Oblivious Routing for Wireless Mesh Networks

Jonathan Wellons and Yuan Xue
Department of Electrical Engineering and Computer Science
Vanderbilt University
Email: {jonathan.l.wellons,yuan.xue}@vanderbilt.edu

***Abstract*—Wireless mesh networks have attracted increasing attention and deployment as a high-performance and low-cost solution to last-mile broadband Internet access. Traffic routing plays a critical role in determining the performance of a wireless mesh network. To investigate the best routing solution, existing work assumes traffic demand is static and known *a priori*. However, recent studies of wireless network traces show that traffic demand, is highly dynamic and hard to estimate. This paper studies an *oblivious routing* algorithm that is able to provide the optimal worst-case performance on all possible traffic demands users may impose on the wireless mesh network. To the best of our knowledge, this work is the first attempt that investigates oblivious routing in the context of wireless mesh networks. A trace-driven simulation study demonstrates that our oblivious routing solution performs competitively.**

I. Introduction

Wireless mesh networks (*e.g.*, [1], [2]) have attracted increasing attention and deployment as a high-performance and low-cost solution to last-mile broadband Internet access. In a wireless mesh network, local access points and stationary wireless mesh routers communicate with each other and form a backbone structure which forwards the traffic between mobile clients and the Internet.

Traffic routing plays a critical role in determining the performance of a wireless mesh network. Proposed approaches usually fall onto two ends of a spectrum. On one end are the heuristic routing algorithms (*e.g.*, [3]–[5]). Although many of them are adaptive to the dynamic environments of wireless networks, these algorithms lack the theoretical foundation to analyze how well the network performs globally (*e.g.*, whether the traffic shares the network in a fair fashion). On the other end of the spectrum are theoretical studies that formulate mesh network routing as optimization problems (*e.g.*, [6], [7]). The routing algorithms derived from these formulations usually claim analytical properties such as optimal resource utilization and throughput fairness. However, traffic demand is usually implicitly assumed as static and known *a priori*. In contrast, recent studies of wireless network traces [8] show that the traffic demand, even being aggregated at access points, is highly dynamic and hard to estimate.

To address this challenge, this paper investigates an optimal routing framework which takes into account the dynamic and uncertain nature of wireless traffic demand. Our goal is the design an *oblivious routing* algorithm that provides the optimal worst-case performance on all possible traffic demands users may impose on the network.

Oblivious routing [9] is a well-studied problem for traffic engineering on the Internet. In [10], Racke et al. prove the existence of a polynomial bounded routing within a network. In [9], Azar et al. present an algorithm which solves the oblivious routing problem via an iterative linear programming (LP) formulation. Most recently, [11] has simplified the model of [9] to allow a single LP formulation and [12] has applied predictive approaches to coping with mild uncertainty. Although routing is an active research topic for the Internet, to the best of our knowledge, this work is the first attempt that investigates the oblivious routing problem in the context of wireless mesh network. In fact, it is a non-trivial issue to extend the existing solutions proposed for the Internet to wireless mesh networks. The main challenge comes from interference and channel capacity constraints which are unique to wireless networks. Based on the method of [11], the optimal oblivious mesh routing problem is converted to a linear programming (LP) problem, which must be optimized over all properly scaled traffic demand patterns.

To evaluate the performance of our algorithms under a realistic wireless network environment, we conduct a trace-driven simulation based on traffic traces collected at the Dartmouth College campus wireless networks. Our results demonstrate that our oblivious mesh routing solution effectively incorporates the traffic dynamics into the routing optimization of wireless mesh networks.

The original contributions of this paper are two-fold. Practically, the oblivious mesh network routing solution proposed in this paper considers traffic dynamics and uncertainty in the mesh network routing optimization. The full-fledged simulation study based on real wireless network traffic traces provides convincing validation of the practicability of this solution. We theoretically redefine the concept of network congestion and extend the wireline network oblivious routing algorithm into wireless mesh networks to handle location dependent interference.

The remainder of this paper is organized as follows. Section II describes our network, interference and traffic models. Section III formulates the oblivious routing problem. Section IV presents the details of solving the oblivious routing problem. Section V presents our simulation study and results. Finally, Section VI concludes the paper.

II. Model

A. Network and Interference Model

In a multi-hop wireless mesh network, local access points aggregate and forward traffic from mobile clients which are associated with them. They communicate with each other and with the stationary wireless routers to form a multi-hop wireless backbone network. This wireless mesh *backbone* network forwards the user traffic to the gateways which are connected to the Internet. We use $w \in W$ to denote the set of gateways in the network and $s \in S$ to denote the set of local access points that generate traffic in the network. In the following discussion, local access points, gateways and mesh routers are collectively called mesh nodes and denoted by the set V.

In a wireless network, packet transmissions are subject to location sensitive interference. We assume that all mesh nodes have the uniform transmission range denoted by R_T. Usually the interference range is larger than its transmission range. We denote the interference range of a mesh node as $R_I = (1+\Delta)R_T$, where $\Delta \geq 0$ is a constant. In this paper, we consider the *protocol model* presented in [13]. Let $r(u,v)$ be the distance between u and v $(u,v \in V)$. In the protocol model, packet transmission from node u to v is successful, if and only if (1) the distance between these two nodes $r(u,v)$ satisfies $r(u,v) \leq R_T$; (2) any other node $w \in V$ within the interference range of the receiving node v, *i.e.*, $r(w,v) \leq R_I$, is not transmitting. If node u can transit to v directly, they form an edge $e = (u,v)$. We denote the capacity of this edge as $b(e)$ which is the maximum data rate. Let E be the set of all edges. We say two edges e, e' interfere with each other, if they can not transmit simultaneously based on the protocol model. Further we define the *interference set* $I(e)$ which contains the edges that interfere with edge e and e itself.

Finally, we introduce a virtual node w^* to represent the Internet. w^* is connected to each gateway with a virtual edge $e^* = (w^*, w), w \in W$. We use E' to denote the union of E and the set of all virtual edges and use V' to denote the union of V and the virtual node w^*.

B. Traffic Demand and Routing

This paper investigates the optimal routing strategy for wireless mesh *backbone* networks. Thus it only considers the aggregated traffic among the mesh nodes. For ease of exposition, we only consider the aggregated traffic from gateway access points to local access points in this paper. In particular, we regard the gateway access points as the sources of all incoming traffic and the local access points as the destinations of all incoming traffic. We denote the aggregated traffic to a local access point as a *flow*. All flows will take w^* as their source. Further we denote the traffic demand from local access point $s \in S$ to w^* as d_s and use vector $\boldsymbol{d} = (d_s, s \in S)$ to denote the demand vector consisting of all flow demands.

A *routing* specifies how traffic of each flow is routed across the network. Here we assume an infinitesimally divisible flow model where the aggregated traffic flow could be routed over multiple paths and each path routes a fraction of the traffic. Thus a routing can be characterized by the fraction of each flow that is routed along each edge $e \in E'$. Formally, we use $f_s(e)$ to denote the fraction of demand from local access point s that is routed on the edge $e \in E'$. Thus, a routing could be specified by the set $\boldsymbol{f} = \{f_s(e), s \in S, e \in E'\}$. Recall that the demand of node $s \in S$ is denoted by d_s. Therefore, the amount of traffic demand from s that needs to be routed over e under routing $\boldsymbol{f}$ is $d_s f_s(e)$.

C. Schedulability

To study the mesh routing problem, we first need to understand the constraint of the flow rates. Let $\boldsymbol{y} = (y(e), e \in E)$ denote the wireless link rate vector, where $y(e)$ is the aggregated flow rate along wireless link e. Link rate vector $\boldsymbol{y}$ is said to be schedulable, if there exists a stable schedule that ensures every packet transmission with a bounded delay. Essentially, the constraint of the flow rates is defined by the schedulable region of the link rate vector $\boldsymbol{y}$.

The link rate schedulability problem has been studied in several existing works, which lead to different models [14]–[16]. In this paper, we adopt the model in [15], which is also extended in [6] for multi-radio, multi-channel mesh network. In particular, [15] presents a sufficient condition under which a link scheduling algorithm is given to achieve stability with bounded and fast approximation of an ideal schedule. [6] presents a scheme that can adjust the flow routes and scale the flow rates to yield a feasible routing and channel assignment. Based on these results, we have the following claim as a sufficient condition for schedulability.

Claim 1. (*Sufficient Condition of Schedulability*) The link rate vector $\boldsymbol{y}$ is schedulable *if* the following condition is satisfied: $\forall e \in E,\ \sum_{e' \in I(e)} \frac{y(e')}{b(e')} \leq 1$

III. Problem Formulation

In this section, we first investigate the formulation of optimal routing for wireless mesh backbone network under known traffic demand. Then we extend this problem formulation to the oblivious mesh network routing where the traffic demand is uncertain.

A common routing performance metric with respect to a known traffic demand is *resource utilization*. For example, link utilization is commonly used for traffic engineering in the Internet [17], where the objective is to minimize the utilization at the most congested link. However, in a multihop wireless network, such as mesh backbone network, wireless link utilization may be inappropriate as a metric of routing performance due to the channel interference. On the other hand, the existing works on optimal mesh network routing [6] usually aim to maximize the flow throughput, while satisfying the fairness constraints. In this formulation, traffic demand is reflected as the flow weight in the fairness constraints.

In light of these results, we first outline the relation between the throughput optimization problem and the congestion minimization problem, and define the utilization (so-called *congestion*) of the interference set as the routing performance metric. We further define the *performance ratio* of a routing as the ratio between its congestion and the minimum congestion under a certain demand. In order to handle uncertain traffic demand, the *performance ratio* is extended to the *oblivious* *performance ratio* which is the worst performance ratio a routing obtains under all possible traffic demands. The definition of *oblivious performance ratio* naturally leads to the formulation of *oblivious mesh network routing* which handles uncertain wireless network traffic.

A. Mesh Network Routing Under Known Traffic Demand

First we present the capacity and flow conservation constraints under known traffic demand. Let $y_s(e)$ be the traffic of s that is routed over $e \in E'$. Obviously the aggregated flow rate y_e along edge $e \in E$ is given by $y_e = \sum_{s \in S} y_s(e)$. Based on the sufficient condition of schedulability in Claim 1 above, we have that $\forall e \in E,\ \sum_{e' \in I(e)} \sum_{s \in S} \frac{y_s(e')}{b(e')} \leq 1$.

Traffic into and out of nodes must be conserved. In particular, for the mesh routers that only relay the traffic, we have the following relations: $\forall u \in \{V - S\}, \forall s \in S, \sum_{e=(u,v), v \in V'} y_s(e) - \sum_{e=(v,u), v \in V'} y_s(e) = 0$.

For local access points $s \in S$, let x_s be the amount of traffic (throughput) to node s, we have that $\forall s \in S, \sum_{e=(s,v), v \in V'} y_s(e) - \sum_{e=(v,s), v \in V'} y_s(e) = -x_s$.

For the virtual node w^* which represents the Internet that originates all the traffic, we have $\forall s \in S, \sum_{e=(w^*,v), v \in V'} y_s(e) - \sum_{e=(v,w^*), v \in V'} y_s(e) = \sum_{s \in S} x_s$

Recall that d_s is the demand of local access point s. Consider the fairness constraint that, for each flow of s, its throughput x_s being routed is in proportion to its demand d_s. Our goal is to maximize λ (so called *scaling factor*) where at least $\lambda \cdot d_f$ amount of throughput can be routed for node s. Summarizing the above discussions, the throughput optimization routing with fairness constraint is then formulated as the following linear programming (LP) problem.

$$
\begin{aligned}
\mathbf{P_T}:\quad & \text{maximize } \lambda \\
\text{given}\quad & \sum_{e' \in I(e)} \sum_{s \in S} \frac{y_s(e)}{b(e')} \leq 1, \forall e \in E \\
& \sum_{e=(u,v)} y_s(e) - \sum_{e=(v,u)} y_s(e) = 0, \\
& \forall u \in \{V - S\}, \forall v \in V', \forall s \in S \\
& \sum_{e=(s,v)} y_s(e) - \sum_{e=(v,s)} y_s(e) = -\lambda \cdot d_s, \\
& \forall v \in V', \forall s \in S \\
& \sum_{e=(w^*,v)} y_s(e) - \sum_{e=(v,w^*)} y_s(e) = \lambda \sum_{s \in S} d_s \\
& \forall v \in V' \\
& \lambda \geq 0, \forall s \in S, \forall e \in E, y_s(e) \geq 0,
\end{aligned}
$$

Note that the above problem formulation follows the classical maximum concurrent flow problem. Although being extensively used to study mesh network routing schemes under known and fixed traffic demand [6], [18], such throughput optimization problem formulation is hard to extend to handle the case of uncertain demand. In light of this need, we proceed to study the congestion minimization routing. This differs from the throughput optimization problem where the traffic demand may not be completely routed subject to the constraints of the network capacity. Rather, the congestion minimization problem will route all the traffic demands which may violate the network capacity constraint, and thus the goal is to minimize the network congestion.

Let $y'_s(e)$ be the traffic of s on edge e under traffic demand d_s. Then $y'_s(e) = f_s(e) \cdot d_s$

Formally, we define the *congestion* of an interference set $I(e)$ using its utilization (*i.e.*, the ratio between its traffic load and the channel capacity) and denote it as $\rho(e)$: $\rho(e) = \sum_{e' \in I(e)} \sum_{s \in S} \frac{y'_s(e)}{b(e)} = \sum_{e' \in I(e)} \sum_{s \in S} \frac{f_s(e) \cdot d_s}{b(e)}$.

Further, we define the *network congestion* $\rho = \max_{e \in E} \rho(e)$ as the maximum congestion among all the interference sets $I(e)$. The congestion minimization routing problem is then formulated as follows:

$$
\begin{aligned}
&\mathbf{P_C}: \\
&\text{minimize} \quad \rho \\
&\text{subject to} \quad \sum_{e' \in I(e)} \sum_{s \in S} \frac{y'_s(e)}{b(e')} \leq \rho, \forall e \in E && (1) \\
& \sum_{e=(u,v)} y'_s(e) - \sum_{e=(v,u)} y'_s(e) = 0, && (2) \\
& \forall u \in \{V - S\}, \forall v \in V', \forall s \in S \\
& \sum_{e=(s,v)} y'_s(e) - \sum_{e=(v,s)} y'_s(e) = -d_s, && (3) \\
& \forall v \in V', \forall s \in S \\
& \sum_{e=(w^*,v)} y'_s(e) - \sum_{e=(v,w^*)} y'_s(e) = \sum_{s \in S} d_s, && (4) \\
& \forall v \in V' \\
& \forall s \in S, \forall e \in E, y'_s(e) = f_s(e) \cdot d_s \geq 0 && (5) \\
& \rho \geq 0, && (6)
\end{aligned}
$$

To reveal the relation between $\mathbf{P_T}$ and $\mathbf{P_C}$, we let $\rho = \frac{1}{\lambda}$ and $y'_s(e) = \frac{y_s(e)}{\lambda}$. Problem $\mathbf{P_C}$ is then transformed equivalent to the throughput optimization problem $\mathbf{P_T}$.

B. Oblivious Mesh Network Routing

Extensive research has been conducted on the optimal mesh network routing problem formulated in Section III-A with fixed and known traffic demand. Recent studies [8], however, show that the even aggregated traffic demand, is highly dynamic. To address this issue, we study routing solutions that are robust to changing traffic demands.

First we need to study the performance metric that could characterize a "good" routing solution. Based on the discussions in Section III-A, we start with the network congestion $\rho(\boldsymbol{f}, \boldsymbol{d})$ under a certain routing $\boldsymbol{f}$ and traffic demand vector $\boldsymbol{d}$, *i.e.*, $\rho(\boldsymbol{f}, \boldsymbol{d}) = \max_{e \in E} \sum_{e' \in I(e)} \sum_{s \in S} \frac{y'_s(e)}{b(e)}$. An *optimal routing* $\boldsymbol{f}^{opt}(\boldsymbol{d})$ for a certain demand vector $\boldsymbol{d}$ would give the minimum congestion, *i.e.*, $\rho^{opt}(\boldsymbol{d}) = \min_{\boldsymbol{f}} \rho(\boldsymbol{f}, \boldsymbol{d})$

Now we define the *performance ratio* $\gamma(\boldsymbol{f}, \boldsymbol{d})$ of a given routing $\boldsymbol{f}$ on a given demand vector $\boldsymbol{d}$ as the ratio between the network congestion under $\boldsymbol{f}$ and the minimum congestion under the optimal routing, *i.e.*, $\gamma(\boldsymbol{f}, \boldsymbol{d}) = \frac{\rho(\boldsymbol{f},\boldsymbol{d})}{\rho^{opt}(\boldsymbol{d})}$

The performance ratio γ measures how far $\boldsymbol{f}$ is from being optimal on the demand $\boldsymbol{d}$. Now we extend the definition of performance ratio to handle uncertain traffic demand. Let $\boldsymbol{D}$ be a set of traffic demand vectors. Then the performance ratio of a routing $\boldsymbol{f}$ on $\boldsymbol{D}$ is defined as $\gamma(\boldsymbol{f}, \boldsymbol{D}) = \max_{\boldsymbol{d} \in \boldsymbol{D}} \gamma(\boldsymbol{f}, \boldsymbol{d})$. A routing $\boldsymbol{f}^{opt}$ is optimal for the traffic demand set $\boldsymbol{D}$ if and only if $\boldsymbol{f}^{opt} = \arg\min_{\boldsymbol{f}} \gamma(\boldsymbol{f}, \boldsymbol{D})$

Note that the performance ratio γ is invariant to scaling. Thus to simplify the problem, we only consider traffic demand vectors $\boldsymbol{d}$ that satisfies $\rho^{opt}(\boldsymbol{d}) = 1$, instead of considering all possible traffic vectors. In this case, $\gamma(\boldsymbol{f}, \boldsymbol{D}) = \max_{\boldsymbol{d} \in \boldsymbol{D}} \rho(\boldsymbol{f}, \boldsymbol{d})$. Formally, the *optimal oblivious routing* problem for wireless mesh network is given as shown in $\mathbf{P_O}$.

$$
\begin{aligned}
\mathbf{P_O}: \quad & \text{minimize } \rho \\
\text{given} \quad & \forall \boldsymbol{d} \text{ with } \rho^{opt}(\boldsymbol{d}) = 1 \\
& \text{Equations (1) - (6) from } \mathbf{P_C} \text{ are true}
\end{aligned}
$$

.

IV. Algorithm

The oblivious mesh routing problem $\mathbf{P_O}$ cannot be solved directly, because it is taken over all demand vectors and $\rho^{opt}(\boldsymbol{d})$ is nonlinear.

$$
\begin{aligned}
\mathbf{D_O}: \quad & \text{minimize } \rho \\
\text{given} \quad & \forall e, e' \in E : \sum_{e} b(e)\pi_e(e') \le \rho \\
& \forall e \in E, \forall s \in S : \\
& \qquad \sum_{e' \in I(e)} f_s(e')/b(e') \le p_e(s) \\
& \forall e \in E, \forall s \in S, \forall e' = s' \to w^* : \\
& \qquad \pi_e(e') + p_e(s) - p_e(s') \ge 0 \\
& \forall e, e' \in E, \pi_e(e') \ge 0 \\
& \forall e \in E, \forall s \in S : p_e(s) \ge 0
\end{aligned}
$$

Here we follow the same idea as presented by Applegate and Cohen in [11]. This method provides a LP formulation of the oblivious routing problem. The key insight is to look at the dual problem of the slave LPs of the original oblivious routing problem. To adopt this method, we introduce interference set weights $\pi_e(e')$ in the dual formulation for every pair of interference sets e, e'. Further let $p_e(s)$ correspond to the length of the shortest path between local access point s and virtual gateway w^*. $\mathbf{D_O}$ summarizes the LP formulation of oblivious mesh routing based on the dual formulation of its slave LPs. Additional exposition is given in our technical report [19]. This set of equations in $\mathbf{D_O}$ represents a linear programming problem, thus we can solve it directly with a LP solver.

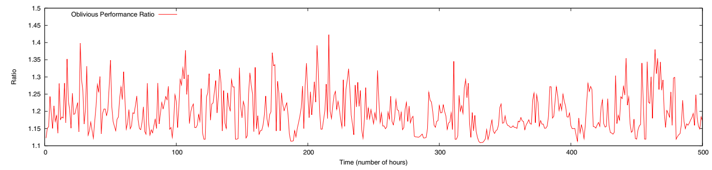

Fig. 1. Oblivious Performance Ratio Over Time, 4 Gateways

V. Simulation Study

A. Simulation Setup

We evaluate the performance of our algorithm with a simulation study, with 60 mesh nodes randomly deployed over a $1000 \times 2000m^2$ region (the full topology is shown in our technical report [19]). 10 nodes at the edge of this network are selected as the local access points (LAP) that forward traffic for clients. Sets of 2, 4 and 8 nodes near the center of the deployed region were selected as gateway access points. We have evaluated the performance of the algorithm with each of the three sets of gateways. Each mesh node has a transmission range of $250m$ and an interference range of $500m$. The data bit rate $b(e)$ is set as 54 Mbps for all $e \in E$.

B. Traffic Demand Generation

To realistically simulate the traffic demand at each LAP, we employ traces collected in a campus wireless LAN network. The network traces used in this work were collected in Spring 2002 at Dartmouth College and provided by CRAWDAD [20]. By analyzing the *snmp* log trace at each access point, we are able to derive their incoming and outgoing traffic volume beginning 12:00AM, March 25, 2002 EST. We argue that the LAPs of a wireless mesh network serve a similar role as the access points of wireless LAN networks at aggregating and forwarding client traffic. Thus, we select the access points from the Dartmouth campus wireless LAN and assign their traffic traces to the LAPs in our simulation.

We evaluate and compare different traffic routing strategies for this simulated network. In addition to Oblivious Routing (OBR), we consider Oracle Routing and Shortest Path Routing.

- *Oracle Routing (OR)*. In this strategy, the traffic demand is known *a priori* and a straightforward LP-based algorithm is run based on each hourly set of demands. In the figures in this section, we represent the quality of the network's oblivious and shortest path routings by their ratio with respect to OR.
- *Shortest-Path Routing (SPR)*. This strategy is agnostic to traffic demand, and returns a fixed routing solution purely based on the shortest distance (number of hops) from each mesh node to the gateway.

C. Simulation Results

First we simulate the Oblivious Routing (OBR), Oracle Routing (OR), and Shortest-Path Routing (SPR) strategies respectively over the network configuration with 4 gateways. In Fig. 1, the performance ratio of Oblivious Routing and

Oracle Routing ($ratio(\gamma) = \frac{\rho_{ORB}}{\rho_{OR}}$) is plotted for each hour in the trace collection. The ratio generally remains in the range of [1.15, 1.3], with occasional spikes. This result shows that our oblivious routing strategy performs competitively against the oracle routing strategy.

We compare the performance ratio of Oblivious Routing and Oracle Routing ($ratio_{ORB} = \frac{\rho_{ORB}}{\rho_{OR}}$) and the performance ratio of Shortest Path Routing and Oracle Routing ($ratio_{SPR} = \frac{\rho_{SPR}}{\rho_{OR}}$) over an arbitrary chosen block of one hundred hours in Fig. 2. In this figure, we observe that although both algorithms are intermittently superior, oblivious routing outperforms SPR most of the time. This observation is illustrated directly in Fig. 3, which shows the sorted performance ratios ($ratio_{ORB}, ratio_{SPR}$). The figure shows that the shortest path routing performs better in cases where very little congestion occurs, but for the majority of cases, oblivious routing is substantially better.

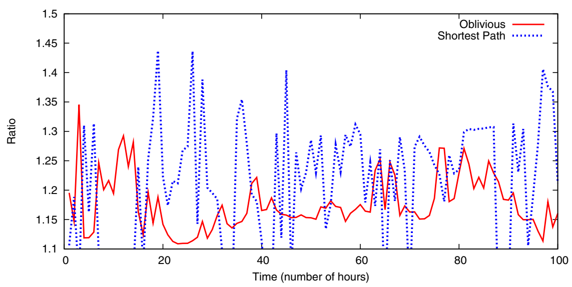

Fig. 2. Comparison of Oblivious Routing and Shortest Path Routing Over Time, 4 Gateways

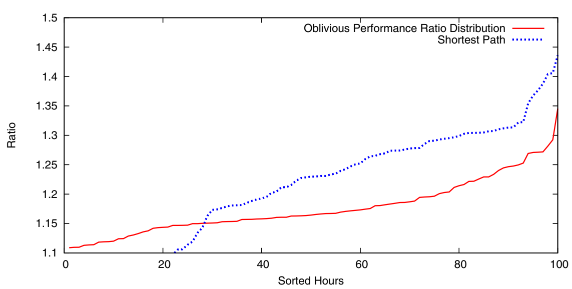

Fig. 3. Sorted Oblivious Performance Ratio Comparison, 4 Gateways

In order to better understand the relation between the number of gateways and the oblivious performance ratio, the simulation was also run with 2 and 8 gateways. Fig. 4 shows the sorted oblivious performance ratios in these three cases.

VI. Concluding Remarks

Unlike existing works which implicitly assume traffic demand as static and known *a priori*, this paper considers traffic demand uncertainty in Wireless Mesh Networks. We formulate the oblivious mesh network routing problem and convert it into a LP problem which can be easily solved. A simulation study shows that oblivious mesh network routing incorporates traffic demand uncertainty and performs competitively against the optimal routing.

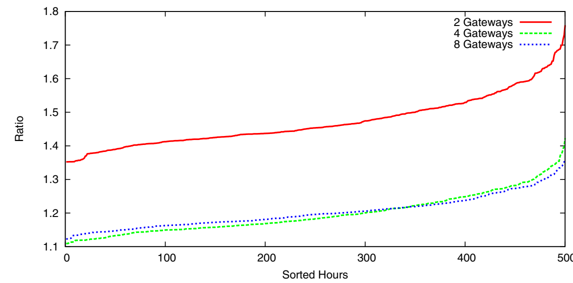

Fig. 4. Sorted Oblivious Performance Ratio, 2, 4, and 8 Gateways

References

[1] "Seattle wireless," http://www.seattlewireless.net.
[2] "Mit roofnet," http://www.pdos.lcs.mit.edu/roofnet/.
[3] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proc. of ACM Mobicom*, 2004.
[4] S. Biswas and R. Morris, "Exor: opportunistic multi-hop routing for wireless networks," in *Proc. of ACM SIGCOMM*, 2005.
[5] A. Raniwala and T. Chiueh, "Architecture and algorithms for an ieee 802.11-based multi-channel wireless mesh network," in *Proc. of IEEE INFOCOM*, 2005.
[6] M. Alicherry, R. Bhatia, and L. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," in *Proc. of ACM MobiCom*, 2005.
[7] J. Tang, G. Xue, and W. Zhang, "Maximum throughput and fair bandwidth allocation in multi-channel wireless mesh networks," in *Proc. of IEEE INFOCOM*, 2006.
[8] X. Meng, S. H. Y. Wong, Y. Yuan, and S. Lu, "Characterizing flows in large wireless data networks," in *Proc. of ACM MobiCom*, 2004.
[9] Yossi Azar, Edith Cohen, Amos Fiat, Haim Kaplan, and Harald Racke, "Optimal oblivious routing in polynomial time," *J. Comput. Syst. Sci.*, vol. 69, no. 3, 2004.
[10] Harald Racke, "Minimizing Congestion in General Networks," in *FOCS '02: Proc. of the 43rd Symposium on Foundations of Computer Science*, Washington, DC, USA, 2002, pp. 43–52, IEEE Computer Society.
[11] David Applegate and Edith Cohen, "Making intra-domain routing robust to changing and uncertain traffic demands: understanding fundamental tradeoffs," in *Proc. of ACM SIGCOMM*, 2003, pp. 313–324.
[12] L. Dai, Y. Xue, B. Chang, Y. Cao, and Y. Cui, "Optimal routing for wireless mesh networks with dynamic traffic demand," *Mobile Networks and Applications*, 2008.
[13] P. Gupta and P.R. Kumar, "The capacity of wireless networks," *IEEE Trans. on Information Theory*, pp. 388–404, 2000.
[14] K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, "Impact on interference on multi-hop wireless network performance," in *Proc. of Mobicom*, September 2003.
[15] V. S. Anil Kumar, M. V. Marathe, S. Parthasarathy, and A. Srinivasan, "Algorithmic aspects of capacity in wireless networks," in *Proc. of ACM SIGMETRICS*, 2005, pp. 133–144.
[16] Yuan Xue, Baochun Li, and Klara Nahrstedt, "Optimal resource allocation in wireless ad hoc networks: A price-based approach," *IEEE Transactions on Mobile Computing*, vol. 5, no. 4, pp. 347–364, April 2006.
[17] H. Wang, H. Xie, L. Qiu, Y. R. Yang, Y. Zhang, and A. Greenberg, "Cope: traffic engineering in dynamic networks," in *Proc. of ACM SIGCOMM*, 2006.
[18] M. Kodialam and T. Nandagopal, "Characterizing the capacity region in multi-radio multi-channel wireless mesh networks," in *Proc. of ACM Mobicom*, 2005.
[19] J. Wellons and Y. Xue, "Oblivious routing for wireless mesh networks, *http://vanets.vuse.vanderbilt.edu/publications/icc08report-wellons-oblivious.pdf*," in *Vanderbilt Technical Report*, 2008.
[20] "A community resource for archiving wireless data at dartmouth," http://crawdad.cs.dartmouth.edu/.