Bandwidth Reservation in Multihop Wireless Networks: Complexity, Mechanisms and Heuristics

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***Abstract*— We prove that link interferences in multihop wireless networks make the problem of selecting a path satisfying bandwidth requirements an NP-complete problem, even under simplified rules for bandwidth reservation. This is in sharp contrast to path selection in wireline networks where efficient polynomial algorithms exist.**

We propose three heuristics to compute Quality of Service (QoS) routes in a multihop wireless networks considering interferences constraints. Our heuristics are based on Dijkstra's shortest path algorithm in which we integrate the notion of node capacity in order to satisfy flows requirements. We show with several simulations that these heuristics not only allows computation of routes that save bandwidth of nodes with low capacity but also that network can handle more QoS-flows.

Finally, we also describe a distributed mechanism for the problem of slot allocation according to bandwidth reservation in a wireless slotted environment.

***Index Terms*— Bandwidth Reservation, Interference, Quality of Service, MANET, Mobile Network, NP-complete, Wireless Network.**

I. Introduction

Multimedia flows need to satisfy certain performance requirements such as, bandwidth guarantees and upper bounds on packet losses and end-to-end delay in order to function properly. These requirements are generally known as Quality of Service (QoS) guarantees. Satisfaction of QoS guarantees has been an active area of research in wireline networks for several years. The same issue becomes more challenging in radio mobile networks where capacity is a scarce resource and packet transmissions are more prone to errors, noise and interference than wireline networks. This is especially true in wireless ad hoc networks, where packets are relayed by mobile nodes, rather than a base station as in cellular systems.

Two common mechanisms for providing Quality of Service (QoS) guarantees are, admission control and resource reservation. When a new flow is to be set between a source and a destination the source examines whether there are enough resources in the network so that the flow can be admitted and be provided with the required QoS, without affecting the already admitted connections (Admission Control). If these resources can be found, they are reserved for the flow (Resource Reservation) and transmission begins.

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In this work we are concerned with bandwidth as a performance requirement of a flow. We assume that a flow needs a certain bit rate in order to satisfy its QoS. We are interested in providing these bandwidth requirements to flows in a wireless ad hoc network. In wireline networks, each link is physically isolated from the other links even if they are attached to the same node. Therefore admission control for a flow consists in finding a path from the source to the destination such that links on the path have enough remaining capacity to satisfy the flow's bandwidth requirements. By "remaining capacity" is meant the link capacity minus the bandwidth already reserved for existing flows. Each node can advertise the remaining capacity of its links by periodically broadcasting this information in the network. Finding a path that satisfies the bandwidth requirements of a flow in a wireline network can be done using a simple modification of Dijkstra's shortest path algorithm in $O(n \log n + m)$ time, in a network with n nodes and m links. In a wireless ad hoc network environment, the situation is different and much more complicated. The links are not isolated: traffic carried by neighbor links may interfere, especially if the links operate on the same channel-frequency, as it frequently happens with existing WLANs.

We address the problem of admission control and bandwidth reservation in wireless networks. We consider a proactive routing scheme where nodes obtain through periodic information exchange knowledge of network topology and state. Such a scheme is appropriate in environments with relatively low mobility and high internode traffic. Compared to reactive schemes, it has the advantage that nodes can use knowledge of network topology and state in order to select judiciously paths and thus avoid delays and a large number of control messages that may overwhelm the network. On the other hand, a reactive scheme that does not rely on knowledge of network topology is more appropriate in environments with relatively frequent topology changes and low internode traffic.

Our objective is to devise a scheme by which the node where the new flow arrives will be able to decide on the path that the traffic flow should follow based on available knowledge of topology and on the "available bandwidth" at the network nodes. The latter quantity (available bandwidth) should be a single number in order to avoid inordinate amount of information exchange throughout the network during the periodic updates. Based on this number, we adopt a simplified bandwidth reservation process that reflects the fact that a

node's transmission or reception affects its neighbors. Even with this simplified scheme, we prove in Section II that the problem of selecting a path satisfying the bandwidth constraints is NP-hard. Moreover, we show that the related optimization problems cannot be approximated in polynomial time within n^{ε}, $\varepsilon > 0$, provided that $P \neq NP$. It was already known [1] that the global optimization of flows admitted in a network, assuming that all flow requests are available at the beginning of time, is an NP-hard problem as it reduces to the multiknapsack problem. However the complexity of admission of a new request was not known. For a slotted wireless system it was known [15] that finding the slot scheduling *along a given path* that satisfies a given bandwidth request is NP-complete.

In Section III, we introduce three heuristics to compute Quality of Service (QoS) routes in a multihop wireless networks considering interferences constraints. Our new heuristics are based on Dijkstra's shortest path algorithm in which we integrate the notion of node capacity in order to satisfy flows requirements. In Section IV, we show with several simulations that these heuristics not only allows computation of routes that save bandwidth of nodes with low capacity but also that network can handle more QoS-flows.

In Section V, we also describe a distributed mechanism for admission control and bandwidth reservation along a given path in a slotted system, that ensure that each flow receives its requested bandwidth once it is admitted by the network. Finally, in Section VI we present implementation issues related to mobile ad hoc routing protocols, such as OLSR.

II. NP-COMPLETENESS

A. Node Remaining Capacity

Consider an undirected graph $G(V, E)$ modelling a wireless network. Link (i, j) means that nodes i and j can communicate. Let N_j be the neighbors of node j. Denote by $N_j(h)$ the set of nodes that are at most h hops away from node j (including node j), *e.g.,* $N_j(1) = \{\{j\} \cup N(j)\}$. Node i has bandwidth C_i, i.e., it can send a message to its neighbors at rate C_i.

A transmission interferes with nodes that are within a number of hops, $\mathcal{H}_I$, from the transmitter and receiver, depending on the signal to noise ratio required for a correct reception. In the general case, for a successful transmission from node i to node j, it must be ensured that no node within $\mathcal{H}_I$ hops from receiver j are *transmitting* at the same time. Moreover, in order to ensure that i 's transmission does not interfere with other ongoing transmissions, it must be ensured that no nodes within $\mathcal{H}_I$ hops from i are *receiving* at the same time. Therefore reserving a unit of bandwidth for transmission from i to j requires the reservation of a unit of bandwidth from all receiving nodes within $\mathcal{H}_I$ hops from i and all transmitting nodes within $\mathcal{H}_I$ hops from j.

To simplify the bandwidth reservation process, one can impose the rule that whenever node i transmits to node j, the nodes in $N_i(\mathcal{H}_I) \cup N_j(\mathcal{H}_I)$ can neither transmit nor receive packets - this is the basic mode of operation in a CSMA-CD system. Therefore, transmitting b units of bandwidth from i to j, requires the reservation of b units of bandwidth on the nodes in $N_i(\mathcal{H}_I) \cup N_j(\mathcal{H}_I)$. Determining the minimal units that need to be reserved is complicated and depends on the selected end-to-end flow path. Instead, we first consider a simplified bandwidth reservation process determined by the following rule.

Rule A: Whenever b units of bandwidth need to be transmitted between nodes i and j, reserve b units of bandwidth on all nodes in $N_i(\mathcal{H}_I) \cup N_j(\mathcal{H}_I)$.

An example of bandwidth reservation is given in Figure 1 for a data flow from node A to node E, which requires one unit of bandwidth. In this example, using this Rule A, we take $\mathcal{H}_I = 1$. As shown on Figure 1(a), each node starts with 10 units of bandwith. In order to handle the flow between A and B, nodes A, B, C, F and G must reserve one unit of bandwidth. For B-C flow, nodes A, B, C, D and G must reserve one bandwidth unit, etc...

We use Rule A in our presentation of NP-completeness results in order to simplify the discussion.

B. Incremental check

Assume that a path $\mathcal{P} = \langle v_1, \cdots, v_k \rangle$ from $s(= v_1)$ to $t(= v_k)$ is established in order to transmit a unit of bandwidth, and $\mathcal{H}_I = 1$. It is easy to see that for this established path, the bandwidth b_i required to be reserved according to Rule A on node i is equal to the number of edges in the established path $\mathcal{P}$ that are reachable within one hop from i. For example, in Figure 1, $b_C = 4$ and $b_G = 3$. Formally, for any node i, $b_i = |E_{\mathcal{P}}(i)|$ where $E_{\mathcal{P}}(i) = \{(v_j, v_{j+1})\}, 1 \leq j < k$, such that $\{v_j, v_{j+1}\} \subseteq \mathcal{P}$ and ($v_j \in N_i(1)$ or $v_{j+1} \in N_i(1)$)$\}$.

Assume that node i has (remaining) capacity C_i. We must have

$$C_i \geq b_i, \ i \in V \tag{1}$$

We can now re-define formally our Bandwidth Admission Control into a "Path with Remaining Capacity problem" as follows.

Definition 1: The Path with Remaining Capacity problem (RC) is defined as:

Instance: A Graph $G = (V, E)$, two vertices s and t from V, and a Capacity $C_i \in \mathbb{N}$ for each vertex i from V.

Question: Is there a simple path from s to t in G that satisfies the constraint $C_i \geq b_i, \ i \in V$?

In the following section, we prove that, because of the basic constraint (1), this problem is NP-complete.

C. NP-completeness proof

We first recall the definition of the *Path with Forbidden Pairs problem (PFP)*.

Definition 2: The Path with Forbidden Pairs problem (PFP) (see [5] and GT54 in [6]) is defined as:

Instance: A Graph $G = (V, E)$, two vertices s and t from V, and a collection $C = \{(x_1, y_1), \ldots, (x_m, y_m)\}$ of pairs of vertices from V.

Question: Is there a simple path from s to t in G that contains at most one vertex from each pair in C?

The PFP problem is known to be NP-complete (see GT54 in [6]). Variants of this problem exist where a measure is the

length of the path (*i.e.,* the number of edges in the path): the shortest feasible PFP and the longest feasible PFP problems. Not surprisingly both variants are NP-complete and also NPO PB-complete [7], *i.e.,* in polynomial time, they cannot be approximated within n^{ε} for some $\varepsilon > 0$, where n is the size of the input, provided that $P \neq NP$.

Theorem 3: With $\mathcal{H}_I = 1$, the Path with Remaining Capacity problem (RC) is NP-complete.

Proof: It is easy to see that $RC \in NP$, because a nondeterministic algorithm needs only to guess a path and check in polynomial time that the constraint $C_i \geq b_i,\ i \in V$ is valid. (Of course, checking the constraint for the vertices of the path and for their neighbors is sufficient.)

We now give a polynomial reduction from this problem to the Path with Forbidden Pairs problem (PFP).

We first transform an instance $(G = (V, E), s, t, C)$ of the PFP problem to an instance $(G' = (V', E'), s, t, C')$ of the Remaining Capacity problem by formally defining:
- $V' = V \cup \{v_{xy} | (x, y) \in C\}$,
- $E' = E \cup \{(x, v_{xy}), (y, v_{xy}) | (x, y) \in C\}$,
- s and t are unchanged,
- C' is the capacity defined as: $C'_i = 2$ for $i \in \{v_{xy} | (x, y) \in C\}$ and $C'_i = |V|$ otherwise.

Informally, G' contains all the vertices of G as well as m vertices representing each forbidden pairs. Let us define F as the set of m vertices in G' representing each forbidden pairs of C. Each vertex of F is only connected to its two respective "forbidden" vertices and is assigned a capacity equal to 2. All other vertices are assigned a capacity equal to $|V|$ that is larger than any possible vertex bandwidth induced by a given established path. Of course, without loss of generality, we assume that (s, t) is not a forbidden pair.

We now prove that a solution of this instance of the RC problem is a solution if and only if it is a solution for the original instance of the PFP problem. Let us first assume that the length of this solution path is at least 3.

It is easy to see that a solution path $\mathcal{P}$ from s to t for the RC problem in $(G' = (V', E'), s, t, C')$ does not include any of the vertices of F, as each vertex v of the path (except, possibly, s and t) requires $b_v \geq 3$. Hence this path $\mathcal{P}$ is also a path $\mathcal{P}$ in G.

Furthermore, none of the forbidden pairs are included in the solution path. Otherwise there would exist a pair of vertices x and y (with $(x, y) \in C$) that both belong to the solution path. This would imply that the vertex v_{xy} is reaching more than 2 edges of the path within 1 hop and that the basic capacity constraint for the vertex v_{xy} is not valid as the bandwidth $b_{v_{xy}} \geq 3 > C_{v_{xy}} = 2$, thus leading to a contradiction. Hence a solution for the RC problem in $(G' = (V', E'), s, t, C')$ is a solution for the instance $(G = (V, E), s, t, C)$ of the PFP problem.

Conversely, given a solution path $\mathcal{P}'$ for the instance $(G = (V, E), s, t, C)$ of the PFP problem, we can verify that the path $\mathcal{P}'$ is a feasible solution path for the RC problem in $(G' = (V', E'), s, t, C')$. Obviously, $\mathcal{P}'$ is a simple path of G' as G is a subgraph of G'. Hence, we just need to verify that the bandwidth induced by the path respects the capacity constraint. It is clear from the reduction that only the nodes of F may jeopardize the feasibility of the solution, as they may not have sufficient capacity. Again, none of them belong to the path. A vertex of F can be a neighbor of a vertex of $\mathcal{P}'$, incurring a bandwidth of at most 2. However, a vertex of F cannot be a neighbor of two nodes in the paths as it can only be neighbor of its forbidden pair which would contradict the feasibility of $\mathcal{P}'$ for the instance $(G = (V, E), s, t, C)$ of the PFP problem.

Finally, in the case that the length of the solution path is smaller than 3, it is easy to check the two remaining possibilities. When the path is direct from s to t, the only forbidden pair of interest is (s, t) which is trivial. When the path is of length 2, say $\mathcal{P} = \{s, v, t\}$, we must also check that (s, v) and (v, t) are not forbidden pairs. All cases take a constant time to check. ■

As the proof follows a polynomial reduction from this problem to the Path with Forbidden Pairs problem (PFP), an immediate corollary follows.

Corollary 4: With $\mathcal{H}_I \geq 1$, the Path with Remaining Capacity problem (RC) is NP-complete.

For other considerations, we may also request that each path reserved is a shortest path. Using the result of Kann [7] on the shortest feasible PFP, it is easy to deduce the following corollary.

Corollary 5: With $\mathcal{H}_I \geq 1$, Shortest Path with Remaining Capacity problem ($SPRC$) remains NP-complete and is also hard to approximate (*i.e.,* NPO PB-complete, cannot be approximated within n^{ε} for some $\varepsilon > 0$, where n is the size of the input, provided that $P \neq NP$).

D. Variants

According to Definition 1, bandwidth reservation is limited to either determine a solution path that respects the capacity constraint or to reject the reservation if none is found (although one may exist; according to Theorem 3 it is unlikely to devise a polynomial algorithm that always finds a solution if one exists). Of course, the answer to a new request depends on the previous requests. In particular, at the initialization of the network, it is unlikely that the first requests will be rejected as the capacity is maximal in each node of the network. However, the protocol heuristic must prevent as much as possible the possible rejection of future requests by attempting to consume as small node capacity as possible and leaving the remaining capacity at each node as large as possible.

Two measures of interest are: the remaining capacity on node i, $C_i - b_i$ and the total consumed capacity $\sum_{i \in V} b_i$. These lead to the two following optimization problems:

1) Least Remaining Capacity (LRC): $\max \min_{i \in V} \{C_i - b_i\}$.
2) Minimum Total Consumed Capacity (TCC): $\min \sum_{i \in V} b_i$.

By Theorem 3, both are NP-hard and hence optimal solutions are unlikely to be found. However, as will be indicated in this section there is the possibility for the development of heuristics that work well in practice.

III. Description of heuristics

The main aim of this section, is to propose QoS heuristics which computes *bandwidth-aware* routes in a wireless multi-hop network subjected to interferences.

Before beginning the description of QoS heuristics, it is important to point out what we expect from these heuristics. Many *best-effort* routing protocols use a shortest path algorithm (*e.g.,* Dijkstra's Algorithm) to compute routes, but such protocols might not suit the basic constraint 1, since they do not take into account the constraint of nodes capacity.

First, QoS heuristics must offer a better route admission capability than a common shortest path algorithm. In other words, we expect the network to handle more traffic flows with QoS heuristics than without.

Next, we want the QoS heuristics to save bandwidth of nodes that have low bandwidth capacity. So, it is suitable that QoS heuristics choose, as a priority, nodes with high capacity.

Moreover, it is suitable that routes are not too long: routes may be longer than those computed with a shortest path algorithm (for instance, longer paths may be used to bypass some nodes with low capacity), but it is important to see that the longest a route is, the largest interferences potentially are.

In order to meet these issues, we introduce three QoS heuristics that are based on modifications of *Dijkstra's algorithm* for which we introduce the notion of nodes capacity. This implies that a node should have a vision of the network topology. This paper is not concerned with topology discovery but we can imagine an underlying mechanism similar to link-state routing protocols.

A. Heuristic based on the remaining capacity of forwarding nodes

In the common *Dijkstra's algorithm*, each edge $(i,j) \in E$ is associated with a weight $w_{(i,j)}$.

Denote by $W_{\mathcal{P}}$ the sum of links weights along a path $\mathcal{P} = \langle v_1, v_2, \ldots, v_{k-1}, v_k \rangle$ (i.e. $W_{\mathcal{P}} = \sum w_{(v_i, v_{i+1})}$, $1 \leq i \leq k-1$). The goal of Dijkstra's algorithm is then to minimize $W_{\mathcal{P}}$.

The idea of this first QoS heuristic H_1 is to choose nodes with regard to their current capacities and to maximize the bandwidth available along the path. In other words we want to minimize the inverse of nodes remaining bandwidth. More precisely, we consider that each node i is associated with a weight w_i equal to the inverse of its remaining bandwidth (*i.e.* $w_i = \frac{1}{C_i}$). The problem amounts to *Dijkstra's shortest path algorithm* since the objective of H_1 is now to compute a route $v_1, v_2, \ldots, v_{k-1}, v_k$ which minimizes $\sum \frac{1}{C_{v_i}}$, $1 \leq i \leq k$. Thus, a large weight is allocated to nodes which bandwidth capacity is low. Since the heuristic tries to minimize $W_{\mathcal{P}}$, it is easy to see that computed routes will tend to bypass nodes with low bandwidth capacity. For instance, if $C_i = 0$ then $w_i = \infty$ and then i will never be chosen by H_1 to route QoS-packets.

B. Extension of the first heuristic

Denote by H_n the generalization of the first QoS heuristic associated with the weight $w_i = \frac{1}{C_i^n}$, $i \in V$. The idea of the second heuristic is the following: whenever a route discovery fails with H_1 (*i.e.* no admissible route has been found with H_1), another try is performed with H_2. If a failure once again occurs with this new weight, another try is performed with H_3 etc.... One can set a bound B and say that if no admissible route has been found with H_B, the route discovery definitely failed.

In the rest of this paper this *incremental heuristic* is denoted by H_{inc}.

C. Heuristic based on the capacity of forwarding nodes neighborhood

Heuristics H_n are only concerned with capacity of nodes that are located on the routing path. But if we now consider the capacity of adjacent nodes, the heuristic comes closer to the network model and nodes then have a more accurate view of their neighborhood effective capacity.

Thus, we propose a third heuristic HN where nodes weights are:

$$w_i = \sum_{j \in N_i(1) \cup \{i\}} \frac{1}{C_j} \text{ with } i \in V$$

If a node i has neighbors which bandwidth capacity is low, w_i becomes large and HN will avoid choosing i for routing. For example if $j \in N_i(1)$ and $C_j = 0$, then $w_i = \infty$ and HN will never choose i for QoS-routing. It is important to note that although this heuristic provides a more accurate vision of capacities, it implies a slightly higher computation complexity. Moreover, one can denote by HN_n the heuristic were,

$$w_i = \sum_{j \in N_i(n) \cup \{i\}} \frac{1}{C_j} \text{ with } i \in V$$

If we consider that interferences propagates within $\mathcal{H}_I = n$ hops from the transmitter, HN_n exactly match the interferences constraint of the network but its complexity is much higher. This shows a tradeoff between the computation complexity and accurate model matching.

IV. Simulation results

In this section we present results of simulations conducted to compare performances of the heuristics we presented on Section III.

In these simulations, we consider a $1000\ m \times 1000\ m$ flat area. Let n be the number of wireless nodes and r their communication range (*i.e.* a node v_1 can receive data from a node v_2 if the distance between v_1 and v_2 is less or equal to r). Denote by δ the average degree of the network graph and let $\pi = \frac{\delta}{n}$. Whenever π becomes close to 1, interferences tend to propagate in the whole network.

In all these simulations we consider that $\mathcal{H}_I = 1$ (*i.e.,* interferences propagates within 1 hop from the transmitter).

We conducted several simulations with $1000 \leq n \leq 1500$, $50 \leq r \leq 300$ and we compared performances of Dijkstra's shortest path algorithm, H_1, H_{inc} and HN_1 heuristics.

A. Number of accepted flows

In the first simulations, we consider that all nodes in the network have 500 units of bandwidth. Then, we try to insert, one by one, 1000 QoS-flows, between random sources and destinations. All these flows require the reservation of 1 bandwidth unit to be correctly handle.

Figure 2 shows simulation results for $n = 1300$ and $r = 150$ ($\pi \approx 0.08$). We can see that Dijkstra's algorithm begins to reject QoS-flows from the 400th flow insertion whereas H_1 and H_{inc} accept flows without any rejection until 700 flows. HN_1 starts rejecting flows from the 900th insertion. At the end of the simulation 650 flows were accepted with Dijkstra's algorithm, almost 900 flows for H_1 and H_{inc} and almost 980 for HN.

If we only consider the final number of accepted flows according to the parameter π for all our simulations, we achieve results presented on Figure 3. We can see that for all the network configurations we simulated, heuristic H_1,H_{inc} and HN always handle more QoS-flows than Dijkstra's algorithm. Results for H_1 and H_{inc} are similar whereas HN always support more QoS-flows since it provides a more accurate vision of interferences.

B. Bandwidth distribution

Another important point to consider is the evolution of nodes capacities. Figure 4 shows, for each algorithm, the bandwidth distribution within the nodes when new flows are inserted.

When the number of inserted flows is low, all nodes have a large capacity. The first highest values have not been drawn in Figure 4 so as to make the representation more readable.

First, we can see that nodes using Dijkstra's algorithm reach a capacity equal to zero faster than with the other heuristics. The convergence to lowest capacity is slower with heuristics since they tend to use nodes with large capacity as depicted on Figure 4(b), 4(c) and 4(d). Dijkstra's algorithm tends to quickly spread bandwidth distribution: we have almost the same number of nodes that have low, medium or large capacity. This leads to creation of congestion areas where flows cannot be routed anymore. On the other hand, H_1, H_{inc} and HN_1 slowly convergence to low capacities and then offer better routing capabilities. Particularly as shown on Figure 4(d) HN_1 concentrate the bandwidth distribution around a relatively high average value.

C. Nodes with different original capacities

For the simulations presented above, each node starts with 500 bandwidth units. We are now interested in the evolution of the bandwidth when nodes do not start with the same capacity. Moreover, we want to show how our heuristics bypass low capacity areas in order to save bandwidth of nodes in these areas.

We take the same $1000\ m \times 1000\ m$ flat area as depicted above. We split this area by drawing a square in the middle of this map. We consider that nodes outside the square start with 500 bandwidth units and nodes inside the square start with 250 units of bandwidth.

Then we try to insert 500 QoS-flows, which all require 1 bandwidth unit, with Dijkstra's algorithm, H_1, H_{inc} and HN_1.

Again, in these simulations, we take $\mathcal{H}_I = 1$.

Figure 5 represents the insertion of 500 flows for $n = 1000$ and $r = 175$. Here 350 nodes start with 250 bandwidth units and 650 nodes with 500 units. We can see that Dijkstra's algorithm begins rejecting flows from 200 whereas H_1 and H_{inc} accept the 350 first flows. Heuristic HN_1 accepts almost all the flows. This can be explained by Figure 6 which represents the bandwidth distribution for these simulations. We also truncated the highest values to make the representation more readable. Figure 6(d) clearly shows how heuristic HN_1 saves bandwidth of nodes with low capacity: these nodes do not take part in routing as much as nodes with larger capacity since the lowest capacity value remains between 150 and 250. On the other hand, nodes capacities quickly converge to 0 with Dijkstra's algorithm. Although there are several nodes with large capacity, flows cannot be routed anymore because of the number of nodes with low capacity. H_1 and H_{inc} also produce a slow convergence to low capacities.

Figure 7 represents the number of inserted routes for all the simulations we conducted. First, we notice that a lot of routes are accepted with HN_1: for $\pi = 0.05$ for example, heuristics HN_1 accepts almost 450 routes whereas Dijkstra's algorithm accepts 200 routes.

H_1 and H_{inc} accept more routes than Dijkstra's Algorithm. Also notice, in this case, the better performance of H_{inc} in relation to H_1.

V. Bandwidth Reservation and Slot Allocation

A. Slotted Model

In this section we assume as in [15] that the channel is slotted, i.e., time is divided in slots of equal length, equal to the length of information packets. Moreover, time slots are divided into frames of length L. This channel may operate in parallel with a separate collision resolution channel. Transmissions that do not require reservation, as well as bandwidth reservation requests, take place on the collision resolution channel, while flows that require bandwidth reservation are transmitted in the slotted channel without collisions. There are several implementation issues concerning the previously described model, one of them being the manner in which slot synchronization can be maintained throughout the network. This can be accomplished by having a system like GPS issue synchronization signals. However, we do not dwell further into these issues, as our main objective at this point is to show how a proposed method of bandwidth reservation, coupled with a relatively simple distributed algorithm for reserving time slots, can ensure that all admitted flows receive their requested bandwidth (slots). Of course, the method does not guarantee that if an appropriate path exists it will always be found since this problem is NP-complete. The point is that using a simplified rule for bandwidth reservation, if a path is selected by the source node based only on partial knowledge of slot allocation at each node, then a slot schedule satisfying the bandwidth requirements of the flow can also be found in a distributed manner.

Assume that a new flow f arrives at network node s, and it is decided to use path $\mathcal{P}_f$ to transmit its packets to its destination t. When we say that a flow is given a bandwidth of $b_f \leq L$ units, we mean that some of the network nodes reserve slots so that all nodes along the path $\mathcal{P}_f$ are able to transmit or receive b_f of flow f's packets within each frame and that these transmissions can take place without interference, i.e., they can be safely delivered to the next hop (in the absence of errors due to channel noise).

In order to motivate our particular method of bandwidth reservation we consider first some examples. In Figure 8 (a) assume that the frame length is $L = 2$, $\mathcal{H}_I = 1$ and that Rule A is used for bandwidth reservation. Let flow f_1 requiring 2 slots per frame be established between nodes h and g. Thus nodes h and g fill-up all the available slots in a frame and announce zero available bandwidth. The same is true for node e, since this node cannot receive packets during a frame, due to node h's transmission. Assume next that a new flow request f_2 arrives at node a requiring again bandwidth 2, and with destination node e. Since node e has available bandwidth 0 according to Rule A, flow f_2 cannot be established, as is indeed the case. However, rule A may overestimate the bandwidth requirements needed to establish a flow along a path, i.e., it may not take advantage of all possibilities of spatial reuse. Assume for example in Figure 8 (a), that flow f_1 has origin node g and destination node h. Then node a will decide again that flow f_2 cannot be established. However, this time f_2 can be established since both nodes h and g will be receiving and therefore there will be no interference (recall that we assumed that $\mathcal{H}_I = 1$).

As another example consider the situation depicted in Figure 8 (b). Assume that $L = 4$, $\mathcal{H}_I = 1$ and that flow f_1 arrives first with $b_{f_1} = 1$. Hence, one slot must be reserved on nodes i and k, two slots on node j (one for reception and another one for transmission) and two slots on node c (to avoid interference during transmissions i to j and j to k. Assume that the first two slots in a frame are reserved on c to accommodate flow f_1. When flow f_2 arrives next, requesting bandwidth $b_{f_2} = 1$, node c must reserve two slots according to rule A i.e., it must reserve the last two slots in the frame. However, a schedule requiring node c to reserve only one slot is easy to construct: node a uses one of the first two slots for transmission from a to b and node b uses one of the last two slots, say slot 3, for transmission from b to c. The possibility of reducing the reserved bandwidth on a node in the previous examples comes at the expense of requiring knowledge of exact allocations of frame slots at each node in the network. The amount of information exchange required to obtain this knowledge can be unacceptable in wireless networks.

Unfortunately, the use of Rule A to determine a path p_f for a new flow f with bandwidth requirements b_f may also be too optimistic. That is, Rule A does not always guarantee that there are b_f available slots in a frame at each node on the path p_f that can be dedicated for the correct transmission of flows f packets. To see this, consider the example in Figure 9. Assume that $\mathcal{H}_I = 1$, and $L = 2$. Assume that flow f_1 arrives first with $b_{f_1} = 1$. Nodes a and b reserve the first slot in the frame for the transmission of flow f_1 packets and hence according to Rule I, nodes g, a, b, c, reserve one unit of bandwidth. Next flow f_2 with $b_{f_2} = 1$ arrives and nodes c and d reserve the second slot in the frame for transmission of flow f_2 packets. Hence nodes b, c, d, e, reserve an additional unit of bandwidth. Hence at this point in time, nodes a, d, g, e, have one unit of available bandwidth. Assume now that flow f_3 with $b_{f_3} = 1$ arrives. According to Rule A, there is available bandwidth on path (e, g) for flow f_3. However, no slot assignment can be found in a frame for this transmission: the first slot is prohibited because of transmission of flow f_1 packets and the second slot because of transmission of flow f_2 packets.

In our approach we would like to ensure that once a path p_f is chosen, the required slots for successful transmission can be found. This way, the likelihood that the connection setup request will fail is minimized. Hence, in order to avoid the last problem, (too optimistic rule) we change Rule A to the following.

Rule B: Whenever b_f packets per frame need to be transmitted between nodes i and j, reserve b_f slots in a frame on all nodes in $N_i(\mathcal{H}_I + 1) \cup N_j(\mathcal{H}_I + 1)$.

Next we show that Rule B, combined with local information that each node has about the use of frame slots by its neighbors in $N_i(\mathcal{H}_I + 1)$, guarantees the correct selection of paths for flow requests that arrive in the system.

Assume that node i knows the slots in a frame that are used for transmission or reception of packets by any of the nodes in $N_i(\mathcal{H}_I + 1)$. The available bandwidth A_i at node i is then defined as the unused slots in the frame. If a request requiring b_f slots arrives and $b_f \leq A_i$, then node i can reserve any b_f of the A_i slots for transmission of flow f packets. This process ensures the correct reception of these packets by the next hop node, say node j. To see this, note that $N_j(\mathcal{H}_I) \subseteq N_i(\mathcal{H}_I+1)$. Hence an unused frame slot at node i implies that no nodes in $N_i(\mathcal{H}_I) \cup N_j(\mathcal{H}_I)$ is using this slot for transmission or reception. This implies that the transmission of a flow f packet from i to j will take place without interference.

Nodes i and j must also inform their neighbors in $N_i(\mathcal{H}_I + 1)\cup N_j(\mathcal{H}_I+1)$ that they are reserving the particular b_f slots in a frame for transmission and reception respectively. Note that the actual number of slots reserved at a node with this process may be smaller than b_f. To see this, consider the example of Figure 8(b) again. According to Rule B, after connection f_1 is established, the remaining bandwidth of nodes b and c is 2,and the used slots are slot 1 and 2 in the frame. When connection f_2 is established, it will be calculated by the source node a that the remaining bandwidth on nodes b and c is zero. However, if node a picks slot 1 in the frame for transmission to node b, and b slot 3 for transmission to node c, then slot 4 will be unused on both nodes b and c. Hence the remaining bandwidth on nodes b and c will be 1. Since we adopt a proactive scheme, each node advertises periodically its remaining bandwidth to the other nodes. Hence the nodes will be informed about the extra remaining capacity of nodes b and c which implies that spatial reuse gain may be obtain.

B. Connection Establishment Mechanism

We now describe a distributed mechanism for slot reservation using Rule B, that results in collision-free transmissions. Node i in the network maintains a list $R_i[k]$, $k = 1, ..., L$. When $R_i[k] = 0$, then slot k in a frame can be used for a new transmission or reception by node i, or to avoid interference with its neighbors in $N_i(\mathcal{H}_I)$. When $R_i[k] > 0$, then slot k is unusable because this slot has been reserved for transmission or reception of already established flows, or in order to avoid interference with its neighbors in $N_i(\mathcal{H}_I)$. We call such a slot, an "occupied" slot. Any flow that causes a slot to be occupied is said to "occupy" the slot. Note that $R_i[k]$ can be larger than one in case the same slot is occupied to avoid interference with more than one neighbors. How to keep track of this is explained below. The "available bandwidth" A_i on node i is defined as number of unoccupied slots in a frame, i.e., the number of slots k for which $R_i[k] = 0$.

In addition to $R_i[k]$, node i keeps track of information for each flow f that occupies some of the slots in a frame, in the form of an array $F_i[f, j, k]$, where $F_i[f, j, k] = 1$ if node j requested slot k on i 's frame to be occupied in order to ensure the collision-free transmission of flow f's packets. Otherwise, $F_i[f, j, k] = 0$. Note that during the process of bandwidth reservation more than one nodes may request slots to be occupied by the same flow f. For example, in Figure 8 (b), node c needs to reserve two slots for flow f_1, one for the transmission of node i and one for the transmission of node j. In this example, $F_c(f_1, i, 1) = 1$, $F_c(f_1, j, 2) = 1$.

We assume that each node knows the available bandwidth of the nodes in the network. During the process of bandwidth reservation, the nodes exchange the lists $F_i[f, j, k]$ with their $\mathcal{H}_I + 1$-hop neighbors.

1) Arrival of a New Flow:

a) New Flow Arrival at the Source Node: Suppose that a new flow with bandwidth requirements b_f arrives at node s from the outside world. Then node i does the following.

1) Attempts to find a path $\mathcal{P}_f$ that joins s to the destination t of the flow and satisfies the requirements of Rule B. Specifically,
   Path Constraints: Let $(i_0 = s, i_1, i_2, ..., i_M = d)$ be the path nodes. The available bandwidth on any node $j \in \cup_{m=0}^{M} N_{i_m}(\mathcal{H}_I + 1)$ must be at least as large as the quantity r_j determined by the following algorithm
   a) Initialize $r_j = 0$ for all nodes in $\cup_{m=0}^{M} N_{i_m}(\mathcal{H}_I+1)$
   b) For each node i_m, $m = 0, ..., M-1$, do
      i) $r_j \leftarrow r_j + b_f$; $j \in N_{i_m}(\mathcal{H}_I + 1) \cup N_{i_{m+1}}(\mathcal{H}_I + 1)$;
   c) endo
   The quantities r_j are in effect the bandwidth that needs to be reserved on the nodes in $\cup_{m=0}^{M} N_{i_m}(\mathcal{H}_I + 1)$ according to Rule B, in order to guarantee interference-free transmission.
2) If a path satisfying the Path Constraints cannot be found then the flow is rejected. Else,
3) Node s picks b_f of slots k such that $R_s[k] = 0$ and makes them one. Moreover, it sets $F_s[f, s, k] = 1$ if slot k is one of the slots picked in this manner.
4) Node s sends a *reservation request* that includes $F_s[f, s, k]$ to all its neighbors in $N_s(\mathcal{H}_I + 1)$ and forwards the path $\mathcal{P}_f$ to the next-hop node i_1.

b) Processing a New Reservation Request: Suppose that a reservation request $F_i[f, l, k]$ arrives to node j from a neighbor i. Then

1) If the elements $F_j[f, l, k]$ $k = 1, ..., L$ are not already set (the discussion that follows explains how this can happen), then
2) Node j sets $F_j[f, l, k] = F_i[f, l, k]$, $R_j[k] \leftarrow R_j[k] + F_j[f, l, k]$, $k = 1, ..., L$.
3) If node j is the next hop on the path $\mathcal{P}_f$, it does the following
4) Node j sends a *reservation request* that includes $F_j[f, l, k]$ to all its neighbors in $N_j(\mathcal{H}_I + 1)$
5) If node j is not the last node on the path, then it acts as if the flow arrived from the outside world with the exception that the flow path $\mathcal{P}_f$ is the one received by node i. That is
   a) Node j picks b_f of slots k such that $R_j[k] = 0$ and makes them one. Moreover, it sets $F_j[f, j, k] = 1$ if slot k is one of the slots picked in this manner.
   b) Node j sends a *reservation request* that includes $F_j[f, j, k]$ to all its neighbors in $N_j(\mathcal{H}_I + 1)$ and forwards the path $\mathcal{P}_f$ to the next-hop.

The reservation in Step 4 ensures that all nodes in $\mathcal{H}_I + 1$ neighborhood of the next-hop node reserve slots for the transmission of node i. The reservation in Step 5b ensures that all nodes in the $\mathcal{H}_I$ neighborhood of node j reserve slots for the transmission on node j (if j is not the last hop on the path). The combination of steps 4 and 5b may result in a node being charged twice for the transmission of the same node. For example, in Figure 8 (b), node c must be charged only once for node i's transmission. However, it will receive the same request twice: first when node i sends the request in step 5b and second when node j sends the reservation request at step 4. The check in Step 1 eliminates this possibility and makes sure that all nodes that belong to the intersection of the $\mathcal{H}_I$ neighborhood of nodes i and j are charged only once.

2) Completion of Flow: When a flow f completes, the established connection must be teared down and the reserved bandwidth must be released. This can be done either by having the sender initiate the process of connection tear-down, or by maintaining the connection in "soft state". In the latter case, which seems more appropriate for a wireless environment, refresh messages are sent while the connection is active, and timers are maintained at each of the intermediate nodes. After each refresh message the timer at a node is set to zero. If the value of the timer exceeds certain threshold, then the node considers that the connection completed and releases the reserved resources.

VI. Application to MANET

The IETF standardization forum is addressing the problem of mobile ad hoc routing in the working group MANET. Several protocols have been proposed in experimental standards. There are two classes of routing protocols: the proactive

protocols and the reactive protocols. The reactive protocols discover routes on demand and they do not seem suitable for the admission control we describe in this paper, since we need an a priori knowledge on the remaining bandwidth of each node in the network before the admission control process.

The OLSR protocol [10], [11] is well suited for the admission control because it contains an embedded broadcast mechanism that optimizes the number of retransmissions. The broadcast mechanism uses specific relay nodes called MultiPoint Relay nodes (MPR) [12]. There exist discussions in order to extend OLSR to QoS management (QOLSR) [9], but these previous works did not address the fundamental problem of link interferences. In the optimized version of OLSR protocol, nodes only advertise a subset of their adjacent links (i.e. their neighbor nodes). For the admission control to work properly, every node must know all the links between the other nodes in order to properly evaluate the radius of interference areas. We shall use F-OLSR, the version of OLSR where nodes advertise their full neighborhood, relayed by MPR. Nodes will advertise their remaining bandwidth in a specific control message, relayed by the MPR. We can call this kind of message, Remaining Bandwidth Advertisement (RBA). This message will be generated periodically. In order to compute their remaining bandwidth, nodes must know the status of the flows at nodes that are within $\mathcal{H}_I + 1$ hops away. To this end every node can broadcast within $\mathcal{H}_I + 1$ hops the identification of the incoming and outgoing flows as well as their bandwidth consumption. This information will be contained in a message called Flow Schedule Advertisement message (FSA). This message will be sent with TTL equal to $\mathcal{H}_I + 1$ in order to avoid broadcasting beyond the $\mathcal{H}_I + 1$ neighborhood of a node. This message can also be used for connection termination advertisement. With the knowledge of the remaining bandwidth of every node and the knowledge of the links of the network, every source node can perform the admission control described so far. OLSR protocol naturally maintains a routing table for best effort traffic. This routing table should not be affected by the QoS management. Instead admitted connections should be routed on the basis of source routing (packets are forced to be routed on the route mentioned in their headers). That way two different connections with the same source and destination may take different routes in order to avoid bandwidth depletion.

VII. Conclusion and Further work

In the previous sections we assumed that the remaining bandwidth is computed on a per node basis. It turns out that this approach may be too conservative, since in the slot scheduling process one has to define the remaining bandwidth of a node as the nominal bandwidth minus the bandwidth emitted or received $\mathcal{H}_I + 1$ hops away. In fact it turns that a more accurate evaluation of the remaining bandwidth must be done on a per link basis. In this case the remaining bandwidth of the link will the nominal bandwidth of the link (i.e. the node) minus the bandwidth emitted $\mathcal{H}_I$ hops from the receiver and the bandwidth received $\mathcal{H}_I$ hops from the sender. Notice that with this definition the remaining bandwidth of a link is not equal to the remaining bandwidth of the reverse link.

The proof of NP completeness should hold since the counterpart of the forbidden pair problem would be the forbidden link pair problem. It is clear that both problem belongs to the same class since they can be derived from each other by polynomial transformation.

In this work we have presented three heuristics based on Dijkstra's Algorithm providing computation of QoS-routes in wireless ad hoc networks under interferences constraints. We have shown that these heuristics handle more QoS flows by saving low capacity nodes and bypassing low capacity areas.

References

[1] K. Bertet, C. Chaudet, I. Guérin Lassous, L. Viennot (2001): Impact of Interferences on Bandwidth Reservation for Ad Hoc Networks: a First Theoretical Study, *GLOBECOM SAWN'2001, IEEE Symposium on Ad-Hoc Wireless Networks*, 2001. (Also INRIA-RR-3895, 2000.)

[2] C. Chaudet and I. Guérin Lassous, BRuIT: Bandwidth Reservation under InTerferences influence, *European Wireless 2002 (EW2002)*, February 2002, Florence, Italy.

[3] A. Velayutham and H. Wang, Solution to the Exposed Node Problem,

[4] L. Georgiadis, P. Jacquet and B. Mans, (2003): *Bandwidth Reservation in Multihop Wireless Networks: Complexity and Mechanisms*, WWAN'2004, IEEE-International Workshop on Wireless Ad Hoc Networking, Tokyo, Japan, March 23-26, 2004, and INRIA-RR-4876, July 2003.

[5] H.N. Gabow, S.N. Maheshwari, L.J. Osterweil, On two problems in the generation of program test paths, *IEEE Transactions on Software Engineering*, SE-2(3), 1976, 227-231.

[6] M. Garey, D.S. Johnson (1979), *Computers and Intractability: a guide to the Theory of NP-Completeness*, Freeman 1979.

[7] V. Kann (1994), Polynomially bounded minimization problems that are hard to approximate, *Nordic Journal of Computing*, 1(3), 317–331.

[8] R. Leung, J. Liu, E. Poon, Ah-Lot. Chan, B. Li., A QoS-Aware Multi-Path Dynamic Source Routing Protocol for Wireless Ad-Hoc Networks, 26th Annual IEEE Conference on Local Computer Networks (LCN 2001), 2001.

[9] A. Munaretto, H. Badis, K. Al Agha, Guy Pujolle (2003) QOLSR: Routage avec QoS dans OLSR. *AlgoTel 2003, 5eme Rencontres Francophones sur les aspects Algorithmiques des Telecommunications*, Banyuls-sur-mer, France, May 12-14, 2003, 109–114.

[10] T. Clausen, P. Jacquet, A. Laouiti, P. Muhlethaler, A. Qayyum and L. Viennot. Optimized Link State Routing Protocol. *IEEE INMIC*, Pakistan 2001

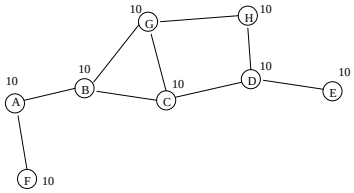
[11] T. Clausen, P. Jacquet, et al., Optimized Link State Routing Protocol, IETF-RFC-3626, `http://www.ietf.org/`

[12] P. Jacquet, A. Laouiti, P. Minet, L. Viennot. Performance analysis of OLSR multipoint relay flooding in two ad hoc wireless network models, INRIA research report RR-4260, 2001.

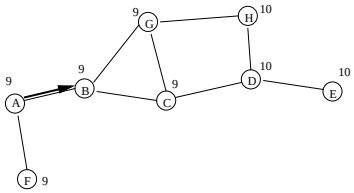
[13] C.E. Perkins, E.M. Royer, S.R. Das, Quality of Service in Ad hoc On-Demand Distance Vector Routing, IETF Internet Draft.

[14] S. Chen, K. Nahrstedt, Distributed Quality-of-Service routing in Ad Hoc Networks, IEEE Journal on Selected Areas in Communications, 1999, 17(8).

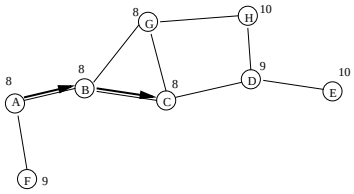
[15] C. Zhu, S. Corson. QoS routing for mobile ad hoc networks. *Infocom* 2002.



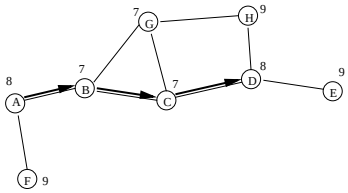
(a) Network



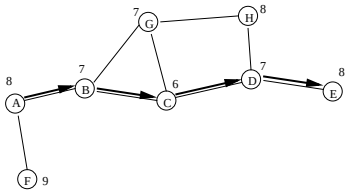
(b) Flow A-B



(c) Flow B-C



(d) Flow C-D



(e) Flow D-E

Fig. 1. Reservation example for a data flow

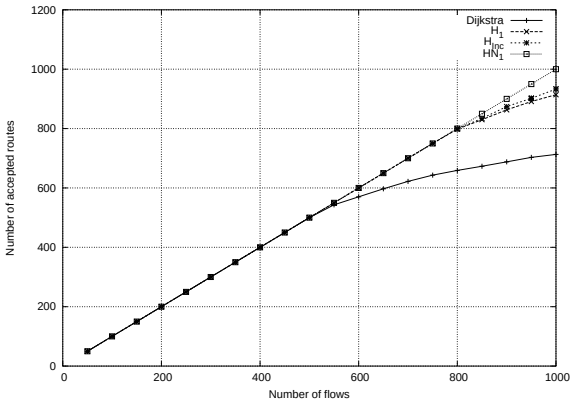


Fig. 2. Insertion of 1000 flows for $n = 1300$, $r = 150$ and $\pi = 0.06$.

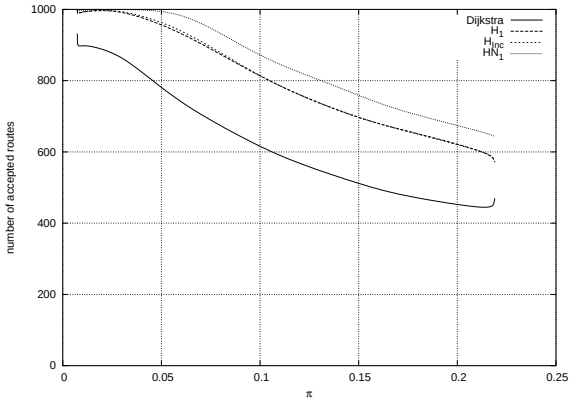
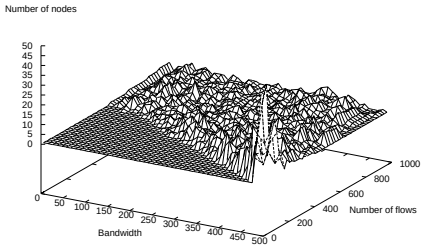
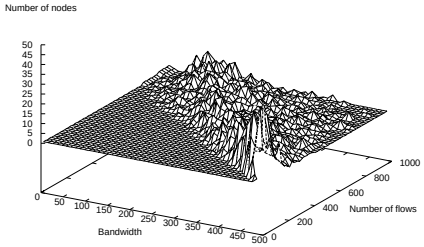


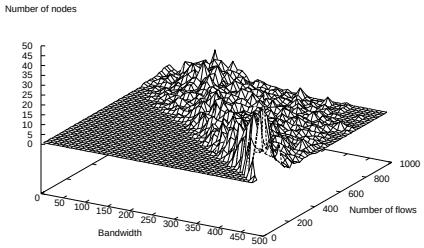
Fig. 3. Number of inserted routes for different values of π



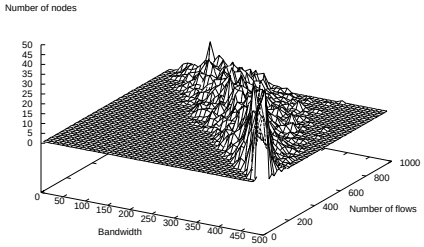
(a) Dijkstra's Algorithm



(b) Heuristic H_1



(c) Heuristic H_{inc}



(d) Heuristic HN_1

Fig. 4. Bandwidth distribution for Dijkstra's algorithm and the three heuristics

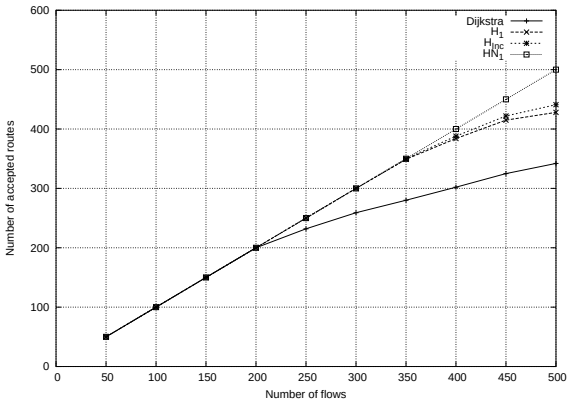
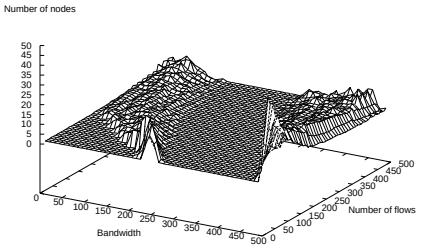
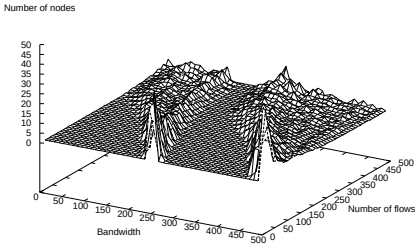


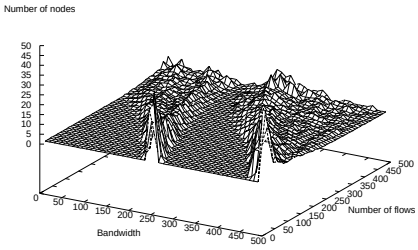
Fig. 5. Insertion of 500 flows for $n = 1000$, $r = 175$ with different original capacities.



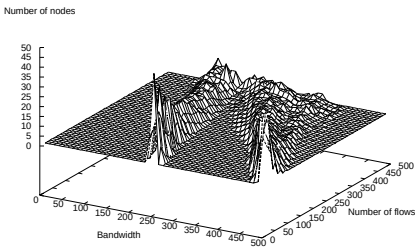
(a) Dijkstra's Algorithm



(b) Heuristic H_1



(c) Heuristic H_{inc}



(d) Heuristic HN_1

Fig. 6. Bandwidth distribution for Dijkstra's algorithm and the three heuristics with different original capacities.

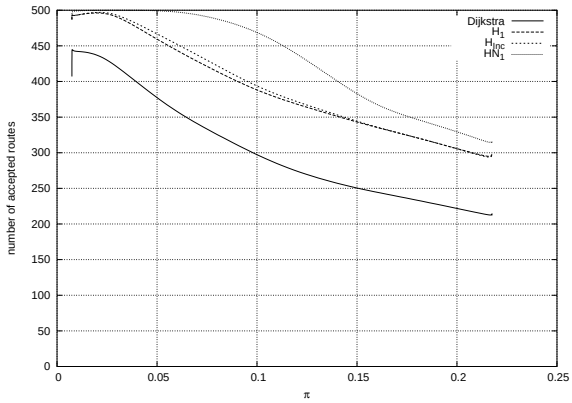


Fig. 7. Number of inserted routes for different values of π

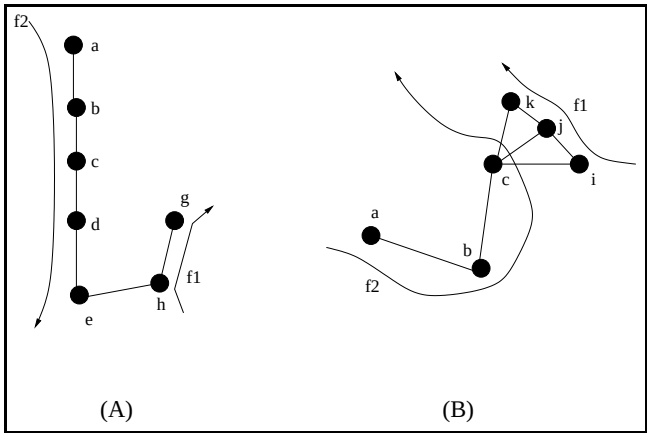


Fig. 8. Examples of Bandwidth Reservation

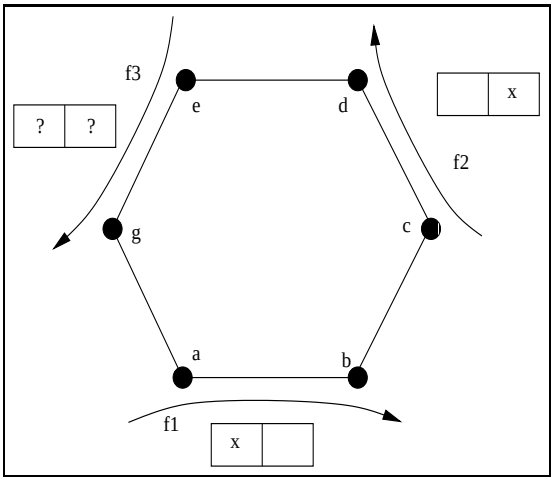


Fig. 9. Why an extra hop is required in Rule B.