Link Capacity Estimation in QOLSR

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Abstract— **Capacity-constrained routing, i.e. the ability to find paths that offer available bandwidth above a required limit, in wireless ad hoc networks requires a way to measure link capacity (available bandwidth). Because of the open and shared nature of the radio medium, the capacity of a link is generally not independent of the capacities of neighboring links. In the present paper, we describe a method we use in QOLSR [1] to estimate link capacity using localized information.**

INTRODUCTION

A mobile wireless ad hoc network (or simply a MANET) is an infrastructure-less, automatically configured network of mobile and stationary nodes that use wireless radio network interfaces to communicate with each other. Each node can act both as a host running applications and as a router that forwards datagrams on behalf of other nodes, which allows distant nodes to be reached using intermediate ones. Because of the mobility of the nodes, implying a dynamic network topology, and the limited resources of mobile hardware, classical routing protocols for wired networks are not suitable. Therefore, specific approaches for MANETs have to be worked out and routing has been an active area of research for now over a decade.

Several routing protocols are today candidates to standardization at the IETF [2], [3], [4], but usually address a very simple form of best-effort routing, finding optimal paths in terms of number of hops. There are now many ongoing projects aimed at providing route calculation in terms of other quality of service (QoS) metrics for MANETs. Many multimedia applications need various constraints on QoS metrics to be satisfied in order to operate correctly (path capacity, delay, packet loss rate, etc).

QOLSR[1] is a project aimed at extending the OLSR [4] protocol to provide QoS routing and security features. Several route calculation algorithms have already been published and support up to four metrics simultaneously.

In the rest of this paper, the metric of interest is the path capacity, or available bandwidth. As we shall see in section I, the general simplistic assumption that a path's capacity is the minimum of the capacities of its constituent links is generally false in wireless networks. This led us to devise a method, described in section II, to achieve fairly accurate estimation of a link's capacity. Then, we describe the way this estimation is achieved in QOLSR in section III and finally present future works in the conclusion.

I. LINK CAPACITY CORRELATION

A. Link Capacity in Wired Networks

In wired networks, the general assumption that the capacity of a path equals the minimum of the capacities of its links relies on the fact that each network interface is connected to at most one link. This implies that the flows on different links do not interfere and capacities of links are independent of each other. The implication of this assumption is twofold: first, a link's total capacity is known and guaranteed; second, the capacity of a path equals the minimum of the capacities of the links it is spanning.

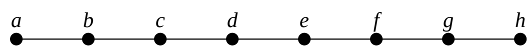
A pretty easy way to achieve capacity-constrained routing in wired networks is then to measure links' capacities periodically and calculate optimal routes using a slightly modified shortest path algorithm on the capacity-weighted topology graph.

B. Link Capacity of The Radio Medium

The previous assumption usually does not hold anymore in wireless ad hoc networks. First, the use of open and shared radio medium exposes links to interference from external sources of radiation or signals transmitted on the link itself bouncing off obstacles and traveling along different paths in parallel. Thus a link's total capacity is fluctuating and cannot be guaranteed. Second, one wireless network interface is generally involved in more than one link, implying that capacities of links are not independent of each other. Moreover, as we shall see shortly, the use of omnidirectional antennae make link capacities correlated with each other.

Let's assume, from this point on, some wireless ad hoc network with exactly one IEEE 802.11-compliant wireless network interface on each node. Consider one node a willing to send a frame to a neighboring node b. It is clear that during a's transmission of the frame, no other node hearing a is allowed transmit, because of carrier sense. This means that any link that has a as one of the endpoint is blocked. For any node that does not hear a, but could be heard by b, transmitting at the same time as a would cause a collision at b. This implies that a link is sharing the same capacity resource as all the links up to two hops away.

If RTS/CTS flow control is used to limit collisions due to hidden nodes, then it is clear that it does not matter which one of a link's endpoints is the transmitter and which one is the receiver. Consider, for example, the following simple topology.



Suppose that d intends to transmit a frame to e. First, d transmits an RTS frame, thus blocking transmission at c and e, then e responds with a CTS frame, blocking transmission at f. Now, since c is blocked, b cannot transmit to c as the latter would not respond with CTS after having received an RTS from the former or, in case RTS/CTS is not used, the latter would not send any ACK frame after the data frame transmission of the former. The same holds for f, hence the blocked links $\{b,c\}$, $\{c,d\}$, $\{d,e\}$, $\{e,f\}$ and $\{f,g\}$.

We say that all links sharing the same capacity resource are **correlated** or **conflicting**. But beyond correlations due only to CSMA/CA, there are correlations induced by nodes which signal power is above carrier sense threshold yet with signal-to-noise ratio too low to be understandable. Moreover, there are nodes which signal power is below carrier sense threshold yet which add up to the noise, making other nodes' signal-to-noise ratio, otherwise above reception threshold, drop. Thus there are practical cases when capacity estimation is impossible without additional tools. Yet as we shall see in the next section, there are ways to approximate this capacity in the general case using only local topology information.

II. Clique Constraints

A. Shared Capacities

Computing the maximum available bandwidth on a link is equivalent to finding a scheduling of links utilization that maximizes that link's throughput while keeping other link's throughput intact. Finding such a scheduling is known to be an NP-complete problem.

Nevertheless, there is a simpler condition: the sum of the throughput of all links belonging to a mutually conflicting subset *must be* lower than that links' shared capacity. If throughput is expressed as ratio of the time that the link is effectively used over the maximum time that only link could be used, instead of simply bit rate, then the sum of all using time ratios must be lower than 1.

Although this condition is necessary, it is alas not sufficient in the general case. There are cases when a scheduling is not possible even though the sum of the throughput's is lower than 1. This condition is only sufficient for so-called *perfect graphs*[1].

B. Cliques in Conflict Graphs

To find the subsets of links that are mutually conflicting, we construct a so-called **conflict graph**, in which vertices are the topological links and edges are the conflict relations between links. Thus a maximal subset of mutually conflicting links is a clique[2] in the conflict graph.

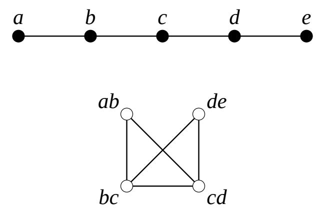


Fig. 1. Topology and conflict graph

In figure 1, the topology graph (top) is a simple branch. In the conflict graph (bottom), there is no edge between ab and de because $\{a,b\}$ and $\{d,e\}$ are not in conflict. Thus there are two cliques $\{\{a,b\},\{b,c\},\{c,d\}\}$ and $\{\{b,c\},\{c,d\},\{d,e\}\}$. This yields a simple linear system of constraints on flows:

$$\begin{cases} \dfrac{F_{ab}}{C_{ab}} + \dfrac{F_{bc}}{C_{bc}} + \dfrac{F_{cd}}{C_{cd}} \leq 1 \\ \dfrac{F_{bc}}{C_{bc}} + \dfrac{F_{cd}}{C_{cd}} + \dfrac{F_{de}}{C_{de}} \leq 1 \end{cases} \tag{1}$$

If we consider that $C_{ij} = C$ for all ij, then the system is even simpler:

$$\begin{cases} F_{ab} + F_{bc} + F_{cd} \leq C \\ F_{bc} + F_{cd} + F_{de} \leq C \end{cases} \tag{2}$$

Although there is no polynomial algorithm for clique calculation for general graphs, it happens that in practice our graphs are of limited order[3] and the algorithms we tested perform pretty well.

Clique constraints can be expressed in matrix form. Let Q^i be the $q \times n$ matrix, with q the number of cliques and n the number of nodes, defined by the following equation.

$$Q^i_{kj} = \begin{cases} 1 & \text{if link } \{i,j\} \text{ belongs to clique } k \\ 0 & \text{otherwise} \end{cases}$$

Then let F^i be the column vector of existing flows on each link from i to each other node and C be the column vector of size n with all entries equal to the total capacity. Now our clique constraints are simply

$$\forall i \quad Q^i F^i \leq C \tag{3}$$

As we have seen in the previous section, the clique constraints are sufficient only in case of perfect conflict graphs. Nevertheless, it happens [5] that clique constraints scaled by a factor of 0.46 are sufficient if the graph of links midpoints form an *unit disk graph* (UDG)[4]. This of course reminds of open air wireless networks in which a link exists if the signal power, decreasing with the distance, is high enough.

If node position is unknown, then the conflict graph cannot be guaranteed to be an UDG. Nevertheless it happens that using a realistic interference model, we are pretty well set if we use some scaling factor β, not necessarily equal to 0.46.

$$\forall i \quad Q^i F^i \leq \beta C \tag{4}$$

Actual simulation results leading to choose a reasonable value for β are given in [6].

[1] A graph is perfect if the chromatic number equals the size of the largest clique for any induced subgraph.

[2] Maximal complete subgraph, i.e. a complete subgraph which is not a strict subset of another complete subgraph.

[3] Number of vertices

[4] A UDG is a planar graph in which an edge exists between two vertices if and only if their euclidean distance is lower that a constant threshold.

C. Link Capacity Estimation

So we use clique constraints to estimate link capacities in an ad hoc network in a distributed fashion. The idea is that for all links a given node is incident to, that node computes the local conflict graph and all the cliques that link belongs to. Then it computes the lowest available bandwidth for that link among all its cliques. Let Γ_{ij} be the available capacity on link $\{i, j\}$, then we have

$$\Gamma_{ij} = \beta c - \max_{k:Q^i_{kj} \neq 0} \left\{ Q^i_k F^i \right\} \tag{5}$$

where Q^i_k is the kth line vector of Q^i and c is the shared capacity.

D. Taking Broadcast Flows Into Account

The previous equations consider only unicast flows. To be even more accurate, we have to take broadcast flows as well.

Broadcast flows do not conflict with each other and with unicast flows in the same way. For a broadcast transmission, no ACK or RTS/CTS frames are used, so links are less conflicting than for unicast. If we look at the topology of section I and suppose that c and e are broadcasting. Since c and e cannot hear each other, they can transmit at the same time. Then links $\{b, c\}$, $\{c, d\}$, $\{d, e\}$ and $\{e, f\}$ are busy and there is a collision at d, with no major consequence in terms of retransmissions, since broadcasts are not reliable.

Now suppose that c alone is broadcasting. Node e cannot transmit unicast datagrams to d at the same time, since d's carrier sense prevents it from transmitting (be in ACK or CTS frames). Nevertheless, e can still transmit unicast datagrams to f.

Clearly, broadcast flows are associated with nodes and not links. Therefore, we need to express addition constraints based on conflicting nodes. A second conflict graph has to be constructed in which vertices are nodes and edges are conflict relations. Cliques in that second graph are sets of nodes which broadcast flows share the same capacity resource. If we consider broadcast alone, independently of unicast flows, then the sum of flows in a clique of the second conflict graph is bounded by the shared capacity.

Let $\mathscr{Q}^i_{kj}$ be the matrix defined by

$$\mathscr{Q}^i_{kj} = \begin{cases} 1 & \text{if nodes } i \text{ and } j \text{ belong to clique } k \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

and $\mathscr{F}$ be the column vector of broadcast flows transmitted by each node. To merge these additional constraints on broadcast flows into equations for unicast flows, we have the following equation:

$$\forall i \quad Q^i F^i + \mathscr{Q}^i \mathscr{F} \leq C \tag{7}$$

Now we can exhibit formulae to calculate capacity for unicast flows and broadcast flows separately.

$$\Gamma_{ij} = \beta c - \max_{k:Q^i_{kj} \neq 0} \left\{ Q^i_k F^i \right\} - \max_{k, l \in \{i, j\}} \left\{ \mathscr{Q}^l_k \mathscr{F} \right\} \tag{8}$$

where $\mathscr{Q}^l_k$ is the kth line vector of $\mathscr{Q}^l$.

III. Capacity With QOLSR

In order to be able to perform capacity-constrained routing in QOLSR, each node has to estimate the capacity of the links it is incident to and MPR nodes have to spread that information into the network. Then each node willing to calculate capacity-constrained routes has the necessary information at hand.

A. Local Total Topology

Each node must be able to compute a conflict graph complete enough to allow calculation of all the cliques to which all the 1-hop links belong. It happens that for a n-hop link correlation model (in previous sections we agreed that n is at least 2), a node needs information about the total topology of the $(n+1)$-hop neighborhood.

In basic OLSR, HELLO messages are not retransmitted and thus each node acquires information about the 2-hop neighborhood. As shown in the following example, this 2-hop information is not enough if the correlation model is n-hop with $n \geq 2$.

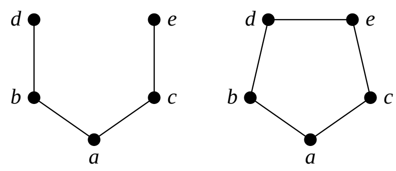


Fig. 2. 2-hop information is not enough.

Consider $n = 2$. If a node a acquires only information about the 2-hop neighborhood, then it is unable to distinguish between the two situations presented in figure 2. Indeed, a receives HELLO messages from b and c which tell that b can reach d and c can reach e and that is about it. Node a has no means to infer that link $\{d, e\}$ exists and thus links $\{a, b\}$ and $\{a, c\}$ belong to the only clique $\{\{a, b\}, \{a, c\}, \{b, d\}, \{c, e\}, \{d, e\}\}$. Without any more information, a could calculate that both links $\{a, b\}$ and $\{a, c\}$ belong to two cliques $\{\{a, b\}, \{a, c\}, \{b, d\}\}$ and $\{\{a, b\}, \{a, c\}, \{c, e\}\}$.

To enable nodes to correctly calculate cliques, we need to diffuse HELLO messages with a TTL of n. Thus with $n = 2$ we need to retransmit HELLO message one time. In example of figure 2, we see that a also receives HELLO messages from d telling that it is a neighbor of b and e and from e telling that it is a neighbor of c and d.

To be able to apply (4), a node also needs to know the actual flow on any link in a clique. To avoid dependence on MAC layer support, nodes perform packet accounting at IP level to measure actual throughput on links. Since it may happen that some packets are sent but lost, we are better off if the accounting is performed on outgoing packets at each node. Thus each node measures the forward throughput on each link separately and advertises this in HELLO messages. The total link usage being the sum of the forward throughput of a link's endpoints, a node also advertises the total link usage in HELLO messages.

Lastly, the computed link capacity is advertised in HELLO messages as well, to enable, as we shall see later, the use of local total topology to compute the set of MPRs, among other things.

To enable broadcast support in capacity calculation, each node performs accounting of broadcast datagrams in addition to unicast on each link. This information is then advertised in HELLO messages.

B. Global Partial Topology

As soon as a MPR node is able to estimate the capacity of the links it is incident to, it can advertise that information in TC messages. Thus each node in the network has capacity information in the global partial topology graph. To calculate capacity-constrained routes, a node needs to take into account intra-flow correlations. Link capacity estimations are accurate but still not independent of each other.

Here a pretty straightforward simplification can take place, as we can consider that a link of the path cannot interfere with another link of the same path that is enough hops away. This is equivalent to considering paths as rectilinear branches as the one presented in section I. The way to go is the following: if the path has a length of one hop, then that path's capacity is the capacity of its only link. If a path has a length of two hops, then that path's capacity is the minimum capacity of its two links divided by 2: only one link can be used at a time. If path has a length of three hops or more, the path's capacity is the minimum capacity of its links divided by 3.

Fig. 3. Optimal flow along a branch

As illustrated in figure 3, the optimal scheduling along such a topology, with $n = 2$ is one where every third link is used at a time.

Simulation results have been published in [6].

CONCLUSION

The capacity-constrained routing presented here is currently being implemented in the Qolyester[7] project. Perspectives for further works are support of broadcast capacity estimation, to allow multicast QoS routing.

The method presented in this paper has its limitations since the MAC layer is left untouched. Its performances depend on the efficiency of the MAC scheduling scheme. Several future enhancements are on their way.

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