Interference-Aware Routing in Multihop Wireless Networks using Directional Antennas

Jian Tang, Guoliang Xue, Christopher Chandler and Weiyi Zhang
Department of Computer Science and Engineering
Arizona State University
Tempe, AZ 85287-8809
Email: {jian.tang, xue, cchandler, weiyi.zhang}@asu.edu

Abstract— **Recent research has shown that interference can make a significant impact on the performance of multihop wireless networks. Researchers have studied interference-aware topology control recently [1]. In this paper, we study routing problems in a multihop wireless network using directional antennas with dynamic traffic. We present new definitions of link and path interference that are suitable for designing better routing algorithms. We then formulate and optimally solve two power constrained minimum interference single path routing problems. Routing along paths found by our interference-aware algorithms tends to have less channel collisions and higher network throughput. Our simulation results show that, compared with the minimum power path routing algorithm, our algorithms can reduce average path interference by 40% or more at the cost of a minor power increase. We also extend our work towards survivable routing by formulating and solving the power constrained minimum interference node-disjoint path routing problem.**

Keywords: Multihop wireless networks, interference-aware routing, directional antennas.

I. Introduction

The limitation of energy availability has become one of the most critical issues in multihop wireless networks. Nodes in such networks, such as wireless sensor nodes, are normally powered by batteries and can only last for a short term, if operated at a high power level. This energy limitation motivates extensive research efforts towards power-efficient routing and topology control.

Transmissions among neighboring nodes in wireless networks may interfere with each other due to contention for the shared wireless channel. The MAC (Medium Access Control) protocols, such as 802.11 DCF or some TDMA (Time Division Multiple Access)-based protocols ([22]), are proposed to resolve contentions by scheduling transmissions that cause channel collisions into different timeslots (TDMA) or randomly delaying some of them (802.11 DCF). If packets are always routed along minimum power paths without considering interference, some spatially close wireless links may become heavily loaded with traffic.This will result in long transmission delays and a substantial reduction of throughput since transmissions along these links have to be scheduled at different times in order to avoid channel collisions. Therefore, a good routing algorithm should be aware of interference as well as power consumption in order to find paths having low interference with existing traffic.

The impact of interference in wireless multihop networks has been observed and studied both theoretically and empirically in the literature. The authors of [7] studied the following problem: given a specific placement of wireless nodes in the physical space and a specific traffic load, what is the maximum throughput that can be supported by the resulting network? They modeled wireless interference using a conflict graph and derive upper and lower bounds on the optimal throughput for the given network. Burkhart *et al.* in a very recent paper [1], gave a concise and intuitive definition of interference. Based on this definition, they showed that most currently proposed topology control algorithms do not effectively constrain interference. Furthermore, they proposed algorithms to find interference-optimal connected subgraphs and spanners.

By using directional antennas, RF energy can be concentrated in the direction where the transmission needs to be made. In this way, energy can be saved and interference can be reduced. The use of directional antennas is especially beneficial in multihop wireless networks because nodes in such networks have very limited energy capability and suffer from the interference. Hence, in this paper, we study interference-aware routing problems in multihop wireless networks using directional antennas with dynamic traffic along the lines of [1], [7]. However, we do not assume that the traffic demand matrix is given *a priori* as in [7]. We study a more practical dynamic traffic model, in which connection demands have random source, destination and arrival time. We present new definitions of link and path interference that are suitable for designing better routing algorithms. We formulate several new routing problems, namely the *Power Constrained min-Max Interference single path (***MIPC***)* routing problem and the *Power Constrained min-Total Interference single path (***TIPC***)* routing problem. We present efficient optimal algorithms for both problems. Routing by means of our interference-aware algorithms can dramatically reduce channel collisions, which

This research was supported in part by ARO grants W911NF-04-1-0385 and DAAD19-00-1-0377, NSF grants CCF-0431167 and ANI-0312635, and a seed grant from CEINT.

will make transmission scheduling easier and result in higher network throughput. In addition, the total power of a routing path found by our algorithms is guaranteed to be bounded by a given tolerance value. By carefully setting this value, routing paths obtained will not only be power-efficient, but also have very low interference values. Furthermore, we extend our work to node-disjoint path routing for the purpose of fault-tolerance. We formulate the *power constrained min-Max Interference Double Path (***MIDP***)* routing problem and give an optimal algorithm. To our best knowledge, this is the first paper which jointly considers interference and power consumption issues for multihop wireless routing and presents interference-aware routing schemes.

The rest of the paper is organized as follows. Related work is discussed in Section II. We define the system model in Section III and then formulate optimization problems to be studied in Section IV. Single path routing algorithms are presented in Section V and node-disjoint path routing algorithm is presented in Section VI. We evaluate the performance of our proposed algorithms via simulations in Section VII. We conclude the paper in Section VIII.

II. Related Work

As we discussed before, a great number of power-efficient routing algorithms have been proposed in the past few years. Chang and Tassiulas [2] formulated the lifetime maximization problem as the well studied multicommodity flow problem and proposed an efficient algorithm to select the route. Moreover, their algorithm can compute an optimal solution for the static routing scenario, i.e., the sequence of packets which will be delivered are given as the input. Li *et al.* presented an on-line algorithm in [11] for the dynamic traffic case. Kar *et al.* in [8] improved the results of [11] in terms of both throughput and lifetime. More importantly, they showed that the worst-case performance of their algorithm is bounded within a factor of $O(\log(\text{network size}))$ of the optimal solution. Li and Wan also formulated and solved several constrained shortest path problems for multihop wireless networks in [12]. Localized power efficient routing algorithms are proposed in [18] and are proven to be loop-free. Recently, Zhu *et al.* ([23]) proposed more comprehensive energy consumption models that consider the energy consumption for data packets as well as control packets. Based on those models, they proposed their minimum energy routing scheme. The algorithms mentioned so far are all single path routing algorithms. Multiple path routing has also been well studied for network survivability and security. Lou and Fang [13], [14] proposed to use multiple paths in wireless ad hoc networks to enhance data confidentiality. Srinivas and Modiano [17] presented elegant optimal algorithms for finding both minimum total power node-disjoint paths and minimum total power link-disjoint paths in a multihop wireless network. In [20], Tang and Xue extended their work to consider trade-offs between total path power and path lifetime by taking into consideration of the residual energy at wireless nodes.

Gupta and Kumar in [6] showed that in a network comprising of n identical nodes, each of which is communicating with another node, the throughput per node is $\Theta(1/\sqrt{n\log n})$ under the consumption of random node placement and communication pattern. The throughput becomes $\Theta(1/\sqrt{n})$ by assuming optimal node placement and communication pattern. The authors in [7] used a conflict graph to model interference in a wireless network and present methods to compute upper and lower bounds on the optimal throughput for a given network and traffic demand matrix. The problem of jointly routing the flows and scheduling transmissions to achieve a given rate vector is studied in [10]. Firstly, the authors ignore the secondary interference and developed tight necessary and sufficient conditions for the achievability of the given rate vector. Based on those conditions, they developed an efficient scheme to solve the single source-destination pair rate achievability problem and showed that it guarantees that the solution obtained is within 67% of the optimal solution in the worst case. They also discussed the method for multiple source-destination pair case and extensions to the general interference model. The most related work is done by Burkhart *et al.* in a very recent paper [1], in which several interference-aware topology control algorithms are proposed.

Recently, wireless networks using directional antennas have received tremendous attention. Several MAC protocols are proposed in [3], [9], [15] for wireless communication using directional antennas. The authors of those papers modified the original 802.11 MAC protocol by exploring the benefits of directional antennas. In [16], the authors addressed energy-efficient unicast routing using directional antennas. They presented a routing algorithm to find an energy-efficient path and a maximal-weight matching based algorithm for transmission scheduling. Energy-efficient multicasting using directional antennas has also been studied in [4], [5], [21].

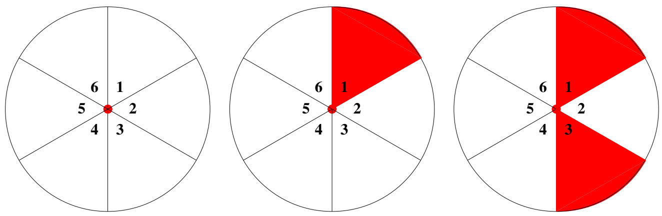
III. System Models

We are interested in various routing problems in a multihop wireless network using directional antennas. We assume that there are n wireless nodes $v_1, v_2, \ldots, v_n$ deployed in the Euclidean plane, with known positions. The Euclidean distance between nodes v_i and v_j is denoted by $d(v_i, v_j)$.

A. Cones and Sectors

We use a similar antenna model as in [15]. We assume that each wireless node only has one transceiver and can receive signals from all directions. However, a wireless node can transmit signals using any number of predefined directions which we call *cones*. Figure 1 illustrates this concept.

We divide the 360-degree whole angle centered at a transmitter into k equal sized angles. These k angles divide the 360-degree whole angle into k *cones*, numbered $1, 2, \ldots, k$ in clockwise order. Figure 1(a) illustrates the case where $k = 6$. If a wireless node wants to transmit a packet to other nodes, it can transmit the packet using any combination of the k cones for this purpose. Figure 1(b) illustrates the case where only cone 1 is used for transmission. Figure 1(c) illustrates the case where both cone 1 and cone 3 are used simultaneously for transmission.



(a) (b) (c)

Fig. 1. Transmission using directional antennas. (a) The k transmission cones, $k = 6$ for this illustration; (b) Transmission using cone 1 only; (c) Transmission using cone 1 and cone 3 simultaneously.

When a wireless node transmits simultaneously in multiple cones, it uses the same power in all cones. Therefore the transmission ranges in all cones used are the same. A cone and a range define a *sector*. For a given transmission range r, the power consumption required for using m cones is given in Equation 1.

$$P(m, r) = \mathcal{K} \times \frac{m}{k} \times r^{\alpha} \tag{1}$$

In the above equation, $\mathcal{K}$ is a positive constant and α is a constant between 2 and 4 depending on transmission medium.

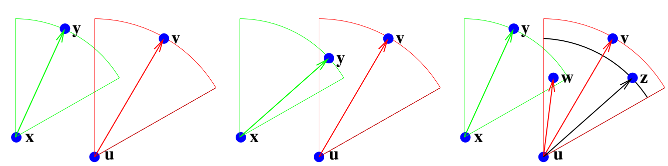
Since the maximum transmit power is fixed and assumed to be the same for all nodes, there is a *maximum* transmission range R_m corresponding to the case in which m cones are used for transmission simultaneously. We will have $R_1 > R_2 > \ldots > R_k$.

B. Connection Requests and Wireless Links

We are interested in two types of connection requests: (1) single path routing and (2) double path routing. For single path routing, we seek a multihop source to destination path. For double path routing, we seek a pair of node-disjoint source to destination paths. Each connection request is specified by its type $\mathcal{T}$, the source node s, the destination node t, and a rate requirement b.

We say there is a wireless link (u, v) if $d(u, v) \leq R_1$. Note that two cones may need to be used simultaneously at source node for some double path routing connection. In this case, some wireless links cannot be used for routing since $R_2 < R_1$, i.e, the node do not have enough power to support using such links. When directional antennas are used for transmissions, there still exists Wireless Multicast Advantage (WMA), i.e, different nodes within the same transmission range can receive the packet without any extra cost. As discussed in [17], this WMA can be taken by source nodes of node-disjoint paths to save transmission power. We need to be aware of WMA when we study the interference of node-disjoint paths. A wireless link may be used by a connection in two different ways. Let ρ be an existing single path routing connection and (u, v) be a wireless link in the network. The link (u, v) is either not used by ρ or used by ρ as a normal wireless link. Let γ be an existing double path routing connection and (u, v) a wireless link in the network. The link (u, v) is either not used by γ or used by γ as a normal wireless link where u is different from the source node of γ, or used by γ together with another wireless link (u, w) with the same ingress node where u is the source node s. In the last case, we say (u, v) and (u, w) form a WMA link pair. Note that *normal wireless link* and *WMA link pair* are concepts defined with respect to a particular connection. It is possible that (u, v) is a normal wireless link with respect to one connection and (u, v) and (u, w) form a WMA link pair for another connection. The links (x, y) and (u, v) in Figure 2(a) do not form a WMA link pair for any connection. The links (u, w) and (u, v) in Figure 2(c) may form a WMA link pair for some connection while the links (u, w) and (u, z) in Figure 2(c) may form another WMA link pair for another connection.

Each normal wireless link corresponds to a unique sector centered at the ingress node (except the cases where the egress node is exactly on the boundary of two adjacent cones centered at the ingress node). As such, the power consumption of a normal wireless link is determined by the radius of the corresponding sector. For each WMA link pair, the two links have a common ingress node which is the source node of the corresponding double path routing connection request. A WMA link pair (u, v) and (u, w) may be in the same sector or in two different sectors. In the first case, the power consumption of (u, v) and (u, w) is determined by the power consumption of the corresponding sector. In the second case, the two sectors for (u, v) and (u, w) must be of equal radius, although $d(u, v)$ and $d(u, w)$ may differ. As a result, the power consumption of (u, v) and (u, w) is determined by the power consumption of the two corresponding sectors.



(a) (b) (c)

Fig. 2. Wireless links, sectors, and interference. (a) No interference; (b) (u, v) interferes with (x, y); (c) (x, y) interferes with the (u, w) and (u, v) pair.

C. Interference

In order to compute more schedulable routing paths, we consider interference between two wireless links. In this paper, we assume that a node can only transmit or receive and be involved in a single communication session at one time.

Let (x, y) be a normal wireless link with ingress node x and egress node y. Let (u, v) be another normal wireless link with ingress node u and egress node v. If the sector corresponding to (x, y) covers node v or the sector corresponding to (u, v) covers node y, we say that the two links interfere with each other. Because simultaneously transmitting along both links will lead to collisions at the receiver.

By this definition, the two links in Figure 2(a) do not interfere with each other while the two links in Figure 2(b) interfere with each other. Let (x, y) be a normal wireless link with ingress node x and egress node y. Let (u, v) and (u, w) be a WMA link pair with common ingress node u. If the sector corresponding to (x, y) covers at least one of v and w, then (x, y) interferes with both (u, v) and (u, w). Because packets along this pair of links are transmitted using just one broadcasting from node u. Similarly, if the sector corresponding to (u, v) and (u, w) (or one of the sectors corresponding to (u, v) and (u, w)) covers node y, then the pair (u, v) and (u, w) interferes with link (x, y). In either case, we say that normal wireless link (x, y) and the WMA link pair (u, v) and (u, w) interfere with each other. In Figure 2(c), the normal wireless link (x, y) and the WMA link pair (u, v) and (u, w) interfere with each other. Note that the WMA link pair (u, v) and (u, w) in Figure 2(c) uses the same sector that is used by the normal wireless link (u, v) in Figure 2(a) and that the normal wireless link (x, y) in Figure 2(c) uses the same sector that is used by the normal wireless link (x, y) in Figure 2(a). In Figure 2(a), the normal wireless links (x, y) and (u, v) do not interfere with each other. In Figure 2(c), however, the normal wireless link (x, y) and the WMA link pair (u, v) and (u, w) do interfere with each other.

Let (x, y) and (x, z) be a WMA link pair with common ingress node x. Let (u, v) and (u, w) be a WMA link pair with common ingress node u. If the sector (or one of the sectors) corresponding to (x, y) and (x, z) covers at least one of v and w, then the pair (x, y) and (x, z) interferes with the pair (u, v) and (u, w). Similarly, if the sector (or one of the sectors) corresponding to (u, v) and (u, w) covers at least one of y and z, then the pair (u, v) and (u, w) interferes with the pair (x, y) and (x, z). In either case, we say that the WMA link pair (x, y) and (x, z) and the WMA link pair (u, v) and (u, w) interfere with each other. The above definitions cover most of the cases where two links (link pairs) are incident in one common node. However, we also consider two links (link pairs) interfering with each other if they share a common ingress node.

IV. Problem Formulations

In this section, we will formally define the problems to be studied, as well as some concepts which are necessary in the definitions of the problems. When we talk about a normal wireless link (u, v), we may omit the corresponding connection and assume that we are talking about all the connections for which (u, v) is a normal wireless link. When we talk about a WMA link pair (u, v) and (u, w), we may omit the corresponding connection as well and assume that we are talking about all the connections for which (u, v) and (u, w) form a WMA link pair.

A. Preliminaries

Definition 1 (Link Power): Let $e = (u, v)$ be a normal wireless link with ingress node u and egress v. The **power of link** e, denoted by $C(e)$, is $P(1, d(u, v))$ (refer to Equation 1). Let $e = (u, v)$ and $e' = (u, w)$ be a WMA link pair with common ingress node u. If v and w are in the same cone centered at u, the **power of link pair** e **and** e', denoted by $C(e, e')$, is $\max\{P(1, d(u, v)), P(1, d(u, w))\}$, If v and w are in different cones centered at u, the **power of link pair** e **and** e', denoted by $C(e, e')$, is $\max\{P(2, d(u, v)), P(2, d(u, w))\}$,

Definition 2 (Path Power): Let $e_1, e_2, \ldots, e_p$ be the links of a path P for a single path connection request. The **power of path** P, denoted by $C(P)$, is $\sum_{i=1}^{p} C(e_i)$. Let $e_1, e_2, \ldots, e_p$ be the links of a path P for a double path connection request and $e'_1, e'_2, \ldots, e'_q$ be the links of the other path Q (node-disjoint with P) for the double path connection request. The **power of path pair** P **and** Q, denoted by $C(P, Q)$, is $C(e_1, e'_1) + \sum_{i=2}^{p} C(e_i) + \sum_{i=2}^{q} C(e'_i)$.

Definition 3 (Link Load): Let e be a normal wireless link. The **load of link** e, denoted by $L(e)$, is the sum of the rates of the existing connections that use link e as a normal wireless link. Let e and e' be a WMA link pair with a common ingress node. The **load of link pair** e **and** e', denoted by $L(e, e')$, is the sum of the rates of the existing connections that use link pair e and e' as a WMA link pair.

Essentially, $L(e)$ ($L(e, e')$) represents the amount of traffic going through link e (link pair e and e'). In the following, we will define the interference value of a link e as the weighted (by link load) sum of the links that interfere with e. Commonly, the interference value of a link e is defined as the sum of the links that interfere with e. This may be viewed as a special case of our definition where all links have equal weight.

Definition 4 (Link Interference): Let e be a normal wireless link. We will use $IE(e)$ to denote the set of normal wireless links and WMA link pairs that interfere with link e. The **interference of link** e, denoted by $I(e)$, is the sum of the link loads among all normal wireless links and WMA link pairs in $IE(e)$, i.e.,

$$I(e) = \sum_{e_1 \in IE(e)} L(e_1) + \sum_{(e_1, e_2) \in IE(e)} L(e_1, e_2).$$

Let e and e' be a WMA link pair. We will use $IE(e, e')$ to denote the set of normal wireless links and WMA link pairs that interfere with link pair e and e'. The **interference of link pair** e **and** e', denoted by $I(e, e')$, is the sum of the link loads among all normal wireless links and WMA link pairs in $IE(e, e')$, i.e.,

$$I(e, e') = \sum_{e_1 \in IE(e, e')} L(e_1) + \sum_{(e_1, e_2) \in IE(e, e')} L(e_1, e_2).$$

Definition 5 (Path Interference): Let $e_1, e_2, \ldots, e_p$ be the links of a path P for a single path connection request. The **maximum path interference of** P, denoted by $I_{max}(P)$, is $\max\{I(e_i) | i = 1, 2, \ldots, p\}$. The **total path interference of** P, denoted by $I_{sum}(P)$, is $\sum_{i=1}^{p} I(e_i)$. Let $e_1, e_2, \ldots, e_p$ be the links of a path P for a double path connection request and $e'_1, e'_2, \ldots, e'_q$ be the links of the other path Q (node-disjoint with P) for the double path connection request. The **maximum path interference of** P **and** Q, denoted by $I_{max}(P, Q)$, is

$$\max\{I(e_1, e'_1), I(e_i), I(e'_j) | i = 2, \ldots, p; j = 2, \ldots, q\}.$$

The **total path interference of** P **and** Q, denoted by $I_{sum}(P, Q)$, is

$$I(e_1, e'_1) + \sum_{i=2}^{p} I(e_i) + \sum_{j=2}^{q} I(e'_j).$$

B. Optimization Problems

Now we are ready to formally define our optimization problems for interference-aware routing in multihop wireless networks using directional antennas. For single path routing, we are interested in the **MIPC** and **TIPC** problems. We also define the auxiliary problems *MICP* and *TICP* which ease the description of the algorithms for **MIPC** and **TIPC** problems. For double path routing, we are interested in the **MIDP** problem. We also define the auxiliary problem *MICDP* which eases the description of the algorithm for the **MIDP** problem. Let ρ be a single path connection request with source node s, destination node t, and rate requirement b. We have the following definitions.

*Definition 6 (***MIPC***):* Let P_{sum} be a total power tolerance. The **Power Constrained min-Max Interference single path** routing problem asks for an s–t path with minimum maximum interference among all s–t paths whose total power is bounded by P_{sum}.

*Definition 7 (***TIPC***):* Let P_{sum} be a total power tolerance. The **Power Constrained min-Total Interference single path** routing problem asks for an s–t path with minimum total interference among all s–t paths whose total power is bounded by P_{sum}.

Definition 8 (MICP): Let I_{max} be a maximum interference tolerance. The *Maximum Interference Constrained minimum Power single path* routing problem asks for an s–t path with minimum total power among all s–t paths whose maximum interference is bounded by I_{max}.

Definition 9 (TICP): Let I_{sum} be a total interference tolerance. The *Total Interference Constrained minimum Power single path* routing problem asks for an s–t path with minimum total power among all s–t paths whose total interference is bounded by I_{sum}.

The above four problems are all concerned with single path connection requests. For double path routing requests, we are interested in the following two optimization problems. Let ρ be a double path connection request with source node s, destination node t, and rate requirement b. The problems are defined as follows.

*Definition 10 (***MIDP***):* Let P_{sum} be a total power tolerance. The **power constrained min-Max Interference Double Path** routing problem asks for a pair of node-disjoint s–t paths with minimum maximum interference among all s–t path pairs whose total power is bounded by P_{sum}.

Definition 11 (MICDP): Let I_{max} be a maximum interference tolerance. The *Maximum Interference Constrained minimum power Double Path* routing problem asks for a pair of node-disjoint s–t paths with minimum total power among all node-disjoint s–t path pairs whose maximum interference is bounded by I_{max}.

V. Single Path Routing

In this section, we present efficient algorithms for solving the single path routing problems **MIPC** and **TIPC**. An efficient algorithm for solving *MICP* is described as Algorithm 1. We will use this algorithm as a subroutine for solving **MIPC**.

Algorithm 1 Solving MICP

INPUT: Existing network status: n wireless nodes; number of cones k; link load of each wireless link; link interference of each wireless link. A connection request ρ with source node s, destination node t and rate requirement b, and a maximum interference tolerance I_{max}.

OUTPUT: An s–t path with minimum total power among all s–t paths whose maximum interference is at most I_{max}.

step_1 Construct a directed graph $G(V, E)$ where V contains all the wireless nodes and E contains all the wireless links whose interference value is at most I_{max}.

step_2 Apply Dijkstra's algorithm to compute an s–t path P in G with minimum total power.

Theorem 1: Algorithm 1 correctly computes an s–t path with minimum total power among all s–t paths whose maximum interference value is no more than I_{max}, provided that there exists an s–t path with maximum interference no more than I_{max}. In addition, the worst-case running time of Algorithm 1 is $O(n^2)$.

PROOF. It follows from the construction of graph G that each link in G has an interference value no more than I_{max}. If there exists an s–t path P whose maximum interference is no more than I_{max}, then P must be an s–t path in G. Therefore our algorithm correctly computes an s–t path with minimum total power among all s–t paths whose maximum interference value is no more than I_{max}.

step_1 takes $O(n^2)$ time, since we only need to consider n nodes and $O(n^2)$ wireless links. step_2 takes $O(n^2)$ time, since this is the worst-case running time of Dijkstra's algorithm. This completes the proof of Theorem 1. □

Now we are ready to present the algorithm for solving **MIPC**. This is listed in Algorithm 2.

Theorem 2: Algorithm 2 correctly computes an s–t path with min-max interference among all s–t paths whose total power is no more than P_{sum}, provided that there exists an s–t path with total power no more than P_{sum}. In addition, the worst-case running time of Algorithm 2 is $O(n^3)$.

Algorithm 2 Solving MIPC

INPUT: Existing network status: n wireless nodes; number of cones k; link load of each wireless link; link interference of each wireless link. A connection request ρ with source node s, destination node t and rate requirement b, and a total power tolerance P_{sum}.

OUTPUT: An s–t path with min-max interference among all s–t paths whose total power is no more than P_{sum}.

step_1 Use bisection on all link interference values to find the minimum interference value I_{max} so that the path computed using Algorithm 1 with maximum interference tolerance I_{max} has a total power no more than P_{sum}. Output the corresponding path P.

step_2 Update the load of each link on path P. Update the interference value of each wireless link in the network.

PROOF. The correctness of the algorithm follows from the correctness of Algorithm 1. **step**_1 takes $O(n^2 \log n)$ time since we have $O(n^2)$ link interference values. In the following, we show that **step**_2 takes $O(n^3)$ time. Once an s–t path P is computed, we need to update the load and interference of each of the $O(n^2)$ wireless links in the network. Note that there are at most $(n-1)$ links on path P. The load of a link will change due to the establishment of path P if and only if the link is on path P. We can update the loads of all links on path P in $O(n)$ time. Updating link interferences is more involved because there are changes in interference values for links on path P as well as for links not on path P. For each link e, we count the number of links on P interfering with e. Let this value be $N_I(e)$. We increase its interference value by $(N_I(e) \times b)$. This will take $O(n^3)$ time, since there are $O(n^2)$ links in the network and $O(n)$ links on path P. So total time complexity is $O(n^3)$. This proves the theorem. □

Using the same argument used in the time analysis of Theorem 2, we can prove that it takes $O(n^3)$ time to update the link loads and link interference values when an existing paths leaves the system. Note that no double path connections are considered here.

In the rest of this section, we turn our attention to solving **TIPC**. Algorithm 3 for solving *TIPC* can be used as a subroutine for this purpose.

Theorem 3: Algorithm 3 correctly computes an s–t path with minimum total power among all s–t paths whose total interference value is no more than I_{sum}, provided that there exists an s–t path with total interference no more than I_{sum}. In addition, the worst-case running time of Algorithm 3 is $O(n^2 I_{sum} + nI_{sum} \log(nI_{sum}))$.

PROOF. It follows from the construction of the graph G that there is an s–t path in the wireless network with total interference no more than I_{sum} if and only if there is an s^0–$t^{I_{sum}}$ path in G. In addition, each s^0–$t^{I_{sum}}$ path in G corresponds to an s–t path in the wireless network simply

Algorithm 3 Solving TICP

INPUT: Existing network status: n wireless nodes; number of cones k; link load of each wireless link; link interference of each wireless link. A connection request ρ with source node s destination node t and rate requirement b, and a total interference tolerance I_{sum}.

OUTPUT: An s–t path with minimum total power among all s–t paths whose total interference is at most I_{sum}.

step_1 Construct a directed graph $G(V,E)$ with vertex set V and edge set E in the following way. For each wireless node v in the network, there are $(I_{sum}+1)$ nodes $v^0, v^1, \ldots, v^{I_{sum}}$. Let (u,v) a wireless link in the network such that the interference value $I(u,v)$ is at most I_{sum}. E contains the following directed links: $(u^i, v^{i+I(u,v)}), 0 \le i \le I_{max} - I(u,v)$. The cost of all such edges are set to the power value of link (u,v). E also contains zero cost edges (t^{i-1}, t^i) for $i = 1, 2, \ldots, I_{sum}$.

step_2 Apply Dijkstra's algorithm to compute an s^0–$t^{I_{sum}}$ path π in G with minimum total cost. π corresponds to an s–t path P in the wireless network.

by ignoring the superscript. Therefore the algorithm correctly computes an s–t path with minimum total power among all s–t paths whose total interference value is no more than I_{sum}, provided that there exists an s–t path with total interference no more than I_{sum}.

For the time complexity analysis, we note that G has $O(nI_{sum})$ nodes and $O(n^2 I_{sum})$ links. Therefore **step**_1 and **step**_2 require $O(n^2 I_{sum} + nI_{sum} \log(nI_{sum}))$ time in the worst-case. As before, **step**_3 requires $O(n^2)$ time. This proves the theorem. □

Algorithm 4 Solving TIPC

INPUT: Existing network status: n wireless nodes; number of cones k; link load of each wireless link; link interference of each wireless link. A connection request ρ with source node s, destination node t and rate requirement b, and a total power tolerance P_{sum}.

OUTPUT: An s–t path with minimum total interference among all s–t paths whose total power is no more than P_{sum}.

step_1 Use bisection on the possible values of total interference to find the minimum total interference value I_{sum} so that the path computed using Algorithm 3 with total interference tolerance I_{sum} has a total power no more than P_{sum}. Output the corresponding path P.

step_2 Update the load of each link on path P. Update the interference value of each wireless link in the network.

Theorem 4: Algorithm 4 correctly computes an s–t path with min-total interference among all s–t paths whose total power is no more than P_{sum}, provided that there exists an s–t path with total power no more than P_{sum}. In addition, the worst-case running time of Algorithm 4 is $O((n^4\mathcal{C}L_{max} + n^3\mathcal{C}L_{max} \times \log n\mathcal{C}L_{max}) \times \log n\mathcal{C}L_{max})$, where $\mathcal{C}$ is the total number of existing connections in the network and $\mathcal{L}_{max}$ is the maximum load among all connection requests.

PROOF. The correctness of the algorithm follows from the correctness of Algorithm 3. For the worst-case time complexity, we only need to analyze the maximum possible values of the interference of a path (which consists of $O(n)$ links). The interference value of a link is bounded by $n \times \mathcal{C} \times \mathcal{L}_{max}$. Therefore the interference value of a path is bounded by $n^2 \times \mathcal{C} \times \mathcal{L}_{max}$. This implies that the worst-case time complexity of $\mathbf{step\_2}$ is $O((n^4\mathcal{C}L_{max} + n^3\mathcal{C}L_{max} \times \log n\mathcal{C}L_{max}) \times \log n\mathcal{C}L_{max})$. As proved in Theorem 2, $\mathbf{step\_2}$ takes $O(n^3)$. So the the worst-case time complexity of Algorithm 4 is $O((n^4\mathcal{C}L_{max}+n^3\mathcal{C}L_{max}\times\log n\mathcal{C}L_{max})\times\log n\mathcal{C}L_{max})$. This proves the theorem. □

VI. NODE-DISJOINT PATH ROUTING

In this section, we shift our attention to node-disjoint path routing. In particular, we will present an efficient algorithm for solving *MICDP*, since this algorithm can be used as a subroutine to solve **MIDP** by applying bisection on the possible link interference values.

Suppose we have a double path routing connection request with source node s and destination node t. Let $e_1 = (s, v)$ be the first link on one of the s–t paths and $e'_1 = (s, w)$ be the first link on the other s–t path. There are two possible cases. In the first case, e_1 and e'_1 use two different sectors. In this case, the power of the two links corresponds to the two sectors used. In the second case, e_1 and e'_1 use the same sector (as in the case of links (u, v) and (u, w) in Figure 2(c)). In this case, the power of the two links corresponds to the single sector used. In both case, the interference of the two links are computed jointly. This leads to the algorithm for *MICDP* as listed in Algorithm 5.

Theorem 5: Algorithm 5 correctly computes a pair of node-disjoint s–t paths with minimum total power among all node-disjoint s–t paths whose maximum interference value is no more than I_{max}, provided that there exists a pair of node-disjoint s–t paths with maximum interference no more than I_{max}. In addition, the worst-case running time of Algorithm 5 is $O(n^4)$.

PROOF. $\mathbf{step\_1}$ computes a pair of node-disjoint s–t paths with minimum total power subject to the maximum interference constraint when Wireless Multicast Advantage is used with a WMA link pair using two different sectors. This is a generalization of the source transmit power selection technique of Modiano *et al.* Since the total number of (v, w) pairs is $O(n^2)$, This step takes $O(n^4)$ time ([19], [20]).

$\mathbf{step\_2}$ computes a pair of node-disjoint s–t paths with minimum total power subject to the maximum interference constraint when Wireless Multicast Advantage is used with a

Algorithm 5 Solving MICDP

INPUT: Existing network status: n wireless nodes; number of cones k; link load of each wireless link; link interference of each wireless link. A connection request ρ with source node s, destination node t and rate requirement b, and a maximum interference tolerance I_{max}.

OUTPUT: A pair of node-disjoint s–t paths P and Q with minimum total power among all s–t paths whose maximum interference is at most I_{max}.

step_1 For each WMA link pair (s, v) and (s, w) such that v and w are in different cones centered at s and that the interference value of this WMA link pair is no more than I_{max}, do the following:
1) Construct a directed graph $G_{svw}(V, E)$ where V contains all the wireless nodes and E contains all the normal wireless links (u, v) such that $u \neq s$ and the interference value of (u, v) is at most I_{max}. E also contains two edges (s, v) and (s, w), both with (artificial) zero power value.
2) Apply Suurballe's algorithm [19] to compute a pair of node-disjoint s–t paths P_{svw} and Q_{svw} in G_{svw} with minimum total power. The total power of P_{svw} and Q_{svw}, denoted by $\pi(P_{svw}, Q_{svw})$, is $C(P_{svw}, Q_{svw})$ plus the (true) power value of the two sectors for the WMA link pair (s, v) and (s, w).

step_2 For each WMA link pair (s, v) and (s, w) such that v and w are in the same cone centered at s and that the interference value of this pair of WMA links is no more than I_{max}, do the following:
1) Construct a directed graph $G'_{svw}(V', E')$ where G'_{svw} is constructed similarly as G_{svw} in $\mathbf{step\_1}$.
2) Apply Suurballe's algorithm [19] to compute a pair of node-disjoint s–t paths P'_{svw} and Q'_{svw} in G'_{svw} with minimum total power. The total power of P'_{svw} and Q'_{svw}, denoted by $\pi(P'_{svw}, Q'_{svw})$, is $C(P'_{svw}, Q'_{svw})$ plus the (true) power value of the sector for the WMA link pair (s, v) and (s, w).

step_3 From the path pairs (P_{svw}, Q_{svw}) and (P'_{svw}, Q'_{svw}), select a pair (P, Q) with the minimum total power and output this path pair.

WMA link pair using a single sector. Since the total number of (v, w) pairs is $O(n^2)$, This step also takes $O(n^4)$ time ([19], [20]).

$\mathbf{step\_3}$ selects the best path pair among $O(n^2)$ pairs. Therefore it takes $O(n^2)$ time. This completes the proof of the theorem. □

As in the case of Algorithm 2 and Algorithm 4, we can use Algorithm 5 as a subroutine and apply bisection on the possible link interference values to obtain an algorithm for solving **MIDP**. Due to the similarity in the design philosophy, we will omit the detailed description of the algorithm for solving **MIDP**.

VII. Performance Evaluation

In this section, we evaluate the performance of our algorithms via simulations. We consider static wireless networks with nodes randomly located in a $1000 \times 1000\ m^2$ region. In all scenarios, only single path connection requests will be generated. Therefore, a wireless node always use only one cone for transmission. Every node has a maximum transmission range $R_1 = 400m$ ([15]). In order to guarantee the correct reception, the power required for transmitting from node u to node v is set to $0.0001 * d(u, v)^2$. The number of cones k is set to 6. Each connections request is generated with a randomly chosen source/destination pair and rate requirement uniformly distributed in $[1, 20]$. In addition to the rate requirement, each connection also has a lifetime which specifies how many time units it will last. In our simulations, this connection lifetime is set to a random integer uniformly distributed in $[1, 100]$. Since this is the first paper addressing the interference-aware routing in the multihop wireless networks, we compare our algorithms with the minimum power path algorithm which finds a shortest path based on the power values of wireless links for each given connection demand. As discussed earlier, our algorithms will seek power constrained minimum interference paths. Here, the power tolerance is given by a *Bound Ratio* multiplied by the path power of the corresponding minimum power path. Although the connection requests are randomly generated, the same random numbers are used for different simulation runs in order to guarantee fair comparisons. The bound ratios are set to 1.5 and 2.0 respectively in the simulations. The average path interference and path power are used as two metrics for performance evaluations. Each entry in the tables reported here is the average over 500 connections.

In the first scenario, we observe how well our algorithms can perform under different traffic loads. We fix the number of nodes at 40. We then change the traffic loads by increasing the connection request arriving interval from 5 time units all the way up to 25 time units. The results are shown in Tables I, II, III and IV.

In all tables, the bottom row represents average values of the corresponding columns. Tables I and II show the average maximum path interference and path power given by Algorithm 2 and minimum power path algorithms under different connection arriving intervals. Regardless of the arriving intervals, our algorithm dramatically reduce the maximum path interference values compared with the minimum power routing algorithm. With the bound ratio set to 1.5, the maximum path interference is decreased by 40% on average and it is reduced further down to 47% if the bound ratio is set to 2.0. The greater the bound ratio, the lower the average maximum path interference can be achieved by using our algorithm. This is due to the fact that a relaxed power tolerance bound can give our algorithms a greater opportunity to find paths with relatively small interference values. If this power tolerance bound goes to infinity, then minimum interference paths will be found. However, these paths may have very high power costs. Our algorithms can be used to find a trade-off between the path interference and path power. We can guarantee power efficiency by setting this bound ratio to be a small value. Table II shows that the average power of paths found by our algorithm is just slightly higher than that of minimum power paths, specifically, 15% on average with the bound ratio set to 1.5 and 26% with bound ratio set to 2.0. The traffic loads decrease with an increase of the arriving interval. When a

TABLE I
Average Max Path Interference with Different Arriving Intervals

IV	Min-Power Path	MIPC(1.5)	MIPC(2.0)
5	90.13	57.34	50.73
10	46.43	28.30	25.26
15	31.77	18.47	15.97
20	23.39	12.54	10.95
25	18.53	10.06	8.99
AVG	42.05	25.34	22.38

TABLE II
Average Path Power with Different Arriving Intervals

IV	Min-Power Path	MIPC(1.5)	MIPC(2.0)
5	10.60	13.00	14.86
10	10.60	12.39	13.89
15	10.60	12.11	13.23
20	10.60	11.78	12.58
25	10.60	11.58	12.18
AVG	10.60	12.17	13.35

TABLE III
Average Total Path Interference with Different Arriving Intervals

IV	Min-Power Path	TIPC(1.5)	TIPC(2.0)
5	328.38	283.49	169.55
10	160.23	119.83	70.63
15	99.03	65.17	42.77
20	72.13	43.19	28.72
25	54.46	29.08	22.80
AVG	142.85	108.15	66.89

TABLE IV
Average Path Power with Different Arriving Intervals

IV	Min-Power Path	TIPC(1.5)	TIPC(2.0)
5	10.60	11.40	14.03
10	10.60	11.52	13.73
15	10.60	11.58	13.11
20	10.60	11.61	12.82
25	10.60	11.56	12.40
AVG	10.60	11.53	13.22

connection request arrives, the computed path is supposed to have greater path interference value if there is a relatively large volume of pre-existing traffic. Table I shows that the average maximum path interference decreases with an increase of the arriving interval no matter which algorithm is used. If we consider the total path interference, our algorithm outperform the minimum power path algorithm as well, but at the cost of a minor increase of path power. All related data are presented in Tables III and IV.

In the second scenario, we fix the connection request arriving interval to be 10 time units, and we randomly generate networks with 20, 30, 40, 50 and 60 nodes respectively. Similar to the results for the first scenario, an almost identical improvement is achieved by Algorithm 2 for maximum path interference and by Algorithm 4 for total path interference. Specifically, our algorithm reduce the maximum path interference by 39% with bound ratio set to 1.5, and 44% with bound ratio set to 2.0 on average. The average total path interference is reduced by 25%(bound ratio = 1.5) and 54%(bound ratio = 2.0). Relaxing the power tolerance value will dramatically decrease total path interference. For the average path power, we also obtain similar results as in the previous scenario. For example, Algorithm 2 increases the average path power from 10.37 to 12.17 by setting the bound ratio to 1.5, which is only a 17% increase.

The average path power should decease with the increase of the number of nodes since replacing a long wireless link with several relatively short ones could save power and a denser network has more short links available. However, it also depends on the deployment of the nodes. Since we do not assume a uniform node distribution , it is possible that the average path power of a network with comparatively large size is even greater than that of a network with small size when the difference of node numbers is not substantial. With regards to interference, especially the total path interference, the situation becomes more complicated. Since in a sparse network, we have to use long wireless links for routing, which leads to large interference scope, but there are not too many neighboring nodes to interfere with. These two factors counteract each other. Therefore we should expect to see some vibrations in interference values with the increase of network size. However, what needs to be pointed out is that no matter how many nodes we have in the network, our algorithms always outperform the minimum power path algorithm in terms of interference with a minor increase of power.

TABLE V
Average Max Path Interference with Different Network Sizes

N	Min-Power Path	MIPC(1.5)	MIPC(2.0)
20	70.60	47.62	43.50
30	47.64	29.25	28.26
40	46.43	28.30	25.26
50	44.92	26.15	23.12
60	42.72	23.78	20.53
AVG	50.46	31.02	28.13

TABLE VI
Average Path Power with Different Network Sizes

N	Min-Power Path	MIPC(1.5)	MIPC(2.0)
20	10.99	13.16	15.01
30	12.83	14.71	16.50
40	10.60	12.39	13.89
50	7.85	9.28	10.51
60	9.57	11.30	12.55
AVG	10.37	12.17	13.69

TABLE VII
Average Total Path Interference with Different Network Sizes

N	Min-Power Path	TIPC(1.5)	TIPC(2.0)
20	184.55	133.05	70.24
30	178.51	119.53	69.95
40	160.23	119.83	70.63
50	153.99	125.91	89.10
60	160.14	129.20	85.38
AVG	167.48	125.50	77.06

TABLE VIII
Average Path Power with Different Network Sizes

N	Min-Power Path	TIPC(1.5)	TIPC(2.0)
20	10.99	11.94	14.43
30	12.83	14.72	17.08
40	10.60	11.52	13.73
50	7.85	8.26	9.36
60	9.57	10.35	12.01
AVG	10.37	11.36	13.32

VIII. CONCLUSIONS

In this paper, we have studied several interference-aware routing problems in multihop wireless networks using directional antennas. We have presented new definitions for the link and path interference that are suitable for designing better routing algorithms. Based on these definitions, we have formulated several optimization problems related to routing in multihop wireless networks. These include the *Power Constrained min-Max Interference single path (MIPC)* and *Power Constrained min-Total Interference single path (TIPC)* routing problems. For each problem, we have presented an optimal algorithm. We have also presented simulation results which show that our algorithms reduce the average path interference by approximately 40% or more at the cost of only a slight increase in average path power compared with the well known minimum power path routing algorithm. We have also presented an optimal interference-aware node-disjoint path routing algorithm which enhances network survivability.

We intend to extend our work to broadcasting and multicasting in wireless networks using directional antennas. We will also study interference-aware fault-tolerant topology control problems.

REFERENCES

[1] M. Burkhart, P. V. Rickenbach, R. Wattenhofer, A. Zollinger, Does topology control reduce interference, *Proceedings of ACM MobiHoc'2004*, pp. 9–19.

[2] J. H. Chang, L. Tassiulas, Energy conserving routing in wireless ad-hoc networks, *Proceedings of IEEE Infocom'2000*, pp. 22–31.

[3] R. R. Choudhury, X. Yang, R. Ramanathan and N. H. Vaidya, Using directional antennas for Medium Access Control in Ad Hoc Networks. *Proceedings of ACM Mobicom'2002*, pp. 59-70.
[4] Q. Dai, J. Wu, Construction of power efficient routing tree for ad hoc wireless networks using directional antenna *Proceedings of ICDCSW'2004* pp. 718–722.
[5] S. Guo, O. W. Yang, Antenna orientation optimization for minimum-energy multicast tree construction in wireless ad hoc networks with directional antennas, *Proceedings of ACM MobiHoc'2004*, pp. 234–243.
[6] P. Gupta, P. R. Kumar, The capacity of wireless networks, *IEEE Transactions on Information Theory*, Vol. 46(2000), pp. 388–404.
[7] K. Jain, J. Padhye, V. Padmanabhan and L. Qiu, Impact on interference on multihop wireless network performance, *Proceedings of ACM Mobicom'2003*, pp. 66–80.
[8] K. Kar, M. Kodialam, T. V. Lakshman, L. Tassiulas, Routing for network capacity maximization in energy-constrained ad-hoc networks, *Proceedings of IEEE Infocom'2003*, pp. 673–681.
[9] T. Korakis, G. Jakllari, L. Tassiulas, A MAC protocol for full exploitation of directional antennas in ad-hoc wireless networks *Proceedings of ACM MobiHoc'2003*, pp. 98–107.
[10] M. Kodialam, T. Nandagopal, Characterizing achievable rates in multihop wireless networks: the joint routing and scheduling problem, *Proceedings of ACM Mobicom'2003*, pp.42–54.
[11] Q. Li, J. Aslam, D. Rus, Online power-aware routing in wireless ad-hoc networks, *Proceedings of ACM Mobicom'2001*, pp. 97–107.
[12] X. Y. Li, P. J. Wan, Y. Wang, O. Frieder, Constrained shortest paths in wireless networks, *Proceedings of IEEE Milcom'2001*, pp. 884–893.
[13] W. Lou, Y. Fang; A multipath routing approach for secured data delivery, *Proceedings of IEEE Milcom'2001*, pp. 1467–1473.
[14] W. Lou, W. Liu, Y. Fang, SPREAD: Enhancing Data Confidentiality in Mobile Ad Hoc Networks, *Proceedings of IEEE Infocom'2004*.
[15] A. Nasipuri, S. Ye, J. You, R.E. Hiromoto, A MAC protocol for mobile ad hoc networks using directional antennas, *Proceedings of IEEE WCNC'2000*, pp. 1214–1219.
[16] A. Spyropoulos, C. S. Raghavendra, Energy efficient communications in ad hoc networks using directional antennas, *Proceedings of Infocom'2002*, pp. 220–228.
[17] A. Srinivas, E. Modiano, Minimum energy disjoint path routing in wireless ad-hoc network, *Proceedings of ACM Mobicom'2003*, pp. 122–133.
[18] I. Stojmenovic, X. Lin, Power-aware localized routing in wireless networks, *IEEE Transactions on Parallel and Distributed Systems*, Vol. 12(2001), pp. 1122–1133.
[19] J.W. Suurballe, Disjoint paths in a network, *Networks*, Vol. 4 (1974), pp. 125–145.
[20] J. Tang, G. Xue, Node-disjoint path routing in wireless networks: tradeoff between path lifetime and total energy, *Proceedings of IEEE ICC'2004*.
[21] J. E. Wieselthier, G. D. Nguyen, A. Ephremides, Energy-aware wireless networking with directional antennas: the case of session-based broadcasting and multicasting, *IEEE Transactions on Mobile Computing*, Vol. 1(2002), pp. 176–191.
[22] C. H. Yeh, H. Zhou, H. T. Mouftah, A time space division multiple access (TSDMA) protocol for multihop wireless networks with access points, *Proceedings of IEEE VTC'2002*, pp. 1185–1189.
[23] J. Zhu, C. Qiao and X. Wang, A comprehensive minimum energy routing scheme for wireless ad hoc networks, *Proceedings of IEEE Infocom'2004*.