Distributed Topology Control for Stationary and Mobile Ad Hoc Networks

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I. Introduction

Topology control for ad hoc networks aims to assign transmission power levels to nodes for maintaining a *specified topology*, such as requiring that the network be connected. Further, the assignment of transmission powers to nodes aims to optimize some function of those powers. Most commonly this is to minimize either the *maximum power* utilized by any node (MinMax), or the *average power* utilized by the nodes (MinTotal).

Over the past several years, the study of topology control in ad hoc networks has encompassed both theoretical and applied issues. In this paper, we begin with a simulation study that compares the performance of four distributed topology control algorithms (CBTC [3], LMST [4], NTC [2], XTC [6]) with a hybrid topology control framework (CLTC [5], [7]). Then, we describe a mobile network model. Since optimal topology control is open under this model, we give a centralized approximation algorithm and establish an upper bound on its performance. The approximation algorithm will be incorporated with XTC [6], an extremely practical method, so as to make XTC adaptable to mobile networks. Finally, we provide a performance evaluation of this combined algorithm.

II. Radio Model and Topology Control

In the ad hoc network model, for each ordered pair (u, v) of transceivers, there is a *transmission power threshold*, denoted by $p(u, v)$, where a signal transmitted by the transceiver u can be received by v only when the transmission power of u is at least $p(u, v)$. In this paper we utilize only *symmetric* thresholds where $p(v, u) = p(u, v)$.

In regard to the topology of the graph induced by the power assignments to the network nodes, the most common objective and the objective considered in this paper is that the network be *connected*.

III. Performance Comparison

This section compares the performance of several distributed topology control algorithms with that of *CLTC* [5] (using MMST [7] for clustering) when the goal is to maintain a connected network. In the performance comparison, we use the centralized algorithm from [1] to provide a lower bound benchmark on power consumption. The discussions of all the algorithms are omitted due to space limitations. Readers are referred to the complete version of this paper at [10].

The experiments were conducted by placing a specified number of nodes in a 4 mile by 4 mile area, using a uniform random distribution. Four network sizes were studied: 50, 100, 150 and 200 nodes. For each number of nodes, ten trials were generated and all of the numbers that we report are averages over those ten trials.

The radio wave propagation model utilized is the *Log-distance Path Loss Model*. In our work all of the parameters are chosen to emulate a 2.4 GHz wireless radio, and if the distance is less than a certain threshold, the transmission power threshold is set to the minimum threshold of 1 dBm. The maximum transmission power is 29 dBm, which corresponds to a transmission distance of 1 mile.

The experimental results are presented in Table I. These results show that LMST and *CLTC* give the best performance, followed by XTC and CBTC. Further, LMST is marginally better than *CLTC* and XTC is marginally better than CBTC. Overall, NTC performs much worse than the others.

Due to space limitations, Figures 1 and 2 show two resulting topologies. Readers are referred to

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Methods / # of Nodes	CLTC	LMST	XTC	CBTC	NTC
50	9%	6%	14%	15%	63%
100	14%	9%	34%	39%	120%
150	18%	7%	51%	59%	166%
200	20%	8%	62%	73%	222%

TABLE I
POWER INCREASE PERCENTAGE OVER THE CENTRALIZED ALGORITHM

the complete version of this paper at [10] for the full discussions of performance analysis.

IV. TOPOLOGY CONTROL FOR MOBILITY

In this section we propose a topology control algorithm aimed at maintaining connectivity in a *mobile* network while minimizing power consumption under the MinMax objective. The algorithm is proactive so that the network connectivity is guaranteed at any time instant.

A. A Practical Mobility Model — DMN

In studying topology control for MANETs, we are given a set of nodes in the plane, each of which may move as time progresses. Associated with each node is its maximum transmission range. The objective is to assign transmission powers to the nodes so that the network is *movement-connected*. That is, at every instant in time, the undirected graph induced by the transmission powers of the nodes is *connected*. Topology control aims to achieve this connectivity under the MinMax objective, and where the power assigned to each node does not induce a transmission range greater than the maximum transmission range of the node.

Ideally, we would solve the topology control problem just once, thereby assigning powers to the nodes so that the MANET is movement-connected throughout the network lifetime. Unfortunately, this requirement is not realistic in that nodes are moving, and with that movement the power requirements needed to achieve connectivity may change dramatically. A more realistic approach is to assign power levels so that the network is connected throughout some prespecified interval of time. At the start of each interval, the power levels of the nodes are recomputed based on the current location of the nodes and taking into account any additional information that is known about the movement of the nodes. Thus, the general problem that we consider is to minimize the maximum power assigned uniformly to any node such that the network is movement-connected throughout a *unit time interval*.

With these preliminaries concluded, we state the **Disk Mobile Network (DMN) Problem**: Consider a MANET in which there are n moving

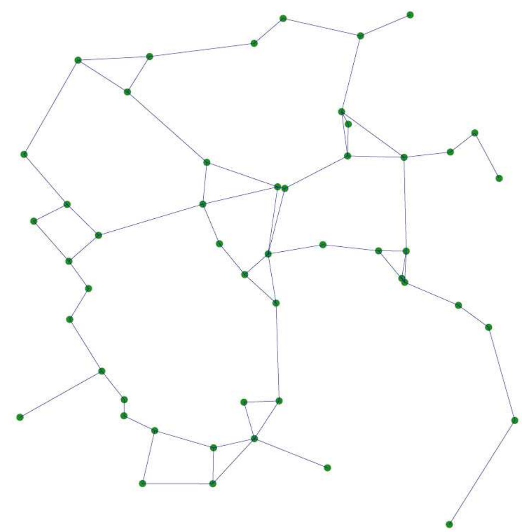

Fig. 1. Topology — XTC

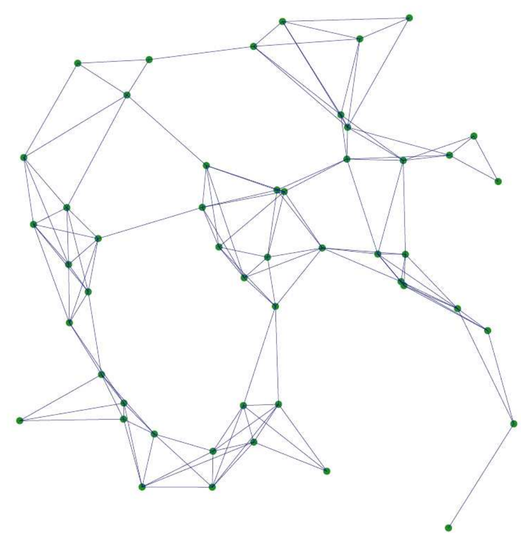

Fig. 2. Topology — NTC

nodes, each of which moves at maximum speed r. Note that the speed need not be constant throughout the unit time interval. Although the starting position of every node is known, nothing is assumed about node's direction of movement. The goal is to minimize the maximum power assigned to any node such that the network is movement-connected in the unit time interval regardless of the movement of the nodes (within the constraints imposed by its starting position and the maximum speed). Readers are referred to [8], [9] for other relevant mobility models.

B. An Approximation Algorithm

Because of the uncertainty of the positions of the various nodes inherent in the problem specification, the existence of a polynomial algorithm producing an optimal solution seems unlikely. Indeed, even exponential time methods that yield the optimal power level are elusive. Thus, in this section we give a fast and simple *approximation* algorithm for the DMN problem. This algorithm, while not necessarily producing the *minimum* maximum power value, will always produce a solution within a certain ratio of that optimal value. Since the algorithm is going to be incorporated into XTC and introduced in the next section, we omit the algorithm, the proof of its correctness and the proof of its performance guarantee here. Readers are referred to the complete version of this paper at [10] for the detailed introduction of the algorithm and the proofs.

Roughly speaking, our algorithm for DMN is based on the observation that while the nominal transmission range of a node is R, we need to account for the possible movement of that node and a node moving in the opposite direction with which it might communicate. We do this by reducing the communication range of the node to account for that movement. We then use those transmission ranges in conjunction with a stationary network and use an existing algorithm to find an optimal solution to that stationary network problem. Note that it is possible that there is no solution to that stationary problem in which case there may or may not be any solution to the instance of DMN. Here, our algorithm simply assigns the full power level to all nodes.

The major advantages of our algorithm are: (1) simple — no sophisticated hardware or software is necessary and any mobile node which has the simplest computing capacity is able to handle this algorithm; (2) fast — a simple transformation produces a stationary network to which any existing fast algorithm for stationary networks can be applied; and, (3) proactive — the algorithm is executed at the very beginning of each unit time interval, and yields a solution that guarantees that at any time instant within the unit time interval the mobile network is connected.

V. XTC + DMN

Recall that XTC is an extremely practical algorithm for stationary ad hoc networks, and DMN is a practical mobility model to enable algorithms for stationary networks to work in mobile networks. In this section, we integrate XTC and DMN to produce a practical distributed topology control algorithm for mobile networks — LBTC (Local Broadcast-based Topology Control for MANETs), which is shown in Figure 3.

Based on XTC and DMN, LBTC is an extremely practical distributed topology control algorithm. In LBTC, collecting local information is not based on any geometric property but rather is only dependent on signal strength. Note in particular that Step 1 does not really need to calculate the distances. Since LBTC can set a signal strength threshold to mask signals which may be lower than that threshold owing to mobility (i.e. the same functionality as Step 1), only nodes whose received signal strength being greater than that threshold will be considered as 1-hop neighbors in Step 3. Hence, LBTC does *not* assume that: (1) the power threshold is symmetric, (2) the maximum transmission range of each node is identical, and (3) the induced graph from the network is undirected. Further, since no geometric property is assumed, LBTC can be applied to both the 2-dimensional plane and 3-dimensional space.

The performance of LBTC is shown in Figure 4, where LBTC1 reflects the power consumption if we use $p_i \leftarrow PL(d_i)$ in Step 7 (i.e. without counting in the mobility) and LBTC2 represents the actual power consumption produced by the LBTC algorithm (i.e. with counting in the mobility). In that simulation, we set the maximum transmission range to be 1 mile, the maximum node speed to be 60 mile/hour, and the unit time interval to be 6 seconds. An interesting observation is that LBTC1 gives a little better performance than XTC when the network has 100 nodes and 150

Input: An instance $\mathcal{N}$ of DMN. Let r be the value of the maximum speed times the unit time interval, and let p_{max} be the common maximum transmission power.

Output: The power assignments to nodes $\{p_1, p_2, ..., p_n\}$ such that $\mathcal{N}$ is movement-connected.

Steps:

Each node v_i independently executes the following steps (note that transmissions utilize power p_{max} before p_i is computed),

1) $R'_i = R_i - 2r$, where R_i is the maximum transmission range of v_i.
2) Update the maximum transmission range of v_i to R'_i.
3) Sort v_i's 1-hop neighbors (within R'_i) into list $L_i = (v_{i1}, v_{i2}, v_{i3}, ..., v_{im})$ in ascending order by the received signal strength $|v_{ik}|$.
4) Broadcast list L_i to every node in L_i.
5) For $v_{ik} \in L_i$ in ascending order do,
    a) If $\{\exists j > k : v_{jk'} \in L_j,\ v_{ik} = v_{jk'}, |v_{ik}| < |v_{jk'}|\}$, then eliminate v_{ik} from L_i; else break out of the For loop.
6) Let d_i be the distance between v_i and the first node in L_i.
7) $p_i \leftarrow PL(d_i + 2r)$, where PL maps distance to power according to the communication radio model being used [10].

Fig. 3. LBTC Algorithm

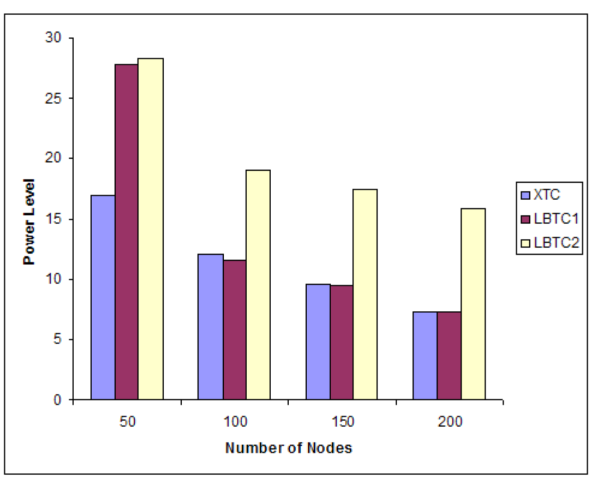

Fig. 4. LBTC Performance

nodes. This is not a surprise since by reducing the maximum transmission range each node may need to guarantee connectivity to fewer nodes. If the network connectivity can be achieved by using the reduced maximum transmission range, then the performance of LBTC1 may be superior to XTC. In contrast, when the network is sparse (50 nodes), the reduced maximum transmission range is likely to result in partitioned networks which leads to every node using full power, hence the performance of LBTC1 is worse than XTC. When the network is dense (such as 200 nodes), the performances of LBTC1 and XTC are identical. Finally, it is notable that when power assignment p_i is augmented by the mobility factor $2r$ then the power consumption of LBTC2 increases significantly over LBTC1.

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[10] A complete version of this paper is located at `www.cis.udel.edu/~elloyd/papers.d/m06full.pdf`