A Simulation-Based Study on the Throughput Capacity of Topology Control in CSMA/CA Networks[*]

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Abstract

Although it is commonly assumed that the use of topology control can improve the throughput capacity of wireless networks, analytical results on this topic are sometimes contradictory and no comprehensive simulation study has been attempted. In this paper, we report the results of a packet-level simulation-based study of topology control in CSMA/CA networks. The results demonstrate significant throughput increases from certain topology control protocols at moderate to high node densities and high loads. The results indicate, however, that very sparse topologies (e.g. the minimum spanning tree) actually reduce throughput considerably compared to networks without topology control. The results also indicate that, within the range of parameters studied, it is necessary to allow nodes to have distinct transmission powers in order to increase throughput.

1. Introduction

The problem of identifying an optimal network topology for maximizing capacity has been widely studied in the literature since the seminal work of Gupta and Kumar [6]. In that work, the authors proved upper and lower bounds on the per-node capacity in wireless ad hoc networks considering different interference models. Some of the results suggest that using the minimal possible transmit power that preserves connectivity is the best choice for maximizing capacity. Motivated by this work and by the fact that lowering transmission power also has the positive effect of reducing node energy consumption, researchers have proposed distributed protocols aimed at building relatively sparse yet connected network topologies [3, 5, 7, 8, 9, 10, 11, 12, 16].

Despite the amount of theoretical work, little evidence of the actual benefits of topology control on network capacity has been presented. To our knowledge, only a few papers report any simulations showing throughput capacity improvements of topology control [8, 10]. In fact, a recent paper [1] partially contradicts the motivation for topology control by showing that, under the physical interference model, the capacity of an ad hoc network is maximized *by increasing* the node transmit power to the maximum possible level. This finding is confirmed by the experimental-based analysis in [15], in which it is shown that transmitting at maximum power with blacklisting (i.e., removing unreliable links) maximizes the packet delivery rate in a wireless sensor network. In another recent paper [4], it is shown that by using more realistic energy and interference models, different conclusions about what is the optimal network topology are drawn.

Summarizing, the fundamental question: "what is the capacity-maximizing network topology?" is still open to date. It is our strong belief that the answer to this question depends on many factors (traffic patterns, node distribution, interference model, MAC protocol, etc.), and that different topologies will turn out to be optimal in different settings.

In this paper, we consider one specific setting, where the MAC is based on CSMA/CA, and we perform an extensive simulation-based study of the effects of different topology control techniques on

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network capacity. We consider a broad range of possible topologies, starting from the sparsest possible connected topology (the MST), up to the maximally-connected topology (i.e., each node is transmitting with maximum power). The results show that protocols that substantially reduce transmission power without generating an extremely sparse topology can produce significant throughput increases compared to the maximally-connected topology.

2. Throughput Capacity in Wireless Nets

2.1. Interference Models

Two models for interference have been used in the literature to evaluate wireless network capacity [6], namely the *protocol* interference model and the *physical* interference model.

In the protocol interference model, each transmission has a range r_{p_s}, which is determined by the transmission power p_s used by the sender s. In this model, a transmission from s is received correctly at a receiver d if and only if:

1. d is at distance no greater than r_{p_s} from s, and
2. any other node $s' \neq s$, which is transmitting at any point during the duration of the transmission from s to d, is at a distance at least $(1+\Delta)r_{p_{s'}}$ from d.

In the physical interference model, a signal propagation model is used to determine transmission strength, which decays with distance. A transmission is received correctly if the signal to noise ratio of the transmitted signal at the receiver is above a specified threshold. In this model, one of two transmissions that interfere with each other can be properly received if its signal strength at the receiver is much greater than the competing signal's strength. The specification of the physical interference model is dependent on the details of the signal propagation model, for which there are several choices.

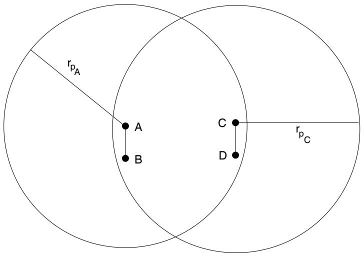

Figure 1. Interference of Transmissions: A to B and C to D

Figure 1 shows a situation where four nodes are communicating, with node A sending to node B and node C sending to node D. In the protocol interference model, both transmissions fail if they are concurrent with each other, because Condition 2 is violated for both receiving nodes B and D. However, in the physical interference model, it is possible that the two transmissions can be concurrent and still be received correctly at the respective receivers.

In [6], it is shown that capacities under the physical and protocol interference models are within a constant factor of each other when signal strength decays as the square of distance (a common assumption for signal propagation models). In [1], it is shown that, assuming the physical interference model with TDMA scheduling but independent of traffic model and node placement, capacity is maximized when each node's transmission power is set high enough to reach all other nodes (i.e. the network is completely connected). Such a result does not hold under all traffic models for the protocol interference model, however. For example, with the protocol interference model applied to Figure 1, the capacity is simply the capacity of the channel because only one node can successfully transmit at a time. However, if nodes A and C reduce their transmission powers so that their transmissions do not interfere, then the capacity is doubled.

Thus, for the physical interference model, high transmission powers do not negatively impact capacity and topology control will not improve capacity. However, in the protocol interference model, high transmission powers *can* negatively impact capacity and it is worth investigating the potential capacity and throughput benefits of topology control.

2.2. Impact of MAC Approach

In this paper, we focus on MAC protocols based on CSMA/CA. This includes the MAC protocols of several standard wireless network technologies, e.g. 802.11 and 802.15.4. In CSMA/CA, when a node has a packet to send, it delays its transmission until it senses that the communication channel is free. Thus, the only way that two transmissions within range of each other can occur at the same time (thus interfering) is if the transmissions are started at the same moment so that both senders think that the channel is free. Random delays are inserted in CSMA/CA at each pending sender when the channel becomes free in order to reduce the probability of simultaneous start times.

The effect of CSMA/CA is to produce network capacity characteristics that are more like those with protocol interference rather than physical interference. This is because concurrent transmissions that are within range to interfere with each other are prevented with high probability. Thus, CSMA/CA will prevent A and C from transmitting simultaneously in the Figure 1 example. Thus, CSMA/CA networks will potentially sacrifice network capacity unless they can reduce interference, possibly through the use of topology control.

3. Simulation Environment

3.1. GTNetS

All of our simulations were performed using the *Georgia Tech Network Simulator (GTNetS)* [13, 14]. GTNetS is a scalable simulation tool designed specifically to support large–scale simulations. The design of the simulator closely matches the design of real network protocol stacks and hardware. The simulator has an object-oriented design, which eases extensibility of existing simulation models. It includes detailed models for many protocols, including TCP, UDP, IPV4, 802.3, 802.11, EIGRP, OSPF, BGP, DSR, and AODV.

For wireless simulations, the accuracy and computational overhead for the physical layer modeling is an important tradeoff. In *GTNetS*, the default model for wireless path loss calculations is a two–ray model with a carrier sense threshold of -78dBm and a receive threshold of -64dBm. Our simulations make use of 802.11 and therefore, the interference behavior is similar to that of the protocol interference model (see Section 2.2).

3.2. Simulation Setup

Our simulation setup is based on the random network model of Gupta and Kumar [6]. In this model, n nodes are independently and uniformly distributed over the deployment region (1 km $\times$ 1 km in our simulations). Each node sends constant bit rate (CBR) traffic to a random destination selected as follows. For each source node, a uniformly distributed point in the deployment region is selected. The destination for this source is then chosen as the node (other than itself) that is closest to the randomly selected point. Aggregate throughput (the sum of per node throughputs) is calculated for varying bit rates and varying n. Values of n considered are 50, 100, 150, and 200. Since the nodes are distributed over a fixed size region, increasing n corresponds to increasing node density.

The topologies simulated are as follows:

- kNeigh [3]: nodes set their transmission range to reach the k closest nodes (k is set to ensure that 95% of the topologies derived from random networks are connected)
- kNeighLev [2]: a version of kNeigh with discrete transmission power levels (power levels are taken from the Cisco Aironet 350 wireless interface card)
- CBTC [16]: the cone-based protocol of Wattenhofer, et al.
- Common Power: each node uses the same transmission power (transmission power is set to ensure that 95% of the topologies derived from random networks are connected)
- MST [7]: a localized algorithm that approximates the minimum spanning tree
- Maximum Power: nodes transmit with the 802.11 maximum range

For a given set of random node locations, the topologies are computed off-line and input into GTNetS by setting the radio range of each node appropriately. Thus, all simulations are done in the restricted topologies. A first simulation phase is executed in which each node pings its destination in order to discover a route to it. Once this first

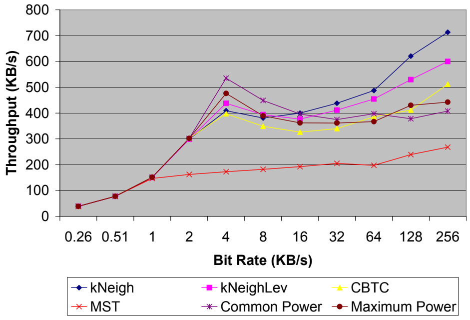

Figure 2. Throughput vs. Bit Rate (n=150)

phase is completed, the CBR sources begin sending using the cached routes. Since nodes are stationary in these simulations, routes remain good for the duration of the simulation and no route discovery packets interfere with this second simulation phase, during which throughput is measured. The GTNetS CBR application sends packets unreliably and, therefore, lost packets are simply dropped and there is no throughput degradation due to acknowledgement packets, recovery of lost packets, nor congestion control.

4. Simulation Results

First, we discuss the behavior of throughput with increasing load and fixed node density. For low node density ($n = 50$), we found relatively small differences between all of the simulated topologies except MST. For all but the lowest bit rates and for all node densities, the throughput of MST is substantially lower (20–25% or more) than any of the other topologies. This indicates that the goal of some topology control protocols to produce the sparsest possible topology is in direct conflict with the goal of maximizing network throughput.

When node density is higher, differences between the topologies emerge. We focus on the $n = 150$ case (see Figure 2), which is the most interesting. In this figure, throughput tracks the maximum possible (150 times the bit rate) up to 2 KB/sec. when collisions and 802.11's RTS/CTS start to impact the results. At moderate bit rates, the differences between topologies are relatively small. However, at higher bit rates, some of the topology control protocols are able to produce significantly higher throughputs as compared to no topology control (Maximum Power). For example, kNeigh's throughput at 256 KB/sec. load is greater than 700 KB/sec., which is almost 75% greater than that of Maximum Power.[1] Both CBTC and kNeighLev significantly outperform Maximum Power as well. These results conclusively show that the use of topology control can produce significant throughput improvements at high loads.

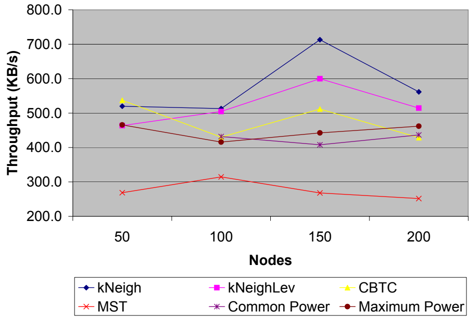

Figure 3. Throughput vs. n (Load = 256 KB/s)

Figure 3 shows throughput performance vs. node density for an offered load of 256 KB/sec. The figure shows that the topology control protocols begin to show throughput improvements at $n = 100$, have dramatic benefits at $n = 150$, and show smaller improvements at $n = 200$. Thus, it is possible that once node density becomes too high, topology control will no longer be able to increase throughput. Verifying this conjecture is the subject of future research.

Some topology control protocols, e.g. [12], ensure that all nodes select a common transmission power, which is typically less than the 802.11 maximum power. In order to set the common power high enough to ensure connectivity, some nodes may end up with a higher transmission power than if heterogeneous power settings are allowed. Figures 2 and 3 show very little difference between Common Power and Maximum Power topologies. This shows that, for the node densities studied, the higher transmission powers of common power protocols do not allow interference ranges to be reduced enough to provide throughput improvements compared to the Maximum Power topologies.

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[1] The min. point of kNeigh's 95% confidence interval is about 35% higher than the max. point of Maximum Power's 95% confidence interval, which is still a substantial difference.

It is also interesting to compare topologies in which transmission powers can be set to arbitrary values to those with a discrete set of power levels. kNeigh and kNeighLev topologies provide such a comparison. The maximum throughput difference between these topologies was about 17% for $n = 150$ and a load of 256 KB/sec, and the discrete kNeighLev topologies still produced significantly higher throughputs than without topology control. This indicates that the use of real network interfaces, which are limited to discrete power levels, does not eliminate the throughput benefits provided by topology control.

One unusual aspect of Figure 2 is the spike in throughput at a load of 4 KB/sec., particularly for Maximum Power and Common Power. As explained previously, the throughputs achieved are the maximum possible up to 2 KB/sec. It appears that the Maximum Power and Common Power topologies continue to track this ideal throughput curve longer than the other topologies. This is probably due to the longer path lengths that are produced when transmission powers are reduced substantially as is the case for kNeigh and CBTC. Longer path lengths mean that the total number of packets in the network is larger. Thus, we expect that the negative effects caused by collisions and 802.11's RTS/CTS occur earlier for these protocols.

5. Conclusion

Results from this study lead to three major conclusions: (1) topology control can produce significant throughput improvement at moderate to high node densities, (2) for the node densities studied, using a common power level does not reduce interference enough to increase throughput, and (3) extremely sparse topologies such as minimum spanning trees have poor throughput performance.

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