Towards a Practical and Fair Rate Allocation for Multihop Wireless Networks based on a Simple Node Model

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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. In this article, we propose a distributed and dynamic rate allocation solution that is based on a simple radio 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.[1]

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network protocols

General Terms

Algorithms

Keywords

Distributed algorithms,protocols,evaluation,IEEE 802.11

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]. 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. 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 appearance of congestion and obtain a better fairness among the flows. The rate allocation is often based on a contention model that tries to capture the dependencies between wireless links. Different models have been proposed as, for instance, the protocol model or the physical model [5]. The solution is then designed according to two steps. In the first step, the wireless links dependencies are computed according to the chosen contention model. 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 solutions for rate allocation in multihop wireless networks are based on a link contention graph. In such a graph, vertices correspond to the wireless links of the network and there is an edge between two vertices in this graph if two flows along the two associated links contend with each other in the network according to the contention model. To find the optimal allocation, these solutions require to identify maximal cliques or maximal independent sets in this graph [9, 13], which 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 of a simple node-based model. The interested reader can refer to a longer version of this article in [11].

In the rest of this article, we assume that the IEEE 802.11 DCF mode is used in the network [6]. This paper is organized as follows: in Section 2, we present our rate allocation algorithm with the chosen node-based model. In Section 3, 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 3. We conclude with some remarks and perspectives.

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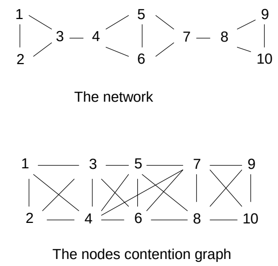

Figure 1: A network and its associated nodes contention graph. The network may correspond to the three pairs scenario.

2. A RATE ALLOCATION ALGORITHM BASED ON A NODE MODEL

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

2.1 A simple node model

We use a simple node-based model that was originally presented in [3]. The goal of this model is to express the medium sharing that exists between emitters within carrier sensing range in the DCF mode. Its goal is to realize a more accurate admission control for QoS flows based on bandwidth usage. 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. This model comes from conclusions deduced from experimentations which showed that the carrier sensing range is around twice as large as the communication range obtained with slow data rates (2 or 1 Mb/s) [4, 1]. Figure 1 shows an example of such a contention graph.

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

$$\forall n \in N \sum_{i \in V(n)} x_i \leq C \tag{1}$$

where N is the set of nodes in the network, and for each n in N, $V(n)$ the set of node n's neighbors in the contention graph.

Of course, 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 could be in its carrier sensing area if d is sufficiently small. On the other hand, using restrictive conditions, as these 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 the distance between two neighbor nodes is slightly larger than half the communication range, 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. Finally, most of the solutions that

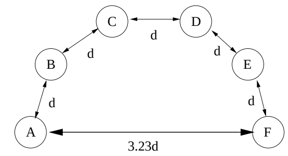

Figure 2: Approximation of the carrier sensing area

are based on a wireless links contention graph suffer from the same imprecisions since they also use approximations of carrier sensing and interference areas, while being more complex than the solution we propose.

2.2 A rate allocation algorithm

Let's consider Φ a set of flows that are transmitted in the network. Each flow f with a rate - or throughput - 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 correspond to the one-hop and two-hop neighbors of n in the network), C the capacity of the wireless medium and x_n the aggregated outgoing throughput of node n. The problem of the flow rates maximization can be written as follows:

$$\begin{array}{ll} \text{MAXIMIZE:} & \prod_{f \in \Phi} \phi_f \\ \text{UNDER THE CONTRAINTS:} & \forall n \in N \sum_{i \in V(n)} x_i \leq C \end{array} \tag{2}$$

$\prod_{f \in \Phi} \phi_f$ expresses the fact the we wish to maximize the rates allocated to flows while ensuring a *proportional fairness* between flows [8].

The Lagrangian optimization is a popular method to solve constrained non-linear optimization problems in a distributed way [8]. For our problem, this method is particularly adapted since it transforms a problem with global variables (the rates of the flows passing through the network) into a dual optimization problem that only uses local variables. This new problem can then be solved in a decentralized 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. It represents the virtual 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 its vicinity $V(n)$. For each flow f, a *price* Π_f is computed. This price depends on the rates 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. 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:

$$\Pi_f^{(s)} = \sum_{n \in N} r_{nf} \times \lambda_n^{(s)} \tag{3}$$

- 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.

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

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

- The nodes modify their rate according to this formula:

$$\lambda_n^{(s+1)} = \lambda_n^{(s)} + \sigma \times \left(C - \sum_{f \in \Phi} \frac{r_{nf}}{\Pi_f^{(s)}}\right) \quad (4)$$

where σ is the gradient step.

It can be shown that after several iterations, the unique value towards which the price of a flow converges is the inverse of the rate with which it can be emitted ($(\Pi_f)^{-1}$). 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.

2.3 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 NS-2.31 [10]. The parameters used in NS2, especially for IEEE 802.11, are given in Table 4. The routing protocol is AODV. 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 two results: the three pairs scenario and a grid scenario. The results are the average of 20 simulations.

The three pairs scenario.

In this scenario, there are three communicating pairs and the two external pairs are in the carrier sensing range of the central pair (and vice versa) while the two external pairs are independent. Unfairness arises with IEEE 802.11 because the central pair cannot access the medium due to asymmetrical contention [2]. 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).

Table 1 shows some results on the convergence speed in function of the number of steps. The stop criterion of the algorithm is the normalized Euclidian distance to the solution[2]. 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 and correspond to the proportionnal fairness. 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 3 shows 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 saturation at the central emitter's queue. 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.

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

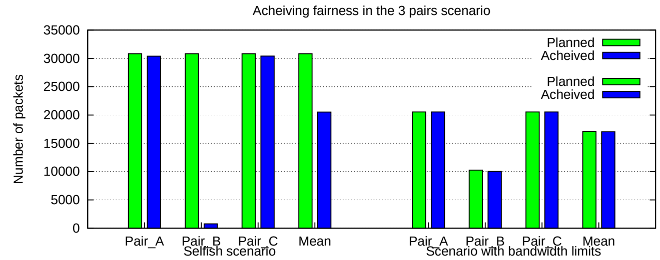

Figure 3: The obtained throughputs with NS2 for the three pairs scenario

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

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

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 rate 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. 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 10-second simulation 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 (per flow) of received packets with NS2 on the grid scenario

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
Radio propagation model	TwoRayGround
Traffic	backlogged / CBR / UDP
Packet size	1000 bytes
RTS/CTS	disabled

Table 4: Summary of the simulation parameters.

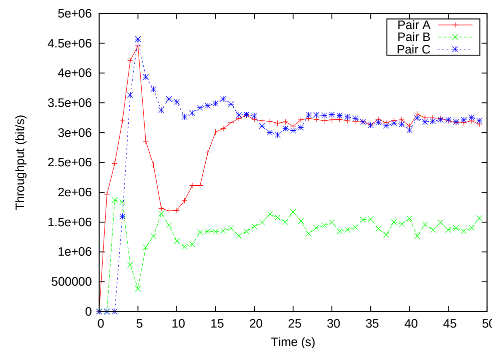

Figure 4: Throughput (3 pairs simulation)

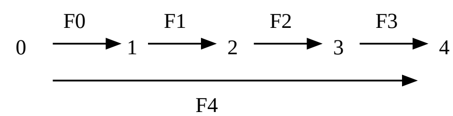

Figure 5: Topology for the line simulation

3. 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.

3.1 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 them 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 3, 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 3) 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 with Hello messages. Thus, the implied nodes can update their costs according to Equation 4.

3.2 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 [12].

3.2.1 *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 4 shows that the prices 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.

3.2.2 *The line*

The line scenario, depicted in Figure 5, 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 6 and 7 show respectively the results of these simulations without rate regulation and with bandwidth regulation. 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. 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 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.

3.2.3 *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 sources' rates. We have carried out a set of 20 simulations with different node placements and sets of flows in order to observe experimentally the properties of our protocol. To leave enough time for our algorithm to converge, we studied the

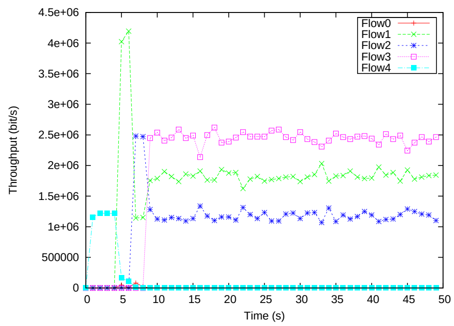

Figure 6: Throughput in the line scenario (no rate regulation)

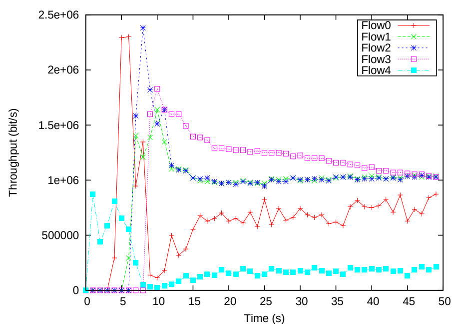

Figure 7: Throughput in the line scenario (with rate regulation)

last 10 seconds of the simulations[3]. Table 5 sums up the different parameters for these simulations.

We use the Jain index [7] to measure the fairness of the obtained allocations. For N flows with throughputs $(x_i)_{i\in[1..N]}$, it is defined by:

$$\frac{(\sum x_i)^2}{N * \sum x_i^2} \quad (5)$$

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 8 shows the cumulative distribution function of the achieved throughputs for the 80 flows simulated (by considering all the simulations). The proportionnal fair allocation reduces very significantly the number of flows that are penalized: the fraction 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.

4. CONCLUSION

This article has described a rate allocation algorithm for multihop wireless networks that is based on a simple radio medium sharing model, called node-based model, simply derived from the network topology. Due to the simplicity of the model and of the constraints, it is possible to derive this algorithm into a protocol.

[3] In most simulations, our protocol needed $20s$ to converge.

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

The first simulations, with NS2, show the feasibility of such an approach and are encouraging.

In the near future, we plan to carry out an extensive evaluation of our protocol so as to evaluate the impact of the different parameters. A careful comparison between the different contention models and constraints should also be done. Finally, we intend to implement our solution on a real platform.

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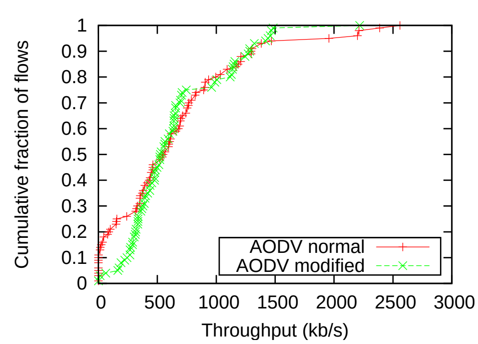

Figure 8: Throughput CDF in the random simulation