Yao graph*. The motivation comes from the fact that an *Yao graph* may closely match an ad hoc network in which each node possess a directional antenna. It also exhibits some other nice properties that are important in construction of topology of an ad hoc network. In an *Yao graph*, at each node u , there are k , (for $k \geq 6$) equally-separated rays whose origin is u (see Figure 2). These rays form k cones at each and every node. For two nodes u and v , choose the shortest edge uv among all edges from u , if there is any, and add a directed link $u \rightarrow v$ and vice versa. Ties, if any, are broken arbitrarily or by node IDs. The resulting directed graph is called the *Yao graph*.

In [5], two localized algorithms are presented to construct connected sparse network topologies. The first structure called *extended Yao-Yao* (EYY), has the node degree at most $O(\log \gamma)$, where $\gamma = \max_u \max_{uv \in MG} (r_u / r_v)$, where $r_i, i = u, v$, is the transmission range of node i . The second structure, called *extended Yao and Sink* (EYS), has node degree bounded by $O(\log \gamma)$, and is a length and power spanner. Both the methods partition the space surrounded by each mobile node as both of them are based on Yao graph structure, and both of them incur a communication cost or an overhead of $O(n \log \gamma)$ in terms of number of messages where each message has a length of $O(\log n)$ bits.

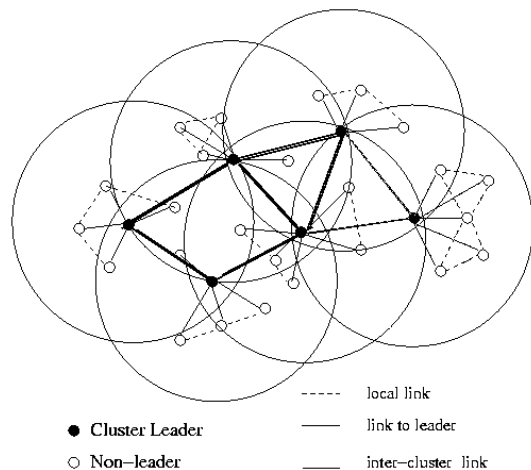


Figure 3: Density based clustering.

Table 2: An overview of topology control protocols.

Protocol	Category	Remarks
SMAC [2]	MAC	Limited view of network topology
MinEnergy [3]	Spatial	Master-slave
MobileGrid [4]	Proximity	Contention-index
k -Neigh [8]	Proximity	Distance-based
CBTC [10]	Directional	Edge pruning
RNG [11]	Directional	Delauney triangulation
GAF & CEC [7]	Directional	Node redundancy
minR, MST, & RNG [6]	Hybrid	Hop diameter, etc
EYY & EYS [5]	Hybrid	Extended Yao graph

However, only analytical model is proposed and the results are not supported using simulations and/or experimentation. Therefore, it is still unclear whether it will perform as expected when applied to practical scenarios. Further, since the algorithms are based on position information from a GPS receiver or any other device telling the location of nodes, therefore, it is not at all free from the demerits of location based protocols.

There can be schemes that may combine the features of the two layers, forming a new class of protocols. For example, energy-efficient MAC and routing protocols can be used together to increase energy conservation. However, we are not going to discuss such protocols as it forms an area in itself.

This completes our survey of protocols or schemes for topology control in mobile ad hoc networks. In that, we confined ourselves to two broad categories the *MAC layer* and the *network layer*. An overview of the protocols reported in literature is shown in Table 2.

In what follows, we describe density-based topology control in mobile ad hoc networks.

3 DENSITY BASED TOPOLOGY CONTROL

In this section, we emphasize the need to have topology control by forming clusters in the network and then propose a protocol to do so.

There is a need to form clusters in the network in some specific applications of an ad hoc network. One such application might be communication in a battlefield. In such an application, soldiers need to take decisions. The decisions might be local or global. There might be groups or clusters of soldiers in the battlefield, each group or cluster may have its own group leader. The group leader may possess an extra amount of resources as and when needed. The soldiers in a group may communicate to soldiers of other group or cluster through their group leaders, if they cannot communicate directly. However, soldiers within a group are free to communicate directly or through their group leader. For global decisions, group leaders may communicate among themselves and may communicate or pass the decisions made to their subordinates. Thus clustering may facilitate local as well as global communication.

However, there should be a basis of forming clusters. In the applications mentioned above, one may consider the density of nodes as a basis for forming groups or clusters. Where there is a relatively higher density of nodes, more clusters or groups are required to be formed and vice versa. The density based clustering is explored in the context of data mining in [12], [14]. One can use density based clustering in maintaining the connectivity between the nodes in the network.

In what follows, we describe a protocol for topology control in mobile ad hoc network that is based on forming the clusters on the basis of node density. First we present a strategy for leader election in ad hoc wireless environment to make the protocol distributed and localized, and then, we describe the connectivity management through density-based clusters.

3.1 Leader Election

We describe here outlines of leader election protocol as it forms a research area in itself. A detailed description of leader election protocols can be seen in [17]. A node announces itself as the candidate leader of the cluster if it does not hear from a leader node within a *leader-dead-timeout*, and iff it is not a connecting node between two or more clusters. Leaders send periodic *leader-alive* messages to their subordinate nodes to signal that their leader is alive so that fresh leader election is avoided. Other nodes that are in the vicinity of this candidate leader send a *support* message to it, indicating that they are the nodes that are alive in its vicinity.

If two or more nodes announce themselves as candidates for the leader, the one that is having more

number of *support* messages is the winner. Ties are broken by IDs. Losers withdraw their candidature. After receiving a minimum number of *support* messages, the candidate leader declares itself as the cluster leader. If a leader falls short of live support of nodes at any time, it sends a *leadership-abandoned* message to both the nodes in its vicinity, and cluster leaders of other clusters, if possible. If no message is received, either by the nodes in the vicinity or by the cluster leaders in *leader-dead-timeout* interval, it is assumed automatically that cluster leader is dead, and a leader election will start for that particular cluster.

If a node other than leader hears from a leader, it will communicate to that leader by sending a *node-alive* signal. The leader hearing from a neighboring non-leader node updates its neighborhood list. It adds address of the node in its neighborhood list if it was not already listed, otherwise, it refreshes its membership. If a leader does not hear from a neighbor node to which it was managing and controlling within a *node-dead-timeout* period, it deletes its entry from its neighborhood list.

3.2 Communication

After the leaders are elected, nodes in the same cluster communicate to their one-hop neighbors directly, and to their indirect neighbors through their

respective leaders. However, they are free to communicate to nodes of other clusters, if they think that involving leader may incur more delay or overhead. Nodes within the same clusters communicate through *intra-cluster* messages. Leaders of different clusters communicate through special messages called *inter-cluster* messages. If a node receives either an *inter-cluster* or an *intra-cluster* message, it forwards the message to the intended node if it is a direct neighbor, otherwise it forwards to the leader of its cluster. The leader can communicate to the target leader either directly or through neighboring leaders depending on whether the target leader is at one-hop distance or at multi-hop distance. Further, leaders maintain list of gateway nodes to other cluster leaders if they cannot communicate directly. The gateway nodes are nodes connecting two or more clusters.

3.3 Connectivity Management

As mentioned earlier, the connectivity management in our protocol is based on the density based clustering as described in [12], [14]. The properties of density based clustering described, therein, can be utilized in density based clustering of an ad hoc network. A description of some of the properties and their implications is as follows.

- The nodes that lie within a radius ϵ of a given node is known as the ϵ -neighborhood of that node. It implies that a set of nodes that fall within the transmission

range of a node forms the set of its neighboring nodes. This feature resembles to an ad hoc network where all nodes are equipped with omni-directional antennas.

- If there are at least a minimum number of nodes (denoted by $MinNodes$, ordinary nodes), in the neighborhood of a node, then that node may become the cluster leader. This property implies that a leader node requires a support of a minimum number of non-leader nodes.
- A node x is said to be *directly density-reachable* from a node y if x is within the ϵ -neighborhood of y , and y is the cluster leader. It implies that a non-leader node that falls within the transmission range of a leader node can directly receive messages from to its cluster leader.
- A node x is said to be *density-reachable* from a node y with respect to ϵ and $MinNodes$ in a set of nodes, S , if there is a

chain of nodes x_1, x_2, \dots, x_k , $x_1 = y$ and $x_k = x$ such that x_{i+1} is directly density-reachable from x_i with respect to ϵ and $MinNodes$, for $1 \leq i \leq k$, $\in S$. It implies

that two leader nodes may be connected with a multihop path, where each hop is comprised of a leader node.

- A node x is said to be *density-connected* to node y with respect to ϵ and $MinNodes$ in a set of nodes, S , if there is a node $h \in S$ such that both x and y are density reachable from h with respect to ϵ and $MinNodes$. It implies that two leader nodes may communicate through a gateway node.

One important thing to mention here is that the relation *density reachability* is a transitive closure of the relation *direct density reachability*, and the relationship is asymmetric. As a result, only cluster leaders are mutually density reachable. However, *density connectivity* is a symmetric relation. It means that if there are two ordinary nodes x and y , and if x is able to communicate to y via a leader node z , then y shall also be able to communicate to x via the same leader i.e. z . Further, a density-based cluster consists of a set of density-connected nodes that is maximal with respect to the relation density-reachability.

On the other hand, a node that is not connected to any cluster is an *alien-soldier-node*. It can either start a leader election by announcing itself as candidate leader or move to become a part of a cluster. If neither of these conditions is satisfied then it waits till it hears transmission from other nodes. If the ϵ -neighborhood of a cluster leader exceeds a limit $MaxNodes$, it may designate a node from the

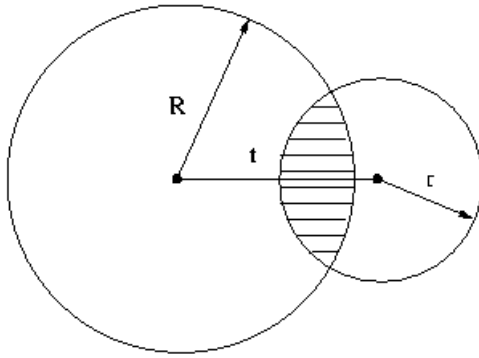


Figure 4: Two discs whose centers are separated by a distance t .

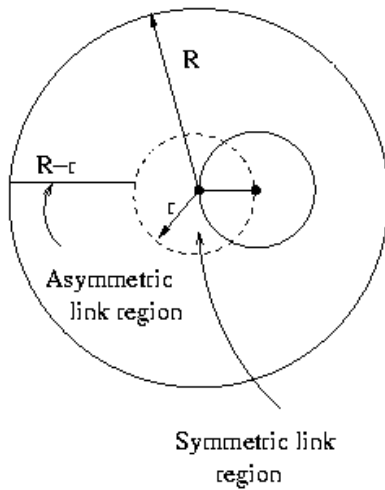


Figure 5: Regions for symmetric and asymmetric link formation.

same cluster to act as leader and divides the nodes in the neighborhood of it with the newly appointed leader. The new leader then announces its neighbors that it is now their leader. The previous leader also

informs about the newly appointed leader to the other cluster leaders. Note that $MaxNodes$ is at least greater than twice of the $MinNodes$ to divide a cluster into two clusters.

A peculiar characteristic of this protocol is that we did not make use of specialized graphs like unit disk graphs, etc. However, the efficiency of the protocol depends, to some extent, on the user-defined parameters. Therefore, the parameters like ϵ , $MinNodes$, $MaxNodes$ should be selected carefully to provide good performance in terms of target topology or connectivity. The characterization of these parameters is beyond the scope of this paper due to space limitations.

In what follows, we present an analysis of what

4 ANALYSIS AND DISCUSSION

In this section, we analyze how far a node is allowed to move so that it remains connected with its neighboring node and/or with its leader. Further, we analyze what should be the transmission range of an ordinary node and leader nodes so as to avoid the *alien-soldier-node* problem.

4.1 Coverage and Movement

Assume that all nodes in the network are equipped with an omni-directional antenna. Let us prove a theorem for symmetric link formation between any two nodes.

Theorem: Assuming an omni-directional antenna, if two nodes have transmission range R , a symmetric link formation between the two nodes yields an interference area

$$A_t = R^2 \left(\frac{2\pi}{3} - \frac{\sqrt{3}}{2} \right) \quad (1)$$

Proof: Suppose there are two discs with radius r and R whose centers are separated by a distance t . For $(r-R) < t < (r+R)$, the area of intersection of two discs, which is shown shaded in Figure 4, is given by

$$\begin{aligned} A(t, r, R) = & r^2 \left\{ \arccos \left(\frac{t+r-R}{2} \right) \right. \\ & \left. - \frac{t^2 + r^2 - R^2}{2tr} \left[4t^2 r^2 - (t^2 + r^2 - R^2)^2 \right]^{1/2} \right\} \\ & + R^2 \left\{ \arccos \left(\frac{t+R-r}{2} \right) \right. \\ & \left. - \frac{t^2 + R^2 - r^2}{2tR} \left[4t^2 R^2 - (t^2 + R^2 - r^2)^2 \right]^{1/2} \right\} \end{aligned} \quad (2)$$

For $r=R$ this simplifies to

$$A(t, R) = 2R^2 \arccos \left(\frac{t}{2R} \right) - \frac{1}{2} t \sqrt{4R^2 - t^2} \quad (3)$$

should be the transmission range of nodes so as to avoid alien-soldier-node problem.

$$\left(\frac{2}{3} \right) \left(\frac{2}{3} \right)$$

Assuming an omni-directional antenna, if R denotes the transmission range of both the nodes, then there will be a symmetric link between the two nodes if and only if $t \leq R$ (it is assumed that signal strength beyond R is below a threshold value required to set up a link). In this case, the area of intersection of the two nodes is,

$$A_I^s = R^2 \left(\frac{2\pi}{3} - \frac{3}{2} \right) \quad \left(\frac{2}{3} \right) \sqrt{\frac{2}{3}}$$

which is the area of interference between the two nodes. This completes the proof.

Note that A_i^s is the area of interference between the two nodes when both of them are assigned an equal radio transmission range. If transmission ranges of two nodes are not equal, and if we assume $R \geq 2r$, then in a circular region of radius r centered about the node with larger transmission range (as shown in Figure 5), there will be a bidirectional link. For this circular region, $0 \leq t \leq r$. The area of

intersection or interference between the two nodes in this particular case is πr^2 as the bigger node completely includes the smaller one. In other words, in this case both the nodes will be able to hear each other's transmissions in the region surrounded by dashed boundary. In a region with area $\pi(R-r)^2$, a unidirectional link is available directed from node with bigger transmission range R to node with smaller transmission range r . Therefore, if a node with radio range r do want to hear the transmission of node with radio range R , then the smaller node should not move beyond a distance R from the center

of the later. However, if $r > R/2$, then, $A^l = \pi r^2$, as the bigger node does not completely include the smaller node. For $r=R$, a bidirectional link between the two nodes is possible if $0 \leq t \leq R$, which we have proved above. In asymmetric case (i.e. $r \neq R$) and assuming that $R/2 < r \leq R$, a bidirectional link exists between the two nodes only if $0 \leq t \leq r$. The

area of interference in this case for $t=R$ is given by

$$A^{\max} = r^2 \arccos \left(\frac{2r^2 - R^2}{2r^2} \right) + R^2 \arccos \left(\frac{R^2 - 2r^2}{2R^2} \right) - \frac{R(2r^2 + 1 - R^2)}{4r^2} \sqrt{4r^2 - 1} \quad (4)$$

With this discussion in mind, let us assume that node with larger transmission range shall be elected the leader node of a cluster and that with smaller range shall remain an ordinary node. An ordinary node can hear the transmission from its leader if it does not move beyond the leader's range. The ordinary node can move toward the leader if it wants to have a bidirectional link or it can increase its transmission range a little bit if it finds that its transmissions is not heard by its leader. Further, in leader election phase, a particular node can estimate the distance of the leaders in its vicinity by measuring signal strength of received messages and connect to the nearest leader to have a strong link. In case, if it goes beyond the range of its leader, it can connect to the nearest leader or should move back so that its connection is maintained with its original leader.

4.2 Avoiding Alien Soldier Node Problem

density of ρ nodes per unit area. For large n and large A , the distribution of nodes can be assumed to be a Poisson Forest [13]. If placement of nodes at particular locations is assumed independent, one can determine the range assignment of all the nodes such that no node is isolated. This can be done using nearest neighbor methods. It is shown in [16] that one can set the radio range of all the nodes to

$$r_0 \geq \sqrt{\frac{-\ln(1 - p^{1/n})}{\rho \pi}} \quad (5)$$

where p , $0 \leq p < 1$, denotes the probability that the minimum degree of all nodes is greater than 0. It has also been shown in [16] that the probability that a network is connected is almost equal to the probability that the minimum degree of the network is greater than 0 for high values of the probability and for toroidal distance metric. Using (5), one may set the transmission range so as to avoid alien-soldier-node problem with a probability p , as all nodes in the network are connected with a probability p .

However, this is a range assignment for homogeneous network. In our case, if one wishes that all leader nodes should only be connected, and all other nodes are connected to their respective leaders, we can simply replace n by number of leaders, say l , in equation (5) giving us

$$r_l \geq \sqrt{\frac{-\ln(1 - p^{1/l})}{\lambda \pi}} \quad (6)$$

where, $\lambda = l/A$, is now the density of leader placement per unit area, provided that λ is constant. Clearly, $r_l > r_0$ as $\rho > \lambda$, meaning that the leader nodes have to be resource rich nodes. Suppose all n nodes are assigned a range equal to r_0 so that none is isolated with a confidence p_0 . Further, l leaders out of these nodes are assigned a range r_l so that no leader is isolated, i.e. all leaders are connected with a confidence p_l . Also, we assume that l leaders are uniformly and randomly distributed with constant intensity λ , while all nodes taken together including leaders are uniformly randomly distributed with

that $A \gg \pi r_0^2$, and $A \gg \pi r_l^2$. We have,

$$r_0 = \sqrt{\frac{l \ln(1 - p_n^{1/n})}{r^2 n}} \quad (7)$$

Suppose a number of nodes n is randomly

$$\ln(1 - p^{1/l})$$



For example, if $l=10$, $n=100$ and

distributed in a region of area A with a constant node

then from equation (7) it comes out that $p_l = p_0 = 0.95$,

$(r_0 / r_l) = 0.378952$. It means that if a range of 38m is assigned in non-leader mode, then leaders need to be assigned a range of 100m. The ratio of leader and leaders plus non-leaders taken together is 0.10. In other words, there are 10 nodes in a cluster on an average including the cluster leader. If the maximum range of nodes is limited to a certain value, say, r_{max} , then there is a threshold on the *MaxNodes* controlled by the cluster leader. Similarly, if we limit that all the nodes are to be assigned a minimum range, say, r_{min} , then there is an average *MinNodes* to be subordinated by the cluster leader. However, these are approximate figures as we have assumed constant intensities ρ and λ and a fairly large area. Practically, there is a bounded area and all the above assumptions might not be satisfied. In that case, one may satisfy oneself with only simulation results rather than going for a model about the connectedness of the network topology.

Figure 6 shows the ratio of transmission ranges to be assigned to nodes in ordinary (i.e. non-leader) and leader modes versus the confidence for connectivity. Here, the number of leaders is 10, and the total number of nodes including leaders is 100. We assume $p_0 = p_l = p$ for the sake of simplicity. It is observed that as we increase desired probability of connectivity, p , the fraction of ranges to be assigned to nodes in ordinary and leader modes is decreased. This is due to the fact that for same confidence of connectivity, the leaders need to be assigned a relatively higher transmission range as compared to ordinary nodes. As the level of confidence is increased one has to increase the transmission ranges of leaders more because they are responsible for inter-cluster connectivity, while ordinary nodes need to connect only to their respective cluster leaders and some of the nodes in their own cluster.

Figure 7 shows the ratio between transmission ranges in ordinary and leader modes as a function of number of leaders for 100 nodes. As the number of leaders is increased, the range ratio r_0 / r_l also increases. The reason is that if number of leaders are more, the burden of connecting to ordinary nodes in their own cluster reduces and also with the same confidentiality level of connectivity they can now connect to other leader nodes which are now not too far apart in an easier fashion, thereby, they do not need a much higher range as compared to the situation when leaders were less and were fairly far apart.

One thing to note that it might be true in a static environment to first choose leaders which have more resources than the ordinary participants. In mobile environment, it would be preferable to have a network such that any node may assume the role of leader. Therefore, as an alternative initially all the nodes may start transmission with r_0 as given by (5),

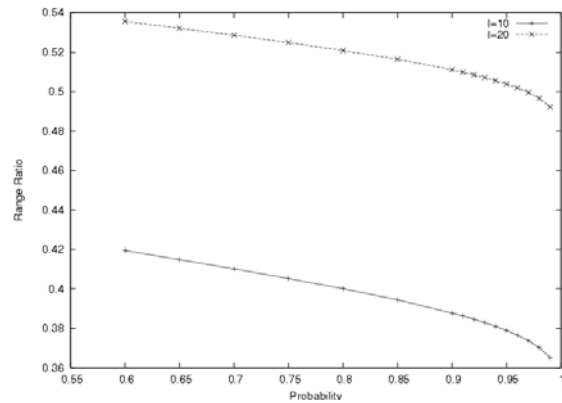


Figure 6: The ratio of transmission ranges r_0 / r_A as a function of confidence for connectivity.

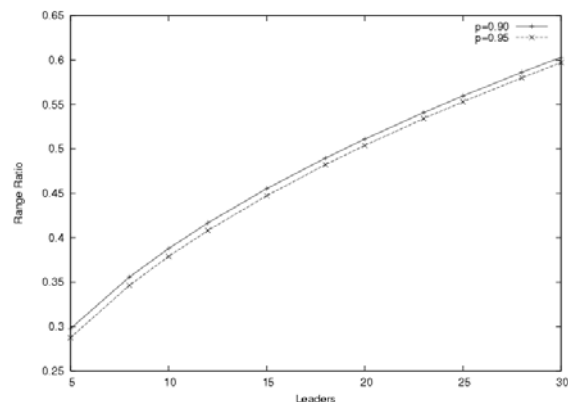


Figure 7: The ratio of transmission ranges r_0 / r_A as a function of number of leaders.

and when the leaders of all clusters are elected, non-leader nodes can transmit using lower transmission ranges as they now need to communicate through their respective cluster leaders. Only leaders are needed to communicate using higher range given by (6). If the ratio of leaders to non-leader nodes is small, one can expect good energy savings while maintaining connectivity that is among main goals of topology control protocols.

5 CONCLUSION

The problem of topology control in mobile ad hoc networks is important as the resources of participating nodes are limited. However, devising an efficient solution is a challenging task. The contributions of this paper are as follows.

- We presented a brief survey of the protocols for topology control in wireless ad hoc networks. In that, we discussed different strategies proposed by different researchers with different perspectives.
- On the other hand, we proposed a protocol

for topology control in mobile ad hoc networks. The protocol is based on the leader election and density based clustering of participating nodes.

- We described a framework for link formation and how much a node is allowed to move inside a cluster so that it may not lose connection with its leader.
- Further, we discussed the alien-soldier-node problem and how to avoid it with reasonable assumptions.
- We discussed that there can be a trade-off between the number of leaders and burden of connectivity to be provided by them.

However, the framework discussed can only be applied when all assumptions are satisfied. The framework may be extended to incorporate more realistic scenarios, for example, arbitrary adjustment of transmission range. Extension and validation of the proposed protocol forms our future work.

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