A Dynamically Configurable Topology Control for Hybrid Ad Hoc Networks with Internet Gateways*

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Abstract. We propose a novel algorithm for topology control, named "Dynamically Configurable Topology Control (DCTC)", in hybrid ad hoc networking environments interconnected to the Internet. Unlike the existing topology control protocols for stand-alone ad hoc networks, the proposed DCTC focuses on hybrid multi-hop wireless networking environments with the Internet gateways. That is, with our DCTC scheme, the optimal network topology for mobile users having Internet traffic can be created and maintained. Also, DCTC can control the network sparseness dynamically based on the principle of maintaining the optimal number of neighbors of each node. Finally, we study the performance of DCTC via simulations, varying the network density and node dispersion patterns. Our simulation results show that DCTC achieves the improvement of the network connectivity and capacity.

1 Introduction

The efficiency of a communication network is dependent upon not only its control protocols, but also its topology. Therefore, one of the major research concerns in multi-hop wireless networks that received a lot of attention recently is the problem of topology control [1][2][3]. Since energy efficiency and network capacity are the two most critical issues in wireless ad hoc networks, most existing algorithms for topology control are based on the multiple objectives which are maintaining network connectivity and reducing energy consumption as well as improving network capacity. That is, the main feature of existing topology control protocols is to allow a node to control its transmission power so that nodes in wireless multi-hop networks can collaboratively form their optimal topology under certain factors such as energy, delay, traffic, and so on.

Typical examples of hybrid ad hoc networks, like wireless mesh networks and wireless sensor networks, have a special type of nodes which has the gateway and the bridging functions (e.g., mesh routers in wireless mesh networks and sink nodes in

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wireless sensor networks). It is however worthwhile to note that many topology control protocols presented for these networks do not consider the existence of such a special node, even though the performance of these topology control protocols can heavily be dependent upon the traffic patterns. Note that most of the traffic in such hybrid ad hoc networks is forwarded to the Internet gateway node. Therefore, we believe that it would be beneficial to consider this unique characteristic of traffic flow when designing topology control protocols. In this paper, we tackle the topology control problem for hybrid multi-hop networking environments with the goal of generating a topology in which the path toward the Internet gateway node is optimized, resulting in the increase of network capacity.

Of course, for the proposed topology control protocol, we consider not only the external traffic to the Internet gateway node but also the internal traffic among normal nodes. When considering the internal traffic, network sparseness would be one of the important factors. As stated earlier, most of the existing topology control protocols seem to require a proper adjustment of nodes' transmission power to control network sparseness. This leads to the latency versus energy efficiency tradeoffs. Table 1 represents some favorable features with a low power transmission (i.e., when nodes transmit at the lowest possible power that guarantees connectivity), and a high power transmission (i.e., when nodes transmit at the highest possible power). As seen from the table, it is clear that a higher power transmission can reduce latency, at the penalty of increasing the possibility of interference with neighboring nodes. Therefore, we need to take an approach that can control transmission power dynamically corresponding to the requirements of network applications.

Table 1. Favorable Factors of Low and High Transmission Power

	Low Power	*High Power*
Favorable Factors	Network lifetime Interference Throughput Packets loss rate	Network connectivity Average number of hops towards destination End-to-end latency

In this paper, we propose a novel algorithm for topology control, named "Dynamically Configurable Topology Control (DCTC)", for hybrid ad hoc networking environments interconnected to the Internet. Unlike the existing topology control protocols for stand-alone ad hoc networks, the proposed DCTC focuses on hybrid multi-hop wireless networking environments with the Internet gateway nodes. That is, with our DCTC scheme, the optimal network topology for mobile users having Internet traffic can be created and maintained. Also, DCTC can also control the network sparseness dynamically based on the principle of maintaining the number of neighbors of every node.

The rest of the paper is organized as follows. Section 2 presents related work regarding topology control in ad hoc networks. In Section 3 explains more details on the DCTC scheme. Section 4 deals with the performance evaluation and finally in Section 5 we provide a conclusion.

2 Related Work

As discussed in the previous section, satisfying connectivity constraints and energy efficiency are critical factors in topology control protocol. Most of the researchers regard the Minimum Spanning Tree (MST) as the best topology satisfying these two objectives. However, MST is impractical because it needs global information. The Localized MST (LMST) builds an approximation of the MST in a localized way [4]. It needs location information. The Cone Based Topology Control protocol (CBTC) is introduced in [5]. The basic idea of the CBTC is that a node *u* transmits with the minimum power P_{up}, such that there is at least one neighbor in every cone of angle *p* centered at *u*. This protocol produces a connected communication graph if $p <= 2\pi /3$. However, the drawback of CBTC is that it requires directional information which might not always be available.

Contrary to the protocols described above, the proposed scheme in this paper does not need any additional information such as location information, directional information, and even global information. In addition, compared with the CBTC, the proposed scheme generates optimal topology considering only the path to the Internet gateway node. CBTC also considers directional traffic but it is for every path at each direction.

According to the classification in [6], there is one class of topology control protocols based on the k-neighbors graph, i.e. the graph in which every node is connected to its k closest neighbors. An example of neighbor-based topology control protocol is the Local Information No Topology (LINT) protocol [1]. The basic idea of LINT is to try to keep the number of neighbors of every node within a low and high threshold centered around an optimal value. Its drawback is that the estimation of the number of neighbors might be inaccurate because silent neighbors are not detected. So the connectivity is not guaranteed. The most widely studied topology control in the literature is the K-Neigh protocol introduced in [7]. This protocol maintains the number of physical neighbors equal to (or slightly below) K. K is chosen in such a way that the graph generated is connected with high probability. This protocol produces symmetric topology and is more energy-efficient than CBTC but it does not ensure the connectivity all the time due to probability-based algorithm.

These two protocols are the closest to our work. Similarly to these protocols, the proposed scheme is neighbor-based protocol. It can control the network sparseness dynamically based on the principle of maintaining the number of neighbors of every node slightly equal to a specific value which depends on the network loads. However, contrary to these protocols, the proposed DCTC scheme considers not only who my neighbors are but also where the Internet gateway node is. Fig. 1 presents two different topology snapshots derived from MST and K-Neigh protocol. In section 4, we will show the snapshots derived from the proposed scheme.

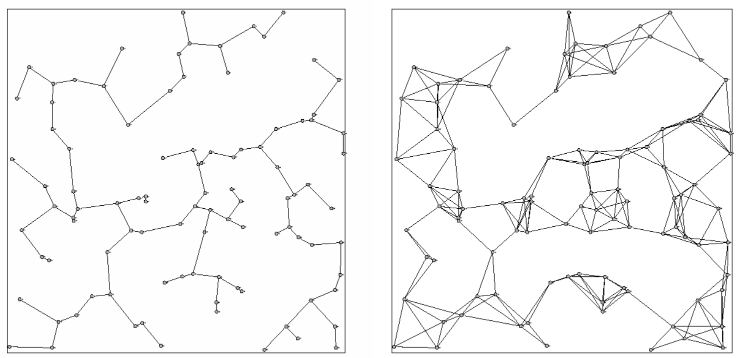

Fig. 1. Topologies derived from MST and the K-Neigh

3 Dynamically Configurable Topology Control (DCTC) Scheme

In this section, we describe our proposed topology control scheme. First, a gateway node periodically broadcasts a special type of control message, called an *Announce Message (AM)*. A period of issuing this control message can be dynamically changed, based on the degree of network mobility. That is, *AM* would be issued more often when nodes' mobility is relatively high, whereas it would be generated less frequently when nodes' mobility is relatively low. This control message includes several parameters, such as gateway ID, a sequence number, forwarding node ID, and the maximum number of neighbors allowed for each node (denoted by *K*). The value of *K* represents the degree of density, meaning that the network becomes denser as *K* becomes larger. Any nodes receiving *AM* are required to forward the *AM* with a special flooding method, called a *Distance-based Flooding*. This flooding method for client nodes is described below:

Distance-based Flooding: To forward the *AM* in order of shortest to longest distance from the Internet gateway node, a node uses holding time denoted by *HT*. The node sets its own *HT* whenever a node receives the *AM* from others. After the *HT*, it sends its own *AM*. So every node sends its *AM* in ascending order of distance from the Internet gateway node. Every node estimates its *HT* using the following equation. (HT_{MAX} means the maximum time duration for which a node can hold a receiving AM without forwarding it to its neighbors. d_{uv} means the estimated distance from receiver node *u* to sender node *v* derived from distance estimation techniques [8][9]. R_{MAX} means the maximum transmission range):

$$HT_u = HT_{MAX} \times \frac{d_{uv}}{R_{MAX}} \quad (1)$$

By performing this flooding, every node collects these control messages from their one-hop neighbors. From these messages, any nodes receiving *AM* construct additional data structures such as Pre-gradient, Post-gradient and Topology Control Table. Topology Control Table consists of two fields: forwarding node ID and the estimated distance of receiving *AM*. The number of records in this table is *K*. When each node receives the *AM*s from its one-hop neighbors, it saves the information of forwarding node ID and the estimated distance into this table in ascending order according to the estimated distance. Pre-gradient is defined as the estimated distance from a node to the forwarding node of the *AM* that is received right before sending its own *AM*. Post-gradient is the estimated distance to the forwarding node of *AM* that is received right after sending its own *AM*. These two variables support the optimal path to the Internet gateway node as well as the full network connectivity.

Finally, each node selects an optimal transmission power for its transmission power to ensure the best path to the Internet gateway node, and that will generate the required network sparseness. The optimal transmission power is the maximum value among three values which are Pre-gradient, Post-gradient, and the maximum distance in Topology Control Table. Then, each node calculates the optimal transmission power based on the optimal transmission range denoted by *d*. Transmission power estimation is described below.

Transmission Power Estimation. A computation of transmission power based on the estimated distance is done by utilizing the two-ray ground reflection model [10] that is designed to predict the mean signal strength for an arbitrary transmitter-receiver separation distance. Assuming that there are two nodes *u* and *v*, node *u* estimates the received signal strength $P_r(d_{uv})$ of the neighbor node *v* at distance *d*, using the following equation [11]:

$$P_r(d_{uv}) = 10 \times \log(\frac{W}{mW}) + 10 \times \log(G_t \times G_r \times H_t^2 \times H_r^2) - 40 \times \log(d_{uv}) \quad (2)$$

In the above equation (2), G_t is a transmitter antenna gain, G_r is a receiver antenna gain, H_t is the transmitter antenna height, H_r is the receiver antenna height and finally d_{uv} is the estimated distance. Now, using equation (3) below, node *u* can estimate the minimum power P_{min} required to successfully communicate with its one-hop neighbor (node *v*).

$$P_{\min}(d_{uv}) = P_r(d_{uv}) + 20 \times \log(d_{uv}) \quad (3)$$

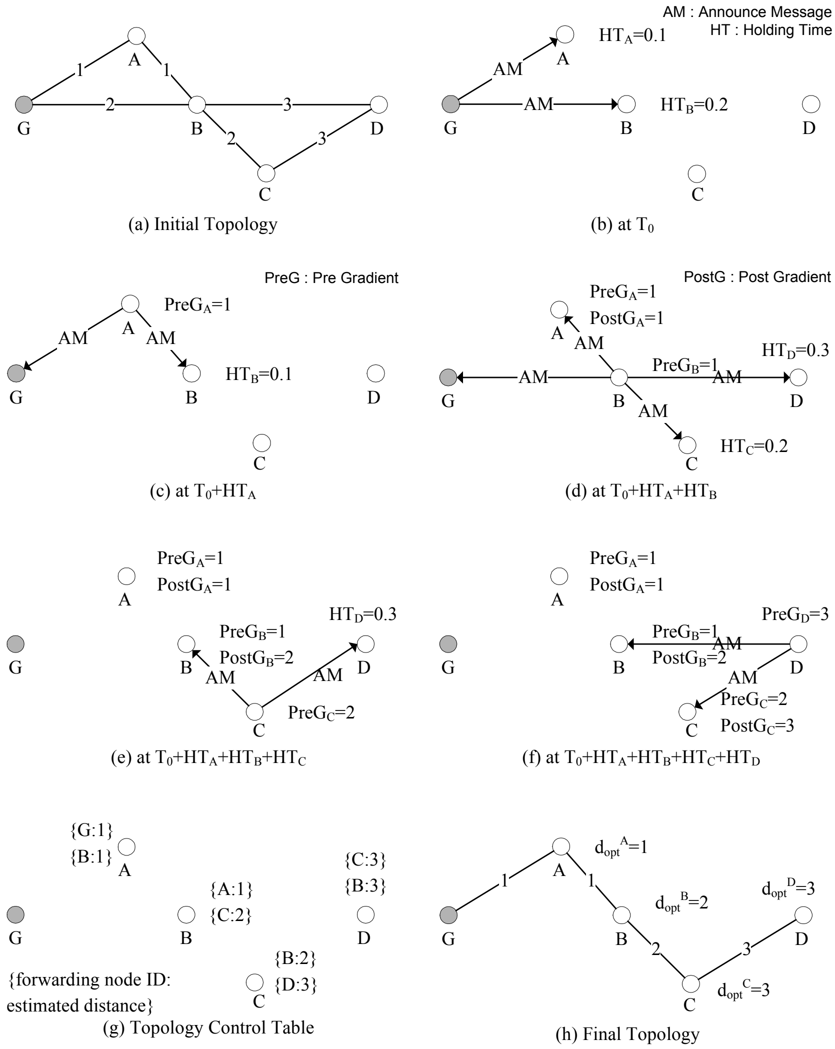

Fig. 2. The Sample Flow of DCTC with K = 2

Fig. 2 shows the sample flow of DCTC. Fig. 2(a) presents the initial topology. There are five nodes: one gateway and four clients. Each node has its unique *ID* such as *G*, *A*, *B*, *C* and *D*. The number on the line specifies the estimated distance between two nodes. As shown in Fig. 2(b), at time T_0, the Internet gateway node *G* sends the first *AM* with a full transmission power. Then, *G*'s one-hop neighbors, nodes *A* and *B*, may receive this *AM* and calculate their *HT* according to equation (1). Note that, for simplicity, R_{MAX} is assumed as 10 and the *K* is equal to 2. In the next step (Fig. 2(c)), at time T_0+HT_A, node *A* sets its Pre-gradient value to 1 and forwards the *AM* with full transmission power. Since the initial *HT* of node *B* (i.e based on the *AM* received from the gateway) is high, it receives the *AM* from node A before forwarding its own

AM packet. Therefore, node *B* re-computes its *HT* according to the last *AM* packet as shown in Fig. 2(c). It then sets its Pre-gradient value to 1 and forwards the *AM* at time $T_0+HT_A+HT_B$, which is received by nodes *A*, *C* and *D* as shown in Fig. 2(d). Further, nodes *C* and node *D* compute their *HT*, where as node *A* set its Post-gradient value, since it is the first *AM* received after sending its own *AM*. Similarly, in Fig. 2(e) and Fig. 2(f), we show that nodes *C* and *D* also set its Pre-gradient and Post-gradient values based on the received *AM* packets.

In Fig. 2(g), we show the topology control table of all nodes. Note that only two neighbors are selected according to the order of received *AM* packets. Each node sets its transmission range according to the maximum value among Pre-gradient, Post-gradient and the maximum distance in the Topology Control Table. Thus, in our example Fig. 2(h), nodes *A*, *B*, *C* and *D* will set its optimal transmission range to 1, 2, 3 and 3 respectively.

4 Performance Evaluation

Using the simulator ns-2, we has implemented three schemes: the proposed DCTC scheme, K-Neigh protocol, and the pure flooding algorithm without transmission power control. The flooding algorithm runs on each node forwarding data to its one-hop neighbors with a default transmission power level (e.g., 24.5dBM in the current ns-2 codes). One node has been selected as the Internet gateway node and another one as a source. K-Neigh on the other hand employs a transmission power reduction and increase based on the number of neighbor nodes. From now on, we explain the simulation scenarios and present our preliminary results. Some information about the parameters is listed in Table. 2.

Table 2. Parameters and their default values in ns-2

Parameters	Meaning	Default value
G_t	Transmitter antenna gain	1.0
G_r	Receiver antenna gain	1.0
H_t	Transmitter antenna height	1.5m
H_r	Receiver antenna height	1.5m

4.1 Simulation Environment

In our simulation model, nodes are randomly placed in a network space of 1000x1000m^2. For increasing a node density in the network, we ran the simulations for 50, 75, 100, 125, 150, 175, 200, and 250 nodes. Following metrics have been used to evaluate our proposed scheme.

- Energy cost (For K-Neigh, Phase 1 is considered only.)
- Average path length of the topologies
- Average logical and physical degree of the topologies

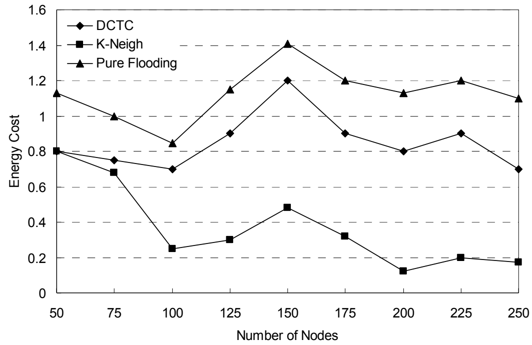

Fig. 3. Energy cost of three topology control protocols (DCTC, K-Neigh, and Pure Flooding)

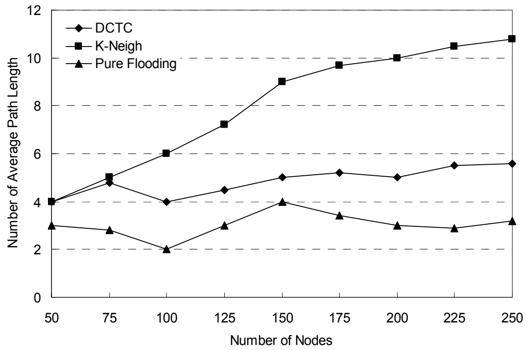

Fig. 4. Average path length generated by three topology control protocols

4.2 Simulation Results

DCTC can control the network sparseness according to the value of *K* from the Internet gateway node. Topology control protocols have to allow network administrator to control the network sparseness according to the network load due to the latency versus energy efficiency tradeoffs. In all simulation results, the value of K is 12 which is the closet value to the optimal value suggested by K-Neigh [7].

Fig. 3 shows the energy cost of different topology control protocols. Again note that, for K-Neigh algorithm, we have conducted Phase 1 only. The figure presents the fact that DCTC may consume more transmission energy compared to K-Neigh because DCTC considers an optimal path to the Internet gateway node. DCTC, however, can send some traffic to the Internet gateway node with lower hop count as shown in Fig. 4. That is, Fig. 4 shows the number of hops from the source to the Internet gateway node. The number of hops means a potential network delay so that DCTC is more favorable than K-Neigh in the view of delay aspect. Moreover, although the number of hops of K-Neigh increases as the number of nodes increase, the number of hops of DCTC is almost fixed and similar to the pure flooding with full transmission power.

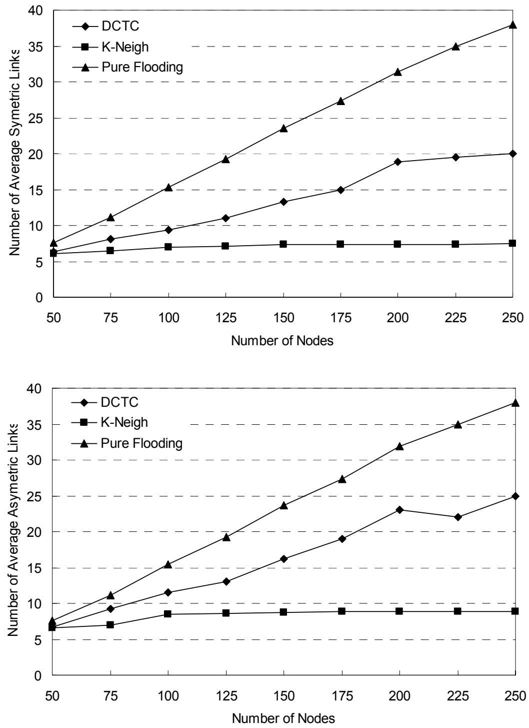

Fig. 5. Average logical and physical degree of the topologies generated by the DCTC, K-Neigh, and pure flooding protocols.

Actually, in wireless networks, asymmetric links are very important factors to consider since it may cause potential interference and affect the network capacity. We have measured the average number of symmetric and asymmetric links of the topologies generated by the DCTC, K-Neigh, and the pure flooding protocols, respectively. Fig. 5 represents the results of this measurement. Here, as the number of nodes increase, the number of symmetric links and asymmetric links increase as well. However, in case that the number of nodes is more than 200 nodes, the values are almost constant.

5 Conclusion

We have studied the effect of directional traffic to the Internet gateway node and a relationship between latency and energy efficiency tradeoffs in hybrid ad-hoc networking environments. We proposed a novel scheme, named "Dynamically Configurable Topology Control (DCTC)" that constructs and maintains a topology considering such directional traffic toward the Internet gateway. The proposed DCTC can control the network sparseness dynamically based on the principle of maintaining the number of neighbors of every node slightly equal to a specific value which depends on the network loads. Moreover, DCTC can make the optimal topology by considering directional traffic to the Internet gateway with heavy loads. Simulation results show that DCTC ensures network connectivity in most of the cases and better performance than other protocols especially when considering the traffic toward the Internet gateway.

A possible direction for future work is to adapt DCTC to deal with various dynamic environments. In a dynamic environment with frequently changed mobility, the topology would be continuously changing so AMs need to be generated dynamically.

References

1. R. Ramanathan and R. Hain, Topology control of multihop wireless networks using transmit power adjustment, in IEEE INFOCOM, 2000.
2. N. Li, J. C. Hou, and L. Sha, Topology control in heterogeneous wireless networks: Problems and solutions, in IEEE INFOCOM, 2004.
3. W.-Z. Song, Y. Wang, X.-Y. Li, and O. Frieder, Localized algorithms for energy efficient topology in wireless ad hoc networks, in ACM MobiHoc, 2004.
4. N. Li, J. C. Hou, and L. Sha, Design and analysis of an MST-based topology control algorithm, in Proc. IEEE INFOCOM, San Francisco, CA, Apr. 2003, pp. 1702–1712.
5. L. Li, J. Y. Halpern, P. Bahl, Y.-M. Wang, and R. Wattenhofer, Analysis of a cone-based distributed topology control algorithm for wireless multi-hop networks, in Proc. ACM Symposium on Principles of Distributed Computing, Newport, Rhode Island, United States, Aug. 2001, pp. 264–273.
6. Paolo Santi, Topology Control in Wireless Ad Hoc and Sensor Networks, International Conference on Mobile Computing and Networking, pp.286-289, 2003
7. D. Blough, M. Leonicini, G. Resta, P. Santi, The k-Neigh Protocol for Symmetric Topology Control in Ad Hoc Networks, Proc. of 4th International Symposium on Mobile Ad hoc Networking and Computing (MobiHoc), June 2003.
8. A. Savvides, C. Han, M. Srivastava, Dynamic Fine-Grained Localization in Ad Hoc Networks of Sensors, Proc. ACM Mobicom 01, pp. 166–179, 2001.
9. L. Girod, D. Estrin, Robust Range Estimation Using Acoustic and Multimodal Sensing, IEEE/RSJ International Conference on Intelligent Robots and Systems, 2001.
10. Y-B. Ko, S-J Lee, J-B Lee, Ad hoc Routing with Early Unidirectionality Detection and Avoidance, in Proc of PWC, September, 2004.
11. Kaveg Pahlavan, Prashant Krishnamurthy, Principles of Wireless Networks, Prentice Hall Communications, 2002.