An Integrated Scheme for Fully-Directional Neighbor Discovery and Topology Management in Mobile Ad hoc Networks

Ece Gelal, Gentian Jakllari, Srikanth V. Krishnamurthy and Neal E. Young
Dept. of Computer Science and Engineering University of California, Riverside
{*ecegelal, jakllari, krish, neal*}*@cs.ucr.edu*

***Abstract*—With directional antennas, it is extremely important that a node maintains information with regards to the positions of its neighbors. This would allow the node to "track" the neighbors as they move; otherwise, a node will have to resort to either omnidirectional or circular directional transmissions (or receptions) fairly often. This can be overhead intense and can reduce spatial reuse. Maintaining directional information with regards to a large number of neighbors can itself be expensive; therefore it is important to limit a node's degree. We propose a topology control scheme (Di-ATC) that works with fully directional communications and offers a low degree bound while preserving network connectivity. The key idea is to execute Di-ATC on the discovered neighbors to select and maintain connectivity with only a subset of these neighbors. The members of this subset are those with high angular separations. We perform extensive simulations and demonstrate that our scheme effectively limits node degree while at the same time, preserves network connectivity and achieves low path stretch.**

I. INTRODUCTION

Performance improvements offered by the deployment of directional antennas in ad hoc networks have been well explored within the last decade; [5], [10], [19], [26] have quantified these performance benefits from the perspective of physical, MAC, and routing layers. Recently, [7], [12] and [20] proposed the use of directional antennas for increasing capacity in wireless mesh networks. With directional antennas, a node can directionally transmit and/or directionally receive. In order to fully exploit the potential spatial reuse and range offered by directional antennas, as well as to avoid problems due to asymmetry, it is desirable to use *both* directional transmissions and directional receptions [11], [9]. However, the use of *fully-directional* communications leads to two major challenges: **neighbor discovery** and **dealing with mobility**. The first important problem has been addressed in [9] and [28]; nodes incorporate random beamforming and send/listen for HELLO messages to discover each other. The second challenge with fully directional communications is that, with mobility the *neighbors* of a node are likely to move out of its *angular range* easily, especially when narrow directional beams are used. In [9], the authors proposed that nodes should periodically *poll* each other to cope with this effect. The periodic polling (sending/receiving HELLO messages) ensures that every node *tracks* the motion of its neighbors and hence, preserves connectivity with each neighbor until the neighbor moves out of its *radial range*. By thus proactively maintaining its neighbors' position information, a node obviates the need to *rediscover* a particular neighbor when it needs to communicate with this neighbor. Hence possible delays and the overhead of reactive neighbor discovery are eliminated [9][28]. On the other hand, the polling process itself could be expensive in terms of energy and bandwidth (unless the network is sparse and mobility is low, which cannot always be guaranteed in real scenarios). The overhead in extreme cases may nullify the gains provided by directional antennas.

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To alleviate the above problem, it is necessary to limit the overhead incurred due to the polling (i.e., to reduce the number of exchanged HELLO messages). Clearly, reducing the frequency of such messages is not an option as the frequency is dependent on speed of motion of the nodes in the network; decreasing the periodicity would trade-off the accuracy of the neighborhood position information. Alternatively, the overhead can be alleviated by requiring that nodes maintain logical connectivity with only a *subset* of their neighbors. In other words, if the maximum node degree of the network were

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to be bounded (by a low constant), the aforementioned overhead could be contained. This necessitates topology control.

Although topology control has been well studied in the last decade, there is little work on networks that use only directional communications. To the best of our knowledge, the few research studies on topology control using directional antennas either resort to temporary omni-directional communications, or are centralized, or assume that all nodes in the wireless network are stationary.

In this paper, we propose a novel scheme that integrates topology control with neighbor discovery and maintenance. The key idea is that nodes maintain/track only a subset of their discovered neighbors. Nodes choose this subset based on the angular separation between their existing neighbors and their node degrees. Towards this, nodes execute our heuristic-based topology control scheme, Di-ATC. Di-ATC tries to minimize the variance of the angular separation between the tracked neighbors of a node. The goal is to construct a well spread topology; the feature is attractive for reducing the *path stretch* and for preserving network *connectivity*. Note that this objective is challenging since node degrees and the shortest-path hop counts are inversely related [6], [29]. Furthermore, the solution to address this problem must be distributed and must not require global knowledge in order that it may find application in practical deployments. Finally, the approach must be lightweight and must use the system resources (power, bandwidth) efficiently. Our approach addresses these requirements. Specifically, the key properties of our integrated scheme are:

- *Fully directional communications.* Di-ATC is tightly integrated with neighbor discovery and maintenance using *fully-directional*[1] communications. Omni-directional transmissions or receptions are not invoked. This approach eliminates known problems that arise due to the inter-play between directional and omni-directional communications viz., deafness and asymmetry in range.
- *Scalable.* Our approach is fully decentralized (no specialized nodes are assumed) and relies only on local information.
- *Low degree bound.* Di-ATC imposes a low bound (six) on the node degree and thus constructs a sparse topology. Simulation results in practical settings demonstrate that the average node degrees are smaller than the imposed bound, even if the original network were to be extremely dense.
- *Connectivity and low path stretch.* With high probability, with our integrated approach, the network is connected. Our approach also offers low path stretch in the topology formed, i.e., routes between any two nodes in the network are stretched by small factors in spite of the low degree constraint.
- *Low complexity.* Di-ATC introduces no communication cost to the network. Topology control decisions are based on the unicast messages exchanged with the discovered neighbors; hence, no broadcasts are necessary to gather/update topology information.
- *Applicable to mobile scenarios.* Our approach supports mobility; we demonstrate its effectiveness in typical mobile scenarios.

We perform extensive simulations using OPNET, to validate our scheme with realistic antenna models. We observe the performance of the integrated scheme, in terms of average node degree and average path stretch of the topology constructed via the invocation of Di-ATC.

The rest of the paper is organized as follows. We summarize related research efforts in Section II. We present the details of our system model in Section III. We describe our integrated scheme and present Di-ATC in Section IV. In Section V we evaluate the performance of our proposed scheme in a large set of possible scenarios, and we conclude in Section VI.

II. Related Work and Importance of Problem

Novel MAC [5], [10], [11], [19] and routing [22], [23], [24] protocols have been designed for use with directional antennas in ad hoc networks. A MAC protocol for use with directional antennas must help combat the problems of *asymmetry in range* and *deafness*. Korakis et al., showed that asymmetry in range can be prevented by allowing *only* directional communications [11]. Efforts in [4] and [17]

[1]Throughout the paper, "transmission (reception)" refers to "*directional* transmission (reception)". The incentives for employing only directional communications are explained in more detail in [9] and [11].

proposed methods to combat *deafness* (a node attempting to communicate with a node that is itself in the process of transmission). In [9] deafness is avoided via scheduled directional communications. The work also describes why resorting to omnidirectional transmissions or receptions degrades possible spatial reuse of the spectrum and reduces possible extension in range.

Many routing protocols require that at least one-hop neighborhood information is available at the nodes. Omni-directional broadcast of HELLO messages are not accurate in providing *directional neighborhood* information (given the different antenna footprint); therefore novel neighbor discovery and tracking mechanisms have been proposed [9][27][28]. Towsley et al., study directional neighbor discovery in static ad hoc networks [28]. They present a probabilistic analysis of neighbor discovery with a slotted, synchronous scheme (called "Direct discovery"); they also propose an asynchronous[2] indirect scheme (called "Gossip-based discovery").

In [9], Jakllari et al., proposed a framework for neighbor discovery and maintenance. The approach uses *only* directional communications; hence, synchronization is assumed as in [28]. With the proposed scheme, nodes need to periodically *poll* their neighbors for maintenance (i.e., each node would exchange HELLO messages with its neighbors so that it can update the AoA[3] information with regards to each of these neighbors). This introduces a messaging overhead, which may lead to significant reduction in throughput in dense deployments or with node mobility. To remedy this problem our integrated scheme constrains the nodes to *poll* only a subset S of their discovered neighbors; they reach the rest of the neighbors via the the nodes in S.

Research on topology control has so far focused on minimizing the overall energy consumption [2][13], bounding the node degree [14][16][29], and reducing the interference to increase effective network capacity [3]. Most topology control solutions in literature attempt to optimize several of these design goals. In particular, many algorithms have been proposed for constructing connected topologies with bounded node degree *and* optimal power consumption (under the degree constraint). These solutions reduce node degrees by adjusting the transmission power in order to avoid long-distance, power-intensive communications [2][14][25][29]. Most of these solutions are distributed and localized; however they have been designed for ad hoc networks that use omni-directional communications, and their implementation with directional antennas will likely introduce the aforementioned asymmetry in range and deafness issues. Furthermore, the problem under consideration will not be the same problem when directional antennas are used, due to two crucial differences at the physical layer: *i)* with a high-gain directional antenna, farther neighbors can be reached without requiring a power increase (*no power overhead*), and *ii)* communicating with farther neighbors does not imply higher interference on other neighbors due to the beamforming property of directional antennas (*no interference overhead*). Another limitation common in most of the aforementioned previous schemes is, their worst case bounds are computed assuming static ad hoc networks, and they are not evaluated under practical conditions of mobility.

A recent study addresses topology control using beam-switching directional antennas [18]. The authors present a centralized algorithm to optimize power consumption in the network where nodes are equipped with switched-beam antennas that may not have uniform gains within the beamwidth. The solution does not consider the cost of having high node degrees, or the effects of mobility.

To the best of our knowledge, the only work on topology control for bounding the node degree in directional antenna-equipped ad hoc networks is [8]. In this work, Huang et. al proposed the implementation of the "Cone-based topology control algorithm", previously proposed for omni-directional antennas [30][13], using sectorized antennas. The scheme suggests neighbor discovery via HELLO messages sent in each sector with increasing power, so that the closest neighbors in each sector are identified. This implementation necessitates the use of both directional *and omnidirectional* modes of communication, which leads to problems of asymmetry and limited spatial reuse. The performance evaluation of the proposed scheme has been performed only in a static ad hoc network and it is unclear if the approach is amenable to mobile scenarios.

Recently, use of directional antennas in wireless mesh networks has attracted interest. In [12], the authors have proposed topology control on mesh net-

[2]In this second algorithm, the synchronization requirement is obviated via the integration of omni-directional receptions.

[3]AoA represents the Angle of Arrival and it aids determining the neighbors' relative positions [26].

works by deploying multiple directional antennas at each node and properly orienting the antennas to create multiple low-interference topologies that are connected. Raman et.al. present a mesh network implementation wherein each node is equipped with two high-gain directional antennas [20]; their measurements showcase the potential for using directional antennas to provide low-cost rural connectivity.

III. System Description

In this section we elaborate on how the directional antenna and the environmental factors are realistically constructed given the simulation platform used.

Network Model: Nodes are placed arbitrarily on the two-dimensional plane. Note that an "arbitrary" distribution of nodes includes by definition, the existence of non-uniformly spread out, sparse and dense regions; thus it contains the scenarios that are possible in real deployments. All nodes in our network model have distinct IDs (e.g. the MAC addresses). All nodes use the same, fixed transmission power. All transmissions and receptions are performed directionally. A pair of nodes u and v in the network can directly communicate if they lie within the *radial communication range* of each other; this is the maximum distance between u and v such that the (directional) transmission of node u can be (directionally) received at node v and vice versa. With this, u is a *neighbor* of v and vice versa.

Antenna Model: Our design assumes that each node in the network is equipped with a steerable antenna system, i.e., each node is capable of pointing its antenna in any desired direction. However, our scheme is also applicable with beam-switching antennas (with little modification). The antenna model used in our simulations includes a main lobe and a small backlobe; it is explained in detail in Section V.

System Model: Our system assumes a time-slotted, synchronous model as in [28], [9]. As mentioned, synchronization is necessary for neighbor discovery using fully directional communications. The duration of the time slots is equal to the duration of the (corresponding) packet exchange[4]. As in previous work (e.g. [30]), we exploit the capability that a receiver can deduce the direction of a sender. This can be accomplished using estimation techniques that provide Angle-of-Arrival (AOA) information [30], [26].

Channel Model: Our integrated scheme does not rely on any assumptions with regards to the channel model. In our simulations we use the path loss propagation model. With this model, the power of a received signal is calculated as a function of many factors, including the relative positions of the nodes, the directions of the two antennas and the gain of each antenna along that direction [1].

Mobility Model: In our simulations, we use the most commonly used "random waypoint mobility model". With this model, each node moves towards an arbitrarily chosen point within the two-dimensional area (of deployment) with a speed it selects from a uniform distribution. After reaching this point it is stationary for a specified pause time; after the pause time the node moves towards another arbitrary point on the region. The model causes continuous changes in the network topology. In our simulations we experiment with different velocities.

IV. Directional Neighbor Discovery - Topology Control - Tracking

In this section using directional communications and we present our framework for topology control integrated with neighbor discovery and maintenance in the wireless networks of interest.

A. Topology Control Problem Statement

Our design objective is to **fully exploit the longer radial range** offered by directional antennas. Thus, we do not consider power control to bound the physical node degrees, as proposed in [8]. Specifically, our proposed topology control scheme works hand-in-hand with *purely directional neighbor discovery*, that is, a node's ability to discover its neighbors if *both* the node itself and the neighbor are using directional beamforming [9], [28]. Our goal, as stated in Section I, is to design a scheme where *all* communications (neighbor discovery and all packet exchange with neighbors) are fully directional, which *(i)* ensures that problems due to fully directional communications (deafness and asymmetry in range) are not factors, and *(ii)* limits the overhead incurred in achieving our objective. In addition, we wish to ensure that the network is connected at all times and the path stretch after topology control is low.

Towards this, we propose Di-ATC ("Angular Topology Control with Directional Antennas")

[4]HELLO packets exchanged for neighbor discovery, packets exchanged after topology control, and packets for rendezvous are small packets; therefore the slot times are short.

which bounds the maximum node degree by a tight (Definition 1) constant.

Definition: We say that the imposed degree bound d is *tight* if $d - 5$ is small, where $d \geq 5$. This definition follows from Lemma 1 below which states that reducing the node degree to less than 5 could lead to loss of connectivity (with the unit disk graph model).

Lemma 1. For a subgraph S of the unit disk graph U, the connectivity of S *cannot* be guaranteed if the maximum node degree in S is less than 5.

Proof. Consider the star topology (using the unit disk model), where the central node (say w) has five neighbors such that: *i)* each of the neighbors are a unit distance away from w, and *ii)* it is infeasible to connect any two of these neighbors with direct links (they are more than a unit distance apart)[5]. In this case, if an edge is removed between w and one of its neighbors (i.e., the degree of w is reduced to four), the topology becomes disconnected. □

Reducing the node degrees in the network has an adverse effect on the hop count of paths between node pairs. This is intuitive, since larger node degrees in the network indicates the existence of additional logical links and therefore enables a node to construct a *shorter* path. On the other hand, paths could become longer in sparser networks. To cope with this effect, Di-ATC imposes that the few neighbors that a node maintains should be maximally apart around this node in terms of angular separation.

B. Proposed Integrated Framework

Our proposed framework integrates three functionalities: directional neighbor discovery, topology control on the discovered nodes, and directional maintenance of the neighbors that are chosen by the topology control. The scheme executes in cycles, as represented in the state diagram in Figure 1. All three functions are performed by each node in the network, in every cycle. We explain the details and the importance of each functionality below.

Neighbor Discovery and Topology Control: Both neighbor discovery and topology control are fundamental for the efficiency of protocols at the MAC and routing layers. The problem of identifying the "neighbors" of a node becomes challenging if only directional communications are to be used.

[5]Note that in the star topology this construction is possible and can be easily verified [6], [15].

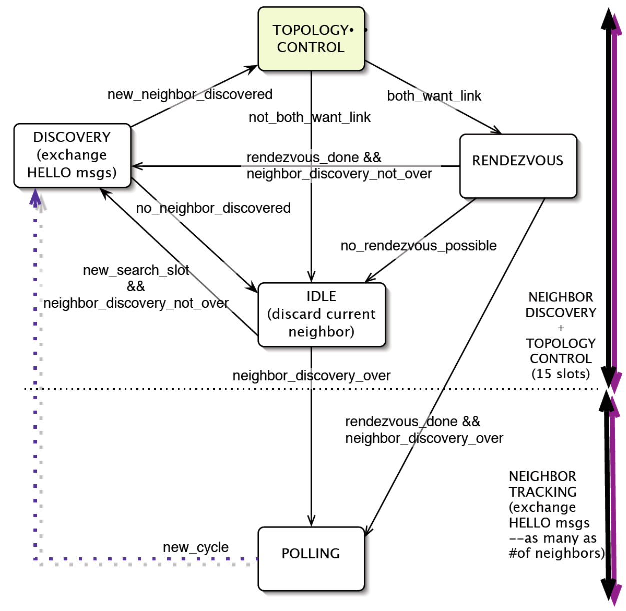


Fig. 1. State diagram depicting the stages of our integrated scheme.

Furthermore, this set of "neighbors" of a node is prone to changes owing to the mobility of nodes or changes in the environment (specifically the variations in channel quality due to shadowing and fading in a dynamic environment). To avoid losing and re-discovering directional neighbors (which is bandwidth and energy consuming), nodes could *maintain* their neighbors by periodically *updating* their locations. However, as discussed before, it is not desirable to maintain all discovered neighbors as one-hop relays. The choice of the most appropriate (considering the optimization criteria) subset of neighbors to maintain is determined by topology control.

Di-ATC differentiates itself from existing work in its execution; it adapts to the probabilistic nature of purely directional neighbor discovery. With directional neighbor discovery, at predetermined discovery instants (or time-slots [9], [28]) each node beamforms to point in a randomly chosen direction; it then either transmits a HELLO packet in this direction or listens to receive from this direction. If a successful transfer occurs, the node to first receive the HELLO message responds with one of its own to complete the handshake. The successful handshake implies that the node pair under discussion have discovered each other. Directional neighbor discovery is a continuous process; nodes attempt to discover new neighbors as the topology changes due to mobility. As shown in Figure 1, in each cycle several time-slots[6] need to be allocated for the directional search for new neighbors. In particular, with purely directional communications -due to the probabilistic nature of the neighbor discovery process- it takes many cycles until nodes discover a fair percentage of their neighbors [9][28].

Di-ATC is executed at each node to identify the subset of discovered neighbors with which the node will maintain direct links. The other neighbors are reached via multi-hop paths through the neighbors that are in this subset. Di-ATC is invoked for every new neighbor that is discovered. A decision as to whether or not to from a link with this new neighbor is made based on the topology information available at that time. This local and dynamic decision making property of our proposed scheme renders the approach scalable and operable under conditions of mobility. Next, we describe Di-ATC in detail.

Angular Topology Control with Directional Antennas (Di-ATC): Our goal is to construct a topology, where the maximum node degree is bounded by a *tight* constant, and any two neighbors of a node are as far apart (in terms of angular separation) as possible without undermining the connectivity of the network. The latter objective has two implications on the constructed topology. *First*, the formation of isolated clusters is prevented if the input topology is connected. *Second*, for any pair of nodes, the path stretch (after the invocation of Di-ATC) as compared to the shortest path in the absence of topology control is extremely small, as evinced by our simulation results. Furthermore, for small beamwidths (of $\leq 52^\circ$ – for a degree bound of 6) Di-ATC limits the number of neighbors in any chosen antenna direction; this decreases contention among the directional transmissions and thus the overall interference levels experienced in the network are reduced.

A node u executes Di-ATC upon discovering a new neighbor v, and determines whether to keep this neighbor given the *spatial distribution* of its existing neighbors (those that have been previously discovered and are being logically maintained). Next, the pair of nodes u,v exchange the outcome of their topology control execution for the corresponding link (u, v). The new link (u, v) is established, if both u and v individually *want* this link (the criterion that determines this decision is elaborated on in the following discussion) *and* can reliably exchange messages to *agree* upon the link construction.

[6]As mentioned in Section III, synchronization at the level of time-slots is necessary to facilitate fully directional neighbor discovery. It can be realized via proposed solutions such as [21].

Node u decides whether to maintain a new node v based on its own current degree, current degree of v (the HELLO message should include the degree of the sender), the angular distribution of its links with its existing neighbors, and the imposed bound on node degree. In determining the angular distribution, u computes the angles between node pairs in its logical neighbor set (the relative directions of the neighbors are obtained using the AOA information [26][30]). Given the imposed degree bound d, u *wants* to add a link to the newly discovered node v, if **any** of the following conditions hold:

- its current node degree ($deg(u)$) is less than d, or
- $deg(u)$=d, but u does not have any other neighbor within $\Theta = \lceil 360/(d + 1)\rceil^\circ$ of the link (u, v) (If this case occurs, u has at least two other neighbors that are angularly apart by less than Θ. u will remove either of these links in favor of adding the link (u, v).), or
- $deg(u) = d$ and u has a neighbor z such that the angle between links (u, z) and (u, v) is less than or equal to Θ, but $deg(v)$ is strictly smaller than $deg(z)$. (In this case u will attempt the removal of link (u, z) in favor of adding the link (u, v).)

The first condition implies that if node u has fewer neighbors than the degree bound imposed by Di-ATC, it will add the additional neighbor. This behavior favors the connectivity of the network as well as the reduction in path stretch. The second and third conditions are motivated by our design requirement that the subset of neighbors chosen for direct connectivity should have as high an angular separation as possible. This allows the nodes to access separated spatial areas or domains with low path stretch. We remark that these decisions do not rely on perfect directional neighborhood information or perfect channel conditions.

Establishing and Maintaining Links: "Tracking" discovered neighbors is crucial with fully directional communications, especially under conditions of mobility. Therefore, each pair of nodes that successfully form a link after Di-ATC execution, will *rendezvous* at a common time-slot to communicate on a periodic basis. Towards this, they exchange their current available slots and try to find a common time-slot for "polling" each other. For this, a polling phase may be incorporated and used as in [9].

Nodes proceed to the neighbor tracking phase after the allocated slots for neighbor search are complete (Figure 1). In this phase each node exchanges polling messages with its selected subset of neighbors determined by Di-ATC. Nodes thus update direction information with regards to each other; this is needed so that nodes will beamform in the right direction to communicate with each other. Nodes also update the "existence" of their polled neighbor. This is because, either of the nodes (w.l.o.g. u) from the pair u,w that "maintain" each other, may in the meantime have discovered a new neighbor and may have abandoned the link (u, w) to form an alternate link with this new neighbor. Therefore, if node u does not repeatedly receive rendezvous messages from w, it assumes that the link is broken and removes w from its set of direct neighbors.

Remark 1. The proposed scheme can also be implemented with beam-switching antennas with slight modifications, as these antennas may be preferable as a less expensive alternative to fully adaptive arrays. In this case, as opposed to the *exact* direction that maximizes the received signal power, nodes will determine the *closest* (in terms of angular separation of the intended direction) predefined sector to the desired direction.

V. SIMULATIONS

In this section we describe our simulation environment and discuss our experiments and results.

Simulation Environment: We implement our integrated scheme in OPNET v.11 [1]. We choose OPNET, as it allows the incorporation of arbitrary antenna patterns in 3-D having arbitrary gain and shape; appropriate sidelobes are automatically generated. Furthermore, one can modify the boresight of the created antenna with specific system calls, and point the main lobe at an arbitrary point on the plane. Upon each transmission in the pointed direction, nodes within the directional footprint that (have their antennas pointed towards the transmitter and thus) receive the packet automatically compute the signal-to-noise ratio (SNR) of the received packet by considering the antenna gains and their positions relative to the transmitter. This setup offers a fairly realistic model of directional communications.

In our simulations, nodes are placed randomly in a 3200 m x 3200 m. flat terrain (unless specified otherwise). This corresponds to a 4x4 unit area with the directional range being approximately 800 m. (for a particular antenna gain and beamwidth). To demonstrate that the performance of our integrated scheme *scales* in moderate to large networks, we performed simulations with different node densities in this area. Each node is equipped with directional antennas as defined in Section III and all nodes use the same antenna model in a single simulation experiment.

We construct a directional antenna pattern with a main lobe and a small backlobe (as in [11],[23],[27]). The maximum gain in the pointed direction is 20dB (unless specified otherwise). The antenna height is set to 3 cm. Nodes transmit at a power of 0.001W (this power is fixed in all simulations; we do not perform power control). The radios operate at the channel frequency of 2.4 GHz. With these values, the *directional* communication range is $\sim$800 meters for a 45° beamwidth directional antenna. This range corresponds to (under the same channel and transmit power conditions) a communication range of about 550 meters with the omnidirectional antennas (again with OPNET). We remark that these (platform-specific) values may differ from the real-life possibilities.

Parameters and Metrics: We study the behavioral dependance of the system on the following parameters.

1) *Node density.* We experiment with various node densities from 4 to 20 nodes per unit area in the region of interest.
2) *Antenna Beamwidth.* We simulate with different antenna beamwidths of 30°, 45°, 60°, 90°; each beamwidth results in a different antenna gain, 24, 20, 16 and 8 dB, respectively.
3) *Speed of Nodes.* To see the effect of mobility on the constructed topology, we simulate a low mobility scenario (in the random waypoint model nodes choose a random speed between 0 and 10m/sec.) and a high mobility scenario (node speeds are randomly selected between 10m/sec. and 20 m/sec.).
4) *Node Degree Bound.* Di-ATC imposes the degree bound a priori; we simulate cases where the imposed maximum degree is 6, 7, 8 or 9.

We quantify our performance results in terms of the following metrics:

1) *Average node degree.* The average over all nodes in the particular scenario (or at the particular time instant for the mobile case).

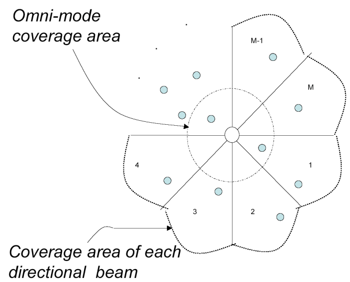
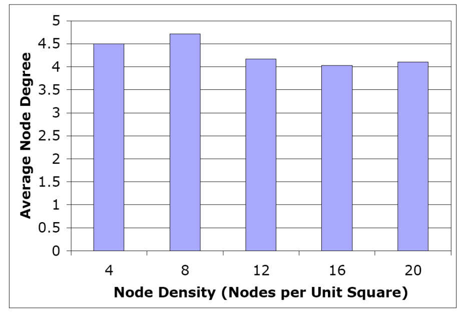


Fig. 2. Neighborhood with the Idealized construction

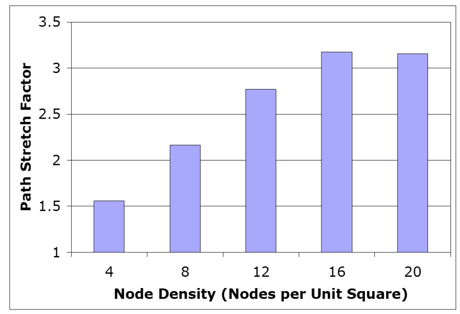
2) *Average stretch in topological path lengths.* We measure the per-edge topological path length stretch: for every node pair u,v that are within each other's directional range in the initial topology, we measure the shortest path (in terms of hop count) between them in the topology formed by Di-ATC. This hop count is called the topological path length stretch of link (u, v) in the input topology; the average is computed over all pairs of nodes that can communicate in the scenario of interest.
3) *95 percentile path stretch.* We quantify the 95% tail[7] of the average topological length stretch; using this metric to represent the path stretch, we eliminate the outliers that could possibly exist due to disconnected nodes. (We quantify the connectivity to capture the likelihood of such outliers separately.)

These metrics capture the effectiveness of Di-ATC in optimizing the *trade-off* between node degree and path stretch (it is desirable that both metrics have low values). Di-ATC imposes a maximum degree; the *average* degree of the constructed topology reflects the joint performance of Di-ATC *and* the neighbor discovery process. The path stretch is important because it reflects the difference in the path lengths between those in the *ideal* topology and in the constructed topology. By "ideal" topology we mean that nodes can discover *all* nodes within their *directional* range (given the antenna gain and beamwidth) *and* maintain *all* discovered neighbors. (This topology would include the shortest paths between all pairs of nodes.) Figure 2 further elucidates the notion of ideal topology. In this figure, neighbors of the central node in the ideal case would be all nodes within its directional range, i.e., all nodes shown in the figure. These neighbors can be potentially reached via circular directional transmissions (and receptions) as in [11]. We note that the computation of path stretch is different for the mobile case (as we explain later), as the topology is dynamic.

[7] x% tail of a set of values, is the value that is bigger than x% of the values in that set



(a) Average Node Degree vs. Node Density

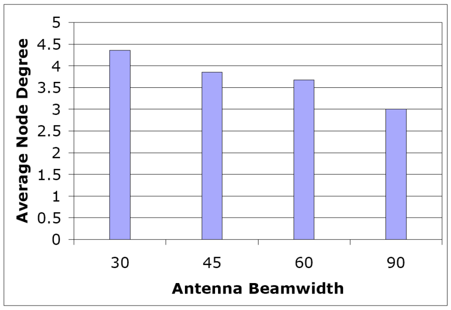


(b) Average Path Stretch vs. Node Density

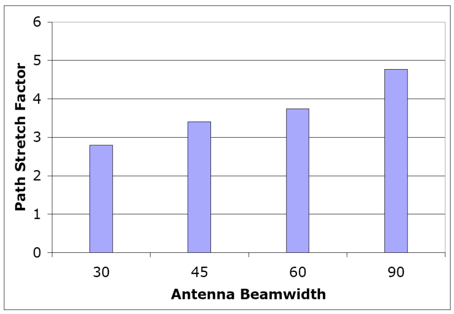
Fig. 3. Distribution of Average Node Degree and Path Stretch for Topologies Generated by Di-ATC at Various Node Densities

Simulation Results and Discussion: For the neighbor discovery phase, we use the method suggested in [9]. In particular, we used 15 search slots, each of length 2 milliseconds, and we used a cycle time of 0.4 seconds. The cycles repeat continuously. Each simulation is run for 100 cycles.

First we compare the distribution of average node degree and average path stretch as the node density within the region is varied. Our results are shown in Figure 3. In these two plots, the maximum node degree imposed by Di-ATC is 6 and the antenna beamwidth is fixed to 45° (corresponding to an antenna gain of 20 dB in our model). We observe in Figure 3(a) that for varying node densities, the average node degree is mostly around 4. The average node degree of the network remains relatively unchanged with varying density. At higher densities, nodes may discover new neighbors that provide better angular separations than before; however, we recall that as new neighbors that provide better angular



(a) Average Node Degree for Different Antenna Beamwidths



(b) Average Path Stretch for Different Antenna Beamwidths

Fig. 4. Average Node Degree and Path Stretch in the Topologies Formed by Di-ATC Using Different Antenna Beamwidths.

separation are discovered, old neighbors are pruned. Figure 3(b) depicts the average path stretch as a function of the node density. The path stretch at low density is very small (around 1.6); this is because *few*[8] of the discovered neighbors are "pruned" at each node, hence the path lengths are not significantly affected. For node densities higher than 6 nodes/unit area (where 6 is the imposed degree bound), path stretch increases with the node density. The increase in path stretch in a denser network is due to the the higher percentage of pruned edges in the final topology as compared to the input graph.

Next, we measure the change in average node degree and path stretch with varying antenna beamwidths. We fix the imposed degree limit to be 6, and the node density per unit region to be 15. The results are depicted in Figure 4(a) and 4(b). The path stretch in this simulation is computed relative to the ideal case corresponding to each antenna beamwidth; for each value, the corresponding antenna gain and therefore the particular radial (directional) range are chosen. Observed average node degree decreases with increasing beamwidth, while the average path stretch increases in contrast. The decrease in node degree for higher beamwidths is due to collisions of HELLO packets in the neighbor discovery process. These collisions are reduced to a large extent when the beamwidth is narrow. Consequently, nodes in the large-beamwidth cases may not discover the appropriate neighbors and thus suffer as compared to the "ideal scenario" in terms of identifying the best paths.

[8]Di-ATC maintains all discovered neighbors as long as the degree bound has not been reached.

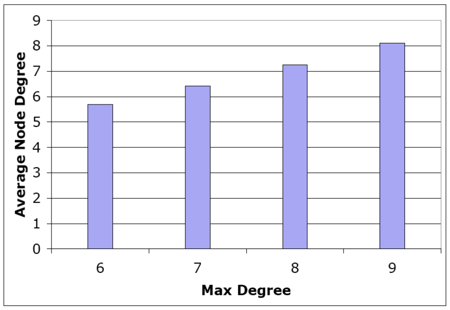
Beamwidth	30°	45°	60°	90°
Connectivity	100%	100%	98.3%	96.4 %

TABLE I
CONNECTIVITY OF THE FORMED TOPOLOGY FOR VARYING ANTENNA BEAMWIDTHS.

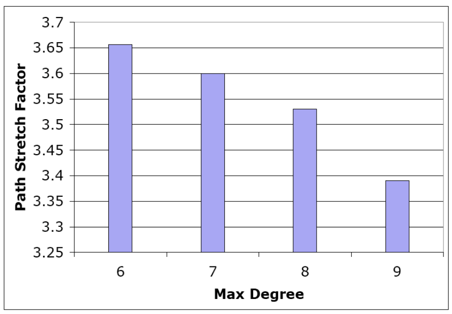
As the average degrees are low in this scenario, we also compute the *network connectivity* for varying beamwidths; this is calculated for every node in the network and represents the fraction of nodes in the network that are reachable from this node. The results are tabulated in Table V. For lower beamwidths of 30° and 45° the formed topology is 100% connected (as one might expect from the results in Figure 4(a) and the corresponding discussion). Connectivity reduces slightly for higher beamwidths and this is attributed to collisions during the neighbor discovery process. Therefore for the high-beamwidth scenario, we compute the 95 percentile path stretch eliminating the outlier nodes of degree zero.

To observe the impact of angular separation on the average degree and path stretch we varied the imposed upper bound on the node degree, from 6 to 9. We fixed the antenna beamwidth at 45° and node density at 15 nodes per unit region, which is a fairly dense network. The simulation results are depicted in Figure 5. We observe that the average node degree increases as the imposed upper bound is relaxed, and the average path stretch decreases accordingly. Nodes are allowed to keep more neighbors with a larger degree bound, and thus more links that make up the shorter paths exist in the topology formed.

Finally, we simulate two mobile scenarios with the random waypoint mobility model. The random waypoint parameters we used are as follows: for low mobility scenario nodes choose a random speed between (0,10] m/sec, and for high mobility scenario between (10,20] m/sec. In both scenarios nodes wait at the arrived destination for 1 sec, which corre-



(a) Average Node Degree vs. Degree Bound



(b) Average Path Stretch vs. Degree Bound

Fig. 5. Distribution of Average Node Degree and Path Stretch in the Topologies Generated by Di-ATC with Different Degree Bounds

sponds to a 2.5 cycle duration. Figure 6 presents the average degree and path stretch at selected cycle instants in time during a simulation run, in the slow and fast mobile scenarios.

As nodes' coordinates are dynamic due to mobility, we compute the path stretch differently for the mobile case. At each particular sample in time (the cycle at which we measure average degree and path stretch), we use the calculation that we used for the static case. In other words, at every particular time instant, we compute the hop count of the shortest path in the topology constructed, and compare it with the ideal topology consisting of the links that could potentially exist at that time (as before, the ideal case assumes that the complete neighborhood is discovered and all fully-directional links are maintained).

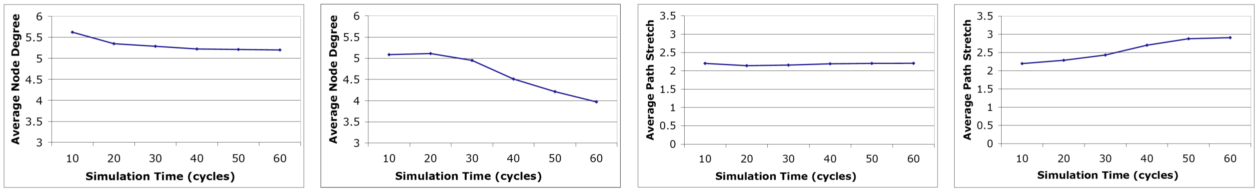
We note from Figure 6(a) that the average node degree does not fluctuate significantly during the simulation of the mobile scenario. This result implies that our integrated scheme is resilient to the effects of mobility. In the high mobility case shown in Figure 6(b) the average node degree drops after the first half of the simulation duration indicating that nodes lose their neighbors at this time. The degree stabilizes at a lower value (than the initial higher value) after a while, because although nodes discover/add new neighbors, they lose others due to the high node speeds. Our scheme still provides satisfactory behavior even under such highly mobile scenarios; yet, these high speeds are not common in current ad hoc network practices (high speeds are more common in vehicular ad hoc networks, but it may be undesirable to use antenna arrays for such networks due to rapidly changing channel conditions).

We also observe from Figure 6(c) that in parallel with the stable degree, the path stretch does not exhibit fluctuations either. The path stretch shows some increase after cycle 30 in the highly mobile scenario (Figure 6(d)) owing to the decrease in the average node degree of the topology. The satisfactory results on the path stretch can be attributed to both the higher range capability of directional antennas and to the functionality of Di-ATC. With the angular separation provided by Di-ATC, the final topology yields *short* paths that are resilient to mobility (longer paths are more likely to be disrupted as the network topology changes due to motion).

We conclude, given our simulation results, that our integrated scheme performs effectively in terms of the metrics of interest in different scenarios.

VI. Conclusions

In this paper we present Di-ATC, a novel topology control scheme designed for directional antenna equipped ad hoc networks. Di-ATC is tightly integrated with *fully directional* neighbor discovery and neighbor maintenance functionalities. In particular, it constrains the overhead incurred in facilitating the latter. The key idea of our approach is to maintain only a subset of discovered neighbors; this subset should be carefully chosen so as to preserve network connectivity and avoid high path stretch. Di-ATC is completely decentralized; nodes make individual local decisions dynamically. Hence, Di-ATC is lightweight and scalable. We perform extensive simulations to evaluate the performance of our integrated scheme in different settings. Our results show that the constructed topology maintains connectivity even if the degree of each node is constrained to a very low value (close to the theoretical minimum for preserving connectivity); and the path stretch factor is 2.0 to 3.0 on average. Furthermore, the simulations confirm that our integrated scheme works effectively even with node mobility.



(a) Average Degree vs. Time (low mobility)

(b) Average Degree vs. Time (high mobility)

(c) Avg. Path Stretch vs. Time (low mobility)

(d) Avg. Path Stretch vs. Time (high mobility)

Fig. 6. Average Node Degree and Path Stretch in the Topologies Generated by Di-ATC in the Low and High Mobility Scenarios.

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