Admission Control based on Dynamic Rate Constraints in Multi-hop Networks

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***Abstract*—This paper presents an admission control algorithm based on dynamic constraints for multi-hop networks. Assuming each node knows the topology and flow reservations within its radio range, local constraints on flow rates can be computed. As long as these constraints are satisfied, flows are accepted. Since computing optimal constraints is not practical, existing approaches compute a system of either necessary or sufficient constraints. In practice, the approach based on necessary constraints tends to overload the network whereas in the latter approach, a significant part of the bandwidth remains unused. In addition, these works assume that the interference model and the sublayers are optimal. In this paper, we propose to take into account the channel state in the constraints computation and, thus, to adjust them according to model relevance. Therefore we give a probabilistic model to evaluate the time spent by the channel in the idle state. By comparing this estimation with the measure value, we evaluate the model accuracy and include the corresponding error rate in the constraints of the admission control. Simulations show that our admission control algorithm outperforms previous work.**

I. Introduction

A multi-hop network is a network where each node is able to join each others transparently. In such networks, two distant nodes cannot communicate directly and use intermediate nodes to relay messages. This ability makes this kind of networks very popular since they can easily cover a wide area for a low cost. But in the same time, this ability makes them complex: the capacity per node tends to null with an increasing number of nodes [1]. Therefore, it is necessary to have an algorithm in charge of accepting or refusing new flows depending on the traffic load. This algorithm is called "admission control".

Admission control has been studied from two main points of view depending on how the traffic load is estimated. It can be deduced by listening to the channel or by summing the reserved flows rates:

1) Related work based on the channel listening consider a cross-layer model where the channel state is available at the MAC layer [2]–[4]. When a node can successfully communicate with another node (*i.e.* within its transmission range), the channel state is "transmitting" for the emitting node and "receiving" for the other one. A node outside this range but close enough to detect the signal would have a "noisy" channel state. Noisy channel nodes are in the emitter's carrier sensing range. The channel state is considered idle if no transmission (or noise) exists. The idle channel time that is the proportion of time spent in the idle state accounts for interference among flows (inter-flow contention) and interference between a flow and itself (intra-flow contention). Therefore idle channel time gives an accurate available bandwidth estimation [5]. Then new flows are accepted only if their requested bandwidth does not exceed the available bandwidth.
2) Related work based on flows reservations compute constraints on flow rates from the local topology and the local interferences. First, an interference model in charge of approximating interfering links must be defined. The most usual approach is to take benefit of the topology and to consider a N-hop interfering model. For example, for N=2, nodes can interfere with their neighbors and the neighbors of their neighbors. Another approach based on localization information is also possible but it cannot consider obstacles. Then, based on this interference model, a system of constraints on the flows rates is computed. New flows are accepted as long as these constraints are satisfied.

But both of these viewpoints have drawbacks.
Approaches based on the channel listening cannot differentiate the traffic's priorities and, thus, do not support quality of service. Moreover, they do not predict the impact of a new flow on the available bandwidth. In addition, they work under the unrealistic hypothesis that flows consume exactly the bandwidth they have requested.
Concerning related work based on flows reservations, the constraints computation is NP-hard [6], [7]. Several heuristics give good approximations for necessary constraints or sufficient constraints but computing optimal constraints is not practical. Moreover, these approaches are based on different models more or less realist. For instance in previous work, neither the bandwidth wastage at the MAC-layer, nor external noise sources, nor interference model errors are considered.

In this paper, we propose to overcome these drawbacks by combining both viewpoints. The key idea is to compute constraints and to readjust them by determining the difference between the idle channel time estimation and the idle channel time measure. We first give a probabilistic analysis based on the interference model in order to estimate the idle channel

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time. By comparing this value with the idle channel time measure, we evaluate the local accuracy of the used interference model, the local MAC overhead and the local external noise. This evaluation is then used to deduce an error rate for a node at a given time and to compute local dynamic constraints. Finally we compare by simulation our algorithm with previous work.

This paper is organized as follows. In section 2, we present our notations. Related work is discussed in section 3. Section 4 is used to describe our admission control algorithm. Simulations results are presented in section 5, before we conclude the paper.

II. Notations

The classical representation of a network is a graph where vertexes are nodes and edges are transmission links. A link (s, d) is a pair of nodes where d is in the transmission range of s. A network topology is a directed graph $G = (V, E)$ where V is a set of nodes and E a set of links. For example, Figure 1 represents a topology of five nodes [1].

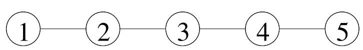

Fig. 1. Network topology

The set of nodes interfering with node n is denoted I_n. Interference models estimate it by considering power control [2], graph connectivity (*e.g.* N-hop interference model) or localization information [8].

The conflict graph of a topology is an undirected graph $CG = (V', E')$ where $V' = E$ is the set of links and where edges belonging to E' join interfering links. Let assume, for example, a 2-hop interference model, where a node interferes with its neighbors and the neighbors of its neighbors. Then, we obtain the conflict graph of Figure 2 from the topology of Figure 1. As nodes 2 and 3 are in the carrier sensing range of node 1, link $(1, 2)$ is interfering with links $(2, 3)$ and $(3, 4)$.

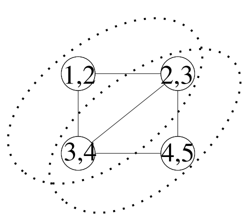

Fig. 2. Conflict graph

We consider that time is slotted and we define t_s as the slot duration. The idle channel time estimation is computed for a given duration $n_s \cdot t_s$ where $n_s \in \mathbb{N}^*$ is the number of slots considered. For the sake of simplicity, we assume that all the links of E have the same capacity c and that the packet size σ is constant. So the transmission delay of a packet is $t_p = \frac{\sigma}{c}$. The reserved bitrate on link l is denoted u_l. The number of packets on link l during $n_s \cdot t_s$ is $n_{p,l} = n_s \cdot t_s \cdot \frac{u_l}{\sigma}$.

[1]To simplify our example, the graph is undirected.

III. Related work

Admission control in ad hoc networks has been largely studied. We focus on admission control algorithms considering that nodes know the topology and the flows within their carrier sensing range. We present in the following subsections existing algorithms to compute optimal, necessary or sufficient constraints.

A. Optimal Constraints

Optimal constraints can be deduced from the conflict graph by grouping not interfering links [6], [7]. An independent set of CG is a set of links which are able to transmit concurrently. A maximal independent set is an independent set where it is impossible to add another link. For example, the maximal independent sets of the conflict graph on Figure 2 are: $\{(1, 2)(4, 5)\}$, $\{(2, 3)\}$ and $\{(3, 4)\}$. Intuitively, only links belonging to the same independent set can transmit simultaneously.

Let K be the set of maximum independent sets of CG and λ_i the utilization rate of the i^{th} independent set. It follows that $\sum_{k \in K} \lambda_k \leq 1$ because the bandwidth is shared among the independent sets. Then, the bandwidth reserved on link l must be lower or equal to the sum of the bandwidth allocated for the independent sets containing l. Hence, we have:

$$\forall l \in E, \quad u_l \leq c \cdot \sum_{\substack{k: l \in k \\ k \in K}} \lambda_k$$

The set of flows is considered feasible if and only if there exists $\lambda_1, \lambda_2, ., ., \lambda_{|k|}$ satisfying theses constraints.

This approach is very interesting but developing a distributed protocol based on independent sets is not practical. Indeed, independent sets bring links which are not interfering together, thus a good knowledge of very far areas is required by each node.

B. Necessary Constraints

To overcome this problem, researchers have focused on an opposite approach: grouping interfering links instead of non-interfering links [8], [9]. A clique C of CG is a set of links interfering with each other. $\mathcal{C}$ is the set of the maximal cliques of a conflict graph CG. For example, the maximal cliques of the conflict graph on Figure 2 are: $\{(1, 2)\ (2, 3)\ (3, 4)\}$ and $\{(2, 3)\ (3, 4)\ (4, 5)\}$. Determining the cliques of a graph is NP-complete but polynomial heuristics exist [10].

Since a clique is composed of interfering links, the bandwidth is shared among its links:

$$\forall C \in \mathcal{C}, \quad \sum_{l \in C} u_l \leq c \qquad (1)$$

These constraints are necessary, so even if they are satisfied, the network can be overloaded.

C. Sufficient Constraints

Another approach gives sufficient constraints when the conflict graph can be modelled as a unit disk graph [8]. Under this assumption, nodes are unit disks and links join nodes having crossing disks. These constraints are the following:

$$\forall C \in \mathcal{C}, \quad \sum_{l \in C} u_l \leq 0.46 \cdot c \tag{2}$$

These constraints are sufficient, so they may wrongly consider that a set of flows is not feasible, leading to an underloaded network.

IV. Solution

In this paper we present an admission control algorithm based not only on the network model but also on the channel state. This solution is interesting because resulting constraints are take into account dynamically the interference model accuracy, the MAC layer overhead and external noise sources.

We fist give a probabilistic model to estimate the idle channel time of any node in the network. Then we present our admission control algorithm.

A. Idle Channel Time Estimation

Because of spatial reusing, two nodes in the carrier sensing range of any node n may be able to transmit at the same time. In this case, node n "sees" the two signals summed on its channel but it has no way to determine how many transmissions are summed, it just knows that its channel is busy [2]. Therefore, the idle channel time of node n depends on spatial reuse.

We first present several definitions. Then we define the lower (resp. upper) bound of idle channel time, that is the value obtained when the nodes which are able to transmit simultaneously do it as often as possible (resp. not at all). We compute the probability to be in each possible point of this interval, the idle channel time estimation being the expected value of the distribution.

1) Definitions:
We focus on the idle channel time of a given node n. Let $\mathcal{C}_n$ be the local clique view of n. More precisely, $\mathcal{C}_n$ contains the cliques of $\mathcal{C}$ where the links for which the source emissions have no impact on the channel of n are removed:

$$\mathcal{C}_n = \bigcup_{C \in \mathcal{C}} \{\{(s,d) \mid (s,d) \in C \ \wedge \ \ s \in \{n\} \cup I_n\}\} \setminus \{\emptyset\}$$

For example, on Figure 2, $\mathcal{C}_1$ contains $\{(2,3)\ (3,4)\}$ and $\{(1,2)\ (2,3)\ (3,4)\}$. We also define L_n as the set of links for which node n is in the source's carrier-sensing-range: $L_n = \bigcup_{C \in \mathcal{C}_n} C$. Following the previous example, $L_1 = \{(1,2)\ (2,3)\ (3,4)\}$.

[2]In the rest of this article, we consider that the channel is busy when its state is receiving, transmitting or noisy.

2) Idle Channel Time Bounds:
We are now interested in bounding the idle channel time. By definition, among the links of a clique, only one can transmit at a time, contrary to links belonging to different cliques. Thus, the maximum number of simultaneous transmissions summed on the channel of n is equal to $|\mathcal{C}_n|$.

M_n, the maximum number of busy slots on the channel of node n during $n_s \cdot t_s$, is equal to the sum of the slots consumed by each link of L_n:

$$M_n = \min\left(n_s; \left\lfloor \frac{t_p}{t_s} \cdot \sum_{l \in L_n} n_{p,l} \right\rfloor\right). \tag{3}$$

N_n, the minimum number of busy slots on the channel of node n during $n_s \cdot t_s$, is equal to the number of slots consumed by the clique having the highest reserved bandwidth:

$$N_n = \max_{C \in \mathcal{C}_n}\left(\left\lceil \frac{t_p}{t_s} \cdot \sum_{l \in C} n_{p,l} \right\rceil\right). \tag{4}$$

By Equations 3 and 4, it derives that the lower and upper bounds on the idle channel time of node n during n_s slots are equal to: $ictmin_n = 1 - M_n/n_s$ and $ictmax_n = 1 - N_n/n_s$.

3) Spatial Reuse Probability:
We are now interested in computing $\widetilde{ict}_n$, the estimation of the idle channel time of n, where $ictmin_n \leq \widetilde{ict}_n \leq ictmax_n$.

We now assume that a node transmits a whole packet in exactly one slot ($t_s = t_p$) and that nodes are synchronized. Let X_n be the discrete random variable giving the number of busy slots on the channel of n among the n_s slots considered and $Pr(X_n = x)$ the associated probability. Thus, $Pr(X_n = x)$ is equal to the number of possibilities to have x busy slots on the channel of n among the n_s slots considered, divided by the total number of possibilities.

Let $g_n(x)$ be the total number of possibilities to transmit the packets of the links belonging to L_n in at most x slots when links are not interfering. Thus, $g_n(x)$ is equal to the number of possibilities for a first link l_1 to have its n_{p,l_1} packets transmitted in at most x slots, times the number of possibilities for a second link l_2 to have its n_{p,l_2} packets transmitted in at most x slots, and so on. Hence, $g_n(x)$ is a product of combinations defined for $x \in [N_n, M_n]$:

$$g_n(x) = \prod_{i=1}^{|L_n|} \binom{x}{n_{p,l_i}} = \prod_{i=1}^{|L_n|} \frac{x!}{n_{p,l_i}! \cdot (x - n_{p,l_i})!}. \tag{5}$$

Let $g'_n(x)$ be the generalization of $g_n(x)$, when links are interfering. In this case, a slot consumed by any link $l \in L_n$ is no more available for the other links interfering with l.

$$g'_n(x) = \prod_{i=1}^{|L_n|} \begin{pmatrix} x - \displaystyle\sum_{\substack{j=1 \\ \{l_i, l_j\} \in E'}}^{i-1} n_{p,l_j} \\ \\ n_{p,l_i} \end{pmatrix} \tag{6}$$

We now consider the number of possibilities to have exactly x busy slots on the channel of node n among n_s slots when links belonging to L_n are transmitting. This function, $f_n(x)$, is defined recursively for $x \in [N_n, M_n]$. Indeed, it is equal to (i) the number of possibilities to have at most x busy slots among n_s slots, minus (ii) the number of possibilities to transmit them in exactly $x-1$ slots times the number of possibilities to choose $x-1$ slots among x, minus (iii) the number of possibilities to transmit them in exactly $x-2$ slots times the number of possibilities to choose $x-2$ slots among x, and so on for $x-3$,$x-4$,..,N_n. The first term is previously defined by $g'_n(x)$. The second, third and following terms are a product of a combination and a recursive call to f. So $f_n(x)$ is equal to:

$$\begin{cases} f_n(x) = g'_n(x) & \text{if } x = N_n \\ f_n(x) = g'_n(x) - \displaystyle\sum_{i=N_n}^{x-1} \binom{x}{i} f_n(i) & \text{if } x \in]N_n, M_n]. \end{cases} \tag{7}$$

It is clear that $Pr(X_n = x)$, the probability to have x busy slots on the channel of n among the n_s slots considered, is null when $x < N_n$ or $x > M_n$. Then, we obtain from Equations 6 and 7 the following property:

$$\begin{cases} Pr(X_n = x) = \dfrac{\binom{n_s}{x} \cdot f_n(x)}{g'_n(n_s)} & \text{if } x \in [N_n, M_n] \\ Pr(X_n = x) = 0 & \text{otherwise.} \end{cases}$$

We show that $Pr(X_n = x)$ is a probability law. Indeed:

$$\begin{aligned} \sum_{x\in\mathbb{N}} Pr(X_n = x) &= \frac{\sum_{i=N_n}^{n_s} \binom{n_s}{i} f_n(i)}{g'_n(n_s)} \\ &= \frac{\sum_{i=N_n}^{n_s-1} \binom{n_s}{i} f_n(i) + f_n(n_s)}{g'_n(n_s)} \\ &= \frac{\sum_{i=N_n}^{n_s-1} \binom{n_s}{i} f_n(i) + g'_n(n_s) - \sum_{i=N_n}^{n_s-1} \binom{n_s}{i} f_n(i)}{g'_n(n_s)} \\ &= 1. \end{aligned}$$

Let $h_n(x)$ be an equivalent non-recursive form of $f_n(x)$ defined as follows for $x \in [N_n, M_n]$:

$$h_n(x) = \sum_{j=N_n}^{x} (-1)^{j+N_n} \binom{x}{j-N_n} g'_n(x + N_n - j).$$

Thus we have the equivalence property:

$$\forall x \in [N_n, M_n], \quad f(x) = h(x). \tag{8}$$

Proof: By recurrence. Equation 8 is satisfied for $x = N_n$, as $h_n(N_n) = g'_n(N_n) = f_n(N_n)$. Assuming that the equation is true for $x \le k$, that is $\forall i \in [N_n, k], h_n(i) = f_n(i)$, we get:

$$\begin{aligned} f_n(k+1) &= g'_n(k+1) - \textstyle\sum_{i=N_n}^{k} \binom{k+1}{i} f_n(i) \\ &= g'_n(k+1) - \textstyle\sum_{i=N_n}^{k} \binom{k+1}{i} h_n(i) \end{aligned} \tag{9}$$

Then we focus on the sum for $i = N_n..k$ of the previous equation. By expanding $h_n(i)$, it becomes:

$$\textstyle\sum_{i=N_n}^{k} \binom{k+1}{i} \sum_{j=N_n}^{i} (-1)^{j+N_n} \binom{i}{j-N_n} g'_n(i + N_n - j). \tag{10}$$

The last term of the inner sum is the only one which contains $g'_n(N_n)$. Thus, we extract and factorize it. This last term is:

$$\begin{aligned} & \textstyle\sum_{i=N_n}^{k} \binom{k+1}{i} (-1)^{i+N_n} \binom{i}{i-N_n} g'_n(N_n) \\ = \quad & g'_n(N_n) \cdot \textstyle\sum_{i=N_n}^{k} \binom{k+1}{i} (-1)^{i+N_n} \binom{i}{i-N_n} \\ = \quad & g'_n(N_n) \cdot (-1)^{k+N_n} \cdot \binom{k+1}{k-N_n+1} \end{aligned}$$

In the same way, we extract the last remaining term of the inner sum of Equation 10 and we successively factorize by $g'_n(N_n+1), .., g'_n(k-1), g'_n(k)$. The sum of these factorizations, equivalent to Equation 10, is:

$$\textstyle\sum_{j=N_n}^{k} (-1)^{j+N_n} g'_n(k + N_n - j) \binom{k+1}{j-N_n+1}$$

Then we increment the indexes of this resulting sum in order to insert the term $g'_n(k+1)$ of Equation 9. So we get:

$$-\textstyle\sum_{j=N_n+1}^{k+1} (-1)^{j+N_n} g'_n(k + 1 + N_n - j) \binom{k+1}{j-N_n}$$

From Equation 9, we obtain $g'_n(k+1)$ minus the previous sum equal to $h_n(k+1)$. ■

This non recursive function can be implemented very efficiently by using the Γ function instead of factorials.

4) Idle Channel Time Estimation: We have defined the probability $Pr(X_n = x)$ to have, on the channel of node n, exactly x busy slots during the interval $n_s \cdot t_s$. Hence, the estimation of the idle channel time of node n can be deduced by computing the expected value of the random variable X_n, that is:

$$\widetilde{ict}_n = 1 - \frac{E(X_n)}{n_s} = 1 - \frac{\sum_{i=0}^{n_s} i \cdot Pr(X_n = i)}{n_s}.$$

B. Admission Control based on Dynamic Rate Constraints

Assuming that the idle channel time measure, denoted ict_n, is retrievable from the MAC layer, we compare it to $\widetilde{ict}_n$ and evaluate the interference model accuracy. Let E_n be the error rate on node n:

$$E_n = \max\left(0, \widetilde{ict}_n - ict_n\right)$$

Then we deduce EC_C, the error rate of clique C, by computing the average of E_n for all nodes of links in C.

Based on this error rate, we can compute dynamic constraints. These local constraints are adjusted according to the local model accuracy. For example, the admission control will be more (resp. less) permissive if the interference model gives more (resp. less) interfering links than in reality. The constraints defined in Equation 1 become:

$$\forall C \in \mathcal{C}, \quad \sum_{l\in C} u_l \le (1 - EC_C) \cdot c \tag{11}$$

Equation 2 presented in the related work section gives sufficient constraints, when the interference model is optimal. But this assumption is not realistic with usual interference models (e.g. N-hop interference model). With our dynamic constraints, $1 - EC_C$ can be lower than 0.46 by taking into account the interference model precision, the MAC overhead and external noise sources. It could even reach 0 in some cases.

We also propose to add a parameter $\gamma \in [0, 1]$ in the previous equation so that it is possible to specify the maximum constraints readjustment:

$$\forall C \in \mathcal{C}, \quad \sum_{l\in C} u_l \le (1 - \gamma EC_C) \cdot c$$

With $\gamma = 0$, this constraints system is reduced to the necessary constraints system of Equation 1.

V. Results

We first evaluate the accuracy of our idle channel time estimation by comparing it to the measure when models are optimal. Then, we simulate our admission control algorithm and we compare it to related work in realistic scenarios.

A. Idle Channel Time

We compare by means of simulations our estimation to the measure of the idle channel time, with and without collisions. We have implemented our solution on a IEEE 802.11b MAC layer under Opnet Modeler with the following parameters: $\sigma = 1500$ bytes, $t_s = 2.5\ ms$, $n_s = 400$ slots.

First, we have simulated a collision-free network where the transmitting links are far enough to avoid interference. Moreover, a specific node n is in the carrier sensing range of all the other nodes. Then, we measure and estimate the idle channel time of this node. Figures 3 and 4 represent the measure, the estimation and the bounds on its idle channel time when the number of nodes is respectively 11 and 61, and when the number of transmitting links is respectively 5 and 30. Graphs are plotted for a total traffic varying from 0 to the maximum capacity, fairly shared among links. We notice that our estimation of the idle channel time is accurate. Indeed, the error rate does not exceed 3%. This difference mainly comes from rounding values used in our computation.

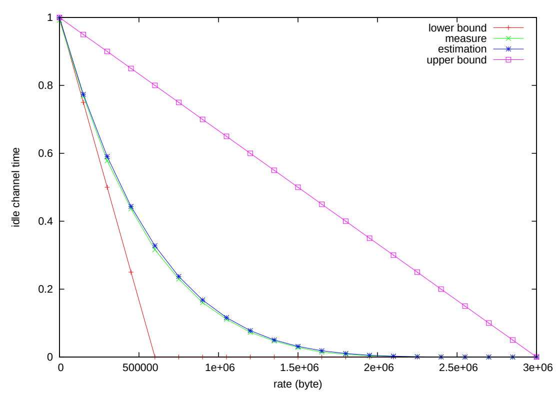

Fig. 3. Idle channel time for a network of 11 nodes without collision

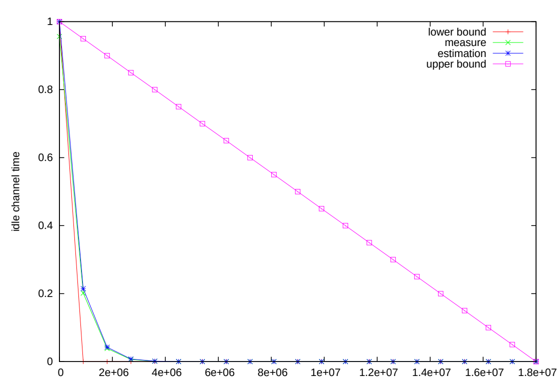

Fig. 4. Idle channel time for a network of 61 nodes without collision

Then we have simulated a network consisting in 5 nodes where there exist interferences among links. Hence, collisions may occur. Figure 5 represents the measure, the estimation and the bounds on the idle channel time of node n, that is the node in the carrier sensing range of the others. As in the previous simulations, the total traffic varies from 0 to the maximum capacity. The more the traffic grows, the less the channel of node n is idle. In theory, the channel of n is completely busy once the traffic has reached the maximum capacity. In practice, even if the traffic is maximum, the channel of n stays idle a small part of time due to the backoff algorithm which addresses the medium access problem. This can be observed on Figure 5, where the idle channel time measure exceeds the upper bound when the total traffic is maximum. This is due to the fact that we have adopted a general network model, without consideration to a given MAC layer. The specificities of a MAC layer can be easily integrated in our model, but this is out of scope of this paper.

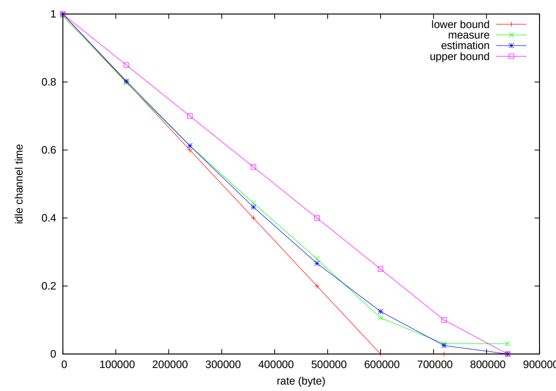

Fig. 5. Idle channel time for a network of 5 nodes with collisions

B. Admission Control

The idle channel time estimation is precise and allows to get a valid node error rate on the accuracy of the considered models. So we have compared under OpNet Modeler our admission control algorithm and previous work with the parameters listed on Table I.

duration	2000 s
area	600 m^2
number of nodes	20
node position distribution	uniform
flow source/destination distribution	uniform
flow duration distribution	uniform (between 1 and 60 s)
flows interarrival distribution	exponential
packets interarrival distribution	exponential
routing algorithm	shortest path
interference model	2-hops interference model
MAC layer	IEEE 802.11b

TABLE I
Simulation Parameters

Figure 6 represents the total bitrate in the network, that is the sent and forwarded bitrate in function of time. Indeed, a packet is sent then possibly forwarded several times and finally received. It shows that the less restrictive the admission control is, the more the traffic is important. However, the total bitrate is limited by the network capacity.

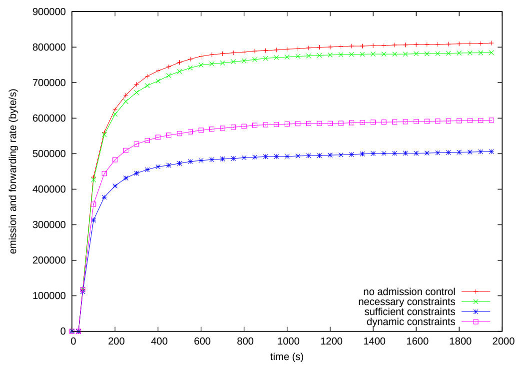

Fig. 6. Sent and forwarded bitrate for 20 nodes

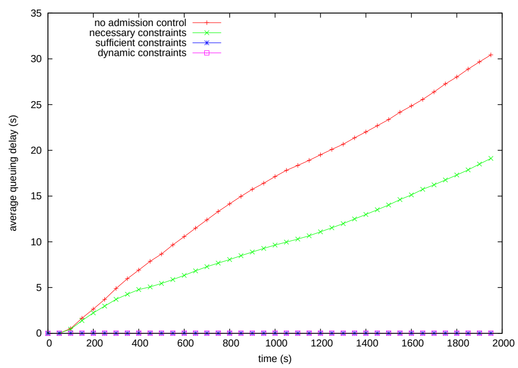

Fig. 7. Queuing delay for 20 nodes

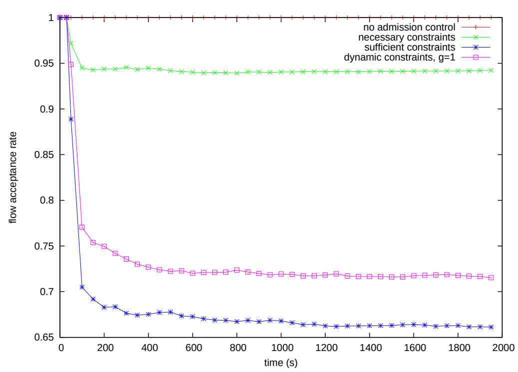

Fig. 8. Flow acceptance rate for 20 nodes

Figure 7 represents the average time spent by packets in waiting queues in function of simulation time. It illustrates that without any admission control or with the admission control based on the necessary constraints, this delay is increasing. As in our simulation the length of the waiting queues is infinite, the packets are not removed but this shows that the network is quickly saturated. The queuing delay with the admission controls based on sufficient and dynamic constraints stays limited. So the network is not saturated when sufficient or dynamic rate constraints are applied.

Figure 8 represents the average flow acceptance rate on time. Without any admission control, all flows are accepted and the network is overloaded. Figure also shows that our admission control, based on dynamic constraints, rejects more flows than this based on necessary constraints. This is the reason why our solution does not overload the network. Moreover, it is important to notice that dynamic constraints accept more flows than sufficient ones, tending towards the optimal constraints.

VI. Conclusion

In this paper, we have given a new admission control algorithm based on dynamic constraints for multi-hop networks. These constraints are locally readjusted, in each node, according to the difference between the idle channel time estimation and the idle channel time measure of the considered node.

First we have presented a probabilistic model to bound and evaluate the idle channel time of a given node. Then, by comparing this estimation to the measure, we have obtained a local evaluation of model accuracy and we have included the corresponding error rate in the admission control constraints. Finally, we have shown by simulations that our idle channel time is precise and that our admission control algorithm gives better results than existing work.

Our approach is original since it is not only based on the channel state or on flow reservations but on both of them. This has several advantages:

- Compared to related work based on channel listening, flows can have different priorities and the prediction of a new flow's impact on the network is much more precise;
- Compared to related work based on constraints, the MAC layer overhead, the interference model errors and external noise sources are considered.

In the future, it would be interesting to refine our dynamic rate constraints by tuning the γ factor according to the admission control policy. Indeed, depending on the kind of traffic, it would be suitable either to limit packet losses or to increase the total throughput.

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