Performance Evaluation of Backoff algorithms in 802.11 Ad-Hoc Networks

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ABSTRACT

Understanding the performance of backoff algorithms in multi-hop ad hoc networks is a key feature to design efficient Medium Access Protocols for wireless networks. The 802.11 backoff algortihm, the Binary Exponential Backoff, and all the enhancement done to this algorithm are studied in depth in a single hop context. Very few analytical studies are done on 802.11 backoff algorithms in a multi-hop context due to the difficulty of modelling. In this paper we propose an analytical study, based on process algebra, of 4 backoff algorithms on 2 multi-hop scenarios. We evaluate the performance of each backoff algorithms from efficiency point of view and when possible from a fairness point of view.

1. INTRODUCTION

The 802.11 protocols stack [1] is the most widespread technology for wireless LAN and for wireless ad hoc networks. Recent studies show some performance and fairness issues when using 802.11 especially in a multi-hop ad hoc context. Many modifications of 802.11 have been proposed to improve both performance and fairness in wireless ad hoc networks. In lots of papers we can see that the fairness and efficiency issues of 802.11 come from its MAC layer. Enhancements have, thus, been proposed to lack these performance and fairness issues, and the literature shows that the binary exponential backoff algorithms of 802.11 is one of problem's origin.

In the last years, simulations and experimental studies show their limitations when studying 802.11. On the other hand, some performance evaluation tools exhibit interresting properties that can allow theoritical studies of 802.11 MAC layer. The use of these tools have been suggested because of the inherent complexity of multi-hop ad hoc networks.

Some recent works try to analytically evaluate the performance of the 802.11 backoff algorithms in a multi-hop ad hoc networks. All these approach show their limitation in both performance metrics and reusability. In this paper we propose to evaluate the performance of four backoff algorithms, based on Performance Evaluation Process Algebra (PEPA), in two mutli-hop scenario. We derive from our analysis some performance metrics and some fairness metrics.

The rest of this paper is organised as follow : In the related work, section 2, we review the literature about some performance evaluations of backoff algorithm in multihop context. In section 3 we remind some background knowledge about Performance Evaluation Process Algebra (PEPA) and 802.11. The section 4 is devoted to the description of the backoff algorithm and the scenarion we study in this paper. Our model are described in section 5. The performance evaluation results are given in section 6. The section 7 is for conclusion and future works.

2. RELATED WORKS

In this section we present an overview of past works about performance evaluation of 802.11 based mutlihop Ah Hoc networks. We will not discuss about Bianchi's markov chain analysis of the Binary Exponential Backoff [3], because the Bianchi analysis is designed for single hop network. Most of the new proposed backoff algorithm study are base on this markov chain. This approach provide an accurate analysis of backoff algorithms, but is hard, not to say impossible, to extend to multihop context.

Li et al, in [9], provide a qualitative analysis of the hidden terminal problem in a 802.11 wireless networks based on markov chain. By qualitative we mean that the authors provide only qualitative metrics, such as fairness, from their analysis. As far as we know this is the first work that deal with multi-hop context. The proposed analysis is not extensible to other multi-hop scenario, because some abstractions are done on the model, on the node interactions, that make the model possible, but make the extension impossible. The proposed analysis only focuses on the Binary Exponential backoff algorithms. This work have been extended in [11] where the authors propose an analysis of the same scenario using process algebra. In this paper some qualitative and quantitative performance evaluation metrics are proposed. Two backoff algorithms are study in this paper. This approach exhibits some interesting properties that make the study of different backoff algorithms easier.

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The work proposed in [11] is a generalisation of the work proposed in [8]. The work in [8] uses process algebra, but the model is divided in only 2 components and the backoff model is included in one of this component. This approach make the study of different backoff algorithms difficult. In this paper, the authors propose the study of three multihop ad hoc networks, especially the 3 pairs scenario. The 3 pairs scenario have been first studied in [5]. The analysis proposed in [5] is based on markov chain, and is very restrictive in such a way that it is very hard to extend to other scenario. The study [8] and [5] give some accurate results on the 3 pairs scenario. In this paper we propose some more results on this scenario such as short time fairness results and EIFS/DIFS use.

A recent work [6] propose the analysis of two multihop scenario, especially the Asymetric Hidden Terminal scenario that was first highlighted in [2]. This scenario is another kind of hidden terminal scenario. The proposed analysis is based on renewal and reward process and allow to derive some quantititive metrics such as throughput. The main problem of this analysis is its extensibility to study different backoff algorithms. In this paper we propose the analysis of the MACAW scenario from a qualitative and a quantitative point of view, and we consider four backoff algorithms in our study.

The literature shows some interesting works about the analysis of multihop ad hoc scenario. The main problem that arise from this state of the art is that the proposed analysis are not flexible enough to allow the study of many backoff algorithms, and to study some different ad hoc scenario except the work proposed in [11]. In this paper we proposed the analysis of the 3 pairs scenario and the Asymetric Hidden Terminal scenario using the same tool and the same model as proposed in [11]. We also extend our analysis to 4 backoff algorithms.

3. BACKGROUND

3.1 802.11 DCF

In this section we introduce a short description of the IEEE 802.11 DCF mode. The 802.11 distributed coordination function (DCF) is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Before emitting a frame on the wireless medium, the nodes sense the channel to determine whether it is free or not. The medium has to be free, during a constant period time called DIFS or EIFS in some conditions see [1]. IEEE 802.11 standard specifies that when a frame is received with an incorrect MAC checksum (FCS) value, this can be due to the distance between nodes, the DIFS waiting time is increased to a value of EIFS, which is more than 7 times DIFS delay in 802.11b. In addition to DIFS (or DIFS), nodes have to wait a random time called backoff (an integer number of a constant duration ($20\mu s$)) during which the medium shall stay free to avoid collision between multiple emitters. At the end of this time (DIFS + Backoff) the frame is transmitted. If during this time the medium becomes busy, the frame transmission is deferred until the medium becomes free again.

The particularity of 802.11 backoff process is that the backoff is decremented slot by slot. If the medium becomes busy during this process, the decrementation process is stopped and will be resumed as soon as the medium becomes free again with the remaining number of slots. When the backoff value reaches 0 the frame is emitted. For each new frame, a new random slot number is drawn.

When an emitters gains access to the medium, the whole frame is transmitted. Collision can occur, when two emitters draw the same backoff. Due to radio medium property, collision detection is impossible at transmission. Nodes can only be aware of the correct reception/transmission of a frame by the reception of the corresponding acknowledgement.

The integer number of backoff time slots is uniformly drawn in an defined interval called contention window. The algorithm used by 802.11 to make this contention window evolving is called Binary Exponential Backoff (BEB). After each successful transmission, the contention window is set to $[0, CW_{min} - 1]$ (its initial value). When i successive collisions occur, the contention window is set to $[0; min(1024, 2^i * CW_{min} - 1)]$. If $i > 7$, the contention window is set to its initial value. It is the retry limit of the BEB algorithm.

3.2 Performance Evaluation Process Algebra

3.2.1 The formalism syntax

A system is viewed as a set of *components* which carry out *activities*. Each activity (α, r) is characterized by an *action type* α and an *activity rate* r which is exponentially distributed. Because of the exponential distribution of the activity duration, the underlying Markov process of a PEPA model is a continuous time Markov chain [7]. PEPA formalism provides a set of combinators which allows expressions to be built, defining the behavior of components. Below, we introduce only the combinators which are necessary to our model. For more details about the formalism, see [7].

Constant: $S \stackrel{\text{def}}{=} P$ It allows to assign names and behavior to components. To component S, the behavior of component P is assigned.

Prefix: $S \stackrel{\text{def}}{=} (\alpha, r).P$ After S has carried out the activity (α, r), it will behave as component P. In the case of cooperation or shared activities, the activity rate of this action is outside the control of this component and is determined by another component. Such actions are carried out jointly with another component. The activity rate is denoted $\top$.

Choice: $P_1 + P_2$ It models competition between components. The system may behave either as component P_1 or as P_2. All current activities of the components are enabled. The first activity to complete distinguishes one of these components, the other is discarded.

Cooperation: $P \underset{L}{\bowtie} Q$ It allows the synchronization of components P_1 and P_2 over the activities in the cooperation set L. Components may proceed independently with activities whose types do not belong to this set. In a cooperation, the rate of a shared activity is defined as the rate of the slowest component. The rate of an activity may be unspecified for a component ($\top$): the rate of this shared activity is defined by the other component in cooperation.

3.2.2 The Markov Process

In a PEPA model, when a component P carries out an activity (α, r) and subsequently behaves as component P', P' is said to be a *derivative* of P. From any PEPA component P, the derivative set $(ds(P))$, is the set of derivatives (behaviors) which can evolve from the component. This set is defined recursively. From the derivative set, we can construct the *derivation graph*. The derivation graph is a directed multi-graph whose set of nodes is $ds(P)$ and whose arcs represent the possible transitions between them. The underlying Markov process of a PEPA model is a continuous time Markov process. The generation of this process is based on the derivation graph of the model. A state is associated with each graph node and the transitions between states are derived from the arcs of the graph.

3.2.3 Solving the Markov chain

PEPA is supported by many experimental tool such as PEPA Workbench and PRISM [10]. From a description of a PEPA model, PRISM provides the stationary behavior (probability distribution) of the modeled system. In this paper we use the PRISM tool.

4. BACKOFF AND SCENARIO

4.1 The backoff algorithms

In this section we present the 4 backoff algorithms we study. These backoff model are presented in figures 1, 2, 3, and 4. In these figures, the number in each circle is the backoff stage. A short description of each backoff algorithm are described below.

1) Binary Exponential Backoff (figure 1): BEB is the classical backoff algorithms of 802.11. As we can see from the figure, we use a retry limite equal to 7. Each stage correspont to the contention window size expressed as $[0; 2^i \times CW_{min}]$ where i, is the backoff stage and $i \in [0, \ldots, 5]$. For $i \geq 6$, the contention window is $[0; CW_{max}]$

2) Binary Exponential Backoff inverted (figure 2): BEB inverted is like the classical 802.11 backoff algorithm but the contention window is reduce upon a collision and increased upon a successful transmission. The contention window size is computed as with BEB. As oppossed to BEB, the initial contention window of BEB inverted is set to the maximum.

3) Double Increase Double Decrease (figure 1): The DIDD algorithm, presented in [4], is the easier way to modify the aggresive behaviour of BEB upon a successful transmission. We can notice that, the backooff state can stay on the two exteme states. The contention window size is computed as with BEB.

4) Multiplicative Increase Linear Decrease (figure 1): The MILD algorithms has been first proposed in [2]. This algorithm propose a king of slow decrease algorithm to better adapt the contention window size to the networl load. With this algorithms, the contention window at each backoff stage is computed as follow: $[0; (i+1) \times CW_{min}]$ for $i \in [0, \ldots, 31]$.

4.2 The scenarios

In this section we present the two studied scenario.

1) The 3 pairs scenario is depicted in figure 5. In this figure the two external pairs are independent each from the other. The central pair can be in communication range (using DIFS) or in carrier sensing rage (using EIFS) from the external pairs. In this scenario, the central pair can access the medium if the silent period of the two external pairs overlap at least for the entire decrementation of the $DIFS$ or $EIFS$ plus the $backoff$. In this context the central pair can “never“ access the medium. In this scenario, we made the assumption that a collision can never occur, this is in fact due to the distance between the emitter and its associate receiver that is close enough. In this case when the central pair and one (or two) of the external pair access the medium the signal to noise ratio is high enough to allow all the packets to be decoded correctly.

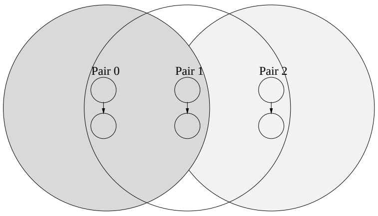

Figure 5: 3 pairs scenario

2) The Asymetric Hidden Terminal is depicted in figure 6. In this scenario, the transmissions of the $Pair1$ have to fit in the silence period of the $Pair0$ to succeed. Depending on the packet size send on $Pair1$ this can never happen, leading to a high collision rate. In our study we do not show the RTS/CTS access method because it correspond to small packet transmissions.

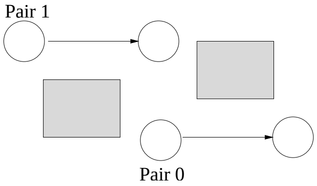

Figure 6: 3 pairs scenario

5. EVALUATION METHODOLOGY

In this section we present the method we used to evaluate the backoff algorithm we wanted to study. This method is based on process algebra that is used to build markov chain. We use, the PEPA tool (Performance Evaluation Process Algebra) as a front end for the process algebra formalism. We also give some performance metrics to evaluate the performance of each backoff algorithm. We use as an efficiency metrics the probability of successful occupation of the medium that can be easily correlated to the aggregated throughput of the network. As a fairness metrics, we use a probability that indicates the monopolisation of the medium by a node. Some details about these metrics are given in this section.

5.1 The PEPA model

Our model is divided in three components that represent. one for the CSMA protocol used in 802.11; The second for

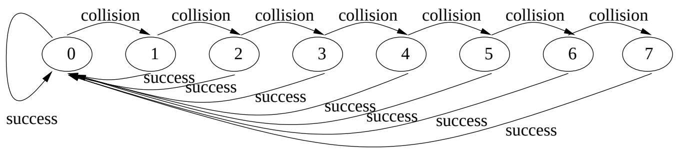

Figure 1: BEB

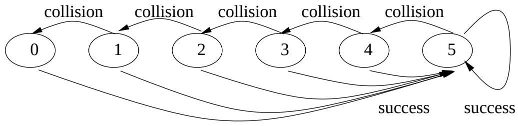

Figure 2: BEB inverted

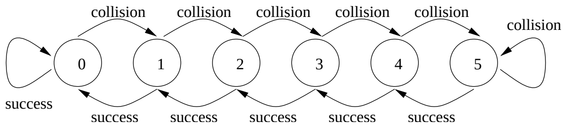

Figure 3: DIDD

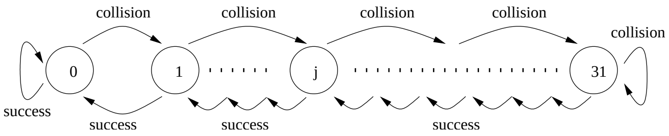

Figure 4: MILD

backoff algorithms; And the third for the interaction between nodes. By dividing our model in such a way we make our model more flexible and reusable.

5.1.1 The nodes

The node model represents the CSMA protocol that is used in 802.11. The key point of this model is to determine and model the right interactions while using CSMA. In other word in this component we model how the node may interact with its neighborhood. If we suppose that two emitters interact each with the other, the node model may include a mutual exclusion system that allow the modelling of a semaphore on the shared ressources. The component described below shows this kind of interactionis.

$$
\begin{array}{lcl}
E\_i\_000 & \overset{def}{=} & (free\_i, \mu\_trans).E\_i\_001; \\
E\_i\_001 & \overset{def}{=} & (difs, \mu\_difs).E\_i\_002; \\
E\_i\_002 & \overset{def}{=} & (free\_i, \mu\_trans).E\_i\_003 + (occ, \mu\_slot).E\_i\_007; \\
E\_i\_003 & \overset{def}{=} & (db\_i, \top).E\_i\_004; \\
E\_i\_004 & \overset{def}{=} & (free\_i, \mu\_trans).E\_i\_005 + (occ, \mu\_slot).E\_i\_007; \\
E\_i\_005 & \overset{def}{=} & (transmit, \mu\_trans).E\_i\_006; \\
E\_i\_006 & \overset{def}{=} & (ack\_i, \top).E\_i\_000; \\
E\_i\_007 & \overset{def}{=} & (free, \mu\_trans).E\_i\_001; \\
E\_i\_008 & \overset{def}{=} & (eifs, \mu\_difs).E\_i\_002;
\end{array}
$$

The action $free$ is a action with a negligible rate that represent the medium state. If the medium is free, the node can leave the state E_i_000 and begin its sending phase. Here we mean by sending phase the time of the *IFS time and the backoff algorithm. Another action *occ* with the mean slot time as a rate is used to represent the acquisition of the channel by another node. Each transmitter of the 3 pairs scenario is modelled with this component.

When the two emitters are fully independent, no mutual exclusion system is used. This kind of interaction is represented below and model the asymmetric hidden terminal scenario's emitter.

$$
\begin{array}{lcl}
E\_i\_000 & \overset{def}{=} & (difs, \mu\_difs).E\_i\_001; \\
E\_i\_001 & \overset{def}{=} & (db\_i, \top).E\_i\_002; \\
E\_i\_002 & \overset{def}{=} & (transmit\_i, \mu\_trans).E\_i\_003; \\
E\_i\_003 & \overset{def}{=} & (ack\_i, \top).E\_i\_004 + (collision, \top).E\_i\_005; \\
E\_i\_004 & \overset{def}{=} & (succ\_i, \mu\_trans).E\_i\_000; \\
E\_i\_005 & \overset{def}{=} & (coll\_i, \mu\_trans).E\_i\_000;
\end{array}
$$

In the two components i is the pair transmitters/receiver number. The action $difs$ and $eifs$ are used to model the usage of EIFS or DIFS in 802.11. *db* is a synchonisation action used to draw the backoff. $transmist$, *ack*, and *collision* represent the different state of the node. The *coll_i* and *succ_i* actions are use to make the backoff algorithm evolve depending on the state of the preceeding transmission. For any other information and detail on each action please refer to the paper [11].

5.1.2 The backoff algorithm

In this section, we present, as an example, the Binary Exponential Backoff (BEB) algorithm used in 802.11. The main principles of BEB are the following: upon a collision the current contention window is double and upon a successful transmission, the contention window is set to its initial value (see Fig. 1). The component *BO_i_x* is associated to the node i, and models the BEB algorithm used in 802.11. 8 transmission attempts are allowed. The rate of the activity *db_i*, called *f_j* - $j \in \{0, 5\}$, depends on the number of consecutive collisions the current transmission has undergone. Because of the memory-less property of the exponential distribution, the mean of *f_j* is the mean duration time of the contention window with j collisions. It means that *f_1* is the mean duration time of the backoff before the first transmission. *f_1* is associated to the initial contention window $[0..2^5]$. Finally, *f_1* is equal to $20\mu s \times (2^5 - 1)/2$. More generally, $\forall i \in \{0..5\}$, *f_i* is the mean duration time of the contention window $[0..2^{5+i}]$. The synchronisation action *coll_i* (resp. *succ_i*) is associated to the evolution of the backoff upon a collision (resp. successful transmission).

We can see that with our modelling methodology, it is easy to modify the backoff algorithm. The only constraint is to maintain the synchronisation actions *coll_i* and *succ_i*. With our approach, modelling nodes using different backoff algorithms is very easy because a particular algorithm can be associated with a particular *node*.

$$\begin{aligned}
BO\_i\_0 &\stackrel{def}{=} (db\_i, f\_0).BO\_i\_0 + (succ\_i, \top).BO\_i\_0 \\
&\quad +(coll\_i, \top).BO\_i\_1 \\
... &\stackrel{def}{=} ... \\
BO\_i\_j &\stackrel{def}{=} (db\_i, f\_1).BO\_i\_j + (succ\_i, \top).BO\_i\_0 \\
&\quad +(coll\_i, \top).BO\_i\_(j+1), \forall j \in [1..6] \\
... &\stackrel{def}{=} ... \\
BO\_i\_7 &\stackrel{def}{=} (db\_i, f\_5).BO\_i\_7 + (succ\_i, \top).BO\_i\_0 \\
&\quad +(coll\_i, \top).BO\_i\_0
\end{aligned}$$

5.1.3 *The medium*

All activities of this component are shared with the nodes. In this component we try to model the complete interaction between each node. This interaction are different from the interaction when the two nodes are in communication range of each other. The component given below represent the *medium* for the 3 pairs scenario. An important feature of this component is the division by four of the data transmission of the external pairs. This is due to the atomic behaviour of PEPA. In other word, when a action is taken, it is drawn till the end, and a concurrent action can not be drawn at the same time. This model the medium access from the external pairs. Even if the two external pairs have the exactly the same behaviour and the same interactions with central pair we have modelled the two pairs with two components. In the *medium* the synchronisation actions with suffix 0 and 2 are for external pairs.

$$\begin{aligned}
Med\_00\_00 &\stackrel{def}{=} (free\_0, infty).Med\_00\_00 \\
&\quad +(free\_1, infty).Med\_00\_00 \\
&\quad +(free\_2, infty).Med\_00\_00 \\
&\quad +(transmit\_0, infty).Med\_00\_02 \\
&\quad +(transmit\_1, infty).Med\_00\_01 \\
&\quad +(transmit\_2, infty).Med\_00\_09; \\
Med\_00\_01 &\stackrel{def}{=} (ack\_1, infty).Med\_00\_01; \\
Med\_00\_02 &\stackrel{def}{=} (frag, \mu\_data25).Med\_00\_03 \\
&\quad +(free\_2, \mu\_trans).Med\_00\_02; \\
Med\_00\_03 &\stackrel{def}{=} (frag, \mu\_data25).Med\_00\_04 \\
&\quad +(free\_2, \mu\_trans).Med\_00\_03 \\
&\quad +(transmit\_2, infty).Med\_00\_06; \\
Med\_00\_04 &\stackrel{def}{=} (frag, \mu\_data25).Med\_00\_05 \\
&\quad +(free\_2, \mu\_trans).Med\_00\_04 \\
&\quad +(transmit\_2, infty).Med\_00\_07; \\
Med\_00\_05 &\stackrel{def}{=} (ack\_0, \mu\_data25).Med\_00\_00 \\
&\quad +(free\_2, \mu\_trans).Med\_00\_05 \\
&\quad +(transmit\_2, infty).Med\_00\_08; \\
Med\_00\_06 &\stackrel{def}{=} (ack\_0, \mu\_data75).Med\_00\_11; \\
Med\_00\_07 &\stackrel{def}{=} (ack\_0, \mu\_data50).Med\_00\_10; \\
Med\_00\_08 &\stackrel{def}{=} (ack\_0, \mu\_data25).Med\_00\_09; \\
Med\_00\_09 &\stackrel{def}{=} (frag, \mu\_data25).Med\_00\_10 \\
&\quad +(free\_0, \mu\_trans).Med\_00\_09; \\
Med\_00\_10 &\stackrel{def}{=} (frag, \mu\_data25).Med\_00\_11 \\
&\quad +(free\_0, \mu\_trans).Med\_00\_10 \\
&\quad +(transmit\_0, infty).Med\_00\_13; \\
Med\_00\_11 &\stackrel{def}{=} (frag, \mu\_data25).Med\_00\_12 \\
&\quad +(free\_0, \mu\_trans).Med\_00\_11 \\
&\quad +(transmit\_0, infty).Med\_00\_14; \\
Med\_00\_12 &\stackrel{def}{=} (ack\_2, \mu\_data25).Med\_00\_00 \\
&\quad +(free\_0, \mu\_trans).Med\_00\_12 \\
&\quad +(transmit\_0, infty).Med\_00\_15; \\
Med\_00\_13 &\stackrel{def}{=} (ack\_2, \mu\_data75).Med\_00\_04; \\
Med\_00\_14 &\stackrel{def}{=} (ack\_2, \mu\_data50).Med\_00\_03; \\
Med\_00\_15 &\stackrel{def}{=} (ack\_2, \mu\_data25).Med\_00\_02;
\end{aligned}$$

Med_00_00 represents the initial state of the *medium*. The action $free$ is a synchronisation with node specifying that the medium is still free. After the action $free$ the medium goes back to Med_00_00. A node takes possession of the medium, with a $transmit$ action. If the central pair takes possession of the medium, the two external pairs can not access the medium (Med_00_01). On the other hand if the external pair access the medium, the other external pairs can also access the medium, this is represented by the choice of the three actions $frag$, $free$, and $transmit$ (for example in Med_00_04). During the transmission of one of the external pair, the central pair cannot access the medium, but the other external pair can access the medium. For example from Med_00_04, when $Pair2$ can get access to the medium when $Pair1$ is transmitting a packet. The remaining time transmission for $Pair1$ is first finished in Med_00_07, then the medium component behaves as Med_00_10. From Med_00_10, $Pair1$ can thus access the medium, and so on. The components from Med_00_02 to Med_00_08 is when $Pair1$ gets acces to the medium before $Pair2$. On the other hand, from Med_00_09 to Med_00_15 the medium is first access by $Pair2$.

$$\begin{aligned}
Med\_00\_00 &\stackrel{def}{=} +(transmit\_0, infty).Med\_00\_01; \\
&\quad +(transmit\_1, infty).Med\_00\_05; \\
Med\_00\_(i) &\stackrel{def}{=} (frag, \mu\_data25).Med\_00\_(i+1) \\
&\quad +(transmit\_1, infty).Med\_00\_(i+8); i \in [1 \ldots 3] \\
Med\_00\_04 &\stackrel{def}{=} (Ack\_0, \mu\_data25).Med\_00\_00 \\
&\quad +(transmit\_1, infty).Med\_00\_12; \\
Med\_00\_(i) &\stackrel{def}{=} (frag, \mu\_data25).Med\_00\_(i+1) \\
&\quad +(transmit\_0, infty).Med\_00\_(i+8); i \in [5 \ldots 7] \\
Med\_00\_08 &\stackrel{def}{=} (Ack\_1, \mu\_data25).Med\_00\_00 \\
&\quad +(transmit\_0, infty).Med\_00\_16; \\
Med\_00\_09 &\stackrel{def}{=} (Ack\_0, \mu\_data100).Med\_00\_20; \\
Med\_00\_10 &\stackrel{def}{=} (Ack\_0, \mu\_data75).Med\_00\_19; \\
Med\_00\_11 &\stackrel{def}{=} (Ack\_0, \mu\_data50).Med\_00\_18; \\
Med\_00\_12 &\stackrel{def}{=} (Ack\_0, \mu\_data25).Med\_00\_17; \\
Med\_00\_13 &\stackrel{def}{=} (collision\_1, collision100).Med\_00\_04; \\
Med\_00\_14 &\stackrel{def}{=} (collision\_1, collision75).Med\_00\_03; \\
Med\_00\_15 &\stackrel{def}{=} (collision\_1, collision50).Med\_00\_02; \\
Med\_00\_16 &\stackrel{def}{=} (collision\_1, collision25).Med\_00\_01; \\
Med\_00\_(i) &\stackrel{def}{=} (frag, \mu\_collision25).Med\_00\_(i+1) \\
&\quad +(transmit\_0, infty).Med\_00\_(i-4); i \in [17 \ldots 19] \\
Med\_00\_20 &\stackrel{def}{=} (collision_1, \mu\_collision25).Med\_00\_00 \\
&\quad +(transmit\_0, infty).Med\_00\_16;
\end{aligned}$$

The preceeding component represents the *medium* for the asymmetric hidden terminal problem. The key feature in this component is that the two emitters always sense the medium as free. Thus the two emitters always send data to their respective receiver. the two emitters have different collision contention region, thus, the $Pair0$ always access the medium correctly (its transmission always succeed). On the other hand, the $Pair1$ transmission can collide. Representing this two collision contention regions is done by introducing first a fragmentation on the data time and collision time, as for the three pair scenario, and second by differentiating the transmission of each node. For example, when $Pair0$ access the medium in Med_00_3, $Pair1$ can also send packet making the component evolving to Med_00_11.

In Med_00_11, the remaining time for the $Pair0$ packet successful transmission is drawn, and the *medium* behaves as Med_00_18. This state is already a collision state for $Pair1$ because the transmission of the 2 pairs overlaps. In this state, Med_00_18, $Pair0$ can transmit a packet again, that make the component evolves to Med_00_14. In this state, the remaining collision time is drawn for $Pair1$.

5.1.4 The general model

The general model of wireless LANs is defined as $Scenario$ and represent the interactions between components. For the 3 pairs scenario we have the following general model.

$$\begin{aligned} Scenario \overset{def}{=} \; & ((E\_0\_000 \underset{J}{\bowtie} BO\_0\_0)|| \\ & (E\_2\_000 \underset{K}{\bowtie} BO\_2\_0)) \underset{L}{\bowtie} Med\_00\_00 \\ & \underset{M}{\bowtie} (E\_1\_000 \underset{N}{\bowtie} BO\_1\_0) \end{aligned}$$

The cooperation sets are defined as: $J = \{db\_0\}$, $K = \{db\_2\}$, $L = \{transmit\_0, Ack\_0, free\_0, transmit\_2, Ack\_2, free\_2\}$ and $M = \{transmit\_1, Ack\_1, free\_1\}$ and $N = \{db\_1\}$. Here we have two instances of the E_0_000 component to model the two external pairs.

The next general component represent the asymmetric hidden terminal scenario.

$$\begin{aligned} Scenario \overset{def}{=} \; & ((E\_0\_000 \underset{K}{\bowtie} BO\_0\_0)|| \\ & (E\_1\_000 \underset{L}{\bowtie} BO\_1\_0)) \underset{M}{\bowtie} Med\_00\_00 \end{aligned}$$

The cooperation sets are defined as: $K = \{db\_0, succ\_0, coll\_0\}$, $L = \{db\_1, succ\_1, coll\_1\}$ and $M = \{transmit\_0, Ack\_0, transmit\_1, Ack\_1, collision\_1\}$.

5.2 The efficiency metrics

The efficiency is measured in the *Medium* and the $Node$ components. The *Medium* express the state of the medium and these states can be classified in 3 categories. *1)* The *Idle* state that represent the state where there is no activity on the medium. *2)* The *Collision* state of the medium that where a collision occurs in the medium. *3)* The last state is for successful transmission ans is measured on the $Medium$ and on the $Node$ components. This state is the probability for a successful transmission on the medium. The successful transmission state gives the probability of successful occupation on the medium from which we can derive the global throughput of the network, and the throughput of each pairs.

5.3 the fairness metrics

The first fairness metric is to compare the throughput of each pairs of emitter/receiver. This metric is for long term fairness measure. From our model this metric can be computed from the medium state distribution.

In order to have an accurate study of the behaviour of each backoff algorithm on each scenario, we have also introduced a both short and long term fairness metric. This metric try to capture the behaviour of each pair while considering successive successful transmission. In other word, even with some long term fairness problem, we wanted to know from a short term point of view if an emitter capture the channel successively for successful transmission. This is a short term fairness metric because it can capture the monopilosation of the medium by a node. In this paper, we have measure this metric only on the pair which undergoes the long term fairness problem. Some slight modifications are done on the model to allow the computation of this metric (see [11] for more details).

6. RESULTS

6.1 Model validation

The figure 7 show the 3 pairs scenario validation. The simulations are carried out with the NS-2 simulator. EIFS is used between the central pair and the external pairs. The figure shows the accuracy of our model of the 3 pairs scenario. This also shows that the assuptions made about the collision free situation in this scenario does not affect the model. The figure 7 shows the throughput of one of the external (the two pairs have exactly the same behaviour) and the central pair.

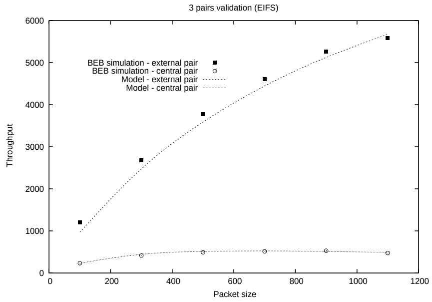

Figure 7: **Backoff distribution**

The figure 8 show the model validation of the asymmetric hidden terminal scenario. Here we can also see the accuracy of our model.

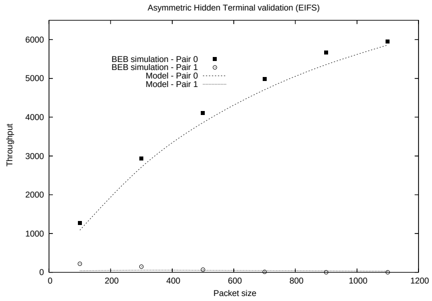

Figure 8: **Backoff distribution**

In these two figures (7 and 8) the throughput derived from our models are computed based on the occupation rate.

6.2 The Asymetric Hidden Terminal scenario

In this subsection we give some qualitative and quantitative results on the Asymetric Hidden Terminal scenario.

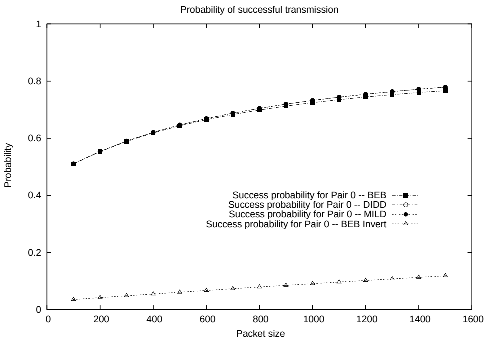

Figure 9: **Success probability for Pair 0**

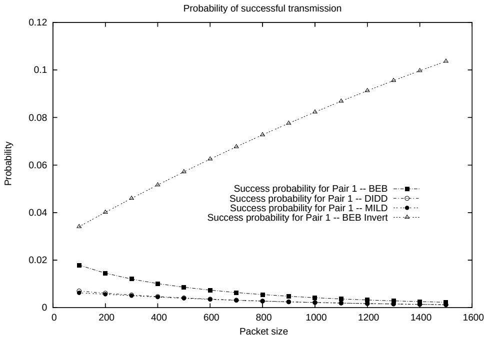

Figure 10: **Success probability for Pair 1**

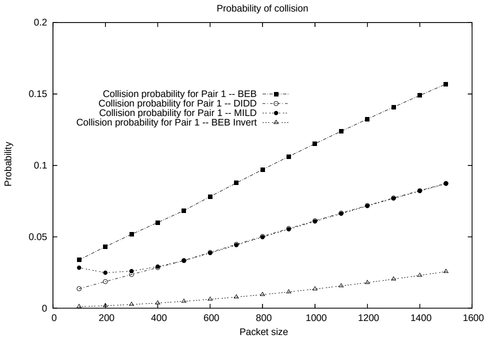

Figure 11: **Collision probability for Pair 1**

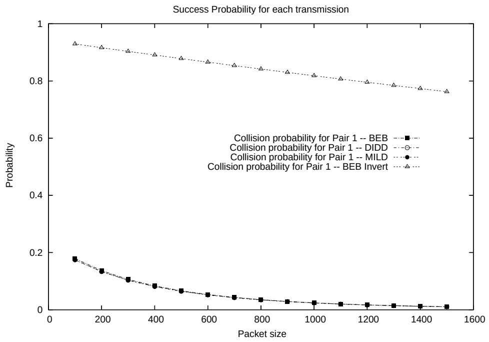

Figure 12: **Success proportion for Pair 1**

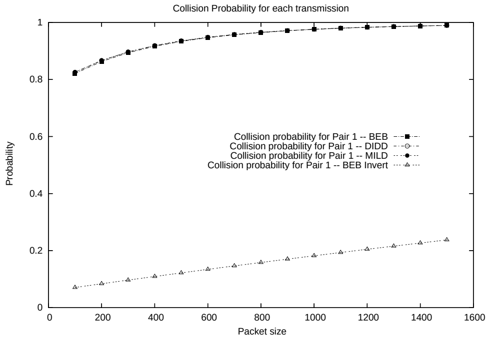

Figure 13: **Collision proportion for Pair 1**

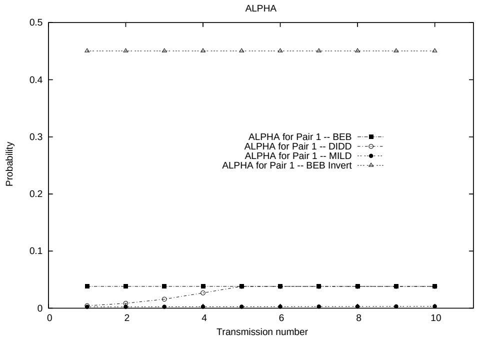

Figure 14: α_i

As stated earlier in this paper, in this scenario, the Pair 1 encouter many collisions due to the asymetry for the two pairs that leads to a long term unfairness. We can see this long term unfairness while considering the throughput of each pairs. We also wanted to see if a short term unfairness/fairness behaviour can be extract from our analysis.

The figure 9 and 10 shows the successful transmission for $Pair0$ and $Pair1$ respectively depending on the packet size (at application level, the packet size stand for both $Pair0$ and $Pair1$). We can see from figure 9 that the successful probability for $Pair0$ is equal for BEB, DIDD, and MILD algorithms. This is due to the collision free situation of $Pair0$, and due to the fact that the 3 cited backoff algorithms have the same initial contention window. The BEB inverted algorithm has very low successful transmission probability compared to the 3 other backoff algorithms because its initial contention window is equal to the maximal contention window size. The four curves in this figure are increasing due to increasing time depending on payload size.

The curves on figure 10 have different behaviour, because the $Pair1$ can encounter many collisions. Contrary to figure 9, for $Pair1$ the most efficient algorithm is BEB inverted, this is due to the fact a $Pair1$'s transmission has to fit in the silent period of $Pair0$ to succeed. As the initial contention window of $Pair0$ is always the maximal contention window (due to collision free situation), the packet of $Pair1$ fits easily in the silent period of $Pair0$. That's also why the $Pair1$ probability of successful transmission increase when payload increase. We can see from this figure that for the 3 other algorithms that the probability of successful transmission decrease because when the packet size increase the probability for this packet to fit in the silent period of the

$Pair0$ (This silent period is packet independent) decrease. We can also see from this figure that BEB probability of successful successive transmission is better than for MILD and DIDD, this is due to the retry limit process and the decresing process of the Binary Exponential backoff because with this retry limit, the $Pair1$ can potentially send more packet that MILD and DIDD because the mean duration of backoff time will be smaller for BEB.

The figure 11 show the collision probability for $Pair1$ depending on packet size. This probability is the time spent by $Pair1$ in transmission that collide. We can see from this figure that BEB inverted as the smallest collision probability (because of teh reason listed above), and that DIDD and MILD have roughly the same collision probability. BEB has the highger collision probability due to its decreasing process and the retry limit. This is due to the fact that on average BEB will send more packet than MILD and DIDD.

An interessting result from these curve is the fair behaviour of the BEB inverted algorithm. From these figure we can see that the successful transmission probability for $Pair0$ and $Pair1$ are roughly equal. Another result that arise from this two figures is the unfairness of BEB, DIDD and MILD. These figures show that the throughput of $Pair0$ and $Pair1$, derived from the successful transmission probability, are very different.

This fairness/unfairness behaviour are confirmed by the result plotted in figure 12 and 13. This figure plotted the proportion of successful and collision transmission over the total number of transmission for $Pair1$. We have not plotted this proportion for $Pair0$ because wa can easly deduce that the collision proportion is equal to 0 and the successful transmission proportion is equal to 1 whatever the packet size. This figures show that BEB inverted is the fairer compared to the other algorithm because, its successful proportion is close to 1 and its collision proportion is close to 0 even if the successful transmission decrease with the increasing packet size, and the collision proportion increase with increasing packet size. For BEB, MILD and DIDD this proportion are roughly equal.The successful proportion reduce when the packet size increase because the probability for the packet of $Pair1$ to fit in the silent period of $Pair0$ decrease. We can see that for a packet size equal to 600 bytes the successful probability is close to 1.

The figure 14 show the probability for Pair 1 to access the medium successively with successful transmission (for 1000 bytes data). This figure plotted the probabilitu of α_i that is the probability for the i^{th} transmission to succeed while the $[1 \ldots (i-1)]$ succeeded and are from the same pair of transmitter receiver. The figure 14 plotted α_i for $Pair1$. The α_i is constant for BEB inverted with a value close to $(1/Number\ of\ flows)$. this means that BEB inverted has a fair behaviour from short term and long term point of view. The fact that α_i is constant is a short term point of view metric, and the fact that α_i is close to $(1/Number\ of\ flows)$ is another long term metric. BEB and MILD have a constant small value of α_i that means that BEB and MILD are not long term fair in this context, but at short term BEB and MILD can be seen as a fair algorithms. The α_i value of DIDD is very small but increase with the value of i. This means that from a long term and a short term point of view DIDD is unfair.

The last result on Asymmetric Hidden Terminal scenario is the backoff distribution. The figure 15 show the probability for a transmitter to be in each backoff stage (for 1000 bytes data). The results for figure 15 is only for $Pair1$ because this probability for $Pair0$ is trivial in such a way that $Pair0$ never encounter collision. As describe in the preceeding section, the MILD backoff as 32 stage, here for the sake of legibility, we have only plotted 5 backoff stage that correspond to the same contention window value of the other backoff algorithm. Also for the sake of legibility the last three backoff stage of BEB, the stage with the same contention window are grouped in only one stage. We can see from these curves that for BEB, DIDD and MILD, the probability is higher for large contention window. This is due to the number of collision. From this result we can deduce some fairness issue because the backoff stage of $Pair1$ is is in higher stage but the backoff stage of $Pair0$ is the smaller contention window. With the BEB inverted algorithm, the backoff distribution is concentrated is like the three other backoff algorithm because the initial contention window is the greatest backoff stage. BEB inverted does not exhibit fairness issue from backoff algorithm distribution because the distribution of the two backoff algorithm will be the same. We can notice that the probability with BEB to be in the largest contention window is smaller that the for the other algorithm due to the retry limit and the decreasing method.

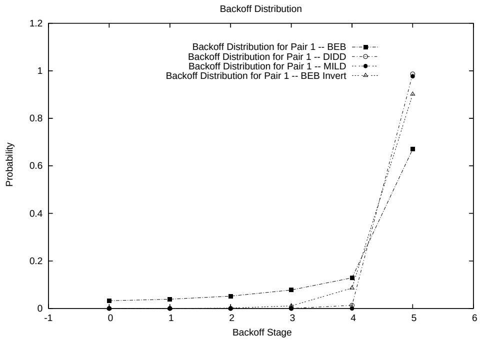

Figure 15: Backoff distribution

In this scenario, introducing fairness can improve the efficiency of these scenario. To introducing this fairness is not easy because of the independence of the two transmitter. A way to solve fairness is to introduce a scheduling between each pair. In a multihop ad hoc context intoducing a distributed scheduling is not so easy.

6.3 The 3 pairs scenario

In this subsection we discuss about the results on the 3 pairs scenario. As with the Asymmetric Hidden Terminal scenario we try to derive some performance evaluation metric for both quantitative (throughput) and qualitative (fairness) aspects. In this section we show two kind of results with having some different topology characteristics. The first case is when DIFS is used between the central pair and the two external pairs. The second case is when EIFS is used between the central pair and the external pairs. With the actual

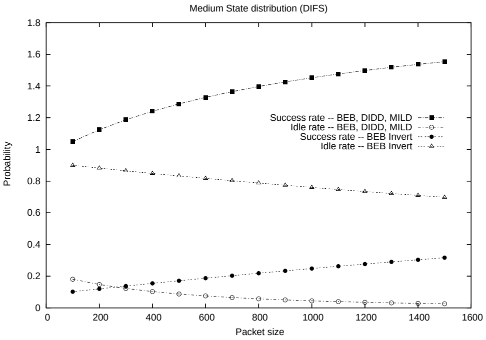

Figure 16: **Medium Distribution while using DIFS**

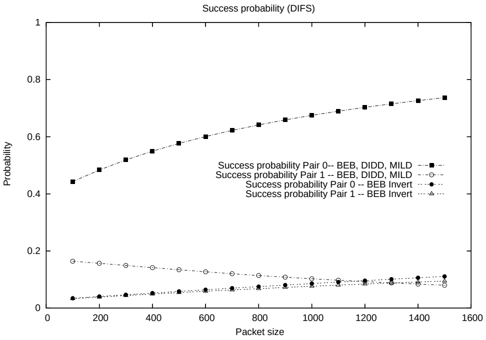

Figure 17: **Success probability while using DIFS**

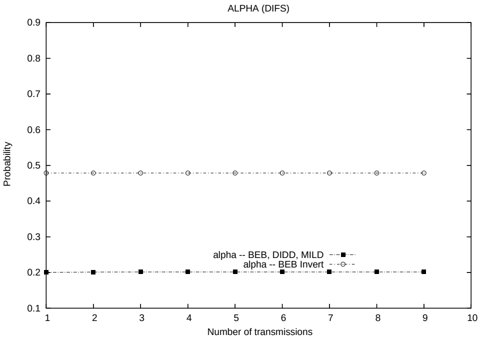

Figure 18: **α_i while using DIFS**

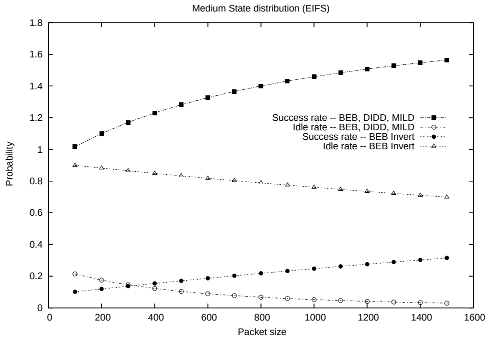

Figure 19: **Medium Distribution while using EIFS**

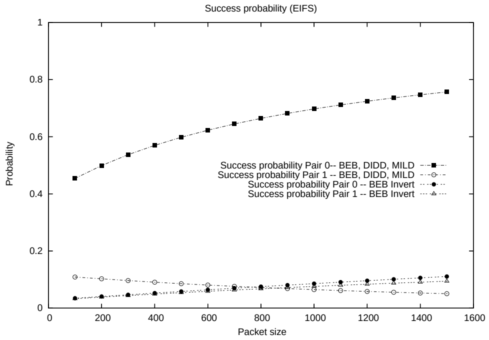

Figure 20: **Success probability while using EIFS**

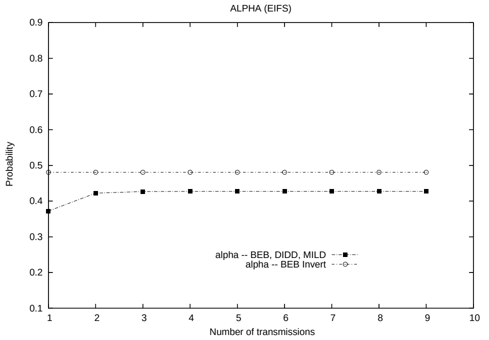

Figure 21: **α_i while using EIFS**

model, we cannot model a DIFS use between the central pair and on of the external pair, and and EIFS use between the central pair and the other external pair. This can be done by using two medium models between the central pair and the external pairs.

The Figures 16, 17, and 18 show the results for the 3 pairs scenario when DIFS is used. The figure 16 show the success and the idle rate of this scenario. As there is no collision in this scenario, the BEB, DIDD, MILD backoof algorithms have the same behaviour. The success rate is greater than 1 for BEB, MILD, and DIDD because the two external pairs can access the medium simultaneously. We can see from this figure that when the packet rate increase, the success rate also increase for the four backoff algorithms. This is a normal behaviour because when the payload increase, the success occupation time increase and thus the success rate also increase. For the BEB inverted algorithm, the idle rate is greater that the success rate because of the length of the initial contention window.

The figure 17 show the success rate for $Pair0$ and $Pair1$. We can see from this results that BEB inverted has a long term fair behaviour because the two pairs have roughly the same success rate. This is due to the fact that the backoff window of the BEB inverted algorithm is large enough to allow the central pair to decrement its backoff algorithm. On the other hand, with BEB, DIDD, and MILD we have an unfair behaviour. This is because the backoff window of these three algorithm are too small to overlap a thus to allow the backoff decreasing process of the central pair.

The figure 18 show α_i probability for the central pair ($Pair1$). From this figure we can see that the BEB inverted algorithm is fair from a long term point of view because α_i is constant and close to 1/2. Here 1/2 is the fair value and correspond to a max-min allocation. On the other hand, the thre other backoff algorithm show an unfair behaviour from a long term point of view because the value of α_i is far from the 1/2 value. But from a short term point of view, the three backoff algorithms have a fair behaviour because α_i is constant.

The results when EIFS is used are shown in figures 19, 20, and 21. The figure 19 show the success rate and the idle rate of this scenario. We can see that the curves of this figures are close to the curves from figure 16. As EIFS is at least 7 times larger than DIFS, one may think that the idle rate when EIFS is used has to be 7 times greater. This is not the case because, EIFS is only used by the external pair when the central pair gets access to the medium.

The figure 20 show the success rate for $Pair0$ and $Pair1$. from this figure we can see as in figure 17 the unfair behaviour of BEB, DIDD and MILD and the fair behaviour of BEB invert. From this figure we can see that compared to the results when DIFS is used, the use of EIFS worsen unfairness.

The figure 21 shows the α_i evolution for the central pair when EIFS is used. We can see here the fair behaviour of BEB inverted from long term and short term point of view. For BEB, DIDD and MILD, we have an unfair behaviour from short term point because α_i is increasing. From a long term point of view, BEB, DIDD and MILD have a roughly fair behaviour. This is because when the central access the medium, the external pairs use EIFS before decreasing their backoff. The short term unfairness can be explain by the fact that, as the EIFS is equal to $356\mu s$ and the mean backoff time added to DIFS is equal to $360\mu s$ (for the central pair) the central pair have an high probability to send successive successful transmission. We have to notice that when plotting α_i we did not plot the probability to send the first packet, we can not express this probability due to our model, but we can deduce from the figure 20 that this probability is not very high. If we suppose that this probability is at the maximum equal to 1/3 we have really a shot term fairness issue here because the successful transmission probability of the second packet is equal to 40%.

From these results, we can see that there is here a tradoff to find between fairness and efficiency. This tradeoff is not easy to find because to fight against asymmetry we have to introduce an asymmetrical behaviour according to the pair.

7. CONCLUSION AND PERSPECTIVES

In this paper we have presented an analysis of four backoff algorithm in a multi hop Ad hoc scenario. We evaluate the performances of these four backoff algorithms from a qualitative point of view, using a fairness metric, and from quantitative point of view, using an efficiency metric. This work falls under the continuity of the work proposed in [11]. The difference between this paper and [11] is the studied scenario and backoff algorithms. Some more imporvements can be done on our model to derive some other metrics and to model other scenario such as an asymmetric 3 pairs scenario where the external pairs are in EIFS ans DIFS from the central pair.

From our analysis we can say that the algorithms proposed in the literature are not efficient and/or fair in some mutlihop ad hoc networks. The problem of designing an efficient and fair backoff algorithm for multihop ad hoc context is at this time an open issue. The analysis of the existing backoff algorithms in multi hop ad hoc networks is the first step to do so.

The next step of this work is to assiciate some backoff algorithms characteristics such as retry limit, decreasing and increasing process to some performance metrics such as fairness, and efficiency.

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