This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

Gateway Selection in Multi-Hop Wireless Networks Using Route and Link Optimization

Hans Livingstone*§, Hidehisa Nakayama†, Takeshi Matsuda* Xuemin (Sherman) Shen‡, and Nei Kato*
* Graduate School of Information Sciences, Tohoku University, Japan
† Department of Electronics and Intelligent Systems, Tohoku Institute of Technology, Japan
‡ Department of Electrical and Computer Engineering, University of Waterloo, Canada
§ Email: hlivings@it.ecei.tohoku.ac.jp

***Abstract*—In recent years, along with the increasing popularity of multi-hop wireless networks, there has been a growing demand in the coupling of these networks to external ones such as the Internet. As traffic destined for external networks increases, special attention is required not only in gateway selection, but also in optimized routing and scheduling in order to maximize the network performance. In this paper we introduce the Ideally Scheduled Route Optimization (ISRO) method to address this concern. ISRO is the combination of three separate optimization problems: optimal routing of gateway traffic under ideal conditions, interference-free scheduling to determine link capacity, and route adjustment in light of the new link capacities. The performance of ISRO is evaluated by experiment which shows significant potential in maximizing the throughput and capacity of the network.**

I. Introduction

Multi-hop wireless networks provide many advantages in terms of reduced infrastructure, accessibility, and convenience which have led to their rapid adoption. In addition to easier deployment and greater connectivity, access to the Internet and rich applications can be offered to client nodes by simply inserting a gateway somewhere into the wireless network. Gateway nodes, which serve as bridges to external networks, can become popular and be overwhelmed with traffic. Attention is needed not only with proper gateway selection, but with optimized routing and scheduling in order to maximize the throughput and available network capacity regarding this resource [1].

Although wireless networks offer many advantages, the shared nature of the wireless medium introduces new problems of scalability and diminished performance as multiple users attempt to transmit simultaneously [2]. The problem of wireless interference, which results in reduced capacity because of contention over access to the wireless medium, continues to be a major roadblock in the performance of wireless networks [3]. Modern applications, such as VoIP, can especially be impacted by interference, because they are susceptible to packet delay and jitter, which is a function of network capacity [4]. Therefore, there is a need to maximize the available network capacity, especially concerning gateways which ultimately receive a majority of this traffic.

In this paper, we introduce the Ideally Scheduled Route Optimization (ISRO) method, which addresses the problem of gateway selection and route optimization. Our approach is the combination of three separate optimization problems designed to find the maximum available capacity of the network as well as the total throughput received by each gateway. The first step finds the optimal flow of traffic from each source node to gateway under ideal conditions. The second step produces an interference-free schedule to satisfy the flow requirements and determines the initial capacity of each link. Using this capacity information, the third step optimizes the routes in order to maximize throughput in light of each links capability.

The remainder of this paper is organized as follows: Section II discusses related work. Our proposed gateway selection and route optimization approach is detailed in Section III. Section IV presents the performance evaluation and Section V concludes the paper.

II. Related Work

Building on the groundbreaking work of Gupta et al. [5], who laid the framework for considering the effect of wireless interference, Jain et al. [6] introduced the conflict graph and ushered in the next major breakthrough in addressing the problem of interference.

Among their several contributions, the conflict graph which models the interference relationships between each wireless link in the network has enjoyed widespread adoption [7], [8]. The vertices of a conflict graph correspond to the active links in the network, and an edge is placed between two vertices if they cannot transmit simultaneously due to wireless contention.

Scheduling is performed by finding the Maximal Independent Sets (Max-IS) of vertices in the conflict graph and assigning each set a unique transmission time-slot. A Max-IS is an independent set which contains the largest amount of unconnected vertices possible, so every vertex in the Max-IS can transmit simultaneously without causing interference. The authors suggest routing and scheduling be performed in the same linear program, and although this can produce a feasible schedule, without separating the steps it can be difficult to maximize performance.

The gateway selection problem is formulated as a Mixed Integer Linear Program (MILP) with the objective to minimize the maximum node utilization throughout the network [7]. A conflict graph is used to account for interference and an optimal schedule is produced by using Max-ISs. Although

978-1-4244-5637-6/10/$26.00

[7] is solely concerned with the traffic flowing from source node to gateway, the conflict graph includes all links in the network, even those without traffic. This can result in reduced link capacity as more schedule time is allocated to inactive links. The possibility of optimal routing is left as a future problem and is not considered.

Wang et. al [8] study the problem of joint routing and link scheduling in wireless multi-hop networks with time division multiplexing in mind. They provide several greedy graph coloring algorithms for both centralized and distributed link scheduling under different interference models. The greedy scheduling algorithms although practical, leave room for improvement in determining optimal network performance.

Xin et al. [9] investigates throughput optimization in multi-hop multi-channel wireless mesh networks with regard to gateway placement. The gateway placement algorithm is formulated as a throughput optimization problem. Interference is modeled by a conflict graph and link scheduling occurs after gateway placement. This two step approach is similar to [8] where a schedule is developed in the second step to satisfy the traffic requirements generated in first step. Their scheme also includes a model for the delay incurred by channel switching and allows for multi-path routing.

Although multi-path routing can provide a higher degree of redundancy and fault-tolerance [10], without careful consideration, there is no guarantee that packets will arrive in-order. As [11] points out, multi-path routing can have a substantial overhead. The re-sequencing delay of out-of-order packets can be quite severe, so without special attention, the increase in recorded throughput could in reality be hiding a significant amount of packet reordering delay. In this paper we focus our attention on single path routing.

III. Proposed ISRO Method

A. Overview

In this section, we present ISRO, a new method designed to maximize the capacity and total throughput of the network in regard to gateway traffic by optimally solving the gateway selection, routing, and scheduling problem. ISRO concentrates on the case of source nodes communicating with Internet gateways and includes the assumption that every gateway provides identical features and is capable of handling all the traffic that it receives. The details of our proposal are given in the following subsections.

The variables used commonly throughout this paper are defined in Table I.

B. Ideal Routing

In this first step, we consider the entire network topology and generate an initial route that will be used as the basis for the analysis performed in later steps. Each source node s is assigned a destination gateway g which will allow it to communicate with an external network. The routes for each source node are chosen by the linear program outlined below which is designed to distribute traffic in the network.

TABLE I: Variables

l_{ij}	Denotes that a direct link exists between nodes i and j. This implies that nodes i and j are within communication range.
L_a	The set of all active links. Any link $l \notin L_a$ is considered inactive. The number of active links is denoted as $\|L_a\|$
N	The set of all nodes in the topology. The number of all nodes is denoted as $\|N\|$
N_{src}	The set of source nodes. The number of source nodes is $\|N_{src}\|$
N_{GW}	The set of gateways. The number of gateways is $\|N_{GW}\|$
C_{ij}	The capacity of link l_{ij} $C_{ij} = C_{ji}$
f_{ijs}	The rate of traffic flowing on link l_{ij} from node i to j which originated from source node s.
f_{ij}	The sum total of all traffic from i to j flowing on link l_{ij}. (Provided that $f_{ij} \neq f_{ji}$) $f_{ij} = \sum_{s \in N_{src}} f_{ijs}$
f_n	The sending and receiving rate of node n. $f_n = \sum_{i \in N} f_{in} + \sum_{j \in N} f_{nj}$
u_{ijs}	Denotes whether or not traffic originating from s flows over link l_{ij}
u_{ij}	The number of traffic flows from i to j on link l_{ij} (Provided that $u_{ij} \neq u_{ji}$) $u_{ij} = \sum_{s \in N_{src}} u_{ijs}$
u_n	The number of traffic flows passing through node n. $u_n = \sum_{i \in N} u_{in} + \sum_{j \in N} u_{nj}$

We recognize that in order to develop this initial route, the exact traffic volume information for each link is not necessary. Rather, the important information is simply in the number of flows passing over each link. Therefore, we make the following substitution:

$$f_{ijs} = u_{ijs} \tag{1}$$

and simply examine the number of flows on the links. In this step the effects of wireless interference are ignored in order to obtain an 'ideal' route.

The ideal routing problem can be formulated as the following MILP:

$$\min_u \max \quad \frac{1}{R_n} \sum_{n \in N} u_n \tag{2a}$$

s.t.

$$\sum_{j \in N} u_{ijs} = \sum_{j \in N} u_{jis} \quad (i \in N \setminus \{N_{src}, N_{GW}\}) \tag{2b}$$

$$\sum_{j \in N} u_{sjs} = 1 \qquad (s \in N_{src}) \tag{2c}$$

$$\sum_{i \in N} u_{iss} = 0 \qquad (s \in N_{src}) \tag{2d}$$

$$\sum_{j \in N} u_{gjs} = 0 \qquad (s \in N_{src}, g \in N_{GW}) \tag{2e}$$

$$\sum_{g \in N_{GW}} \sum_{i \in N} u_{igs} = 1 \qquad (s \in N_{src}) \tag{2f}$$

$$\sum_{j} u_{ijs} \leq 1 \qquad (s \in N_{src}, i \in N) \tag{2g}$$

$$\sum_{i} u_{ijs} \leq 1 \qquad (s \in N_{src}, i \in N) \tag{2h}$$

where R_n is the nominal data rate of node n.

Eq. (2b) requires flow conservation, Eqs. (2c, 2d) place restrictions on the traffic sent by source nodes, Eqs. (2e, 2f) force one gateway per flow. Since u_{ijs} is a boolean value, Eqs. (2g, 2h) ensure that each flow is routed through a single path.

Using the results of the MILP, the ideal route can then be built as follows: given a source node s, the route to its assigned gateway g can be found by selecting all links l_{ij} which contain traffic sent by s, where $u_{ijs} > 0$.

Additionally, the total number of flows on link l_{ij}, the link's flow requirement, denoted as q_{ij}, can be obtained from u_{ij} as follows:

$$q_{ij} = u_{ij} + u_{ji} \tag{3a}$$

where $q_{ij} = q_{ji}$

C. Link Scheduling

Given the flow requirements q_{ij} from the previous step, this section considers the effects of wireless interference and builds an interference-free transmission schedule. The resulting schedule is then used to obtain feasible capacity constraints to be passed onto the next step. In order to produce a tighter schedule, inactive links are cut from the network. Any link l_{ij} with a corresponding flow requirement of $q_{ij} = 0$ is removed from L_a.

Next, a conflict graph is built which models the interference relationships between all of the active links. From the conflict graph, the set of all Max-ISs is found and extracted. Although this an NP-hard problem, various approximation schemes exist which can be employed to address the intractability of the problem [6]. Each Max-IS, I_k, is then assigned a temporary position in the schedule matrix B according to the following definition.

$$B = \begin{array}{c} \\ I_1 \\ \vdots \\ I_k \\ \vdots \\ I_K \end{array} \begin{array}{c} \begin{array}{ccccc} l_1 & \dots & l_l & \dots & l_{\|L_a\|} \end{array} \\ \begin{pmatrix} b_{11} & \dots & b_{1l} & \dots & b_{1\|L_a\|} \\ \vdots & \ddots & \vdots & & \vdots \\ b_{k1} & \dots & b_{kl} & \dots & b_{k\|L_a\|} \\ \vdots & & \vdots & \ddots & \vdots \\ b_{K1} & \dots & b_{Kl} & \dots & b_{K\|L_a\|} \end{pmatrix} \end{array} \tag{4}$$

Here, each row corresponds to a time-slot and each column corresponds to one of the active links in L_a which utilize the current time-slot. Initially, every row k in B, contains Max-IS I_k such that element b_{kl} is defined as:

$$b_{kl} = \begin{cases} 1 & (l_l \text{ belongs to } I_k) \\ 0 & (\text{otherwise}) \end{cases} \tag{5}$$

The amount of time a link l will be active during a schedule period is the sum:

$$T_l = \sum_{k=1}^{K} b_{kl} \tag{6}$$

Therefore, while T_l must remain as large as possible in order to achieve the necessary capacity to satisfy l's flow requirement, K must be minimized in order to reduce the schedule period and increase the capacity of the entire network. If K remains large, then the network throughput will be reduced due to the longer period.

We employ the following MILP to solve this problem and ensure that every link receives enough time-slots to satisfy its flow requirements (one time-slot per flow) while minimizing the overall number of time-slots:

$$\min_{I} \quad K \tag{7a}$$

$$\text{s.t.} \quad T_{l_{ij}} \geq q_{ij} \qquad (l_{ij} \in L_a) \tag{7b}$$

The result is a schedule for the maximum transmission time of each link used in the ideal routing. From this we can calculate the capacity of each link l with the following:

$$C_l = W \frac{T_l}{K} \tag{8}$$

where W is the link's bandwidth capability.

D. Route Optimization

In this section we employ another MILP designed to maximize the flow of traffic on each active link in regard to the capacity calculated in the previous step.

The MILP which also employs constraints similar to Eq. (2b) – (2h), is as follows:

$$\max_{f} \quad \sum_{s \in N_{src}} \sum_{g \in N_{GW}} \sum_{i \in N} f_{igs} \tag{9a}$$

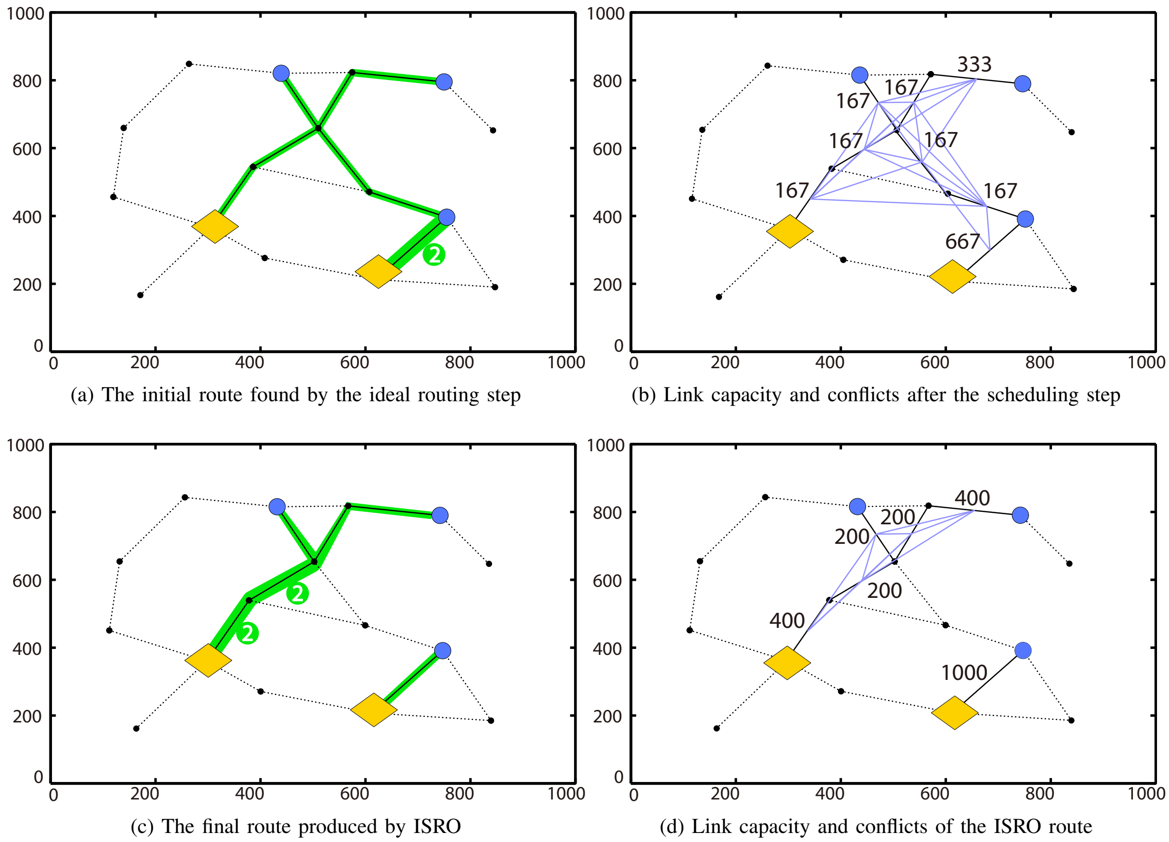
s.t.

$$\sum_{j \in N} f_{ijs} = \sum_{j \in N} f_{jis} \qquad (i \in N \setminus \{N_{src}, N_{GW}\}) \tag{9b}$$

$$\sum_{s \in N_{src}} (f_{ijs} + f_{jis}) \leq C_{ij} \qquad (l_{ij}, l_{ji} \in L_a) \tag{9c}$$

$$\sum_{j \in N} f_{sjs} = \sum_{g \in N_{GW}} \sum_{l_{ig} \in L_a} f_{igs} \qquad (s \in N_{src}) \tag{9d}$$

where Eq. (9b) enforces flow preservation, Eq. (9c) places an upper bound on the flow rate of each link, and Eq. (9d)



(a) The initial route found by the ideal routing step

(b) Link capacity and conflicts after the scheduling step

(c) The final route produced by ISRO

(d) Link capacity and conflicts of the ISRO route

Fig. 1: The results of the ISRO method on an example topology

ensures that the volume of traffic sent by source node s equals the volume received from s at its chosen gateway.

The effect of this optimization is that links with spare capacity are consolidated and the total number of active links in the network is reduced while throughput and capacity are increased. The final optimized routes can be found by using the procedure described in Section III-B after swapping u_{ijs} with f_{ijs}. Additionally, a new schedule can be produced to take advantage of this new route.

TABLE II: Evaluation Environment

Dimension	1000×1000 units
Number of Nodes (N)	16 (N_{src}: 3, N_{GW}: 2)
Node Placement	Uniform
Physical layer model	Protocol Model
Link Bandwidth	1000kbps
Communication Range	250m
Interference Range	325m

IV. Performance Evaluation

In this section, we discuss the performance of our approach evaluated in MATLAB.

A. Experiment Setup

We show an example of a static environment with 16 uniformly placed nodes, 3 of which are sources, 2 are gateways, and the remaining 11 nodes are relays. The network topology is shown in Fig. 1, where source nodes and gateways are depicted as blue circles and orange diamonds respectively. Node connectivity is constructed as a Unit Disc Graph (UDG) where each node has a 250m communication range. The interference range is defined as 325m (1.3 times the communication range). The Protocol Model described in [6] is used to model interference.

All nodes are given a 1000kbps radio operating on the same channel which is limited only by wireless contention. Each gateway is given a wired connection to the Internet. We assume that all traffic originating from source nodes is destined for the Internet and that other nodes only serve as relays. Each gateway is capable of handling all of the traffic that it receives and each source node will use all the link capacity that is available to it.

Under these assumptions, we compare the ISRO method against two other approaches.

The first approach, uses linear programming based routing combined with the centralized scheduling algorithm defined in [8]. This scheduling method uses a graph coloring algorithm to build a transmission schedule by greedily assigning as few time-slots as possible. We denote this method as LPR+CS.

The second comparison method uses linear programming based routing and a linear programming based scheduler

TABLE III: Performance Evaluation Results

Method	Throughput (Link Utilization at Gateway)	Average Link Utilization	Average Available Capacity
LP Routing and Centralized Scheduling (LPR+CS)	333	125	167
LP Routing and LP Scheduling (LPR+LPS)	833	208	250
Ideally Scheduled Route Optimization (ISRO)	1200	333	400

designed to satisfy the route requirements and minimize the schedule period. We denote this method as LPR+LPS and compare against it in order to show the improvement offered by ISRO.

B. Experiment Results

The numerical results of each method, LPR+CS, LPR+LPS, and ISRO for the example topology are shown in Table III. We provide three comparison metrics, total throughput which is the measured link utilization at the gateways, average link utilization, and average available capacity, the latter two being arithmetic means taken from the active links in the network.

In LPR+CS, although the schedule period is minimized, because each link only receives one time-slot, the capacity of every link is limited to the average available capacity (167kbps). Since each link can only carry the same amount of traffic, throughput is limited to the total number of links active at the gateway, allowing only 333kbps in this case. LPR+LPS provides a higher throughput of 833kbps, by assigning multiple transmission time-slots to each link, as well as attempting to minimize the schedule period.

The results of each intermediate step of the ISRO method on the example topology are displayed in Fig. 1. The path generated by the ideal routing step is shown in Fig. 1a. The green lines trace the path of each traffic flow from source (blue circle) node to gateway (orange diamond). The number of flows active on a link, the value of q, is also shown (in green), next to each link for values greater than 1.

The outcome of the link scheduling step including the initial capacities of the active links are shown in Fig. 1b. Inactive links, those which have been removed from consideration are drawn with dotted lines. Conflicts between links due to interference are illustrated by blue lines. It can be seen that in this rather dense network with many conflicting links, reducing the number of active links by consolidating traffic flows where appropriate, can lead to a significant improvement.

The final route obtained by the ISRO method accomplishes this and is shown in Fig. 1c. By consolidating the two flows onto the leftmost path, the number of conflicting links has been reduced, allowing for an improved transmission schedule with a shorter period. The maximized link capacities and reduced conflicts of the ISRO route are shown in Fig. 1d. In this case, the capacities of the links in the leftmost path have been increased to values of 200kbps and 400kbps. Additionally, neighboring links are also benefited by the reduced contention, as shown by the isolated link which is now capable of transmitting at a full 1000kbps capacity. This allows for a total throughput of 1200kbps which offers a notable improvement over the other methods.

V. Conclusion

In this paper, we studied the problem of gateway selection and optimized routing and scheduling in multi-hop wireless networks. Because gateways can attract a significant amount of traffic destined for the Internet, there is an ongoing need to further improve the utilization of this resource. With this problem in mind, we introduced ISRO, a new three step optimization method designed to maximize the available capacity and throughput in regard to gateway traffic. This process involves initial routing under ideal settings, producing an interference-free schedule in order to determine link capacity, and finally using this information as constraints to optimize the route. Through a performance evaluation we provide evidence which shows that ISRO not only increases throughput but also raises the total capacity of the network.

References

[1] T. Matsuda, H. Nakayama, S. Shen, Y. Nemoto, and N. Kato. On Gateway Selection Protocol for DYMO-Based MANET. *Wireless and Mobile Computing, Networking and Communication, IEEE International Conference on*, 0:32–37, 2008.

[2] M. Kodialam and T. Nandagopal. Characterizing Achievable Rates in Multi-Hop Wireless Mesh Networks with Orthogonal Channels. *Networking, IEEE/ACM Transactions on*, 13(4):868 – 880, Aug. 2005.

[3] J. Chen, S. He, Y. Sun, P. Thulasiramanz, and X. Shen, Optimal Flow Control for Utility-Lifetime Tradeoff in Wireless Sensor Networks. *Computer Networks (Elsevier)*, Vol. 53, Issue 18, pp. 30313041, 2009

[4] Q. Gong and P. Kabal. A New Optimum Jitter Protection for Conversational VoIP. In *Wireless Communications Signal Processing, 2009. WCSP 2009. International Conference on*, pages 1 –5, 13-15 2009.

[5] P. Gupta, P. Kumar, The Capacity of Wireless Networks, in *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 2000.

[6] K. Jain, J. Padhye, V. Padmanabhan, L. Qiu, Impact Of Interference On Multi-Hop Wireless Network Performance, in *Proc. of the 9th Annual International Conference on Mobile Computing and Networking*, 2003, San Diego, USA. pp 66 - 88.

[7] F. Hoffmann, D. Medina, Optimum Internet Gateway Selection in Ad Hoc Networks, in *Proc. IEEE ICC 2009*, June 2009, Dresden, Germany.

[8] Y. Wang, W. Wang, X.-Y. Li, and W.-Z. Song. Interference-Aware Joint Routing and TDMA Link Scheduling for Static Wireless Networks. *Parallel and Distributed Systems, IEEE Transactions on*, 19(12):1709 – 1726, Dec. 2008.

[9] Q. Xin and Y. J. Wang. Gateway Selection Scheme for Throughput Optimization in Multi-Radio Multi-Channel Wireless Mesh Networks. *Mobile Ad-hoc and Sensor Networks, International Conference on*, 0:187–195, 2009.

[10] H. Zafar, D. Harle, I. Andonovic, and Y. Khawaja. Performance Evaluation of Shortest Multipath Source Routing Scheme. *Communications, IET*, 3(5):700 –713, May 2009.

[11] V. Kolar, N. Abu-Ghazaleh, and P. Mahonen. Decomposition for Low-Complexity Near-Optimal Routing in Multi-Hop Wireless Networks. In *Communications, 2009. ICC '09. IEEE International Conference on*, pages 1 –6, 14-18 2009.

978-1-4244-5637-6/10/$26.00 ©2010 IEEE