A Topology Control Approach to Using Directional Antennas in Wireless Mesh Networks

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***Abstract*— Directional antennas in wireless mesh networks can improve spatial reuse. However, using them effectively needs specialized protocol support at the MAC layer, which is always not practical. In this work, we present a topology control approach to effectively using directional antennas with legacy MAC layer protocols such as IEEE 802.11. The idea is to use multiple directional antennas on each node and orient them appropriately to create low interference topologies while maintaining network connectivity. Our approach is based on a well-known approximation algorithm to compute minimum degree spanning trees. We show via empirical studies that this approach can reduce interference significantly without increasing stretch factors to any appreciable extent. Detailed wireless network simulations also show that this approach improves end-to-end throughput of multihop flows relative to using omni-directional antennas. Three or four directional antennas per network node with only moderate beamwidths are sufficient to improve the saturation throughput of multihop flows by a factor of 3–4.**

I. Introduction

The advantages of directional antennas over more traditional omni-directional antennas in wireless networking are currently well-known. Directional antennas can focus energy in only the intended direction and thus automatically improves *spatial reuse*, an important performance factor in wireless network design. An additional benefit comes from the fact that directional antennas tend to have a longer range when using the same power as omni-directional because it concentrates its energy in one direction instead of spreading it out on all directions. In wireless multihop networks, such as ad hoc or mesh networks, recent studies have shown that directional antennas can contribute significantly to improving capacity relative to their omni-directional counterparts [21].

Simply replacing omni-directional antennas by directional ones in the multihop network, however, is not very effective. Many studies have shown that effective performance improvement needs protocol support in the medium access control (MAC) layer, and thus several new protocols have been developed [6], [16], [11]. Most of these protocols are variations of the commonly used CSMA/CA-based MAC protocols, such as the IEEE standard 802.11 [5].

In this paper, we study the use of directional antennas from a more "practical" perspective, where new MAC protocols for directional antennas are not viable. In recent years, there is a strong interest in wireless mesh networks [1] (as opposed to more general mobile ad hoc networks [12]). These are simply backbone, multihop networks of wireless routers. The applications are typically related to community or metro-area networking where there is a significant demand for bandwidth. This makes use of directional antennas quite appropriate. In mesh networks, the routers are stationary, powered from mains outlet, and portability or small size is not a critical requirement. However, cost realism is an issue, and accordingly use of off-the-shelf radios running standards compliant protocols is important. Proprietary MAC layer protocols are thus ruled out. These requirements prompted us to look at the use of directional antennas from a completely different angle – from a more upper layer's point of view. Instead of using either steerable beam or switched beam directional antennas that can potentially communicate in *any* direction, we use low-cost, non-steerable directional antennas. Essentially, we ask ourselves this question: can we provide each node of the mesh network with multiple directional antennas and *orient* them appropriately to form interesting topologies such that some notion of network capacity is improved? Of course, one constraint is to use a legacy MAC protocol (e.g., 802.11). Such a system can see deployments in practical settings and can provide improved performance.

The rest of the paper is organized as follows. In Section II we provide a background of the problem and provide a formulation. Section III describes the algorithm. Section IV describes the performance of the algorithm in terms of topological properties as well as using a detailed wireless network simulator. Section V describes the related work. We conclude in Section VI.

II. Background and Problem Formulation

In this section, we briefly describe the node and antenna model. We use mesh networks with omni-directional antennas as a base case and point of comparison. Let us denote that transmission range of the omni-directional antenna is R_o, and that of the directional antenna is R_d. If the directional antenna beamwidth is θ and the same transmit power is used at the radio for both the directional and omni-directional cases, the ratio R_d/R_o is equal to $2/\tan(\theta/2)$ following the model given in [13].

We assume that each node has k directional antennas each with beamwidth θ. We assume that the antennas are connected to the radio interface via a switching logic. At the listening state the radio interface listens on all antennas. The signals are simply combined before they reach the radio. For transmission, the radio chooses an appropriate antenna to transmit. The other antennas are turned off. For reception also only one antenna is typically used. This is accomplished by the switching logic by monitoring the signal power incident on all antennas. If the power is more than the *receive threshold* of the radio interface (i.e., enough power for the radio to be able to receive successfully) on any one antenna, only that antenna is kept active; the rest of the antennas are turned off. This can be accomplished during the data packet's physical layer preamble. This technique reduces probability of collisions due to different packet receptions on different antennas that are overlapped in time. Note that our topology control technique is meaningful even without such switching logic. However, in the modeling and experiments that follow we assume such apparatus for improved performance.

Now, assume that we are given a mesh network with an omni-directional antenna on each node such that the network topology graph is connected. We want to replace the omni-directional antennas with k directional antennas on each node, each with beamwidth θ ($k\theta < 360°$). The essential topology control problem now is how to *orient* the k antennas on each node such that the network still remains connected and some notion network throughput is maximized. Since we do not have any direct mechanism to model network throughput in graph theoretic terms, we will assume that maximizing throughput is equivalent to *minimizing interference.* Interference can be modeled relatively directly. For transmission on each link the number of nodes that are able to hear this transmission provides a metric to model interference. This interference metric can be evaluated directly from the network topology. Existing literature has also considered similar metrics in topology control problems [3].

However, with the use of directional antennas, the connectivity in the network (denoted by the average node degree) reduces. While this reduces interference; this may also increase path lengths in the network for multihop flows. A multihop flow now will need to make additional hop-wise transmissions to reach the destination, and thus will create (and be exposed to) additional interferences. Thus, care must be taken so as not to increase average path lengths too much (relative to the base omni-directional case) that will undercut the improvement in the interference measure.

Based on the above discussion, an optimization problem arises: k directional antennas on each node are to be oriented such that the network connectivity is preserved, and the total interference experienced along the shortest path (sum of the interference metric for all links on the path) between a node pair – averaged over the shortest paths between all pairs of nodes – is minimized.

This is a hard problem. To see this, let us make some simplifying assumptions (we will relax these later). Assume that the transmission ranges for directional and omni-directional antennas are the same (i.e., $R_o = R_d$), and that θ is arbitrarily small such that a node can communicate with only one neighbor using one directional antenna. Assume that $G = (V, E)$ is the unit-disk graph modeling the network created

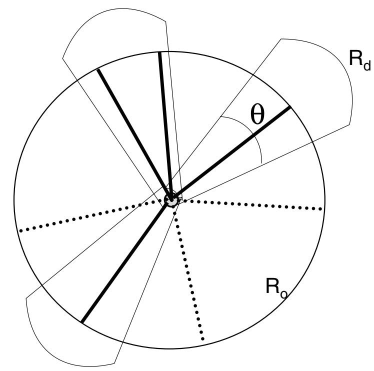


Fig. 1. Operation of the algorithm. The thick edges are chosen by the algorithm to create a minimum degree spanning tree, leaving out the dashed edges. The three ($k = 3$ here) antennas are oriented such that the thick edges are covered.

by omni-directional antennas on all nodes. Then, the above optimization problem becomes equivalent to determining a spanning subgraph $G' = (V, E')$ of G such that the maximum node degree in G' is k and G' also has additional structural properties that either constrain or minimize interference. However, even discounting these additional structural properties, the simpler question of deciding whether a given graph G has a spanning tree with maximum degree k is NP-hard [4]. Thus, computing a subgraph G' with maximum node degree k is NP-hard as well. However, polynomial-time approximation algorithms do exist in literature that can compute the minimum degree spanning tree of a graph within one from the optimal degree [4] that form the basis of our technique used in this paper.

For tractability reasons, we solve the simpler problem of orienting k antennas on each node such that the connectivity is preserved. We expect that the reduced node degree will help reducing interference enough that specific constraint on the interference is not necessary. Thus, we do not use any explicit interference constraint. We use a technique based on an existing approximation algorithm that computes a minimum degree spanning tree for a given graph within one more than the optimal [4]. Relaxing the assumption of very small θ, the problem now becomes one of computing a subgraph $G' = (V, E')$ of a unit disk graph $G = (V, E)$ such that all outgoing edges of a node can be divided into at most k groups such that the maximum angle subtended at that node by any pair of edges in the same group is at most θ.

III. Algorithm Description

Our technique is based on Fürer and Raghavachari's algorithm on approximating a minimum degree spanning tree [4]. This algorithm is remarkably efficient. It runs in time that is slightly more than the product $|V||E|$, and produces a spanning tree with a maximum degree that can be *at most one* more than the optimal. The basic idea is to start with the network graph $G = (V, E)$ formed by using only omni-directional antennas. We run Fürer and Raghavachari's approximation algorithm on G to determine a minimum degree spanning tree $T = (V, E')$. The algorithm works as follows. It starts with a random spanning tree T and iteratively improves on it. Let d denote the degree of T. Let S be the set of vertices having degree d or $d-1$ in the current spanning tree. Let $T_1, \ldots, T_r$ be the subtrees comprising $T - S$. The algorithm terminates if there is no edge between these subtrees. If, on the other hand, there is an edge between the subtrees T_i and T_j, this edge is inserted in T and another suitable edge is removed from T resulting in a spanning tree with fewer vertices having degree at least $d - 1$. Thus, the degree of the spanning tree T is iteratively reduced. One can show that number of iterations is $O(n \log n)$.

After the algorithm terminates, we use k arcs of angle θ and radius R_d on each node to cover all edges in E'. These arcs represent individual directional antennas. See Figure 1. In rare cases, this approach may fail as k and θ are fixed in advance and some edges cannot be covered. This can happen, for example, when the maximum degree of T is larger than k, and θ is not large enough to ensure that more than one edge of the maximum degree node can be covered by one antenna. In such cases, we use omni-directional antennas in these nodes. This provides a fail-safe mechanism to keep the network connected. However, in the simulation experiments that we ran, we used reasonably large values of θ (corresponding to inexpensive, off-the-shelf antennas), and we never came across such a situation.

This is a centralized algorithm that could be run from a central network operation center or a central management switch, depending on the actual network architecture. While distributed algorithms to solve this problem will be interesting, we feel that it is not of a significant value. In practical settings a mesh network topology will not change at any fast time scale. Thus, the topology can be computed at a slow time scale or on demand when new nodes are added or nodes are taken down. This can be done centrally. Antenna orientations can be changed simply by attaching servo or stepper motors at the antenna base.

IV. Performance Evaluation

We have evaluated the performance of our method by a set of comprehensive simulations on the qualnet network simulator [17]. All simulations are done with a network of 100 randomly placed nodes, the "nominal" transmission range of each node being 70 meters, when using omni-directional antennas. The nodes are placed randomly in a square area of varying size depending on a density parameter. This enables us to evaluate the impact of varying spatial density.

The following experimental parameters were used.

- The field size is varied from 300 and 500 square meters so that the network topology is varied from sparse and dense extremes. The extreme ends correspond to *average* node degrees of approximately 5 and 13, respectively.
- Three different antenna beamwidths have been chosen (30°, 45° and 60°) – corresponding to commonly available low-cost directional antennas.
- The number of antennas at each node is chosen to be either 3 or 4. Note that only 2 antennas make the problem equivalent to the Hamiltonian path problem. We felt that more than 4 antennas are too many from practical set up point of view.

For the simulation experiments shortest path (in number of hops) routing is used. Since the mesh network is stationary, for the purpose of the reported experiments it is sufficient to set up shortest path routes at the beginning of the experiments by running any shortest path routing protocol. The routing protocol is run only at the beginning and not during the experiments so that purely application performance can be measured without any interaction from the routing protocol.

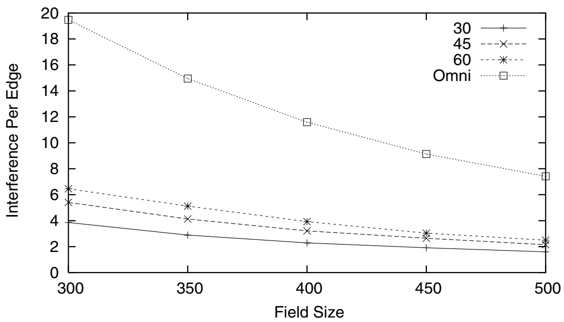
Three performance metrics are evaluated. The first two correspond to *topological properties* of the network graph – i) *average interference per network link*, and (ii) *average stretch factor*. Interference for a network link is represented by the number of nodes that are interfered by this link (i.e., the number of nodes that will defer to the transmission on this link). For omni-directional antennas, this metric for a link (u, v) is the number of nodes that are within a distance R_o from the transmitting node u. For directional antennas, this is the number of nodes (e.g., x) such that x is within a distance R_d from u, and x is within an antenna beam of u, and vice versa. The interference metric is averaged over all links in the network.

Solely evaluating interference per link is not sufficient. This is because as the topology control limits the network degree, the hop-wise distance between node pairs can increase. This will make a multihop flow to traverse more hops (make more transmissions), thus potentially increasing overall interference. Thus, we also evaluate the *stretch factor*, which represents the ratio of the shortest path lengths with directional antennas (as oriented by our algorithm) and omni-directional antennas in the mesh network. This quantity is averaged over all node pairs in the network to determine the stretch factor.

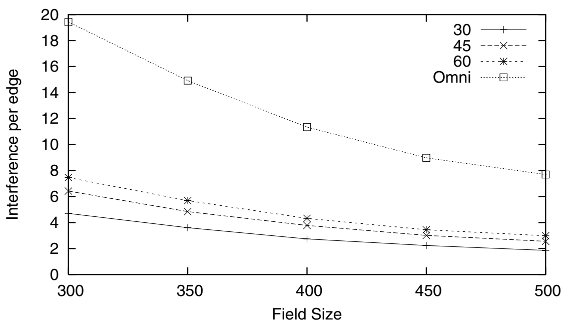
Interference and stretch factor are evaluated directly on the network graph for the omni-directional and directional cases, without requiring qualnet simulation. While evaluation of such topological properties provide us with insights into the topology control aspects, it still does not directly show how *application-visible throughput* might improve with the use of directional antennas. To evaluate application-visible throughput, qualnet simulations are run for both omni-directional and directional antenna cases – complete with the 802.11-based MAC layer model and appropriate antenna models in the physical layer. A set of CBR flows are set up between random source-destination pairs. The packet delivery fraction is evaluated as a measure of application-visible throughput for long-running simulations.

A. Evaluating Topological Properties

Figures 2(a) and (b) plot the average interference per link with varying density of the network (from dense to sparse)

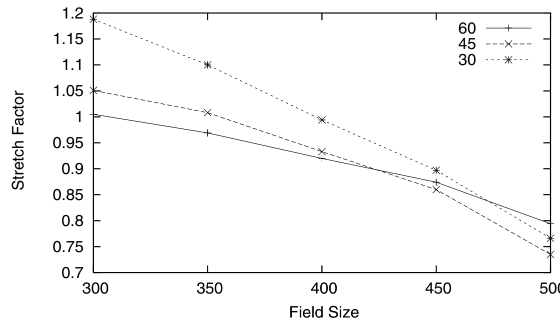


(a) 3 antennas per node.

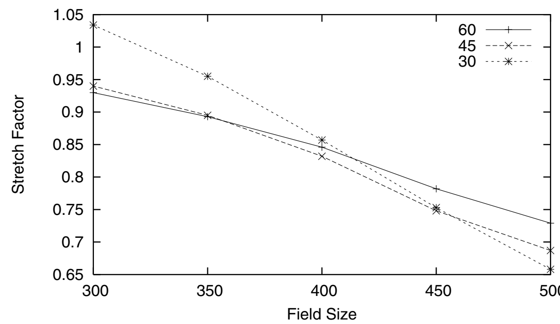


(b) 4 antennas per node.

Fig. 2. Average interference per link with different beamwidths.



(a) 3 antennas per node.



(b) 4 antennas per node.

Fig. 3. Average Stretch factors with different beamwidths.

and with different beamwidths. It is seen that as the field size increases (i.e., the network becomes sparser) the interference decreases as each node has fewer neighbors to interfere with. For the same reason, interference decreases with decreasing beamwidth, as the antenna has more limited coverage decreasing the number of neighbors. Similarly, with 4 antennas interference is slightly more than with 3 antennas.

Figure 3(a) and (b) plot the average stretch factor with varying density of the network. We notice two distinct phenomena here. First, the stretch factor decreases with decreasing density. Second, as the density decreases, antennas with smaller beamwidth perform better than antennas with larger beamwidth. Notice the cross-over of the curves.

B. Evaluating Application Visible Throughput

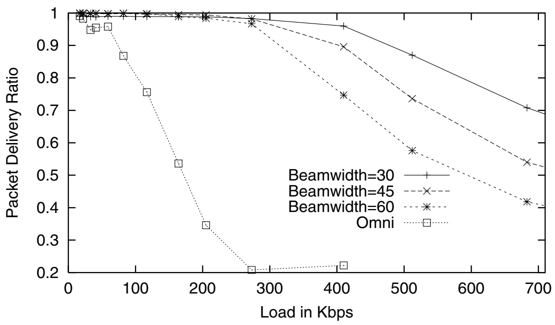
Here, we present the throughput measurements performed in the qualnet simulator on application traffic. Two networks are used with 100 randomly placed nodes: sparse (500 sq meters area) and dense (300 sq meters area). The network topology is computed when omni-directional antennas are used using the nominal transmission range of omni-directional antennas. This topology is used as the input to compute the orientation of the directional antennas. Figure 4 plots the packet delivery fraction for 50 CBR flows the network between a random set of source-destination pairs, for 3 and 4 directional antennas per node and various beam-widths. Each point in the plots is the average for six different random networks. The omni-directional performance is shown for comparison. The packet rate on the CBR flows is increased to increase the offered load in the network. The plots clearly demonstrates the much superior performance with directional antennas. Roughly the packet delivery plots start dropping significantly for the directional cases at roughly 3-4 times larger offered load. This represents a 3-4 fold increase in application visible capacity of the network.

Note that for a sparse network (500 sq. meters field size, Figure 4(a),(c)) small beamwidth antennas work better. This is also confirmed from the stretch factor and interference plots presented earlier. Note the sparse extreme of those plots. On the other hand, for a dense network (300 sq. meters field size, Figure 4(b),(d)) stretch factor favors the large beamwidth whereas interference favors the small beamwidth antenna (see the prior plots). These two factors compete against each other; but overall still small beamwidths tend to perform better.

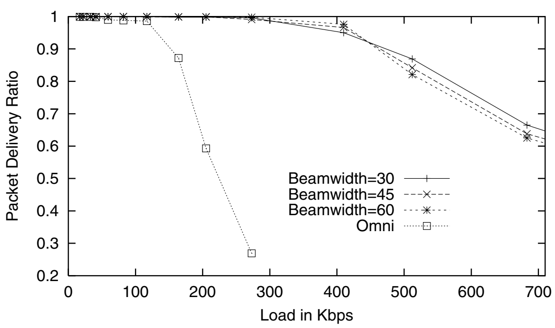
V. Related Work

There are two sets of related work for our approach — MAC protocols that utilizes directional antennas and topology control approaches in multihop wireless networks.

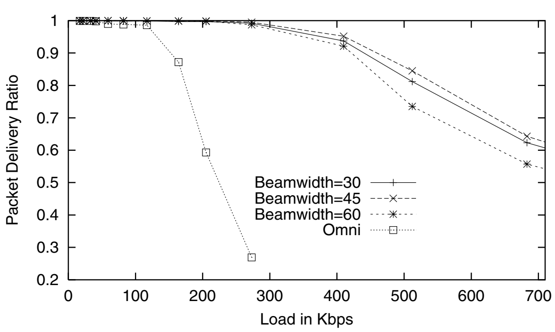
Ramanathan in [13] did a broad-based analysis of the



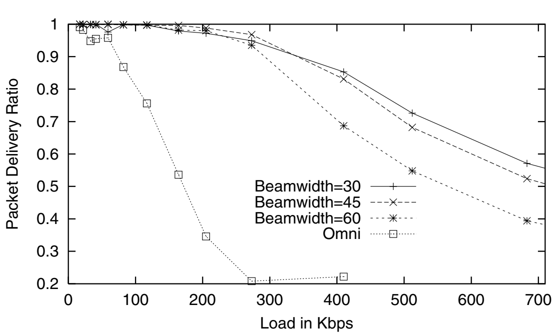
(a) 4 antennas per node. Sparse network.



(b) 4 antennas per node. Dense network.



(c) 3 antennas per node. Sparse network.



(d) 3 antennas per node. Dense network.

Fig. 4. Packet delivery fraction for qualnet simulations with 100 nodes and 50 flows.

impact directional capabilities of antennas may have on network performance and protocol support needed to support directional antennas effectively. In [6] the authors argued that conventional MAC protocols such as 802.11 are not suitable in presence of directional antennas. Since then several MAC protocols were proposed to effectively use the directional antennas capabilities. Examples include [6], [11], [18]. An experimental testbed using directional antenna based ad hoc network has been described in [15]. These works differ in the exact directional antenna model used and on hardware assumptions such as availability of location information, angle of arrival information, etc. They often address specific MAC layer problems that arise (such as deafness or new forms of hidden terminal problem) due to the use of directional antennas.

In our knowledge, there has not been any prior work on topology control using directional antennas. However, several approaches are close to our work in spirit as they directly or indirectly seek to create subtopologies that have lower degree and thus lower interference. In [2] authors propose to use the *Relative Neighborhood Graph (RNG)* for topology initialization in wireless networks. The network topology thus derived has been reported to give good overall performance in terms of power usage, interference and reliability. In [8] authors propose a *Local Minimum Spanning Tree* algorithm, where the topology derived preserves connectivity and the degree of any node in the resulting topology is bounded by 6. In [9] authors present *Localized Delaunay Triangulation*, a localized protocol that constructs a planar spanner of a given unit disk graph. The topology contains all the edges that are both in the unit disk graph and the delaunay triangulation of all nodes. It is proved that the shortest path in this topology between any two nodes u and v is at most a constant factor of the shortest path connecting u and v in the unit disk graph. In [19] the authors present an algorithm for localized construction of a *bounded degree planner spanner*. It provides very good results in simulations, but the bound on the highest degree of a node is large (approximately 19).

Finally, a significant amount of research has been performed for topology control approaches in the context of transmit power control (TPC) either to conserve power or to reduce interference. See, for example, [7], [10], [14], [20].

VI. Conclusions

In this work, we presented a topology control approach to using directional antennas in wireless multihop networks. The goal is to design a system using simple directional antennas and legacy MAC layer protocols (such as 802.11) and find orientations of the antennas so that network remains connected. The problem is addressed by assuming that a reasonable number of directional antennas (k) are available on each node that can be oriented (statically) at will, and then using a known approximation algorithm to create a minimum degree spanning tree. Interference metrics or resultant changes in path lengths are not directly controlled. However, evaluations show that the resultant topology has low interference and stretch factor.

Simulations using the qualnet simulator demonstrate that with only 3 or 4 antennas on each node with beamwidths between 30°– 60°, it is possible to increase the end-to-end saturation throughput for multihop flows by a factor of 3–4. There is a tendency for small beamwidth antennas to perform better. This presents a significant opportunity for using commodity directional antennas to improve performance in a wireless mesh network even with legacy 802.11 MAC protocol.

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