Towards Interference-Aware Routing for Real-time Traffic in Multi-hop Wireless Networks

Vinay Kolar and Nael B. Abu-Ghazaleh
Dept. of Computer Science
State University of New York, Binghamton
{vinkolar,nael}@cs.binghamton.edu

Abstract

We formulate the real-time routing problem in static multi-hop wireless networks as an optimization problem, whose solution is the optimal routes relative to an end-to-end delay based objective. The problem is formulated as a mixed integer linear program. The variance of the delay with respect to the aggregate interference measures is empirically studied and a linear approximation is proposed. We show that this formulation yields routes that significantly outperform the best routes obtained by OLSR. Finally, we discuss the applications of such a model both in terms of capacity analysis, on-line algorithms for static scenarios, and extensions to allow the development of distributed protocols that solve the optimization problem.

1 Introduction

In Multi-hop Wireless Networks (MHWNs), such as Mesh networks and sensor networks, nodes collaborate to route traffic among each other. Real-time traffic is common in MHWNs as real-time events are detected and relayed, or as users access multimedia content on the move. Supporting real-time traffic is significantly more difficult than in wired networks because of the time-varying properties of the wireless channel and the complex and unpredictable nature of interference among nearby nodes [5].

Existing real-time solutions use local heuristics to estimate link quality or to differentiate traffic based on real-time deadlines(e.g., [6, 8]). While such distributed protocols are directly deployable in MHWNs, they use a greedy routing strategies that do not coordinate among competing flows. As a result, they may be unable to find an optimal (or even efficient) configuration for the routes in the network. In this paper, we formulate the real-time routing problem as an optimization problem whose solution is the routing configuration that optimizes a delay based objective. As such, we are better able to judge the ability of the network to support the required traffic given its deadlines.

While the basic model is centralized, it provides valuable insight into the available capacity of the network and the shape of optimal routes, which can then be used to guide the construction of distributed protocols. It can be also be directly applied as on-line tool for providing QoS guarantees, admission control, or for guiding provisioning decisions for real-time traffic in static MHWNs. Finally, its been shown that such formulations, for example in the context of TCP congestion control, can lead directly to distributed protocols (using the decomposition based approaches) [2].

Optimal routing of multiple connections is an instance of a well-known network flow problem called Multi-commodity Flow (MCF) problem [1]. Such routing models are Mixed Integer Linear Programming (MILP) which are known to be NP-hard. In a previous work, we developed a similar model for optimizing the capacity of the network [7].

2 Model Formulation

In this section, we describe the classic MCF problem formulation and extend it to account for interference. We develop a heuristic approach to estimate the delay from the level of interference experienced by a link. We the delay estimates then to specify an objective function to minimize the end-to-end delay of the connections in the network. Finally, we discuss how this delay minimization problem can be extended to support real-time traffic.

Assumptions and Notations: An MHWN is represented as a graph $G(N, E)$ where N is a set of wireless nodes. E denotes a set of all the edges (i, j) such that node i is able to transmit to node j. Let Γ_{ij} be the coupling (or gain matrix) which indicates how a node i interferes with node j. For simplicity, we assume a two-disk model of interference, where node i can transmit/interfere to/with a node j if its within a reception/interference range; thus Γ_{ij} is a boolean matrix where an element γ_{ij} is 1 if node i interferes with node j. Future extensions will explore more realistic interference models, which can be readily expressed in the framework. Let (s_n, d_n, r_n) denote source, destination and the rate of the n^{th} connection. The rate of connection, r_n, is the number of bits to be sent per unit time. Let C be the set of connections and let U be the capacity of the wireless channel. Let x_{ij}^n represent the flow that the edge (i, j) is carrying for the n^{th} connection.

Flow formulation: We start with the classical MCF constraints [1], which specify traffic sources and destinations, as well as edge capacity (we dont present these constraints for space considerations). The formulation is capable of providing a multiple routes for a given connection. However, many applications require a single route from source to destination to reduce the routing protocol overhead and to avoid the multi-path routing side-effects (like packet re-ordering). Hence, we introduce a new constraint to force the use of a single-route for each connection (Equation 1). The variable y_{ij}^n is a boolean variable which is set to 1 if the edge carries the traffic for the n^{th} connection and 0 otherwise. Under such conditions, the problem transforms into a integer MCF problem.

$$x_{ij}^n = r_n \cdot y_{ij}^n \quad \forall n \in C, \forall (i, j) \in E \tag{1}$$

The key difference in the wireless problem is the impact of interference. Specifically, in the wired problem, the link capacity is constant, and one has only to worry about which flows use what links. In wireless networks, nearby sources interfere and the capacity of an edge in the network graph is a complex function of traffic at other edges. Furthermore, many forms of interference arise (e.g., interference from a hidden node, vs. interference from a node close enough for the MAC protocol to avoid collisions).

Modeling Interference: Capturing the effect of interference faithfully under a realistic physical and MAC protocol is a challenging problem. Precise estimation of interference, even under a simple physical model, requires accounting for detailed scheduling intricacies of the MAC protocol like IEEE 802.11, which is extremely complex [5]. Computing the sets of edges that are concurrently active under a given MAC protocol is an instance of "Maximal independent sets" graph theory problem, which is NP-hard for general graphs. Moreover, the scheduling effects are a function of the routing configuration (which determines which edges are active), and have to be re-evaluated for every candidate routing configuration. Thus, we target simplified models of interference to reduce the complexity of the solution.

We now describe an approximation model to capture interference. A link (i, j) has interference from a link (a, b) if: (1) the sources interfere with each other, i.e $\Gamma_{ai} = 1$; or (2) the destination of the link can be interfered by another source, i.e. $\Gamma_{aj} = 1$. Hence, the amount of "busy time" an edge (i, j) experiences due to interference is given by Equation 2.

$$I_{ij} = \sum_{n \in C, (a,b) \in E, \Gamma_{ai}=1 \vee \Gamma_{aj}=1} x_{ab}^n \quad \forall (i, j) \in E \tag{2}$$

The total amount of traffic carried by an edge (i, j) is represented as *Signal* ($S_{ij} = \sum_{n \in C} x_{ij}^n$). Thus, the channel as viewed from a link (i, j) is busy for the duration of its transmissions in addition to the duration of interference from nearby links (that is, $S_{ij} + I_{ij}$); we call this quantity the *commitment period* of link (i, j) (denoted by $\mathcal{C}_{ij}$). For feasibility, the commitment period should be less than the capacity of the wireless channel (U). For the edges which do not carry any traffic (passive edges), the commitment periods are immaterial for the routing objective. Thus $\mathcal{C}_{ij}$ is $S_{ij} + I_{ij}$ for active edges, and zero for passive ones.

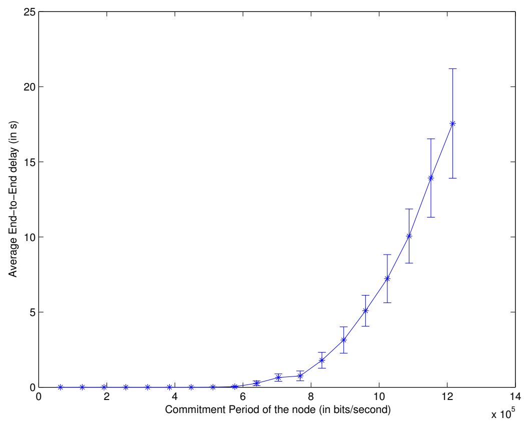


Figure 1. Variation of End-to-End delay with Commitment Period

Before formulating the objective function, we seek to establish the relationship between the commitment period and delay. We assume that all flows are equally important to simplify the presentation. However, direct extensions to differentiate flows based on their respective deadlines are possible. The commitment period of an edge approximates the amount of delay over an edge since it represents the channel reservation at the link.

In order to verify this, we simulated 100 random scenarios in a 1000x1000 MHWN with 2Mbps capacity. We varied the number of one-hop connections in the network to alter the amount of traffic on the channel. The commitment periods of different active edges and the end-to-end delay of the packet as observed in simulation are plotted in

Figure 1. It can be seen that the average delay almost monotonically increases with the calculated commitment period, which suggests that commitment period can be used as an approximation for the end-to-end delay. The delay is very small (orders of transmission time of the packet) for commitment periods until 30% of the capacity, after which the delay grows acutely (approximately an exponential curve).

The threshold point at which there is a sharp growth in the delay is also a function of the packet sending rate and the number of interferers. Capturing such variances would require precise characterization of the interference with respect these parameters. An additional problem is to represent them as a linear/convex equation in an optimization problem. This is a part of our future work. However, the approximately monotonic increase in the delay with commitment period can be assumed for simplification and we use this relationship for formulating the objective function.

Objective function:

The total delay of a connection over all the hops can be represented as a the sum of the commitment periods.

$$\text{Delay for Connection } n = \sum_{(i,j)\in E} \mathcal{C}_{ij}^n$$

Minimizing the delays for all the connections will convert the formulation to a multi-objective function, which is harder to solve than a single objective function. Hence, we convert the objective function to minimize the sum of delays of all the connections (Equation 3).

$$\text{Minimize} \sum_{n\in C,(i,j)\in E} \mathcal{C}_{ij}^n \tag{3}$$

A real-time routing model can be directly extended from the above delay-sensitive routing formulation. The real-time delay deadlines for each connection can be mapped back to the respective commitment period deadlines by means of the empirical function shown in the Figure 1. Hard-real time deadlines can be added by constraining the delay on each connection to its commitment period deadlines. For soft-real time guarantees, a dual-optimization problem can be formed to account for the difference between the expected delay and the deadline. We wish to pursue this direction in our future work.

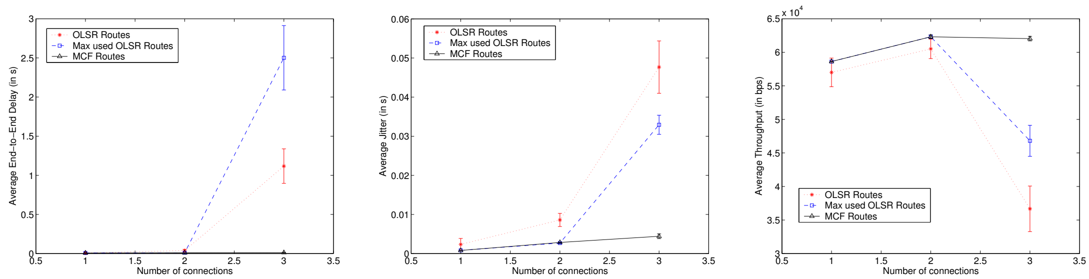
3 Simulation Results

In this section, we the evaluate the developed model against OLSR, an optimized and widely used routing protocol for ad hoc networks [3]. The Linear Programming formulation for the model was solved using the CPLEX solver [4]; the model instance is derived automatically from the scenario file (which changes the number of nodes and edges, the sources and destinations, as well as the Interference matrix Γ). The Qualnet simulator [10] was used to measure the performance of the proposed schemes under the IEEE 802.11 protocol.

We first demonstrate the shape of delay optimized routes using representative scenarios. We consider a 6x6 grid topology. CBR connections resembling VoIP G.711 codec (160 byte packets at 20MS interval) is simulated [9]. Each scenario is run for 20 random seeds and the 95% confidence interval is shown. In order to provide a fairer comparison that eliminates the dynamic routing overheads and route flapping from OLSR, we extract the set of *most used* route that was discovered by OLSR for each connection and use it under static routing. Such routes are referred as *Max used OLSR routes*.

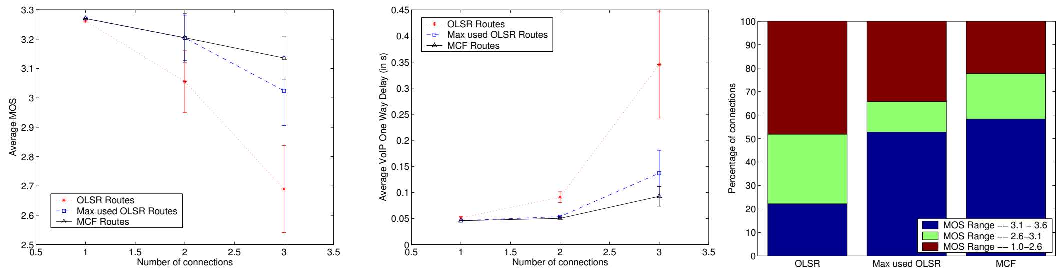
In this first study, the connections are separated such that the source and destinations are 5 hops away from each other. We increase the traffic (and therefore interference and delay) by adding more connections. Figure 2 compares the end to end delay, jitter and throughput, achieved by the formulation to those of OLSR. It can be seen that the all the protocols perform equally well under a lightly loaded network. As the number of connections increases above 3, we see that the formulation routes (MCF routes) outperform the other two in all the performance metrics. The exponential increase of delay due to slight variations in commitment periods is pronounced in 3 connection scenario where orders of magnitude difference in end-to-end delay is observed between the *Max used OLSR routes* and the MCF routes. Since OLSR does not account for interference, it is unable to route the connections effectively under high load.

The second study compares the performance of the MCF routes under real-time traffic in a random scenarios in a $1000 \times 1000m^2$ area. VoIP traffic with G.711 codec is used. 20 random scenarios were simulated under such a traffic and the Mean Opinion Scores (MOS) and End-to-End delay were measured as the number of connections were altered. MOS scores for VoIP traffic measure the user satisfaction and ranges from from 1 (worst) to 5 (best). Figure 3(a) and Figure 3(b) present the average MOS and one-way delay respectively. Figure 3(c) categorizes the MOS score according to VoIP categories; A MOS value of 3.6 and above is generally considered as acceptable limits for a satisfactory call [9]. It can be seen that the MCF routes out-perform the OLSR routes significantly both in terms of MOS (it has the largest population of high quality connections) and delay. Especially in the higher interference regions, MCF is able to find low delay routes.



(a) End-to-End Delay (b) Jitter (c) Throughput

Figure 2. CBR traffic – Grid scenario



(a) MOS (b) VoIP Delay (c) Percentages of connections in each MOS Category

Figure 3. Performance for VoIP traffic

4 Conclusions and Future Work

This paper formulates the delay-sensitive routing problem in MHWNs as an network flow problem whose solution is a routing configuration that optimizes an objective function in terms of end-to-end delay. To formulate the objective function, we characterize delay behavior in the presence of interference using simulation. Extensions of the model for real-time routing are discussed. Simulations show that large improvements in end-to-end delay and jitter over OLSR are obtained.

The scheme is centralized, but can be used for on-line optimization in static networks where it would not have to be invoked frequently. However, similar formulations have resulted in distributed protocols that essentially solve the optimization problem [2]. This is a topic of future work.

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