A Comprehensive Survey on Topology Control Algorithms for Wireless Ad-Hoc Networks

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Abstract
In recent years, the technological improvement in wireless communication and mobile computing stimulated a consistent growth both in number and types of implementations for wireless networks. Minimizing power consumption thus improving power efficiency can significantly extend the wireless devices battery longevity and its serviceability. A node must learn neighbourhood nodes that are in direct communication range, before it initiates communication. The gathered relevant information is kept in its internal data structures to apply with routing. The wireless ad-hoc nodes acclimatize dynamically its topology knowledge range, leading to faster convergence of its neighbouring nodes. The intention of topology control is to restrict communication deliberately and use multi-hop paths instead of direct communication links between nodes, even if they are within the communication range of each other. Thus, connectivity or fault-tolerance is preserved while reducing transmission power, improving network capacity, better SNR and also enhanced spatial reuse. In this paper, we present an overview of a range of centralized and distributed topology control algorithms. We also provide an extensive comparison of these algorithms and suggest the metrics to refine future topology control algorithms.

Keywords
Mobile Ad-Hoc Networks, Issues, Topology Control Algorithms, Transmit Power Control

I. Introduction

All mobile devices have a maximum transmission power which establishes the largest transmission range of the device [5, 17, 20]. The topology of a multi-hop wireless network is a set of connections that are coupled directly or via multi-hops, between a pair of nodes. As the nodes are mobile, the links between them can break quite often depending on their spatial orientation. The mobile wireless devices out of communication range can use other nodes in their communication range to relay the transmitted packets.

Some constraints of wireless ad-hoc networks are limited bandwidth, low battery power of nodes, frequent link breakage due to mobility [21]. Topology can also depend on node mobility, interference, noise, weather, antenna direction, transmission power and multi-channel communications [20]. Inappropriate topology can reduce network capacity by limiting spatial reuse of the communication channel and impact network robustness [27]. For instance, sparse topology increases the chances of network partitioning thereby impacting end-to-end packet delays. Contrarily, excessively dense topology may escalate interference among the nodes and the worst is that the nodes may drain their energy quickly. Networks that do not incorporate topology control results in shorter battery life and / or poor connectivity. However, topology control can offer substantial control over network resources and reduce redundancy in network communications.

Fig. 1 and 2 Shows Topology control at maximum power and Modified Topology control with reduced power still maintaining connectivity. Much simpler topologies are derived or constructed from the original one under the common maximum transmission range by the topology control algorithms. All routing algorithms then establish routes based on the new topology.

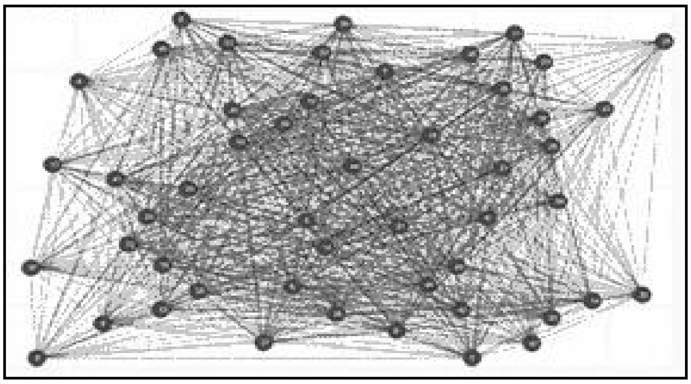

Fig. 1: TC with Max Power

The remainder of this paper is organised as follows: section II, consists of the review of work relating to the optimal number of neighbors and topology control. This section begins by presenting the theoretical framework that is used to analyse the related work and ends with the design criteria necessary for a topology control algorithm. In section III, we present a detailed survey on the present topology control algorithms based on the evaluation parameters identified. Finally, section IV, presents the conclusion and possible future work.

II. Related Work

Topology control for wireless multi-hop networks is an effort to automate the process of procuring and maintaining the optimal node degree (number of neighbors)[22]. Nodes having too few neighbours results in reduced route redundancy, which reduces the robustness of the network whilst too many neighbours results in increased interference and contention for the transmission medium. The necessity to control the number of neighbors that a node possesses stems from the need to minimise interference, maximise the network capacity and throughput and to reduce the power consumption of the nodes in the network. Several researchers have developed topology control schemes, and many of these schemes are based on the application of Graph Theory to create and maintain an optimal network topology.

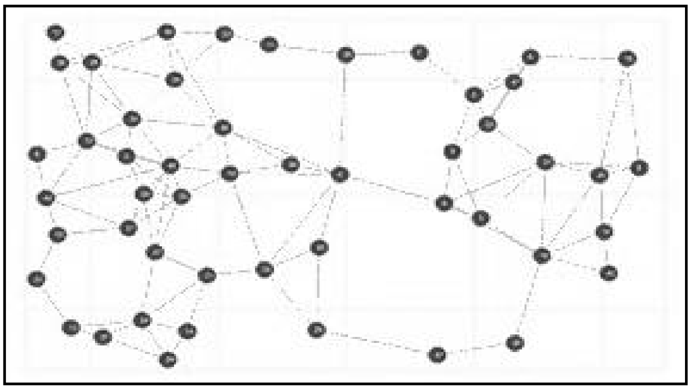

Fig. 2: Modified TC with Reduced Power

In [4] the authors prescribe that the optimal number of neighbours is six in terms of maximising the network capacity and throughput. Their work is based on the use of the Slotted ALOHA medium access control scheme whilst present day wireless multi-hop networks use DCF, to gain access to the transmission medium. The authors also articulated that every node always has data to transmit and will transmit at every opportunity which is not realistic. In [5] the author suggests that the transmission range be dynamic and adjusted at the beginning of every transmission. The routing strategy used was to adjust the node's transmission range in order to reach a neighbour node in the direction of the intended destination node. The authors [6] deals with the optimal transmission power required to maximise the expected one-hop progress that is made in delivering data to its destination. The optimal transmission radii for nodes that are randomly distributed are calculated for both the ALOHA and Carrier Sense Medium Access (CSMA) protocols. The researchers found that the MAC scheme employed affected the value obtained for the optimal number of neighbours. The optimal number of neighbours for networks that used the ALOHA medium access control scheme was determined to be approximately eight.

In the work of [7], the question of the optimal number of neighbours was investigated from a hitherto unique position. The authors considered the impact of three different routing strategies on the transmission range adjustment and ultimately on the optimal number of neighbours. The three transmission strategies considered were: 1) Most Forward with Fixed Radius (MFR) – the routing strategy that forwards packets to neighbours with the greatest forward progress, regardless of the position of the receiving neighbour; 2) Nearest with Forward Progress (NFP) - Packets are forwarded to the nearest neighbour that will result in forward progress. The transmission power will be adjusted so that it is just strong enough to reach the receiving neighbour, and 3) Most Forward with Variable Progress (MVR) - Same as MFR with the exception that the transmission power IS adjusted so that the distance between the sender and receiver is successfully traversed.

The authors [8], establishes a relationship between the optimal number of neighbours and the area of the plane in which the nodes are distributed. Both lower and upper bounds for the optimal number of neighbours are presented. The bounds presented in this work are also dependent on the process followed when distributing nodes across the plane being considered and this could affect the bounds. The plane considered in this work is assumed to be a square. This may not be a realistic assumption in real-world deployments of wireless multi-hop networks.

The work developed by authors [9], heuristics that can be applied to any wireless multi-hop network, independent of the total number of the nodes in the network. The heuristics provided help to arrive at the lower and upper bounds for the connectivity of the network. The optimal number of neighbours lies somewhere within the bounds proposed. The paper [10], determines the minimum number of neighbours for uniform (each node has on average the same number of neighbours) wireless multi-hop networks. Existing work is extended by establishing relationships between the minimum number of neighbours and the transmission power and node spatial density in a two-dimensional plane. Critical values for the required transmission power and node spatial density are established and the failure to meet the critical values means that the full connectivity of the network cannot be guaranteed. The authors determined that the magic number guaranteeing a fully connected uniform network is on average equal to it, provided that the critical values for the transmission power and node density are met.

The work [11], is an improvement upon the upper bound for the optimal number of neighbours. The authors suggested that if each node in the network was able to connect to a maximum of 2.71810g(n) nearest neighbours then the resultant network topology would be almost surely connected. A major disadvantage of this work is the implicit requirement that each node in the network knows the total number of nodes in the network at any point in time. This requirement is a drawback especially when the case of co-unity-driven wireless multi-hop networks is considered. These types of networks are typically expected to grow unaided over time and therefore the knowledge of the total number of networks is not a practical consideration.

III. Topology Control Algorithms

The topology control problem in wireless ad hoc networks is to choose the transmission power of each node in such a way that energy consumption is reduced and some property of the communication graph (typically, connectivity) is maintained. Besides reducing energy consumption, topology control increases the capacity of the network, due to reduced contention to access the wireless channel. Given the limited availability of both energy and capacity in ad hoc networks, topology control is thus considered a major building block of forthcoming wireless networks.

Ideally, a topology control protocol should be asynchronous, fully distributed, fault tolerant, and localized (i.e., nodes should base their decisions only on information provided by their neighbors). Furthermore, it should rely on information that does not require additional hardware on the nodes, e.g. to determine directional or location information. A final requirement of a good topology control protocol is that it generates a connected and relatively sparse communication graph. These latter features, besides reducing the expected contentions at the MAC layer, ease the task of finding routes between nodes.

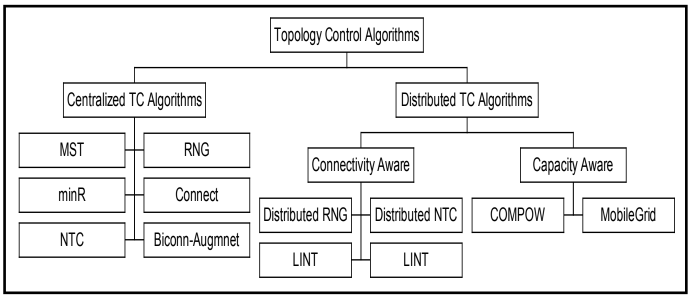

Fig. 3: Algorithms for Topology Control

Most existing topology control protocols focus on initial construction of a good topology. These protocols concentrate on static network environments where one-time topology construction is sufficient, but do not explicitly consider how to maintain a good topology as network conditions change. Sources of dynamism in ad hoc networks include mobility, failures, and dynamic joins of nodes. One approach, designed primarily to deal with node failures, is to construct an initial topology that is highly redundant and can therefore tolerate some dynamic changes without impairing basic network properties such as connectivity. However, this approach is not sufficient to deal with highly dynamic environments such as those arising from node mobility. In addition, due to the high level of redundancy in the initial construction, these topologies are inefficient in that they force nodes to use higher transmission powers than necessary at a given time to withstand potential future changes. The higher than necessary transmission powers result in higher energy consumption by nodes, which reduces network lifetime, and increased interference in the network, which degrades network performance. Thus, these static approaches favour short-term dependability at the expense of longer-term network survivability, while at the same time incurring very serious performance costs. The algorithms to control topology can be grouped under two categories as shown Figure 3: Centralized topology control algorithms and Distributed topology control algorithms. Global topology information to build topology adjustment decisions is adopted in Centralized topology control algorithms. Distributed topology control algorithms are influenced by partial link state information such as neighbor count to preserve network connectivity.

A. Centralized Topology Control Algorithms

1. Novel Topology Control Algorithm

This work of [12] portrays the generation of network with good connectivity via the use of the Delaunay Triangulation (DT) algorithm, and the subsequent network topology's capacity is optimized. Central node is realized with DT algorithm, and the entire triangle's minimum angle of original topology is maximized. NTC algorithm did not reveal criteria for central node selection and the process of notifying other network nodes about the identity of the selected central node. Topology control process may be introduced with unnecessary latency using centralized NTC algorithms. When the number of nodes grows, the average path length of nodes in the network to the central node will also increase, which increases the latency. The probable risk is that the changes in transmission power of intermediate nodes may initiate route modifications between central node and other nodes in the network. This algorithm's communication overhead increases, as new routes would have to be detected, which is the major concern of scalability of NTC algorithm.

2. Relative Neighborhood Graph (RNG)

Attempts removing redundant edges while still maintaining the connectivity. An edge (u, v) is redundant if there is a node w satisfying d(w, u) < d(u, v) and d(w, v) < d(u, v), where d(u, v) is the distance between u and v. The constructed topology is the remained graph after removing all redundant edges.

3. CONNECT and BICONNECT Algorithms

These algorithms aim is to establish a fully-connected wireless multi-hop network

Table 1. Characteristics of Centralized Topology Control Algorithms

Algorithm	Paper Ref	NC	IR	LC	Connectivity Flexibility
NTC	[12]	Heterogeneous	Neighbour-Based	Symmetric - Bidirectional	K-Connectivity, Flexible
CONNECT	[13]	Heterogeneous	Location-Based	Symmetric - Bidirectional	K-Connectivity, Non Flexible (k=1)
BICONNECT	[13]	Heterogeneous	Location-Based	Symmetric - Bidirectional	Non Flexible (K=2)
LILNF	[20]	Homogenous	Neighbour-Based with Interference Load	Bidirectional	Non Flexible
LILST	[20]	Homogenous	Neighbour-Based with Interference Load	Bidirectional	Non Flexible
FGSSk	[21]	Homogenous	Neighbour-Based & Location Based	Symmetric -Bidirectional	K-Connectivity Flexible
NC – Node Characteristics IR – Information Requirements LC – Link Characteristics					

topology by minimizing the maximum transmission power utilized [13]. Two centralised topology control algorithms were proposed to accomplish the authors' objective. The first algorithm, named CONNECT was intended to create k-connectivity, where k=1. This results in the formation of a connected network that contains the minimum amount of route redundancy and the formation of many critical nodes; whose failure would result in the partitioning of the network. These critical nodes are also potential bottlenecks for the network's throughput. The second centralised topology control algorithm named BICONNECT was specially planned to create a k-connected network where k=2. The resultant network is an enhancement on the CONNECTed version, as the route redundancy is improved and the impact of the performance bottlenecks that existed earlier has been curtailed. Due to the centralized control of the CONNECT and BICONNECT topology control algorithms, they experience the same imperfections that are discussed in our previous analysis.

4. Low Interference-Load Neighborhood Forest (LILNF) Algorithm

The primary objective of this work [20] was to deliver an interference-efficient wireless multi-hop network topology through the exploitation of the Low Interference-Load Neighborhood Forest (LILNF) algorithm. The interference load relates to the number of nodes that cause interference to a node. This algorithm attempts to minimize the interference load of every node in the network while diligently maintaining the network connectivity. Network connectivity is ensured by inspecting the existence of a path between every pair of nodes in the network. The disadvantages of LILNF algorithm are, the usage of a centralized node for computations. The underlying assumption is that if such a node exists, the communication overhead incurred during the transmission of every node's local neighborhood information, as well as the delay in receiving the output from the central node will increase. An extension to the LILNF topology control algorithm, the Low Interference-Load Spanner Topologies algorithm, is an effort to preserve a low interference network topology while

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ensuring that the path lengths between every pair of nodes in the network are lesser than a certain threshold.

5. FGSSk Topology Control Algorithm

This work [21] aimed to conserve redundancy of the wireless multi-hop network by carefully preserving its k-connectivity. By minimizing the maximum transmission power of the nodes, entire network's connectivity is preserved and also maximize the network lifetime.

B. Distributed Topology Control Algorithms

1. Cone-Based Distributed Topology Control Algorithm

The Cone-Based Topology Control [14] algorithm enables every node to individually adjust its transmission power. Each node breaks up its transmission range into dissimilar cones according to some value of angle of a cone in degrees). CBTC attempts to minimize the maximum transmission power needed to guarantee that the node has a neighbor in every cone in its transmission range. Although CBTC is a distributed algorithm, it cannot be deployed on wireless multi-hop network nodes because it necessitates the nodes possess the capability to assess the direction from which transmissions are being received, which helps in identifying the cones in which its neighbours reside.

The focus on minimizing each node's transmission range in the network may also unintentionally lead to a reduction in the redundancy of the network, significantly increasing the possibility of network partitioning, which negatively affect the network's throughput. The lack of synchronization between neighboring nodes is a major trouble, as CBTC requires appropriate feedback from its neighbours in the form of acknowledgements to Hello messages. Non receipt of acknowledgement to a broadcasted Hello message may inadvertently stimulate an increase in the broadcast node's transmission power as it searches for a neighbor in that cone.

2. Cone Based – 3D Algorithm

The CBTC-3D algorithm was extended version of CBTC by improving the redundancy of the network topology as well as considering a 3-dimensional scenario [16]. The ability to detect neighbours in 3- dimensional space was also introduced by using the concept of cones that was introduced in the CBTC algorithm. The review of papers [14-15] indicated that the CBTC algorithm reduced the redundancy in the network, thereby reducing the fault-tolerant nature of the network [16], aimed to guarantee the fault-tolerant nature of the network by ensuring the resulting network that preserves k-connectivity. The disadvantages of this work include the necessary requirement of the nodes in the network to possess the ability to determine the relative directions of its neighbours in 3-dimensional space. Another disadvantage is the lack of synchronization between neighboring nodes that could inadvertently increase the transmission power required to maintain the k-connectivity of the network.

3. CPC and IPC Algorithms

Prior work has dealt with exploiting the minimum power needed to achieve k-connectivity. This work [17] in contrast, aims at tuning the transmission power of every node in the network to achieve the maximum accomplishable throughput. The two topology control algorithms presented throughout this work establish the optimal transmission power for each node in the network, based upon the total number of nodes in the network, the traffic load experienced by each node and the area covered by the network.

The first algorithm, named Common Power Control (CPC) set a common transmission power to all the nodes in the network. CPC abstains the use of a centralised node by having each node ascertain its own optimum transmission power based on local information and subsequently floods the network with this information through advertisements. All the nodes in the network then adopt the largest advertised transmission power. CPC does possess some drawbacks that weaken its practicality. First, the use of the broadcast mechanism to determine the largest transmission power does not promise that all the nodes in the network will receive the largest transmission power advertisement. Flooding is an inherently unreliable communication mechanism due to the potential for collisions, which result in the loss of transmission power adjustments.

Table 2: Characteristics of Distributed Topology Control Algorithms

Algorithm	Paper Ref	NC	IR	LC	Connectivity Flexibility
D-NTC	[12]	Heterogeneous	Neighbour-Based	Symmetric - Bidirectional	K-Connectivity Flexible
Cone-Based	[14]	Heterogeneous	Direction-Based	Bidirectional – (After optimization)	Flexible
Cone-Based -3D	[16]	Heterogeneous	Direction-Based	Bidirectional – (After optimization)	Flexible
CPC	[14]	Heterogeneous	Neighbor-Based with traffic load	Both Directional and Bidirectional	Non-Flexible
IPC	[14]	Heterogeneous	Neighbor-Based with traffic load	Both Directional and Bidirectional	Non-Flexible
XTC	[18]	Heterogeneous	Neighbor-Based	Bidirectional	Non-Flexible
LMST	[19]	Homogeneous	Neighbor-Based, Location Based	Both Directional and Bidirectional	Flexible, Bounded to a maximum node degree of 6.
NC – Node Characteristics IR – Information Requirements LC – Link Characteristics					

This phenomenon is compounded as the size of the network grows. As a result either one of two situations may occur; either a suboptimal transmission power is globally adopted if that exceptional transmission power advertisement was heard by all the nodes in the network, or differing transmission powers will be brought into effective action in varying regions of the network. Both circumstances may result in a less than maximum network throughput regardless of the disproportionate overhead formulated by the broadcasting mechanism. Secondly, the utilitization of the traffic load as one of the transmit power adjustment criteria is also a disadvantage. The traffic load is dynamic and thus may alter rendering a node's transmission power advertisement virtually obsolete during the time taken to receive the common transmission power.

The second algorithm, termed Independent Power Control (IPC) was intended to authorize each node in the network to select its own transmission power, thus avoiding the latency and overhead introduced by CPC. IPC chooses its transmission power based on the traffic load. IPC suffers from two important disadvantages; first, it neglects the synchronization needed to assist in preserving the connectivity of the network in the course of the process of applying the algorithm. Second, the use of the traffic load as a transmit power adjustment criterion could lead to unstable network topology.

4. XTC - Topology Control Algorithm

The distributed XTC algorithm [18] caters for 3-dimensional circumstances and permits a node to order its neighbours by lowering link quality. Each node generates its neighbor order and interchanges it with its neighboring nodes. The nodes in the network ascertain their local collection of neighboring nodes after receiving the neighbor orders from all of its neighbours.

In general, the node A builds or maintains a direct communication link to node B if node A has no other neighbor (node C) that can more easily reach node B. Whilst this process does guarantee that links with the highest quality are maintained, it does add to the computational complexity of the algorithm, because the neighbours orders of neighboring nodes must be consulted when deciding on the local neighborhood.

Additional detriments of this approach include the overhead formed during the process of exchanging a node's neighbor orders among its neighbours, the reduction in the redundancy of the network created by the XTC algorithm, as well as the lack of synchronization among neighboring nodes.

5. LMST Topology Control Algorithm

LMST builds a global network topology by having each network node organizing its own local MST independently [19]. The algorithm defends against a situation in which a node has too many neighbours by imposing an upper bound of 6 on the number of neighbours deliberated. This enables for the origination of a global network topology where the node degree is bounded by 6, thereby minimizing the MAC-level interference and contention. LMST in its basic form, created a network topology that may consist of both uni-directional and bi-directional links. Uni-directional links do not approve for the proper functioning of the Medium Access Control (MAC) mechanisms of the IEEE 802.11 standard. LMST addresses this inconvenience by providing an optional optimization that ensures that all the links in the network are bi-directional. By using Prim's algorithm, the time complexity of LMST is computed to be O(n2) when using simple searching and O(m+n log n) when using Fibonacci heap. Here, m is the number of edges and n denotes the number of vertices.

Simulation of LMST [19] revealed that it significantly reduces the MAC-level contention, but at the cost of the overall redundancy and resulting credibility of the network. LMST is shown to successfully accomplish an average node degree of 2, which does not fall within the optimal range of neighbours [4 - 9], depending on the appropriations made and the overall network model utilized.

IV. Conclusion

Topology Control algorithms were devised to automate the process of ensuring the creation and subsequent maintenance of optimal wireless multi-hop network topologies. These algorithms often have competing design criteria, and as a result they are usually a compromise between a node's transmission range, its node degree (number of neighbours), the network throughput, the interference levels experienced and the average number of distinct paths between every source and destination pair in the network. These topology control algorithms can also lead to network instability due to a lack of synchronization among neighboring nodes (possibly resulting in a partitioned network). According to our study of the optimal node degree (number of neighbours) and topology control algorithms we identified the design criteria necessary for a practical topology control. The list of identified design criteria are - The use of a distributed algorithm, Minimal computation, Minimal communication overhead, Minimal node degree, Minimal latency, Maintenance of network connectivity, Maintenance of the optimum levels of redundancy, Provision of synchronicity between neighboring nodes and Heterogeneous transmission radii, optimal minimum number of neighbours that each network node should maintain, wherever possible, in a practical network topology.

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