Retransmission-based Available Bandwidth Estimation in IEEE 802.11-based Multihop Wireless Networks

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ABSTRACT

Estimating the available bandwidth in IEEE 802.11-based multihop wireless networks is a very difficult task due to the medium sharing among contending nodes and collisions between hidden stations. Several methods have been proposed so far for these networks to compute the available bandwidth on wireless links. If some recent solutions such as ABE and IAB now take into account collisions and their impact on the mean backoff, none considers the packet retransmissions due to collisions although these retransmissions have an impact on the available bandwidth. In this article, we propose a new available bandwidth estimation for multihop wireless networks called RABE (Retransmission-based Available Bandwidth). This method integrates the average number of retransmission attempts in the available bandwidth estimation. RABE is evaluated by simulation and the obtained results show that RABE can achieve a mean error ratio of 17% in comparison with the real measurement. Furthermore RABE is at least two times more accurate than ABE and ten times more accurate than IAB.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*; C.2.5 [**Computer-Communication Networks**]: Local and Wide-Area Networks; C.4 [**Performance of Systems**]: Measurement Techniques

General Terms

Measurement, Performance

Keywords

Available bandwidth estimation, Multihop wireless networks, IEEE 802.11, Quality of service

1. INTRODUCTION

Multihop wireless networks can be deployed in environments where networking architectures with fixed and wired infrastructure are costly and/or difficult to deploy. Mesh wireless networks are such multihop wireless networks that can be considered as an alternative to access networks [2]. In order to offer applications with good performance, similar to traditional access networks, QoS mechanisms often require an estimation of available resources, like for instance the available bandwidth. The available bandwidth of a wireless link can be defined as the maximal throughput that can be transmitted from the sender to the receiver of the link without disrupting ongoing close flows [7].

Several solutions have been proposed for estimating available bandwidth in multihop wireless networks. Many solutions assume that the used wireless technology is IEEE 802.11 with the distributed access mode (DCF - Distributed Coordination Function) [6], because 802.11 wireless cards are very popular and easy to use. We make the same assumption in our work: all the nodes are equipped with a single 802.11 wireless interface card communicating with the DCF mode.

Active estimation methods, like the ones described in [1, 4], use probing packets to derive available bandwidth on paths. Such an approach can take time because it requires to send probing flows before sending data flows and can also impact the rates and the traffic profiles of on-going flows. Passive methods, like the ones proposed in [3, 7, 8], estimate the available bandwidth without sending extra packets but only by observing what happens locally, *i.e.* on each node and on its neighbourhood. This approach requires an evaluation of different parameters like, for instance, the available bandwidth per node, the collision probability on each node and the synchronization of idle periods between senders and receivers of wireless links. But none of the proposed passive solution do not take into account the fact that, in case of collisions, packets are retransmitted with 802.11 DCF and that packets are dropped when the retransmission limit is reached. These packets retransmissions and drops clearly impact the available bandwidth.

In this paper, we present a novel passive available bandwidth estimation method that integrates the impact of the retransmission attempts on the available bandwidth. Our solution, called RABE for *Retransmission-based Available Bandwidth Estimation*, takes into account, in its estimation, the bandwidth wasted by extra waiting times and medium occupancy due to retransmissions. This estimation requires to compute the collision probability and the mean number of retransmission attempts. Note that we assume, throughout this article, a perfect physical layer and that packet loss is only due to MAC collisions.

The paper is organized as follows: Section 2 discusses the importance of retransmissions on the available bandwidth estimation. In Section 3, we describe the solution we propose, called RABE. This estimation method is based on the average number of retransmission attempts. In Section 4, we evaluate the performance of RABE by simulations carried out with ns2. We also compare RABE with other solutions under different topologies and traffic. Finally, Section 5 concludes our work.

2. MOTIVATION: PACKET RETRANSMISSIONS

Recent works, dedicated to the available bandwidth evaluation in multihop wireless networks, can be divided into two categories:

- *Active estimation methods* In these methods [4, 1], probing packets (or flows) are injected into the network in order to estimate the available bandwidth on paths and/or links. This estimation is based on the packet delay or the inter-packets delay measured on probing packets at destination nodes. The main drawbacks of this approach are the impact of the probing packets on the existing flows and a use of bandwidth that is already a scarce resource.
- *Passive estimation methods* These methods rely on information that can be locally sensed or decoded. These methods are not fully passive insofar as information can be exchanged with the nodes' neighbours. As these exchanges consume additional bandwidth, it is important to limit them (in time and to the neighbourhood). But on the other hand, they can bring up-to-date and useful information for the available bandwidth estimation. Very often, as they take profit of broadcast packets used in other protocols, like Hello packets sent in routing protocols, these methods are considered as passive.

Since the proposed solution in this article is a passive approach, we only consider here the main recent passive estimation techniques known in the literature. In Adaptive Admission Control (AAC) [3], each node measures the busy periods duration to deduce the fraction of idle periods on a measurement interval, and then deduces the available bandwidth per node. The available bandwidth of a link is computed as the minimal available bandwidth between the two end nodes of the link. Collisions are not taken into account in this solution.

Among passive estimation methods, Available Bandwidth Estimation (ABE) was the first to integrate the impact of collisions into the available bandwidth estimation [7]. To this aim, the authors compute the collision probability of Hello packets thanks to the Hello packets sent by several routing protocols for multihop wireless networks. Then, they derive the collision probability of data packets from the collision probability of Hello packets via off-line computations and Lagrange interpolated polynomials. One weakness of this technique is that it assumes that Hello packets are periodically sent and thus periodically received, which can not be true with a 802.11 DCF access. Moreover, this solution assumes that the distribution of idle periods for each node is uniform and independent.

To overcome the assumption on the independence of the idle periods distributions, Improved Available Bandwidth (IAB) [8] takes into account the common medium occupation periods between two end nodes of each link, and thus the independent occupation periods. They are computed thanks to the sensing busy state during which one end node senses the medium busy while its neighbor senses the medium idle. This computation assumes a uniform distribution of nodes in the network.

In passive methods, like ABE [7] and IAB [8], the authors consider that a communication can happen on a wireless link whenever the sender and the receiver are both idle. This means that, at the first transmission of the packet, the transmission has succeeded or failed. However, this is not true with the retransmission mechanism used in IEEE 802.11 DCF. This mechanism is shown on Fig. 1: a packet may be retransmitted several times until the transmission succeeds or until the packet is dropped due to the retransmission limit.

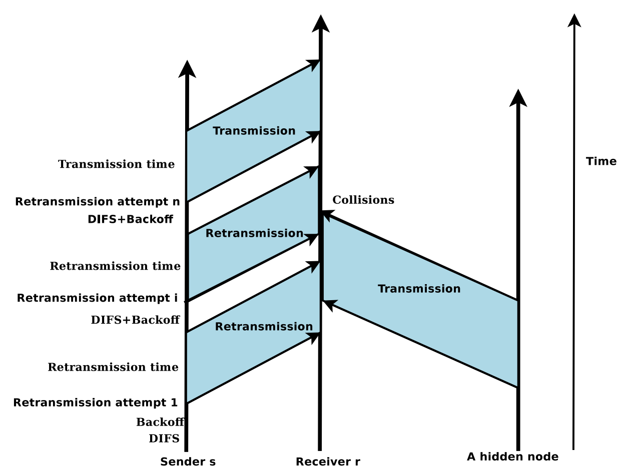

Figure 1: The communication model on a wireless link with IEEE 802.11 DCF

Let us consider the asymmetrical hidden scenario given in Fig. 2. By using NS2, we now study this simple scenario

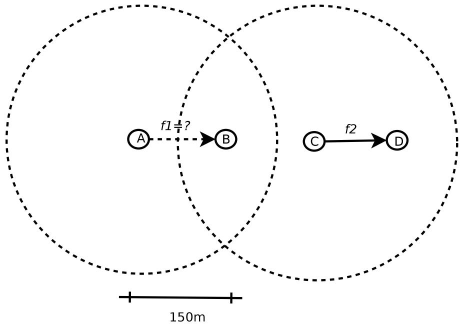

Figure 2: Asymmetrical hidden terminals scenario

that consists of four nodes A, B, C, D. The nodes have the same configuration given in Table 1.

SIFS	10 μs
DIFS	50 μs
Transmision range	200 m
Carrier sensing range	250 m
Physical rate	2 Mb/s
Packet size	1 kbytes
Retransmision limit	7
Contention window size (min, max)	31, 1023
The rate of the flow f_2	250, 500, 750, 1000 kb/s

Table 1: The nodes' configuration in the simple scenario

The distribution of the number of retransmission attempts at the sender A of the flow f_1 in function of the rate of the flow f_2 is shown in Fig. 3. The results in Fig. 3 show that, when the rate of the flow f_2 is low (250 and 500 kb/s) , the maximal number of retransmission attempts for sending the packets of the flow f_1 is 2. Next, at higher rates of the flow f_2, more retransmissions are needed to send a frame, due to a higher number of collisions. Especially, when the rate of the flow f_2 is 1000 kb/s, for all sent frames, the number of retransmission attempts is maximal meaning that all packets have been dropped.

Retransmissions imply additional medium occupancy (with the packets retransmission) and additional waiting times (with an increase of the backoff time). Moreover, when the retransmission attempts limit is reached, the packet is dropped. It means that the link is saturated.

3. RABE: RETRANSMISSION-BASED AVAILABLE BANDWIDTH ESTIMATION

In this section, we describe a new solution, called RABE (Retransmission-based Available Bandwidth Estimation), that provides an estimation of the available bandwidth per link. This estimation is based on the following parameters: the available bandwidth per node, the collision probability, the average number of retransmission attempts, the extra backoff times due to retransmissions and the packet loss ratio.

The next sub-sections describe how RABE computes these different parameters. In the following description, RABE is applied on a link (s, r).

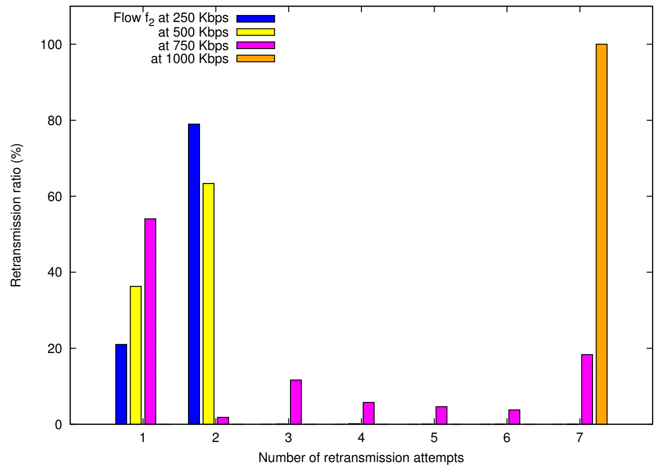

Figure 3: The distribution of the number of retransmission attempts

3.1 Estimation of the available bandwidth per node

As defined in [7], we consider that, given the fraction of idle periods of a node over a measurement interval, denoted κ^i, the available bandwidth per node for any node n can be evaluated as:

$$C_n = \kappa_n^i * C_{max} \quad (1)$$

where C_{max} is the physical rate of the node. Such a measurement takes into account the bandwidth used in the transmission range as in the carrier sensing range.

3.2 Estimation of the collision probability

3.2.1 *Classification of collisions*

Estimating the collision probability in multihop wireless networks is a tricky part. In multihop networks, as described in [5], following the geometric relationship of the stations, the collisions can be divided into four categories: collisions due to coordinated stations (senders in a cell draw the same backoff and access to the medium at the same time), collisions due to information asymmetry (corresponding to the asymmetrical hidden nodes scenario), collisions due to near hidden terminals and collisions due to far hidden terminals (corresponding to the symmetrical hidden nodes scenario). Several works on available bandwidth estimation, like in IAB [8] for instance, consider only the collision probability due to coordinated stations in a cell. But in [5], the authors show that the collision probability of this first category is negligible. In ABE [7], the collision probability is derived from on-line experiments on Hello packets to compute the collision probability of Hello packets and from off-line computations to derive the collision probability of data packets of a given size. One weakness of this technique is that it assumes that Hello packets are periodically sent and thus periodically received, which can not be true with a CSMA/CA access. In [5], the computations on the collision probabilities of the different categories require to gather neighbourhood information and to handle cliques operations. These tasks are complicated to integrate into an available bandwidth estimation solution that must provide accurate results in almost real-time. To simplify the computation of the collision probability, we consider unconditional probabilities. The results provided in Section 4 show that this assumption is acceptable.

In our method, we consider two types of collisions on a wireless link:

- Collisions between packets sent by two hidden emitters (EE): An example of this type of collision is given in Fig. 4. The two emitters A and C are hidden from each other. The receiver B is in the interference range of the sender C. In this case, the packets sent by A and the packets sent by C collide at B.
- Collisions between a packet sent by an emitter and a packet sent by a hidden receiver (ER): An example of this type of collisions is given in Fig. 5. The emitter A and the receiver D are hidden from each other. The receiver B is in the interference range of the other receiver D. In this case, the packets sent by A collide with the packets sent by D at B. Note that, in this case, as D is a receiver on the link (C,D), then D can only send control packets like acknowledgements or CTS for instance.

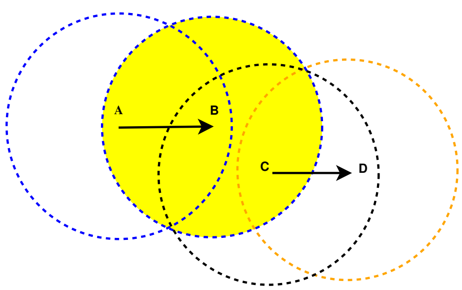

Figure 4: Collisions between packets sent by two hidden emitters (EE)

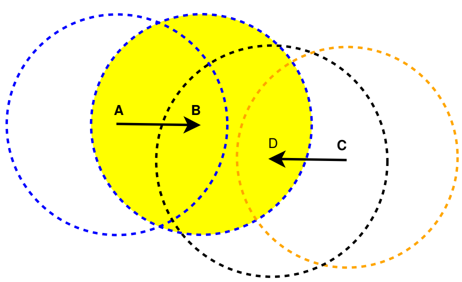

Figure 5: Collisions between packets sent by an emitter and packets sent by a hidden receiver (ER)

If the RTS/CTS mechanism is disable, then the collision type EE corresponds to collisions between data packets, while the collision type ER corresponds to collisions between data packets and acknowledgement packets. Hereafter, we consider that the RTS/CTS mechanism is disable. But the analysis can be easily modified to integrate this mechanism.

3.2.2 *Unconditional collision probability estimation*

First, we estimate the collision probability between data packets sent by hidden emitters (EE). For simplicity, we assume that, on the hidden node, packets generation follows a Poisson process with the following parameters:

- the rate of the packets generation is λ^{DATA} (expressed in packets per time unit),
- the packet duration is T^{DATA} (time units per packet),
- $\lambda^{DATA} * T^{DATA} < 1$.

At the receiver r, we have the following probabilities due to the emissions of the hidden node:

- The probability that r is busy due to packets reception is $\rho_h = \lambda^{DATA} * T^{DATA}$
- The probability that there is no packet arrival at r during the time interval T (time units) is:

$$P[N(t+T) - N(t) = 0] = \frac{e^{-\lambda^{DATA}*T}(\lambda^{DATA} * T)^0}{0!} = e^{-\lambda^{DATA}*T}$$

  where $N(t+T)-N(t)$ is the number of packets arrivals during the time interval $(t, t+T]$.

We assume that, at the node s, the emitter on the link (s, r):

- the inter-arrival times of generated packets are exponentially distributed with the rate λ_s (packets per time unit),
- the packet duration is T_s (time units per packet),
- $\lambda_s * T_s < 1$.

Then, the probability that the link (s, r) is busy due to packets transmission of node s is $\rho_s = \lambda_s * T_s$ and the probability that there is no packet arrival from node s on the link (s, r) during T (time units) is $e^{-\lambda_s * T}$.

There is a collision (of type EE) on the link (s, r) at the receiver r if:

- during the transmission of the node s on the link (s, r) with a packet duration T_s, there is another emission of a node hidden to s. The probability for this to happen is:

$$p_s^{EE} = \rho_s * (1 - e^{-\lambda^{DATA} * T_s}) \quad (2)$$

- during the emission of a node hidden to s with a packet duration T_{DATA} by reception, there is a transmission from node s. The probability for this to happen is:

$$p_h^{EE} = \rho_h * (1 - e^{-\lambda_s * T^{DATA}}) \quad (3)$$

Therefore, the unconditional collision probability of type EE occurring at the receiver r of the wireless link (s, r) is estimated as:

$$p^{EE} = 1 - (1 - p_s^{EE}) * (1 - p_h^{EE}) \quad (4)$$

Secondly, we estimate the collision probability between a packet sent by an emitter and a control packet sent by a hidden receiver (of type ER). We assume that acknowledgement packets arrivals follow a Poisson process of intensity λ^{ACK}. Since the size of acknowledgements is small, we assume that the probability that there is a packet transmission from the emitter s during the transmission of an acknowledgement from a hidden node is negligible. We only consider the probability that there is an acknowledgement emission by a hidden node during a packet transmission of s. This probability, p^{ER} is estimated as:

$$p^{ER} = p_s^{ER} = \rho_s * (1 - e^{-\lambda^{ACK} * T_s}) \quad (5)$$

Finally, the unconditional collision probability on the receiver r is:

$$p = 1 - (1 - p^{EE}) * (1 - p^{ER}) \quad (6)$$

3.3 Estimation of the average number of retransmission attempts

In this section, we estimate the average number of retransmission attempts given the collision probability computed previously. Note that the probability of failure of the first retransmission attempt is the unconditional collision probability. Then, the probability of failure for the other retransmission attempts is conditional and can be estimated in the following way. Given the unconditional collision probability p on the receiver r and the maximal number of packet retransmission attempts M, the probability of k retransmission attempts of a packet at the sender s is calculated as in [7, 8]:

$$P(X = k) = \begin{cases} p^k(1-p), & 0 < k < M \\ p^M, & k = M \\ 0, & k > M \end{cases} \quad (7)$$

The average number of retransmission attempts (including the transmission itself) can be written as:

$$\begin{aligned} \overline{n} &= 1 + \sum_{k=1}^{M-1} kP(X=k) + Mp^M \\ &= 1 + p(1-p) + 2p^2(1-p) + ... + (M-1)p^{M-1}(1-p) \\ &\quad + Mp^M \\ &= 1 + p - p^2 + 2p^2 + ... + (M-1)p^{M-1} - \\ &\quad (M-1)p^M + Mp^M \\ &= 1 + p + p^2 + ... + p^{M-1} + p^M \end{aligned}$$

$$\overline{n} = \frac{1 - p^{M+1}}{1 - p} \quad (8)$$

The evolution of the average number of packet retransmission attempts according to the collision probability is shown in Fig. 6. In 802.11 DCF, there are two retransmission limits: Short Retry limit (7 retransmissions) that is used for packets of short size and Long Retry Limit (4 retransmissions) that is used for packets of long size [6]. From Fig. 6, we see that the retransmissions fail if the collision probability at the receiving side is more than 0.965 for Short Retry Limit and more than 0.89 for Long Retry Limit.

The retransmission mechanism impacts the available bandwidth of a link, since it increases the time needed to transmit a packet at the sender side and packets are lost due to the collision and when the retransmission attempt limit is reached. In the next two-subsections, we estimate this impact.

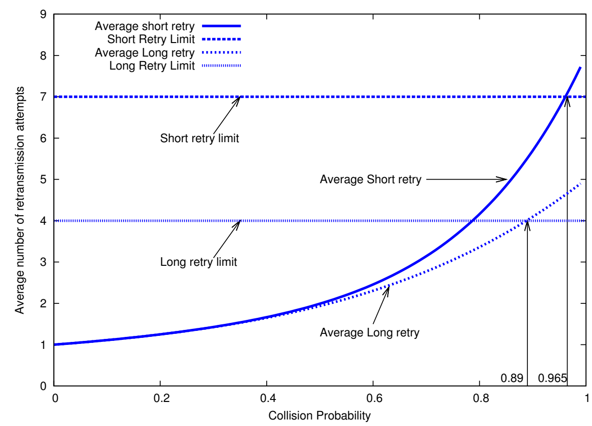

Figure 6: Evolution of the average number of packet retransmission attempts

3.4 Taking into account the extra time to send a packet

In this section, we estimate the waste of the bandwidth due to the additional time induced by retransmissions. Retransmission and backoff mechanism can be seen as a way for the sender to adapt its transmission rate to the reception rate of the receiver. This rate adaptation can be considered as a kind of synchronization.

- At the sender s, due to the retransmissions and the backoff mechanism, the total duration to send a packet is:

$$\overline{n} * (DIFS + T) + \overline{backoff} \quad (9)$$

where T includes, in addition to the time required to transmit a packet, a SIFS plus the time required to send the acknowledgement. $\overline{backoff}$ is the average backoff time estimated as follows (see [7, 8]):

$$\overline{backoff} = \frac{1 - p - 2^N p^{N+1}}{2 - 4p} CW_{min} - \frac{1}{2} \quad (10)$$

Therefore, the available bandwidth of the sender is decreased by a factor $\tau_s = \frac{DIFS + backoff + T}{\overline{n} * (DIFS + T) + \overline{backoff}}$ where $backoff$ is the average backoff time when the minimal contention window size is used.

The available bandwidth at the sender s is then estimated as:

$$AB^s_{RABE} = \tau_s * C_s \quad (11)$$

- At the receiver r, a packet is received with success at the MAC layer if the receiver is idle. The available bandwidth at the receiver r is then estimated as

$$AB^r_{RABE} = C_r \quad (12)$$

3.5 Estimation of the packet loss ratio

Packets are dropped when the retransmission attempt limit is reached. As RABE is based on the average number of retransmission attempts, we need to estimate the packet loss ratio according to this average number of retransmission attempts.

Given the retransmission attempts limit M and the average number of retransmission attempts $\overline{n}$, the maximal number of retransmissions is $(M-1)$ and the average number of retransmission failures is $(\overline{n}-1)$ (obviously, we do not take into account the successful transmission). The packet loss ratio is then estimated as $\frac{\overline{n}-1}{M-1}$. Therefore, the available bandwidth of the link must be scaled with the following factor:

$$K = \begin{cases} 1 - \frac{(\overline{n}-1)}{(M-1)} = \frac{M-\overline{n}}{M-1}, & \overline{n} \leq M \\ 0, & \overline{n} > M \end{cases} \quad (13)$$

In Eq. 13, when $\overline{n} > M$, we consider that the wireless link is saturated since all the packets sent from the sender to the receiver are dropped due to the retransmission limit that is reached.

3.6 Estimation of the available bandwidth of a wireless link

Finally, given the available bandwidth AB^s_{RABE} at the sender s and the available bandwidth AB^r_{RABE} at the receiver r, we consider that the available bandwidth on the wireless link (s, r) is:

$$AB_{RABE} = K * min\{AB^s_{RABE}, AB^r_{RABE}\} \quad (14)$$

Denoting $K_s = K * \tau_s$ and $K_r = K$, the available bandwidth of a wireless link can be rewritten as

$$AB_{RABE} = min\{K_s * C_s, K_r * C_r\} \quad (15)$$

4. SIMULATIONS

In this section, we use the simulator NS2 to evaluate the performance of RABE. We randomly generate topologies in an area of 1000m x 1000m. We present the results obtained on two topologies. The first topology, denoted 50/80/CBR topology, consists of 50 nodes and 80 one-hop point-to-point flows generated according to a CBR/UDP traffic model. The second one, denoted 100/135/Poisson topology, consists of 100 nodes and 135 one-hop point-to-point Poisson flows (the packets of each flow are generated according to a Poisson process). Note that the network may be disconnected, which is not a drawback for our study. An example of a generated network is shown in Fig. 7. The nodes are configured with the same parameters as the ones given in Table 1. Moreover, we configure the flows with the same mean transmission rate (denoted as x).

We now drop two nodes at the center of the topology: the sender s is located with the coordinates $(300m, 500m)$ and the receiver r is located with the coordinates $(450m, 500m)$. Since the communication range is $200m$, the two nodes s and r can communicate directly. Moreover, we keep the network configurations so that some flows are in the sensing range of the sender (and/or the receiver) and some others are not. This means that s and r have common and hidden nodes, which implies common and independent busy periods.

Our aim here is to evaluate the available bandwidth on the link (s, r) according to the load variation in the network. To this end, we simply vary the value of x in order to change the background traffic. For each simulation, we also measure the real collision probability and the real available bandwidth of the link (s, r).

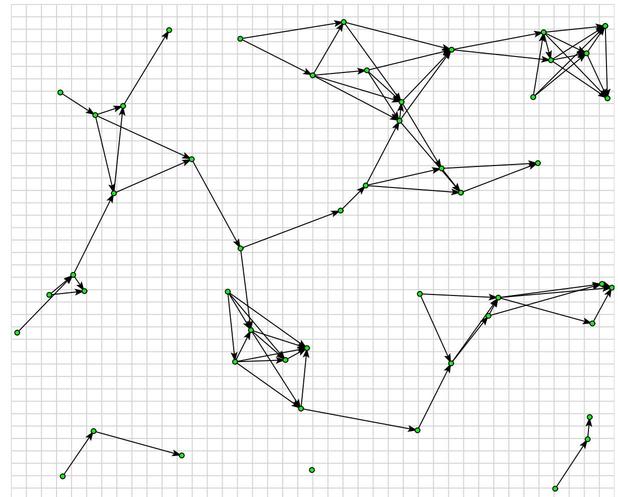

Figure 7: A 50/80/CBR topology

4.1 Estimating the available bandwidth with RABE

In this section, we describe how RABE is implemented in the simulator. Each node records, on a measurement interval, the following parameters: the number of data packets sent and received, the number of acknowledgements sent and received, the number of collisions that are perceived and the transmission times of data packets and acknowledgements. Based on these parameters, each node calculates its available bandwidth as defined in Eq. 1.

To implement RABE, we need to know the number of data packets and acknowledgements arrivals at the receiving side of the link (λ^{DATA} and λ^{ACK}). However, some packets may collide and then can not be decoded by the receiver. As the node can not decide if the collided packet is a data packet or an acknowledgement, then we apply the following approximation: the number of collisions on data packets (acknowledgements respectively) is derived as the total number of collisions multiplied by the percentage of received and decoded data packets (acknowledgements respectively). With this approximation, we consider that the ratio between data packets and acknowledgements is the same on decoded packets as on collisions. At the end, λ^{DATA} (λ^{ACK} respectively) is computed as the number of data packets (acknowledgements respectively) received and decoded plus the estimated number of collided data packets (acknowledgements respectively).

To estimate the collision probability if a flow was emitted on the link (s, r), we also need to estimate the number of generated data packets at the sending side s (λ_s). By assuming that the packet size of the flow to be emitted is known (and denoted T_s), then we apply the following estimation:

$$\lambda_s = \frac{C_s}{T_s} \quad (16)$$

where C_s is the available bandwidth per node computed by the sender s. The parameters λ_s and T_s must be sent to the receiver r.

4.2 Measuring the real available bandwidth

To measure, by simulation, the real collision probability and the real available bandwidth on the link (s, r), a flow $f_{(s,r)}$ is transmitted on the link (s, r). For each value of x, the rate of this flow is increased step by step. If one of the other flows existing in the network sees its rate decreased by more than 5%, then the rate increase of flow $f_{(s,r)}$ is stopped. The achieved rate by $f_{(s,r)}$ is considered as the available bandwidth on the link (s, r).

We also record the number of collisions perceived ($n_{collision}$) and the number of packets received ($n_{received}$) at the receiver r to compute the real collision probability as follows:

$$p_{real} = \frac{n_{collision}}{n_{received} + n_{collision}} \quad (17)$$

Note that the collision probability p estimated by Equation 6 may differ from p_{real} since p does not take into account collisions due to coordinated nodes, in the same communication area, that access to the medium at the same time.

4.3 Simulation results

For each value of x, simulations are repeated ten times on the same topology. For each simulation, the available bandwidth on the link (s, r) is computed after each measurement interval and the final available bandwidth on this link is the average of the values obtained on the measurement intervals. The plotted values are the average on the different simulations performed for a value of x. The obtained average values are also associated with a confidence interval of 95%.

Firstly, we compare the collision probability estimated by RABE and the real collision probability according to the flows mean rate. This comparison is given on Figs. 8 and 9. On the 100/135/Poisson topology, the difference between the two collision probabilities is small whatever the flows mean rate. On the 50/80/CBR topology, this difference is a bit higher even though acceptable. This can be explained by the assumption on the packets generation following a Poisson process. In this case, the collision probability estimated by RABE is lower than the real collision probability.

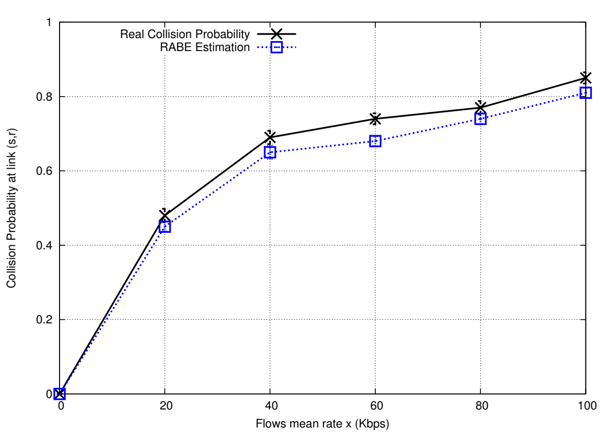

Figure 8: Comparison of the collision probability estimated by RABE with the real collision probability on a 50/80/CBR topology

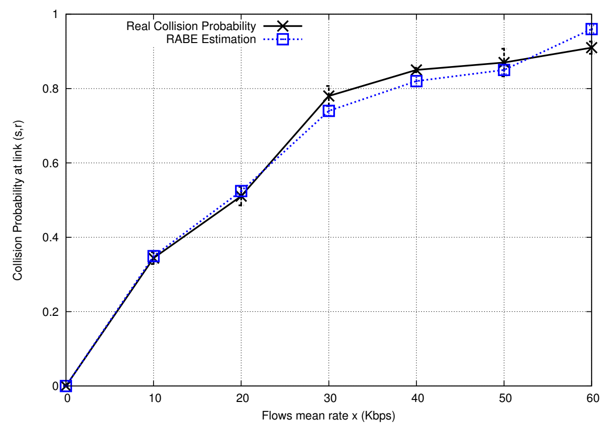

Figure 9: Comparison of the collision Probability estimated by RABE with the real collision probability on a 100/135/Poisson topology

Secondly, we compare RABE with the real available bandwidth, as with other available bandwidth estimations, namely ABE and IAB. The measurement interval is the same for the three solutions and equal to 1s. Figs. 10 and 11 show the obtained results on the two tested topologies according to the flows mean rate. We see that, in both scenarios, IAB is not accurate since the provided estimation is always very far from the real value as soon as x is higher than 20 kb/s. This can be easily explained by the fact that only collisions due to coordinated stations are taken into account and the estimation is almost insensitive to collision.

We see also that ABE under-estimates the available bandwidth. This can be explained by the assumption on the uniform and independent medium occupancy distribution and by the fact that the available bandwidth is scaled in the ABE estimation even if there is no collision.

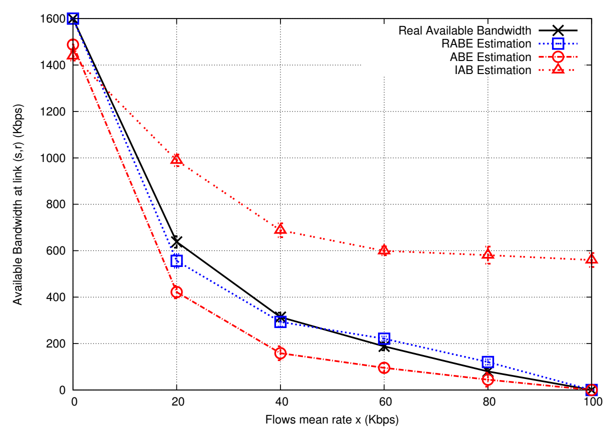

Figure 10: Available bandwidth estimation with RABE, ABE and IAB on a 50/80/CBR topology. Comparison with the real available bandwidth

From these results, we can see that RABE provides the most accurate estimation among the three tested solutions, and this whatever the scenario and the flows mean rate. The accuracy of the solutions are given in Figs. 12 and 13. In the 50/80/CBR topology, the mean estimation error of RABE is 17.49%, the one of ABE is 36.7% and the one of IAB is 205,8%. Based on the mean error ratio we can con-

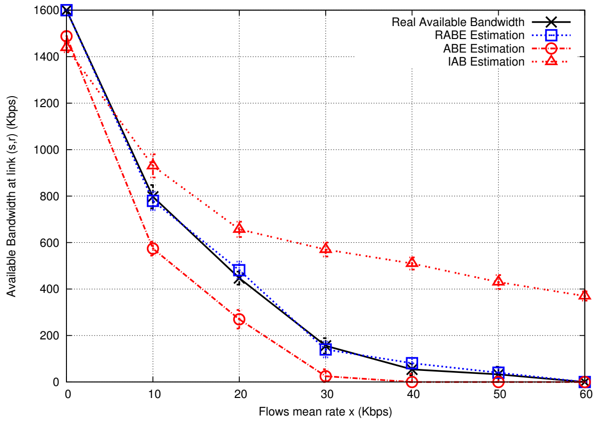

Figure 11: Available bandwidth estimation with RABE, ABE and IAB on a 100/135/Poisson topology. Comparison with the real available bandwidth

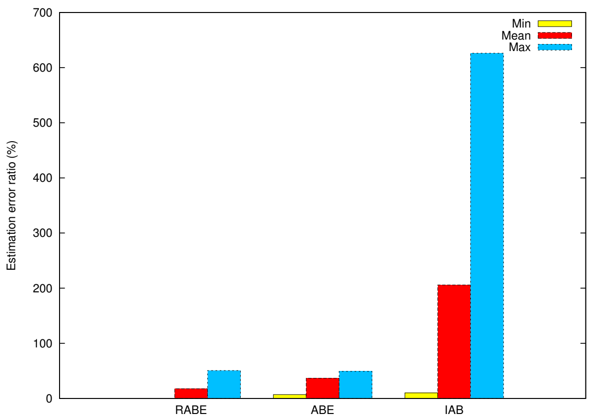

Figure 12: Estimation error (in percentage) for ABE, IAB and RABE on the 50/80/CBR topology

clude that RABE is two times more accurate than ABE and ten times more accurate than IAB. In the 100/135/Poisson topology, the mean estimation error of RABE is 15.79%, while it corresponds to 59.76% and 397% for ABE and IAB respectively. In other words, RABE is four times more accurate than ABE and twenty six times more accurate than IAB. In some simulations, the estimation error can achieve 1200% for IAB.

5. CONCLUSION

In this paper, we propose RABE, a novel available bandwidth estimation method in IEEE 802.11-based multihop wireless networks. As opposed to previous solutions, this method takes into account the retransmission mechanism of 802.11 DCF that impacts the available bandwidth. RABE is based on the available bandwidth per node, the collision probability on the link to evaluate and the mean number of retransmission attempts. From this mean number, RABE estimates the additional time needed to retransmit a packet that collides and the packet loss ratio due to the retransmission limit.

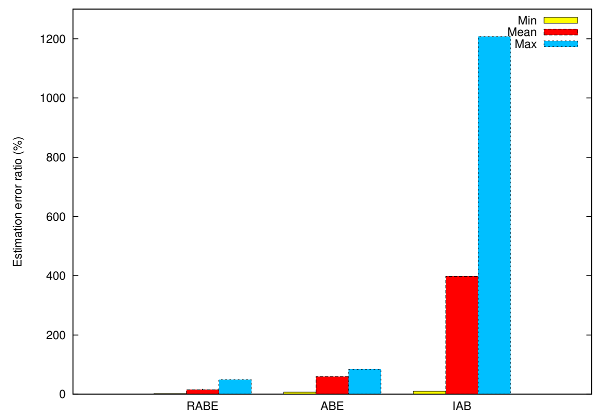

Figure 13: Estimation error (in percentage) for ABE, IAB and RABE on the 100/135/Poisson topology

Our evaluation, carried out by simulation, shows that RABE is more accurate than the other solutions, namely ABE and IAB, in different topologies and under different traffic models and loads. We think that RABE is a clear improvement compared to previous solutions.

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