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N° 6538

May 2008

Thème NUM

Rapport de recherche

ISSN 0249-6399 ISRN INRIA/RR--6538--FR+ENG

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Thème NUM — Systèmes numériques
Projet RESO

Rapport de recherche n° 6538 — May 2008 — 18 pages

Abstract: IEEE 802.11 is often considered as the underlying wireless technology of multihop wireless networks. But the use of 802.11 in such networks raises issues, like efficiency and/or fairness issues. Different kinds of solutions have been proposed to overcome these problems. One approach is to design new MAC protocols that provide alternatives to the IEEE 802.11 MAC protocol. Although these solutions are of some interest, it should probably take some time before new wireless network interface cards based on one of these solutions are developed and released. Another approach is to consider that 802.11 will remain the underlying wireless technology and to design solutions above it. Several solutions based on rate allocation have been proposed so far. The main drawback of the proposed solutions is that they rely on a radio medium sharing model that is difficult to compute in a wireless, distributed and mobile environment. Indeed, very few of these solutions have been derived into a network protocol.

In this article, we propose a distributed and dynamic rate allocation solution that is based on a simple sharing model. Due to its simplicity, we can derive a network protocol that can be practically used in multihop wireless networks. This protocol provides a fair bandwidth sharing between end-to-end flows while maintaining an efficient overall throughput in the network. This solution has been implemented in NS2 and evaluated by simulations.†

Key-words: Distributed algorithms, protocols, evaluation, IEEE 802.11

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† This work was partially supported by the european integrated project AEOLUS.

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Vers un protocole de répartition de débit équitable et réaliste pour les réseaux sans fil multi-sauts basé sur un modèle par nœuds

Résumé : On considère souvent IEEE 802.11 comme la technologie sous-jacente aux réseaux sans fil multi-sauts. Pourtant, dans de tels résaux, 802.11 s'avére dans de nombreuses situations inefficace et/ou inéquitable. Pour faire face à ces problèmes, de nombreuses solutions ont déjà été proposées. Une première approche consiste à fournir une alternative à la couche MAC de 802.11. Cependant, il faudra du temps avant que de nouvelles cartes réseau s'appuyant sur l'une de ces solutions voient le jour. Une autre approche consiste à considérer que 802.11 restera durablement, et donc à développer des solutions reposant sur 802.11. Des solutions de ce type, basées sur la régulation de débit, ont été proposées, mais elles reposent sur un modèle de partage du medium radio complexe, et difficile à utiliser dans un contexte sans fil, distribué et mobile.

Dans cet article, nous proposons un algorithme d'allocation de débit dynamique et distribué, reposant sur un modèle de partage simple. Grâce à sa simplicité, nous avons obtenu un protocole simple et réaliste pour les réseaux radio multi-sauts. Ce protocole permet de garantir un partage équitable de la bande passante entre flux, tout en assurant une utilisation efficace du réseau. Cette solution a été implémentée sous NS-2, et évaluée par simulation.[‡]

Mots-clés : Algorithmes distribués, Protocoles, Evaluation, IEEE 802.11

[‡] Ce travail a été financé en majeure partie par le projet Européen AEOLUS

1 Introduction

IEEE 802.11 is often considered as the underlying wireless technology of multihop wireless networks. But the use of 802.11 in such networks raises some issues. The two main problems concern fairness and efficiency [2]. With the fairness issue, some flows obtain very small throughput (even null in some cases), while some others can almost use the whole capacity of the wireless medium. With the efficiency issue, a part of the network capacity is not used and wasted, even if the flow rates are increased. These problems are mainly caused by the MAC protocol of 802.11.

Different kinds of solutions have been proposed to overcome these problems. One approach is to design new MAC protocols that provide alternatives to the IEEE 802.11 MAC protocol and that try to increase fairness or/and efficiency in the network. More and more solutions are now proposed. However, the main challenge, when designing a MAC protocol for wireless multihop networks, is still to achieve a good trade-off between efficiency and fairness. Some solutions are fair at the price of a low efficiency while the others are efficient but achieve a low fairness. Although these solutions are of some interest, it should probably take some time before new wireless network interface cards based on one of these solutions are developed and released. Moreover, as these solutions try to be as simple and local as possible (important features for a MAC protocol), it is difficult for them to tend towards a targeted fairness scheme.

Another approach is to consider that 802.11 will remain the underlying wireless technology for a while and that solutions to the aforementionned issues should be designed at higher layers, above IEEE 802.11. Some solutions suggest to regulate the rate incoming at the MAC layer. This regulation is achieved via a rate allocation in order to limit the congestion appearance and obtain a better fairness among the flows. The rate allocation is often based on a model that tries to capture the dependencies between wireless links. Different models have been proposed as we will explain in Section 2. The solution is then designed according to two steps: the first step computes the wireless links dependencies according to the chosen model and the second step is the rate allocation based on the dependencies computed during the first phase. These tasks are all the more complicated that they have to be developed in a context that is wireless, multihop, distributed and mobile.

Most of the solutions for rate allocation in multihop wireless networks require to identify maximal cliques or maximal independent sets in the wireless link contention graph. In such a graph, vertices correspond to the wireless links of the network and there is a link between two vertices in this graph if two flows along the two associated links contend with each other in the network. Therefore, these solutions are based on a complex medium sharing model that is likely to be slow to compute in practice.

In this article, we propose to use a simpler medium sharing model that can be directly deduced from the network topology. From this model, called node-based model hereafter, we design a rate allocation algorithm that achieves a fair bandwidth sharing between flows. This algorithm has been obtained by using Lagrangian optimization methods. It is well adapted to multihop wireless networks since it is distributed and adaptive. Moreover, this algorithm has been derived into a network protocol. The goal of this work is twofold: i) to design a practical and fair rate allocation solution for multihop wireless networks and ii) to study the accuracy degree (or the inaccuracy degree) that can be obtained when using such a simple node-based model. We also give a synthesis of the different models on the radio medium sharing.

In the rest of this article, we assume that the IEEE 802.11 DCF mode is used in the network [9]. Due to space limitations and as much litterature is now available on IEEE 802.11, we assume that this mode is known by the reader. This paper is organized as follows: in Section 2, we give a state-of-the-art along with the description of the different models that have been used to describe the radio medium sharing of multihop wireless networks. We also present, in this section, the simple node-based model we have chosen. In Section 3, we present our rate allocation algorithm based on the node-based model given in the previous section. This section ends with an evaluation of our algorithm. In Section 4, we derive our algorithm into a network protocol by taking advantage of the routing protocol AODV. This protocol has been implemented in the NS2 network simulator and the evaluation results are also presented in Section 4. Finally, we end this article with some concluding remarks and perspectives.

2 Modeling the radio medium sharing

Few solutions have been proposed for rate allocation of multihop flows in multihop wireless networks. However, modeling the radio medium sharing in such networks is a challenging task that has been addressed in several studies. In this section, we describe the main models that have been used to represent the constraints that arise in these networks. We also highlight the main references that deal with rate allocation of multihop flows.

But before describing these models, we remind the different ranges that are used in IEEE 802.11. The *transmission range* is the range within which a frame can be successfuly transmitted. The *carrier sensing range* is the range within which a node detects a transmission (and thus it refrains itself from transmitting). The *interference range* is the range within which a transmitting node (other than the associated source) will induce collisions at the receiver, which happens as soon as the signal-to-interference ratio at the receiver is smaller than a given threshold often called *capture threshold*.

2.1 The two seminal contention models

In [7], the authors introduce two contention models, *i.e.* the *protocol model* and the *physical model*. In the protocol model, a node can successfully receive packets from another node if these two nodes are within transmission range and no other node is transmitting within the interference range of the receiver. It is possible to adapt this model to IEEE 802.11-style MAC protocols by also ensuring that no other node is transmitting within the carrier sensing range and the interference range (in order to receive the ACKs successfully) of the sender. In the physical model, a transmission is successfully received if the signal-to-interference ratio at the receiver is not smaller than the capture threshold.

These two models are often considered as the basis of the contention models upon which radio medium sharing models are built to express the dependencies between multiple flows in the whole network.

2.2 Wireless links contention graph

In [13], the authors describe the *wireless links contention graph*. In such a graph, vertices correspond to the wireless links of the network and there is a link between two vertices in this graph if two flows along the two associated links contend with each other in the network. The contention is very often modeled according to one of the two models previously mentioned. From this graph, different methods are proposed to write the constraints that are required for the rate allocation.

2.2.1 Maximal independent sets

A first method requires to identify the *maximal independent sets* in the wireless link contention graph. Let's denote n the number of nodes in the contention graph (and thus the number of wireless links in the network), C the capacity of the radio medium and I_1, I_2, ..., I_z, the maximal independent sets of the contention graph. Then, the rates x_1, x_2, ..., x_n of the different wireless links are feasible if and only if it exists z non negative weight, λ_1, λ_2, ..., λ_z such that:

$$\sum_{i=1}^{z} \lambda_i \leq 1 \text{ and } \forall j \in [1, n] \quad x_j \leq C \sum_{i/j \in I_i} \lambda_i \tag{1}$$

This set of conditions is necessary and sufficient to ensure that there exists a scheduling of the communications in the network such that two neighbor wireless links in the contention graph are not activated at the same time. The problem with this approach is that maximal independent sets are computationally expensive and difficult to obtain in a distributed way.

In [13], the authors use this method to provide a fair allocation of single-hop flows coupled with a new MAC protocol. In this work, two flows are considered as contending with each other if either the sender or the receiver of one flow is within the transmission range of the sender or the receiver of the other flow. This contention model corresponds to the protocol model where the interference area and the carrier sensing area are considered as being the communication area.

2.2.2 Maximal cliques

A second approach for writing the constraints between flows is to consider *maximal cliques* in the wireless links contention graph[1]. In a maximal clique, the associated links mutually contend for the radio medium. If Q is the set of maximal cliques, then the constraints are:

$$\forall q \in Q \qquad \sum_{i \in q} x_i \leq C \tag{2}$$

The advantage of maximal cliques, compared to maximal independent sets, is that they are local structures which can be computed with localized algorithms. On the other hand, the clique constraints provide only necessary conditions that may not give a feasible schedule over links [10].

The work of [18][2] is one of the first to design a fair rate allocation on multihop flows based on the maximal cliques. From these cliques, the authors design a distributed and fair rate allocation by using Lagrangian optimization methods. They propose a decentralized clique construction that requires to know the one-hop and two-hop neighbor wireless links. This construction may only provide an approximated solution when the interference area is larger than the transmission area (which is usually the case in practice), because the interference area is not necessarily equivalent to the two-hop transmission area.

In [4], the authors also propose a rate allocation based on the maximal cliques of the contention graph. This algorithm also uses the Lagrangian optimization but the chosen utility function is discrete. A comparison of this approach with the algorithm of [18] is given in [14]. The results show that using a discrete utility function is often more efficient when the network is highly mobile and/or loaded.

In [8], the authors introduce the notion of *scaled clique constraints*. By scaling the capacity of the cliques by a certain factor (less than 1 and depending on the interference range), then the clique constraints become sufficient conditions that give a feasible schedule over links, but also conditions within a bounded factor of the necessary constraints. In this work, the contention graph is computed according to the protocol model and thanks to position information obtained with GPS.

2.2.3 Row constraints

In the work of [8], the authors also propose another set of sufficient conditions based on the links contention graph. These constraints, called *row constraints*, are obtained via the conflict graph incidence matrix: for each node of the contention graph, then the sum of the rates on this link and on the neighbor links (in the contention graph) should not exceed the radio medium capacity. The problem with such constraints is that they are sufficient but not necessary and thus may lead to an allocation that is far to be optimal. Nonetheless, there are some cases where the row constraints are less pessmistic than the scaled clique constraints. Therefore, these constraints may be of some interest, because they are easier to obtain than the clique constraints.

2.3 Nodes contention graph

All the approaches described in the previous sub-section are rather difficult to use in practice. Indeed, they first require to build the wireless links contention graph and then to compute either the maximal independent sets or the maximal cliques, which is computationally expensive. The simplest solution, proposed so far, is to compute the row constraints. But this solution still needs to know the links contention graph which implies extra time, especially in a mobile environment.

[1]A clique of a graph G is a sub-graph of G such that all the nodes are neighbors and a maximal clique is a clique which is not contained in any other clique.

[2]This is an extended version of a work published in 2003.

2.3.1 Node-based interference model

In [17], the authors propose to use a *node-based interference model* in order to avoid the enumeration of maximal cliques or maximal independent sets. This theoretical study uses the signal-to-interference ratio to model interferences and contentions. This model requires to know the contending nodes for each node, the distance between nodes, the path gain function as the signal-to-noise threshold and the signal-to-interference threshold for each node. From this model, the authors propose a distributed gradient-based rate allocation algorithm.

This work has been published recently and more investigations from our side should be done on the proposed approach. Nonetheless, after a first reading, we think that this model is still quite complicated to use for a practical setting because it depends on some pieces of information that are rather difficult to obtain via a protocol. Note also that only a distributed algorithm is proposed and evaluated by numerical simulations and no protocol implementation is discussed in this article.

2.3.2 A simple node-based model

In this work we propose to use a simpler model that can be usable in practice. But before describing this model, let's come back to the different ranges of IEEE 802.11. The values of these ranges are not easy to obtain practically because they are variable and depend on several parameters (environment, wireless cards, time, weather, etc.). For instance, in the simulator NS2, the default transmission range is equal to 250 m while the carrier sensing range and the interference range are the same and equal to 550 m. But in practice, these values may be very different. For instance, in [5, 1], the experiments show that these ranges are shorter and variable: the transmission range depends on the data rate, the carrier sensing range is almost constant, while the interference range depends on the distance between the sender and the receiver. Some conclusions that can be of some interest for this work are: i) the carrier sensing range is around two times the communication range obtained with slow data rates (2 or 1 Mb/s) and ii) the interference range may be larger than the carrier sensing range.

We use a simple node-based model that was originally presented in [3] to realize admission control in multihop wireless networks. In this model, the contention graph is deduced from the communication network since the nodes of the contention graph correspond to the nodes of the network. There is an edge between two nodes in the contention graph (that could be called *nodes contention graph*) if these nodes are within two hops in the network. Figure 1 shows an example of such a contention graph.

The constraints that we write from this nodes contention graph are:

$$\forall n \in N \sum_{i \in V(n)} x_i \leq C \tag{3}$$

where N is the set of nodes in the network (or in the contention graph), and for each n in N, $V(n)$ the set of node n's neighbors in the contention graph. These constraints can be seen as the row constraints of [8] but deduced from the nodes contention graph.

Discussion Initially, the goal of this model was to express the medium sharing that exists between emitters within carrier sensing range in order to realize a more accurate admission control for QoS flows based of bandwidth usage [3]. Therefore, this choice models the radio medium sharing imperfectly since i) it models only contending emitters and ii) the two-hop communication area only approximates the carrier sensing area and the interference area. For instance, Figure 2 shows a configuration where, although the network is connected, node A is within five hops of node F but also in its carrier sensing area. On the other hand, using restrictive conditions, as these row constraints, may allow to integrate some constraints at the receivers side and that arise in interference area. For instance, let's consider the configuration $A \rightarrow B - C - D - E \rightarrow F$. The constraints we consider from our node-based model imply that A and E share the medium, which can seem to be overconstrained, since they are 4 hops away, and can potentially be out of carrier sensing range. But if

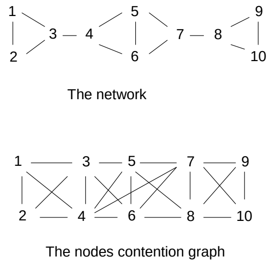

Figure 1: A network and its associated nodes contention graph. The network may correspond to the three pairs scenario.

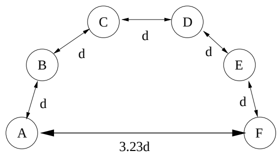

Figure 2: Approximation of the carrier sensing area

the distance between two neighbor nodes is slightly larger than half the communication range (see Sec. 3.2.2), then it is likely that the emission of node E will interfere on node B. In this case, nodes A and E share the medium indeed. Moreover, most of the solutions that are based on a wireless links contention graph suffer from the same imprecisions since they also use approximations of carrier sensing and interference areas. The work of [8] uses GPS to provide good approximations of these areas but this approach requires the interfering nodes to communicate the positions informtion, which is not always possible. Finally, note that only the work of [18] proposes a rate allocation protocol.

The aim of our study is i) to design a practical and fair rate allocation solution for multihop wireless networks (that is simpler than the one of [18]) and ii) to study the accuracy degree (or the inaccuracy degree) that can be obtained when using such a simple node-based model.

3 A rate allocation algorithm

In this section, we design a rate allocation algorithm that is based on the simple node-based model described in Section 2.3.2. This algorithm is distributed and dynamic.

3.1 Description

Let's consider ϕ a set of flows that are transmitted in the network. Each flow f with a rate ϕ_f goes through a set of nodes. These nodes contribute to the transmission of this flow. We denote N the set of the wireless nodes of the network, $V(n)$ the neighbors of node n ($n \in N$) in the nodes contention graph (which corresponds to the one-hop and two-hop neighbors of n in the network) and C the capacity of the wireless medium. The problem of the flow rates maximization can be written as follows:

$$\begin{array}{ll} \text{MAXIMIZE:} & \prod_{f \in \Phi} \phi_f \\ \text{UNDER THE CONTRAINTS:} & \forall n \in N \sum_{i \in V(n)} x_i \leq C \end{array} \quad (4)$$

$\prod_{f \in \Phi} \phi_f$ expresses the fact the we wish to maximize the rates allocated to flows while ensuring a *proportional fairness* between flows [12].

The Lagrangian optimization is a popular method to solve, in a distributed way, non-linear optimization problems with constraints [12, 18, 4]. For our problem, this method is particularly adapted since it transforms a problem with global variables (the rates of the flows all over the network) in a dual optimization problem that only uses local variables. The latter problem can then be solved in a de-centralized way via a distributed gradient method.

The algorithm to solve our maximization problem and based on the Lagrangian method is similar to a game where prices between flows and nodes are negotiated. To each node n, a *cost* λ_n is associated. This value represents the cost for a flow to use this node's bandwidth. We consider that a flow uses a node n if this flow is transmitted by this node or by a node in $V(n)$. For each flow f, a *price* Π_f is computed. This price depends on the costs of the nodes that the flow will pass through. We assume that the path used by each flow is known. Our algorithm is then iterative and for each step s of the algorithm:

- each node computes, in a distributed way and for each flow f, the price $\Pi_f^{(s)}$ that this one should pay to use its route. If r_{nf} is the number of nodes transmitting packets of flow f in $V(n)$ for node n, then:

$$\Pi_f^{(s)} = \sum_{n \in N} r_{nf} \times \lambda_n^{(s)} \quad (5)$$

- The price of each flow is then forwarded to all the nodes used by this flow, *i.e.* within the two-hop neighborhood of all the nodes of the path along which f is routed.

- The nodes modify their cost according to this formula:

$$\lambda_n^{(s+1)} = \lambda_n^{(s)} - \sigma \times \big(C - \sum_{f \in \Phi} \frac{r_{nf}}{\Pi_f^{(s)}}\big) \quad (6)$$

  where σ is the gradient step.

It can be shown that after several iterations, the unique value towards which the prices of the flows converge corresponds to the inverse of the rate with which they can be emitted. The gradient step σ is an important parameter of the algorithm since it controls the algorithm convergence speed. A low value of σ may slow down the algorithm convergence, while the algorithm may diverge with a large value.

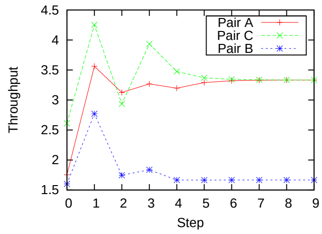

Figure 3: Convergence of the algorithm on the three pairs scenario

3.2 A first evaluation

Before deriving a rate allocation protocol from this algorithm, we carry out a first evaluation in order to check whether it is worth going further with this approach. To this end, we implement our algorithm in a C program. For different configurations, we compute the rate allocation with our program and then inject the computed rates into the same configurations simulated with the network simulator NS2 [15]. The parameters used in NS2, especially for IEEE 802.11, are given in Table 4. We use AODV for the routing protocol. Thus, we obtain an evaluation of our algorithm in terms of throughputs and convergence and we can check, at a first glance, if the obtained rates are feasible in a more realistic context with IEEE 802.11 as the underlying technology. In this part, we also implement a rate allocation algorithm based on the maximal cliques deduced from the wireless links contention graph in order to compare the node-based model and the maximal cliques model. This algorithm is based on different constraints but uses the same Lagrangian optimization method. For each evaluation, the parameter σ is optimized according to the chosen model in order to maximize the convergence speed in each of the two models. Due to space limitation, we only present three scenarii. The results are the average of 20 simulations.

3.2.1 The three pairs scenario

In the three pairs scenario, there are three communicating pairs and the two external pairs are in the carrier sensing of the central pair (and vice versa) while the two external pairs are independent [6]. Unfairness arises with IEEE 802.11 because the central pair cannot access the medium due to asymmetrical contention. Figure 1 shows the three pairs scenario when three flows are in the network, one between nodes 1 and 2 (pair A), one between nodes 5 and 6 (pair B) and one between nodes 9 and 10 (pair C).

Figure 3 shows the evolution of the allocated rates (in Mb/s) for the three pairs according to the algorithm's step. We see that the convergence is achieved in several steps. It lets us think that the algorithm is reactive enough to consider a protocol version. Table 1 shows some results on the convergence speed in function of the number of steps. The stop criteria of the algorithm is the Euclidian distance to the solution[3]. We see that the number of steps is quite similar between the two models (besides a little bit smaller for the maximal cliques model). The computed rates are similar between the two models.

Stop threshold	10^{-3}	10^{-5}
Node-based model	7	11
Maximal cliques model	5	10

Table 1: Convergence speed in the number of steps on the three pairs scenario

We then simulate this scenario in NS2 in order to evaluate the feasibility of the allocation when IEEE 802.11 is used as the underlying technology. The tested transmission rates for the three pairs are the rates computed with our algorithm and the saturation rate when IEEE 802.11 is used without rate control. Figure 4 shows

[3]If we denote x^* the vector containing the optimal rates then the normalized distance between x and x^* is $\frac{\|x^*-x\|_2}{C}$

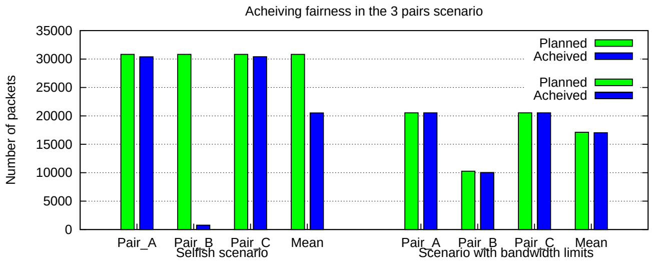

Figure 4: The obtained throughputs with NS2 for the three pairs scenario

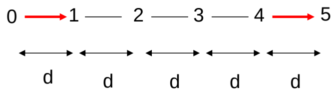

Figure 5: The two flows scenario.

the number of CBR packets received and sent at the application level for each pair during a simulation of 50 seconds. In the selfish scenario without rate control, all the three pairs emit at full capacity, which results in a very low bandwidth for the central pair. Note that these losses are not due to collisions in this configuration but to the queue that is saturated in the central emitter. By simply limiting the rates at which the pairs emit, we can ensure that the central pair has its share of bandwidth. Note that the mean throughput is slightly higher in the selfish scenario. Indeed, there is a trade-off between fairness and overall throughput. Both scenarios are Pareto-optimal, in the sense that no pair can increase its throughput without decreasing another one's, but while the first scenario is optimal in terms of maximizing the total throughput, the second scenario optimizes proportionnal fairness.

3.2.2 Two flows scenario

In the previous scenario, the optimal allocation computed by our algorithm was scheduled successfully by the 802.11/MAC layer. Since the external pairs can detect the emissions of the central pair, they refrain from emitting during the central pair's emissions and then become synchronized. However, the fact that a schedule exists for a given allocation doesn't necessary mean that 802.11/MAC will manage to schedule it. We show this problem with a simple example, depicted in Figure 5. In this scenario, there is a flow between nodes 0 and 1 and another one between nodes 4 and 5. Nodes i and $i+1$ are within a distance d ($0 \leq i \leq 4$). Figure 6 sums up the results obtained with and without the bandwidth regulation provided by our algorithm. The same allocations are given by the cliques model.

- With $d = 90m$, node 0 and node 4 are within carrier-sensing range. As expected, without bandwidth regulation, the flows share the 5Mb bandwidth, but flow 0→1 has significantly less than flow 4→5. This asymetry can be accounted for by the 802.11 EIFS[4] mechanism, which requires that a node that senses a packet it ca not decode should refrain from transmitting so as to leave the receiver of the packet enough time to send an acknowledgement. Since node 4 both senses node 0's data packets and node 1's MAC acknowledgements, while node 0 does not sense node 5, it is harder for the former to access the medium. With bandwidth regulations, the bandwidth is shared evenly.
- When $d = 100m$ however, node 0 and node 4 can not sense each other. In this case, they may transmit at the same time. Without bandwidth limits, node 4 saturates the medium and provokes collisions at node 1. This problem is only partially solved by reducing the rate of node 4, because the achieved throughput for flow 0→1 is smaller than the rate computed by our algorithm. It shows that, even if the sum of the flows

[4]Extended Inter-Frame Space

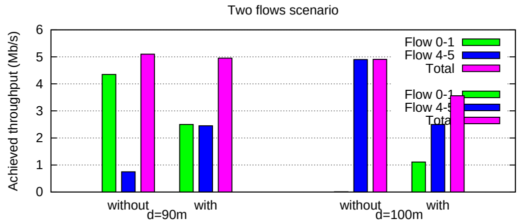

Figure 6: The obtained throughputs with NS2 for the two flows scenario with different values for d

rates does not exceed the medium capacity, 802.11/MAC fails in providing a schedule of this allocation. Nonetheless, flow 0→1 obtains a throughput that is much better than with 802.11 without rate control.

3.2.3 A grid scenario

We consider a network with 49 nodes on a 7×7 grid. The distance between two adjacent nodes is 140 m. Eight links are chosen randomly and each link receives a flow. The rates allocations are computed with the two different models. Table 2 shows the convergence speed in function of the number of steps. We see that the convergence speed is better with the node-based model than with the maximal cliques model. It can be explained by the fact that with larger graphs, the number of constraints depends on the number of maximal cliques that increases exponentially with the network size. With the node-based model, the number of constraints corresponds simply to the number of nodes.

Stop threshold	10^{-3}	10^{-5}
Node-based model	46	115
Maximal cliques model	71	177

Table 2: Convergence speed in the number of steps on the grid scenario

The rates allocated are then simulated with NS2. Table 3 shows the mean number of CBR packets received and sent at the application level for each flow during a simulation of ?? seconds for the two different models and with 802.11 without rate control. We see that the two models give almost the same mean number of received packets and that the loss rate is much smaller than with 802.11 without rate control. We have also compared the product of the flows throughputs (utility function corresponding to the proportionnal fairness) of the two allocations: the difference between the two models is less than 1% under a geometrical average.

	Received / Planned packets	Loss rate
Node-based model	11955 / 12390	3.51%
Maximal cliques model	12200 / 12600	3.17%
802.11 without rate control	17680 / 41000	56.9%

Table 3: Mean number of received packets with NS2 on the grid scenario

4 A rate allocation protocol

Implementing a rate control algorithm into a real protocol poses a number of challenges, such as limiting the overhead of the protocol and dealing with asynchronism and lost packets.

4.1 Description

So as to minimize the overhead, we have taken advantage of the Hello messages used by the AODV routing protocol and made slight changes to it so that its Hello messages carry the various information our algorithm needs. In AODV, these Hello messages are broadcasted every second so as to enable other nodes to have an updated view of their immediate neighborhood and detect broken links. According to Equation 5, emitting nodes need to know the costs (λ_n) of all the nodes in their 2-hop neighborhood. Thus, we include a field in the Hello messages containing the costs of the 1-hop neighborhood.

The price of a flow (Π_f in Equation 5) is computed by the nodes along the route of the flow. A special kind of packet called *unicast price message* is added for this purpose to send this information to the source of the flow. It consists in a small packet issued every second by the last emitter of the flow in the route and going backwards along its route. Each node in the route updates this flow price. The source of the flow can then regulate its rate according to the flow price it receives. We make sure at least a small part of the bandwidth remains for the control packets by using 2% of the capacity for these packets.

Then, the new price of the flow is sent to the transmitting nodes which in turn broadcast this information to their two-hop neighborhood. For this purpose, *broadcast price messages* are used. Thus, the implied nodes can update their costs according to Equation 6.

4.2 Simulations

We have simulated this protocol in NS2. For our simulations, we have used the parameters of a 802.11b Avaya card, summarized in Table 4. The code of these simulations can be found at our website [16].

NS version	2.31
Physical rate	11 Mbps
Real throughput	5 Mbps
Transmission range	160 m
Carrier sensing range	397 m
Interference range	397 m
Capture threshold	12 dB
Radio propagation model	TwoRayGround
Traffic	backlogged / CBR / UDP
Packet size	1000 bytes
RTS/CTS	disabled

Table 4: Summary of the simulation parameters.

4.2.1 The three pairs scenario

We evaluate the influence of asynchronism and lost packets by comparing the theoretical convergence speed in the 3 pairs scenario with the one obtained by simulation. The topology we used is the one depicted in Figure 1, with 270m and 2 intermediate nodes between each pair. All sources are 100m away from their respective sink.

Figure 8 shows that the prices (from which the transmission rate is calculated - see Figure 7) do not vary as smoothly as they do in the theoretical experiment, especially for pair B, around where prices and Hello packets are often delayed or subject to collisions (8% of the received packets). Nonetheless, the algorithm achieves convergence after around 20s, which can be compared with the theoretical results by noting that one step of the algorithm lasts roughly 1s, because of the frequency of the Hello messages. 20s may indeed seem quite slow.

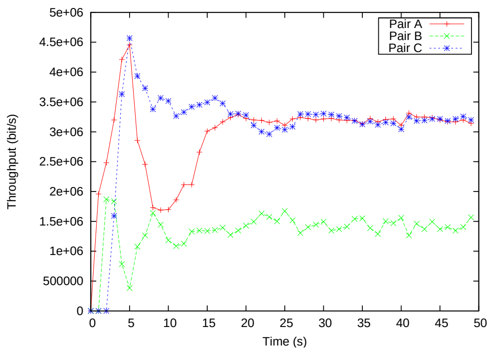

Figure 7: Throughput (3 pairs simulation)

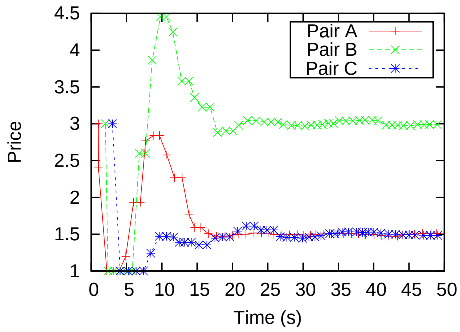

Figure 8: Flow prices fluctuations (3 pairs simulation)

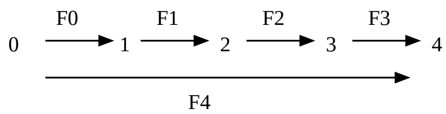

Figure 9: Topology for the line simulation

However, if you imagine a wireless user in the position of pair B, and thus getting only 3% of the medium capacity, he will be happy to see his bandwidth increases at that rate.

4.2.2 The line

The line scenario, depicted in Figure 9, was designed to show how our protocol reacts to collisions. The distance between two nodes is equal to 150 m, slightly less than the communication distance. In that configuration, for example, if node 0 transmits a packet to node 1 while node 3 is transmitting, collisions occur at node 1.

Figures 10 and 11 show respectively the results of these simulations without rate regulation and with bandwidth regulation. Note that flows are not started at the same time to prevent collisions with the AODV Route Requests at start. Without rate regulation, node 1, being exposed to the emissions of node 3 can not receive any packet as soon as the medium is saturated. On figure 10, we can see that flows $F0$ and $F4$ get no bandwidth at all, while the other flows get the rest of the capacity. On figure 11 however, we can see that in spite of collisions, our protocol manages to share the bandwidth according to the proportionnal fair allocation, *i.e.* 20% of the capacity to the one-hop flows, and 5% to flow 4, which is four hops long. We can also see that flow 0 and flow 4 statistically lose 20% of their allocated bandwidth because of collisions at node 1, provoked by emissions at node 3.

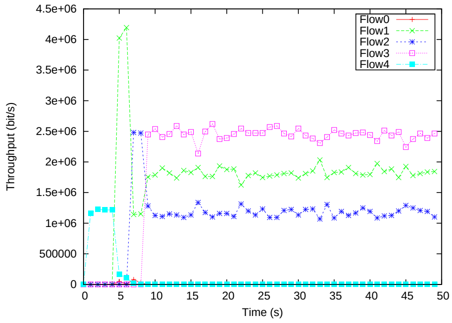

Figure 10: Throughput in the line scenario (no rate regulation)

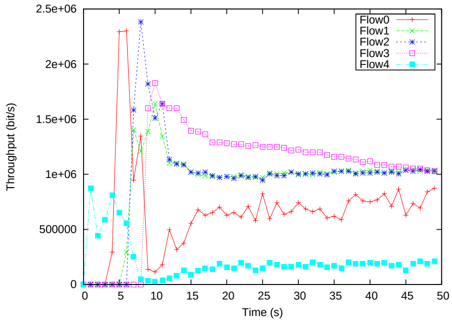

Figure 11: Throughput in the line scenario (with rate regulation)

4.2.3 Random simulation

In the random simulation, 25 nodes are placed randomly on a $400m \times 400m$ square area. Four of them are randomly chosen as sources, while four others play the role of the sinks. Sources and sinks can be as far as four hops away. Initially, each source attempts to transmit a flow to its sink at full capacity. Our protocol then regulates the rates of the sources. We have carried out a set of 20 simulations with different node placements and sets of flows in order to observe the properties of our protocol in a more realistic context. To leave enough time for our algorithm to converge, we studied the last 10 seconds of the simulations - in most simulations, our protocol needed $20s$ to converge. Table 5 sums up the different parameters for these simulations.

Number of nodes	25
Simulation size	400×400
Nature of the flows	Backlogged / UDP / CBR
Number of simulations	20
Simulation duration	50s

Table 5: Random simulation parameters

	Mean throughput (kb/s)	Mean Jain Index
w/out rate allocation	647.33	0.67
w/ rate allocation	650.26	0.81

Table 6: Results for the random simulation

We use the Jain index [11] to measure the fairness of the obtained allocations. For N flows with throughputs $(x_i)_{i\in[1..N]}$, it is defined by :

$$\frac{(\sum x_i)^2}{N * \sum x_i^2} \tag{7}$$

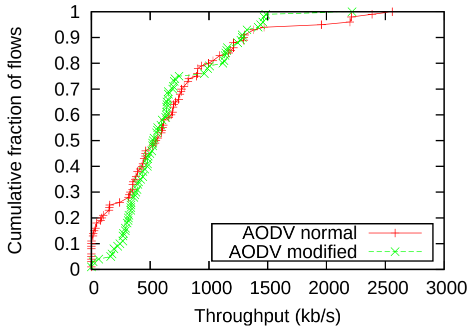

Figure 12: Throughput CDF in the random simulation

Its value ranges from $\frac{1}{N}$ (unfair) to 1 (all flows get the same throughput).

The results of these simulations are summarized in Table 6. While the mean throughput remains unchanged, our protocol has greatly increased the fairness of the allocations.

Our protocol is more efficient too, in terms of network utilization: our algorithm tends to give less bandwidth to multi-hops flows, thus increasing the mean throughput. Figure 12 shows the cumulative distribution function of the achieved throughputs for the 80 flows simulated (by considering all the simulations). One can clearly see that our bandwidth regulation algorithm reduces very significantly the number of flows that are penalized since the number of flows with less than 50kbps is reduced from 20% to 5%. Indeed, in these simulations, only one flow had no bandwidth at all: the emitter of this flow was simply out of communication range from the rest of the network.

5 Conclusion

This article describes a rate allocation algorithm for multihop wireless networks that is based on a simple radio medium sharing model. This model, called node-based model, is simply derived from the network topology and does not need to compute complex objects like indepent sets or cliques. The algorithm, based on Lagrangian optimization, is distributed and dynamic. This algorithm has been implemented in a C program. The first results show the interest in controlling the rates. They also show that the computed rates with this node-based model are rather close to the ones computed with the maximal cliques model and that the convergence speed is smaller with the node-based model in large networks. Due to the simplicity of the model and of the constraints, it is possible to derive this algorithm into a protocol. This protocol takes advantage of the routing protocol AODV and allows the sources to compute their authorized rate. The protocol has been implemented in NS2. The first simulations show the feasibility of such an approach and are encouraging.

In the future, we intend to work on several directions. First, we plan to carry out an extensive evaluation of our protocol so as to evaluate the impact of the different parameters. The protocol could also be improved by piggybacking some information in data packets, rather than using extra packets. Second, a careful comparison between the different models that are discussed in this article should be done. We also plan to compare the protocol of [18] with our protocol in NS2. This comparison is not straightforward because these protocols are implemented in two different versions of NS2. Third, we intend to integrate this allocation into a QoS routing protocol that guarantees bandwidth. Indeed, the goal of many QoS routing protocols is to provide bandwidth to QoS applications without considering the co-existence with Best-Effort flows. We plan to work on this co-existence in order to ensure a fair sharing to the Best-Effort flows while guaranteeing bandwidth to sensitive applications. Finally, we intend to implement our solution on a real platform. Such experimentations would be the best way to test the feasibility of our approach and the relevance of the model we used in a real context.

To conclude, we think that the main challenge when designing a rate allocation protocol for IEEE 802.11-based multihop networks is how communicate useful information without explicit messages as we use, since these messages give only an approximation of the contention.

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http://www.inria.fr
ISSN 0249-6399