Investigating Unfairness Scenarios in MANET using 802.11b

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ABSTRACT

An experimental study of MANET using 802.11b has shown that there exist several configurations where this standard does not guarantee fairness for the channel access. In this paper, we investigate the performance of the WiFi protocol in such configurations using the analytical modelling technique PEPA. The proposed model appears to be generic as it can be used to model any mobile node implementing this protocol. To provide a better understanding of such a problem we analyse the protocol behaviour and evaluate its cost in terms of medium utilisation and throughput for the communicating pairs. The results obtained are compared to simulation results.

Categories and Subject Descriptors: I.6.5 [Model Development]: Modeling methodologies

General Terms: Performance

Keywords: Ad hoc networks, 802.11b, unfairness, process algebra, performance analysis.

1. INTRODUCTION

A Mobile Ad-hoc NETwork (MANET) is an autonomous network of mobile nodes that communicate through wireless links. Such a network is characterised by a dynamic topology where spontaneous connections may take place. Communications can be established any time and anywhere using nodes collaboration in order to provide network services as routing or localization. In fact, each mobile node acts as a router as well a host. Because of the heterogeneity and the mobility of the nodes, these networks give rise to issues like routing protocols, mobility management, ... However, so far MANETs have been studied essentially from the point of view of routing protocols [1]. The routing protocols have been evaluated in versatile and mobile environments using essentially simulation [7]. In such a context, simulation allows the modeller to evaluate the main performance parameters. Other performance modelling techniques based on Markovian processes have also been used to investigate the throughput and the latency in these networks [8]. Graph theory provides also an interesting framework to study MANET [11]. In such studies, the radio interface is omitted and the assumption of ideal channel conditions is used (no hidden terminals, no signal interferences) and the channel access fairness for all mobile nodes is assumed [2].

Practical experiments of MANET using IEEE 802.11 [3] have been made [6]. The goal was to show the feasability of MANET using this radio protocol. It has been designed to offer multiple throughputs, to take into account critical radio transmissions and to guarantee fairness between nodes. However, in one of the experiments about MANET using 802.11 [6], it has been shown that there exist configurations where 802.11 does not garantee fairness for the channel access as it is assumed to do. The authors have highlighted three practical configurations where communicating nodes cannot send packets because the access mechanism to the medium has an unfair behaviour towards them.

The literature provides many performance evaluation studies of IEEE 802.11 which investigate the backoff protocol impact, the saturation effect, etc. [8] [2]. Many studies deal with performance evaluation of short-term or long-term fairness. Nevertheless, such studies do not include the three scenarios we consider [4, 5]. Similarly, the results of the experiments in [6] point out the configurations and discuss the unfairness surrounding them, but without leading any study to provide a better understanding of the access mechanism behaviour in these cases. Moreover no investigations have been made to assess the impact of the protocol unfairness in terms of performance measures.

In this paper, we investigate the fairness properties of 802.11 in the case of the three configurations where unfairness has been reported. Our goal is not to provide a solution to this problem but to give a better understanding of unfairness through an analytical model. Instead we analyse the WiFi protocol behaviour in these configurations and evaluate its cost in terms of medium utilisation and throughput. We have developped a *generic* analytical model of the scenarios using the process algebra performance technique PEPA (Performance Evaluation Process Algebra). This compositional approach has been introduced in 1994 [10] and widely used since in the performance analysis area. Simulation models of the scenarios have also been developed and their tests results have been compared to the analytical model results.

The paper is structured as follows: in Section 2 we in-

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troduce the IEEE 802.11b technology and describe the unfairness scenarios. In Section 3, we give an overview of the PEPA formalism whereas the proposed PEPA model of the unfairness scenarios is developed in Section 4. The numerical results we have obtained are discussed in Section 5. A conclusion with useful remarks are given in Section 6.

2. FAIRNESS ISSUE IN MANET

2.1 How CSMA/CA works with basic access

The IEEE 802.11 MAC layer defines two architecture modes [3]. The first one is the *Point Coordination Function* which is an optionnal centralized MAC protocol. We focus our study on the second one, the *Distributed Coordination Function* (DCF) which is a random access scheme based on *Carrier Sense Multiple Access* with *Collision Avoidance* (CSMA/CA). We consider only the basic access mechanism.

A node listens to make sure the channel is free and waits for a random time period called *backoff* before sending packets. The DCF uses an exponential backoff scheme. The backoff is uniformly chosen in the range [0, w-1] where w is the *contention window*. w depends on the number of transmission failures for the current packet to transmit. At the beginning w is equal to the minimun contention window ($CW_{min} = 32$). Each unsuccessful transmission involves the multiplication of w by 2 and the maximum value is CW_{max} (2^{10}). The backoff mechanism is associated with the collision avoidance of the protocol. The backoff objective is to minimize the collision rate between stations which have packets to transmit. It is tuned to a slot time equal to 20 μs in order to allow a station to detect if the channel is used. Once the backoff time has been generated, the mobile station monitors the channel activity. If the channel is idle during a sufficient long time called *Distributed Inter Frame Space* (DIFS, $50\mu s$) then the station decreases its backoff. When the backoff is equal to 0, the packet is transmitted. Otherwise, if the channel is busy, the station monitors the channel until it becomes idle. Then the station decreases its backoff. The backoff interval time is decremented as long as the channel is free and is frozen when the node detects a transmission. At the end of this transmission, when the channel remains idle during a DIFS, the decrementation starts again. Figure 1 illustrates such a transmission scheme. In fact, during the backoff decrementation, if the mobile station detects a signal but, due to noise or interferences, not a transmission in progress, then instead of using a DIFS, the station uses an *Extended Inter Frame Space* (EIFS, $364\mu s$). After a successful transmission, the receiver sends an ACK after a duration called *Short Inter Frame Space* (SIFS). As the SIFS ($10\mu s$) is shorter than the DIFS, there is no station which sees the channel free until the end of the ACK transmission.

2.2 Unfairness scenarios

One of the main results of the experimental study in [6] is to point out three scenarios of MANET topology where 802.11 has an unfair behaviour: a mobile node which has a packet to send may not have access to the channel because it seems always busy. These scenarios are referred to as the *three pairs scenario*, the *hidden nodes-like scenario* and the *transitive communications scenario*. In these scenarios, each communicating pair is composed of a transmitter and its associated receiver. Saturation traffic conditions are considered as the transmitters have always a packet to send. The receivers act as sinks; ACK are sent in the case of successful reception. Before describing theses scenarios, we introduce useful notations where A and B are mobile nodes.

Notation 1: $TR(A, B)$ means B is in the transmission range of A: A and B share the medium to send packets. We assume $TR(A, B)$ implies $TR(B, A)$.

Notation 2: $SR(A, B)$ means B is in the carry detection of A: if A sends a packet, B hears an activity on the medium but cannot identify the transmission. As notation 1, $SR(A, B)$ implies $SR(B, A)$.

2.2.1 *The three pairs scenario*

This is the more common because of its general properties (Figure 2). The dependency properties are:

- Both external pairs are fully independent. When a transmitter of these pairs sends a packet, the other transmitter sees the channel as free.
- The central pair may see the channel occupied by both external pairs. In fact, for the central pair, the medium is shared with both external pairs whereas for each external pair, the medium is shared with the central pair only. Therefore, we have TR($Pair_A$, $Pair_B$) and TR($Pair_B$, $Pair_C$).

Clearly the central pair will have less medium access than the other pairs, hence the unfairness.

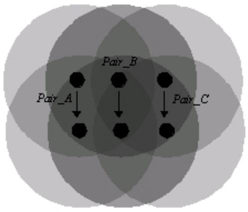

Figure 2: The three pairs scenario

2.2.2 *The hidden nodes-like scenario*

This scenario, with only two communicating pairs (Figure 3), is similar to the hidden terminal problem in wireless networks. However, the classical *Ready To Send/Clear To Send* mode appears to not be very efficient in MANET [9]: the basic access is used for performance but the hidden problem remains. The dependency properties are:

- The couples of nodes ($A1$, $B1$), ($A1$, $B2$) and ($B2$, $A2$) are independent. Moreover the packets sent by $A1$ do not perturbe the reception of $B2$, and vice versa. Similarly $B2$ and $A2$ do not perturbe each other when they send their ACK packets.
- Node $A2$ cannot identify, and thus acknowledge, the packets sent by its corresponding transmitter if $B1$ is sending packets at the same time. This results in the retransmission of the packets by node $A1$. We have TR($A2$, $B1$), TR($A1$, $A2$) and TR($B1$, $B2$).

$Pair\_A$ is the penalized pair by the 802.11 unfairness.

2.2.3 *The transitive communications scenario*

Two communicating pairs are considered (Figure 4). The dependency properties are as follows:

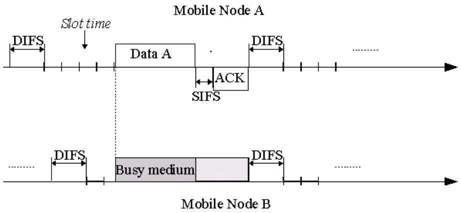

Figure 1: IEEE 802.11 basic access mechanism

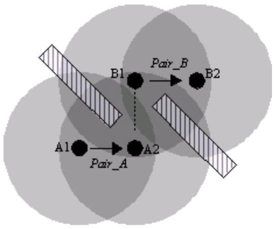

Figure 3: The hidden nodes-like scenario

- The couple of nodes ($B2$, $A2$) is fully independent. Thus the transmission of an ACK packet by one receiver does not pertub the reception of the other.
- Moreover, we have TR($A1$, $A2$), TR($B1$, $B2$), TR($A1$, $B1$) and SR($B1$, $A2$).

$Pair\_B$ is the penalized pair by the 802.11 unfairness.

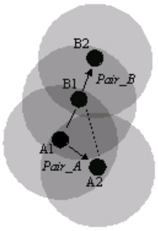

Figure 4: The transitive communications scenario

3. PEPA

In PEPA, a system is viewed as a set of *components* which carry out *activities*. Each activity is characterized by an *action type* and a duration which is exponentially distributed. Thus each activity is defined by a couple (α, r) where α is the action type and r is the *activity rate*. Because of the exponential distribution of the activity duration, it has been shown that the underlying Markov process of a PEPA model is a continuous time Markov process.

PEPA formalism provides a set of combinators which allows expressions to be built, defining the behaviour of components, via the activities they engage in. Below, we present informally only the combinators which are necessary to our model. For more details about the formalism, see [10].

Constant: noted $S \overset{\text{def}}{=} P$, it allows us to assign names to components. To component S, we assign the behaviour of component P.

Prefix: noted $(\alpha, r).P$, this combinator implies that after the component has carried out the activity (α, r), it will behave as component P.

Choice: noted $P_1 + P_2$, this combinator represents 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: noted $P_1 \underset{L}{\bowtie} P_2$, 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. A particular case of the cooperation is when $L = \emptyset$. In this case, components proceed with activities independently and are noted $P_1 || P_2$. 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 and is noted $\top$. Such a component is said to be *passive* with respect to this action type and the rate of this shared activity is defined by the other component in cooperation.

4. FAIRNESS MODELLING USING PEPA

As all pairs implement the same protocol, they have the same behaviour: the same PEPA component is used to model them. What is different from one scenario to another is the behaviour of the medium. Modelling the medium means modelling the nodes interactions and as these interactions are different from one scenario to another, we need to use a different PEPA component for the medium, according to the scenario we want to model.

4.1 The three pairs scenario

This scenario can be modelled as the interaction of four components: $Pair\_A$, $Pair\_B$, $Pair\_C$ and $Medium\_F$. The external pairs are modelled using respectively $Pair\_A$ and $Pair\_C$ whereas the central pair is modelled using $Pair\_B$. As explained before, all pairs have the same behaviour, however to distinguish between them we use different names for the components.

Component $Pair\_A/Pair\_C$: After a backoff draw, modelled using action type *draw_backoff*, an external pair may start decreasing its $DIFS$ with activity $(count\_difs, f \times \mu_d)$. As this activity is in concurrency with the shared activity $(queue, \top)$, both are enabled at the same time. However, the function used f ensures that if the channel is already occupied by the central pair (see the definition of f below), activity $count\_difs$ is cancelled and *queue* is completed, which means that the external pair has to wait the time the central pair is transmitting its packets (action type *wait*). If the medium is free, action *queue* can not be undertaken. Indeed as this action is shared between components $Pair\_A$ and $Medium\_F$, both must be ready (in the right state) to carry it out at the same time. So if the channel is free, then component $Medium\_F$ cannot be in the right state for that. Therefore, action $count\_difs$ can be completed and followed by the decrease of the backoff initially drawed. According to the probabilities p and q ($q = 1 - p$), the decrease of the backoff is ended when action *end_backoff* is completed. Similarly, if the channel is or becomes busy ($Pair\_B$) during the decrease of the backoff, function f disables both actions *count_backoff* and *end_backoff* and action *queue* is executed leading to the external pair to be in the waiting state. If activity $(end\_backoff, q \times f \times \mu_{bck})$ completes then the pair can use the medium and transmit its data. After a successfull transmission, the sender receives an (ACK).

$$
\begin{array}{lcl}
Pair\_A & \stackrel{def}{=} & (draw\_backoff, r).Pair\_A_0 \\
Pair\_A_0 & \stackrel{def}{=} & (count\_difs, f \times \mu_{difs}).Pair\_A_1 \\
 & + & (queue, \top).Pair\_A_5 \\
Pair\_A_1 & \stackrel{def}{=} & (count\_backoff, p \times f \times \mu_{bck}).Pair\_A_1 \\
 & + & (end\_backoff, (1-p) \times f \times \mu_{bck}).Pair\_A_2 \\
 & + & (queue, \top).Pair\_A_5 \\
Pair\_A_2 & \stackrel{def}{=} & (transmit, \mu_{data}).Pair\_A_3 \\
 & + & (queue, \top).Pair\_A_5 \\
Pair\_A_3 & \stackrel{def}{=} & (count\_sifs, \mu_{sifs}).Pair\_A_6 \\
Pair\_A_4 & \stackrel{def}{=} & (count\_difs, f \times \mu_{difs}).Pair\_A_1 \\
 & + & (count\_eifs, f \times \mu_{eifs}).Pair\_A_1 \\
 & + & (queue, \top).Pair\_A_5 \\
Pair\_A_5 & \stackrel{def}{=} & (wait, \mu_{data}).Pair\_A_4 \\
Pair\_A_6 & \stackrel{def}{=} & (Ack, \mu_{ack}).Pair\_A \\
 & + & (collision, \top).(resize\_W, s).Pair\_A
\end{array}
$$

Component Pair_B: We use the same activities as for external pairs, except for the shared activities with the medium. That is the activities specifying that $Pair\_B$ is using the channel ($transmit$), has to wait for the channel ($queue_B$) and is sending an ACK packet (Ack_B). This distinction is necessary to ensure that from the point of view of PEPA there will not be any ambiguity between the external pairs and the central one. Function g has the same role as f in $Pair\_A$.

$$
\begin{array}{lcl}
Pair\_B & \stackrel{def}{=} & (draw\_backoff, r).Pair\_B_0 \\
Pair\_B_0 & \stackrel{def}{=} & (count\_difs_B, g \times \mu_{difs}).Pair\_B_1 \\
 & + & (queue_B, \top).Pair\_B_5 \\
Pair\_B_1 & \stackrel{def}{=} & (count\_backoff, p \times g \times \mu_{bck}).Pair\_B_1 \\
 & + & (end\_backoff, (1-p) \times g \times \mu_{bck}).Pair\_B_2 \\
 & + & (queue_B, \top).Pair\_B_5 \\
Pair\_B_2 & \stackrel{def}{=} & (transmit_B, \mu_{data}).Pair\_B_3 \\
 & + & (queue_B, \top).Pair\_B_5 \\
Pair\_B_3 & \stackrel{def}{=} & (count\_sifs, \mu_{sifs}).Pair\_B_6 \\
Pair\_B_4 & \stackrel{def}{=} & (count\_difs_B, g \times \mu_{difs}).Pair\_B_1 \\
 & + & (count\_eifs_B, g \times \mu_{eifs}).Pair\_B_1 \\
 & + & (queue_B, \top).Pair\_B_5 \\
Pair\_B_5 & \stackrel{def}{=} & (wait, \mu_{data}).Pair\_B_4 \\
Pair\_B_6 & \stackrel{def}{=} & (Ack_B, \mu_{ack}).Pair\_B \\
 & + & (collision, \top).(resize\_W, s).Pair\_B
\end{array}
$$

Component Medium_F: All activities of this component are shared activities; $Medium\_F$ has to cooperate with the other components to carry out its activities. Initially the medium is free and can be occupied by either an external pair ($transmit$) or the central pair ($transmit_B$). In the former case, it can be used by the second external pair as well, it can be freed by the first one (ACK) or the central pair which tried to use it is put in the waiting state ($queue_B$). In the latter case, an external pair which tried to use the medium is put in the waiting state ($queue$) or the central pair frees the channel (Ack_B). $Medium\_F_1$ models the case where $Pair\_B$ is using the channel, state $Medium\_F_2$ the case where one of the external pairs is using it and $Medium\_F_3$ the case where both external pairs are transmitting.

$$
\begin{array}{lcl}
Medium\_F & \stackrel{def}{=} & (transmit, \top).Medium\_F_2 \\
 & + & (transmit_B, \top).Medium\_F_1
\end{array}
$$

$$
\begin{array}{lcl}
Medium\_F_1 & \stackrel{def}{=} & (Ack_B, \top).Medium\_F \\
 & + & (queue, \lambda_{oc}).Medium\_F_1 \\
Medium\_F_2 & \stackrel{def}{=} & (transmit, \top).Medium\_F_3 \\
 & + & (Ack, \top).Medium\_F \\
 & + & (queue_B, \lambda_{oc}).Medium\_F_2 \\
Medium\_F_3 & \stackrel{def}{=} & (Ack, \top).Medium\_F_2 \\
 & + & (queue_B, \lambda_{oc}).Medium\_F_3
\end{array}
$$

The complete system: The model component $Scenario_1$ is viewed as the interaction between the external pairs, the central pair and the medium. As there is no interaction between the external pairs, we use symbol $''||''$ to model this absence of interaction in their behaviour.

$$
Scenario_1 \stackrel{def}{=} \Big((Pair\_A || Pair\_C) \underset{K}{\bowtie} Medium\_F\Big) \underset{L}{\bowtie} Pair\_B
$$

The cooperation sets are defined as $K = \{transmit, Ack, queue, collision\}$ and $L = \{transmit_B, Ack_B, queue_B\}$.

Functions f and g are defined according to the state X of component $Medium\_F$ as follows:

$$
f(X) = \begin{cases} 0 & if\ X = Medium\_F_1 \\ 1 & otherwise \end{cases}
$$

$$
g(X) = \begin{cases} 1 & if\ X = Medium\_F \\ 0 & otherwise \end{cases}
$$

Remark 1. In the external pairs specification, an activity *collision* is defined to model the collision phenomenon. However, as it is a collision-free scenario, such activity is not enabled. Indeed activity *collision* will never be enabled in this scenario because it is defined as a synchronising activity between the medium and an external pair, but it does not appear as an activity of the medium. Similarly activity *resize_W* will never be enabled because it follows a *collision* activity. This activity models the behaviour of a pair transmitter when it has to resize its transmission window after a collision. Activities *collision* and *resize_W* have been defined to fullfill the characteristics of the second scenario.

Remark 2. In this scenario, the activities $count\_difs$ and $count\_eifs$, modelling the process of decreasing the DIFS and the EIFS counters respectively, are not shared activities. However, as they appear in the synchronizing set of $Pair\_B$ with the medium in scenario 3, we have renamed them as $count\_difs_B$ and $count\_eifs_B$ in this component.

4.2 The hidden nodes-like scenario

Here, there are only two communicating pairs which are modelled using components $Pair\_A$ and $Pair\_B$, previously defined. The third actor of this scenario is the medium which is modelled using a new component $Medium\_S$.

Component *Medium_S*: Only two pairs are considered and a collision phenomenon can be observed when both transmitters send their packets at the same time. The receiver of $Pair\_A$ will not be able to identify the packets sent by its corresponding transmitter and therefore it will not acknowledge their reception. In this case, the sender of $Pair\_A$ will recompute the size of its contention window before retransmitting its packets.

In this component, the initial state ($Medium\_S$) models the state where the medium is idle whereas $Medium\_S_3$ is the state where both transmitters are sending a packet. State $Medium\_S_1$ ($Medium\_S_2$) is the state where $Pair\_A$ ($Pair\_B$) transmitter is using the channel.

$$\begin{aligned} Medium\_S &\stackrel{def}{=} (transmit, \top).Medium\_S_1 \\ &+ \; (transmit_B, \top).Medium\_S_2 \end{aligned}$$

$$\begin{aligned} Medium\_S_1 &\stackrel{def}{=} (Ack, \top).Medium\_S \\ &+ \; (transmit_B, \top).Medium\_S_3 \\ Medium\_S_2 &\stackrel{def}{=} (transmit, \top).Medium\_S_3 \\ &+ \; (Ack_B, \top).Medium\_S \\ Medium\_S_3 &\stackrel{def}{=} (collision, rc).Medium\_S_2 \end{aligned}$$

The complete system: The PEPA component defining the complete system ($Scenario_2$) is the following.

$$Scenario_2 \stackrel{def}{=} \Big(Pair\_A || Pair\_B\Big) \underset{M}{\bowtie} Medium\_S$$

The synchronising set is defined as $M = \{transmit, Ack, transmit_B, Ack_B, collision\}$.

4.3 The transitive communications scenario

Two communicating pairs are considered which are modelled using components $Pair\_A$ and $Pair\_B$. The medium is modelled using a new component $Medium\_T$ because unlike the first scenario we have only two pairs and unlike the second scenario we do not have collisions.

Component *Medium_T*: The transmitters listen to each other and therefore they cannot send their packets at the same time. Moreover as we have SR($B1$,$A2$), the transmission of ACK packets by the receiver of $Pair\_A$ will force it to decrement its EIFS counter.

In this component, $Medium\_T_1$ ($Medium\_T_2$) models the state where $Pair\_A$ ($Pair\_B$) transmitter is using the channel. $Medium\_T_3$ represents the state where $Pair\_B$ is in its waiting process. In this case, $Pair\_A$ may finish its transmission which leads to $Medium\_T_4$ where $Pair\_B$ can complete its waiting process or a new packet can be sent by $Pair\_A$. $Medium\_T_5$ models the resulting state of the latter case: $Pair\_B$ may decreases its EIFS counter. This state models also the case where $Pair\_A$ may once again free the channel before $Pair\_B$ decreases its EIFS counter.

$$\begin{aligned} Medium\_T &\stackrel{def}{=} (transmit, \top).Medium\_T_1 \\ &+ \; (transmit_B, \top).Medium\_T_2 \\ Medium\_T_1 &\stackrel{def}{=} (Ack, \top).Medium\_T \\ &+ \; (queue_B, s).Medium\_T_3 \\ Medium\_T_2 &\stackrel{def}{=} (queue, s_1).Medium\_T_2 \\ &+ \; (Ack_B, \top).Medium\_T \\ Medium\_T_3 &\stackrel{def}{=} (count\_difs_B, infty).Medium\_T_1 \\ &+ \; (Ack, \top).Medium\_T_4 \\ &+ \; (queue_B, s).Medium\_T_1 \\ Medium\_T_4 &\stackrel{def}{=} (count\_eifs_B, \top).Medium\_T \\ &+ \; (transmit, \top).Medium\_T_5 \\ Medium\_T_5 &\stackrel{def}{=} (count\_eifs_B, \top).Medium\_T_1 \\ &+ \; (Ack, \top).Medium\_T_4 \end{aligned}$$

The complete system: The complete behaviour is modelled using component $Scenario_3$ which is defined as follows.

$$Scenario_3 \stackrel{def}{=} \Big(Pair\_A || Pair\_B\Big) \underset{N}{\bowtie} Medium\_T$$

The synchronising set N is defined as $N = \{transmit, Ack, transmit_B, Ack_B, queue, queue_B, count\_eifs_B, count\_difs_B\}$.

Remark 3. To remove any ambiguity concerning the synchronizing activities of the pairs with the medium, we have renamed all the synchronizing activities of component $Pair\_B$ (see 4.1). However, note that we can rename all the activities of this component, not only the synchronizing ones, without altering the semantics of the component or the complete model. This would have been perhaps more convenient as the shared activities of $Pair\_B$ change according to the scenario. Indeed, as the medium is modelled using a different component in each scenario, $Pair\_B$ activities in the synchronising sets with the medium are different.

Although for each scenario we have used a different component to model the medium, we have used the same components to model the communicating pairs. This implies that our model is generic to model any scenario where the communicating pairs implement the WiFi protocol. Only the interactions of these pairs with the medium are different.

5. PERFORMANCE RESULTS

Numerical results are obtained after solving the PEPA model using the PEPA Workbench [12]. From a description of a PEPA model, this tool provides the stationary behaviour (steady-state probability distribution) of the modelled system. This allows us to compute various performance measures. Moreover, we have developed a simulation model using the network simulator OPNET Modeler and the 802.11 model protocol. In the following, we first show the effect of unfairness on both the medium utilisation rate by the pairs and their throughput. Then we investigate the behaviour of IEEE 802.11 to understand how and at which stage the unfairness happens.

5.1 Effect of unfairness

5.1.1 Scenario 1

The channel utilisation rate for both external pairs increases as the packet payload size increases (Figure 5). This is due to the channel occupancy time increasing because of the packet size increasing too. As several channel throughputs (1, 2, 5 and 11 $Mbits/s$) are considered, the channel utilisation rate increases as the channel throughput decreases. Indeed when the channel is faster in transmitting a packet, this one spends less time in it. The utilisation time of the channel by the pair is then reduced.

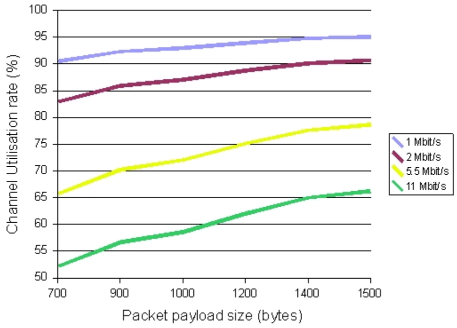

Figure 5: Channel utilisation rate (external pairs)

Unlike for the external pairs, the channel utilisation rate for the central pair decreases as the packet payload size increases (Figure 6). The central pair has more access to the medium as the throughput increases. When the channel utilisation by the external pair increases, the channel utilisation by the central pair decreases and vice versa. However, the channel access for the central pair is very limited as it can hardly exceed 4%. Thus most of the time, the medium is occupied by the external pairs. As we can see, the simulation results validate our analytical results as they are very similar.

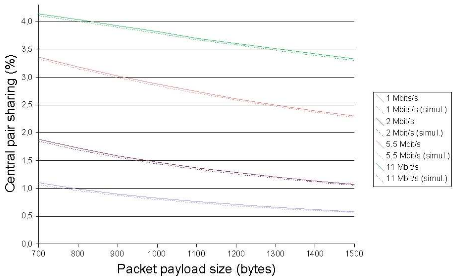

Figure 6: Channel utilisation rate (central pair)

Moreover, the unfairness in terms of throughput (Figure 7) confirms the results of Figure 6. These simulation results show that for a medium throughput of $11Mbit/s$, the throughput for the central pair is unsignificant compared to the throughput for the external pairs. Although the theoretical throughput is $11Mbit/s$, the practical one is slighty lower than $6Mbit/s$ (Figure 7). Unfairness does not really affect the throughput of external pairs whereas the impact on the central pair throughput is very important as this throughput is lower than $300kbit/s$.

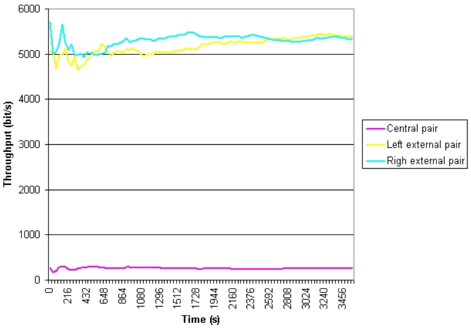

Figure 7: Throughput of the three pairs

From both previous figures, it appears that unfairness becomes more striking when the channel utilisation time increases. There are two ways to increase channel utilisation time: either to transmit at a lower throughput or to increase the packets length to transmit.

As the simulation results are very similar to the ones obtained using the analytical model, we omit the presentation of the simulation results for the following scenarios.

5.1.2 Scenario 2

Figure 8 shows the channel utilisation rate for $Pair\_A$ (penalized pair). This rate is measured when no collisions occur. The results obtained are similar to the central pair results in the three pairs scenario. Indeed the channel utilisation rate decreases as the packet load size increases and as the medium throughput decreases. We note however that the unfairness impact is slightly more striking in this scenario since for a medium throughput of $11Mbits/s$ the utilisation rate is clearly lower than 4%.

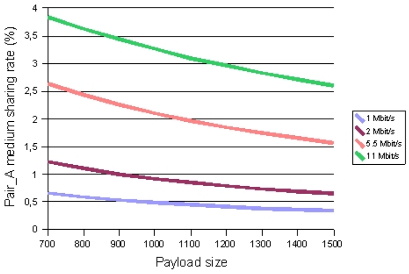

Figure 8: Channel utilisation rate ($Pair\_A$)

Figure 9 shows the collision probability for $Pair\_A$. The collision probability is very important and increases as the packets size increases and the medium throughput decreases. Indeed for low throughput ($1Mbits/s$), the collision probability may exceed 95%, whereas it remains lower than 70% when the throughput is higher ($11Mbits/s$). These results make sense because if a packet x has a bigger size than a packet y, the former will require more time to be transmitted and this for all medium throughput. Thus it will spend more time in the medium which increases the collision probability with another source packet. Similarly for a specific packet size, if the throughput is slower in transmitting a packet, the collision probability becomes higher.

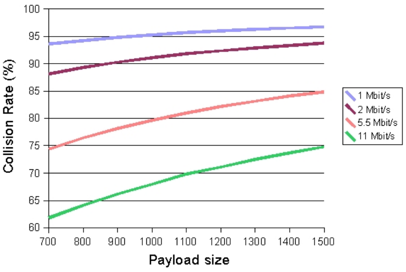

Figure 9: Probability of collisions

From both figures, it is clear that the transmitter of $Pair\_A$ spends most of its time retransmitting its packets because of the collision phenomenon. This transmitter views the medium always free, but when both transmitters send their packets at the same time, the receiver of $Pair\_A$ is not able to recognise the packets sent for him and therefore does not acknowledge them.

5.1.3 Scenario 3

Figure 10 shows the utilisation rate for $Pair\_A$, the pair which takes advantage from the protocol malfunctioning. As expected this rate increases as the packet size increases and the channel throughput decreases. However we can note that this rate is much lower than the one we obtained for the external pairs in the three pairs scenario.

Figure 11 depicts the channel utilisation rate for $Pair\_B$. Two points seem important to note. First, the channel utilisation rate of the less lucky pair in this scenario is three times greater than the one computed for the central pair in the first scenario or $Pair\_A$ in the second one. Secondly, unlike in both previous scenarios, this rate increases as the packets size increases and as the throughput decreases.

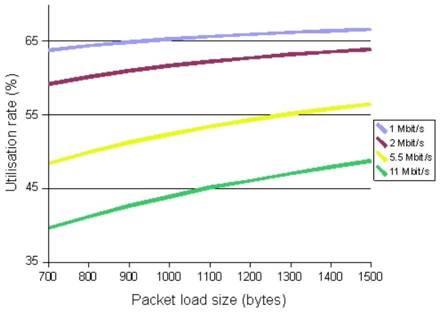

Figure 10: Channel utilisation rate ($Pair\_A$)

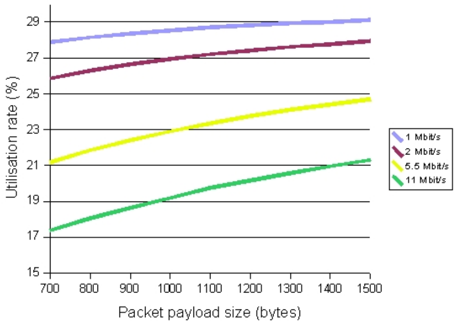

Figure 11: Channel utilisation rate ($Pair\_B$)

The first point implies that the unfair behaviour of the protocol is less striking in this scenario. The second point gives rise to the question: why the evolution of the channel utilisation as a function of the packets size and the medium throughput is completely opposite to the one in the previous scenarios ? To be able to answer to this question, we have investigated the performance of a fourth scenario. In this scenario the protocol has the ideal behaviour as the medium is fairly shared by the two communicating pairs in this scenario. The results obtained show that for a fixed medium throughput ($11Mbits/s$) when the packet size is 700 $bytes$, both pairs have a channel utilisation rate equal to about 29% whereas when the packet size is bigger (1500 $bytes$), this rate is about 35%. Moreover, for a fixed packet size (700 $bytes$), the channel utilisation rate for each pair is 46% when the channel throughput is equal to $1Mbits/s$, and only 29% when the throughput is equal to $11Mbits/s$. Even if these results do not give a direct answer to our question, they suggest both with the results of the third scenario that the effect of the protocol malfunctioning is more complex than an unfair access to the medium for certain pairs. Indeed they suggest that as long as a certain degree of the protocol malfunctioning is not reached, the right evolution of the channel utilisation rate may be preserved.

5.2 Understanding unfairness of 802.11

More investigations are necessary to understand at which stage of the protocol and how unfairness occurs. Using the PEPA model the probability distribution of the states where a mobile node decreases its EIFS counter, its DIFS counter, the backoff and finally the waiting time before sending a packet or decreasing one of the counters are computed.

In the following, we do not give all these measures for all scenarios, only those which are pertinent for each scenario.

5.2.1 Scenario 1

The results obtained show that the unfairness is mainly due to the medium sharing and not to the interframe spacing. Unlike the external pairs, the central pair spends most of its time in the waiting state and this for all values of the medium throughput (Figure 12).

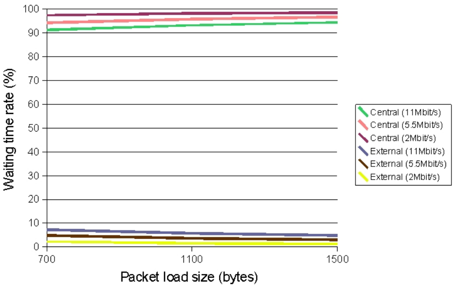

Figure 12: Waiting time distribution

Other results which are not presented here show that: (i) for the central pair, decreasing its DIFS counts only for less than 0.5% of its time in the best case ($11Mbits/s$); (ii) the time ratio where the EIFS is decreased is unsignificant ($< 0.2\%$); (iii) the central pair decreases the backoff during less than 1% of the time while the external pairs decrease their backoff during about 10% of the time.

5.2.2 Scenario 2

In this case, $Pair\_A$ is the pair which suffers from the protocol malfunctioning. As we have seen in Section 2.2.2, this pair is fully independent and thus is completely free to use the channel whenever it has a packet to transmit. Therefore computing the waiting time distribution in this context is not pertinent. However the DIFS and the backoff distributions are pertinent values to compute since $Pair\_A$ spends a lot of its time retransmitting its packets because of the collision phenomenon characterising this scenario. Figure 13 shows that $Pair\_A$ spends more time in decreasing its DIFS counter than the central pair in the previous scenario and even more than the external pairs.

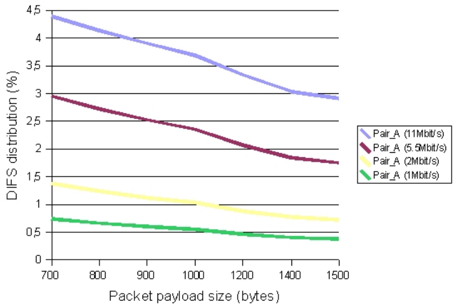

Figure 13: DIFS distribution

Other results show that $Pair\_A$ may spend a lot of time decreasing its backoff. It may reach 18% when the medium throughput is important ($11Mbits/s$). This represents almost twice the time spent by an external pair in the first scenario. This is due to the high percentage of transmissions with collisions that this pair may experience. $Pair\_A$ spends also almost 1% of its time resizing its transmission window when the channel throughput is $11Mbits/s$. Increasing or decreasing the size of the transmission window is not a time consuming task, but as the pair has to do it each time a collision happens, it ends up doing it often.

5.2.3 Scenario 3

The EIFS and the DIFS time distributions, and the backoff distribution for *Pair_B* are computed. It is important to note that the penalized pair (*Pair_B*) has the highest medium utilisation rate of the penalized nodes of all scenarios. As Figure 14 shows, the distribution time of the EIFS interframe spacing is important because of the interactions between the transmitter B_1 and the receiver A_2.

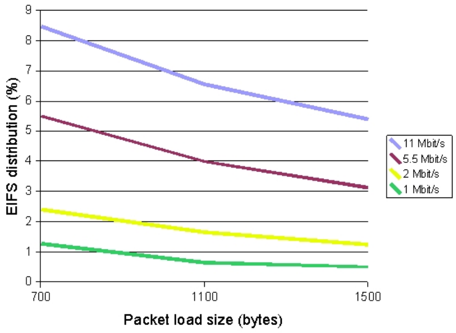

Figure 14: EIFS distribution (*Pair_B*)

Other results not shown here indicate that *Pair_B* undergoes much more the EIFS mechanism than the DIFS mechanism. This is due to the property $SR(B1, A2)$ (see 2.3.3). It is also interesting to note that, when comparing these results with the ones obtained for the first scenario, *Pair_B* (the penalized pair in the third scenario) spends more time in decreasing its DIFS counter than the central pair and less time than the external pairs.

Moreover *Pair_B* decreases its backoff during about 1% of its time in the worst case ($1Mbits/s$). Remember that 1% is the best case for the central pair of scenario 1 whereas it is 10% for the external pairs. Like for the EIFS counter, the penalized pair of the third scenario spends more time decreasing its backoff than the central pair and less time than the external pairs. Similarly, *Pair_A* of the second scenario spends more time (almost three times) decreasing its backoff than *Pair_B* in the current scenario.

As the utilisation results, the results obtained for the third scenario show that this scenario is the best one because the unfairness of the protocol is much less striking. Globally all results we have obtained show that the third scenario is the one approaching the ideal scenario.

6. CONCLUSION

In this paper, we have investigated the fairness issue in mobile ad hoc networks using 802.11 technology. We have analysed the performance of the WiFi protocol in the context of the three configurations where unfairness has been reported. For that we have developed an analytical model using the process algebra formalism PEPA. The resulting model appears to be generic to model any communicating pair which implements 802.11b, the interactions between the pairs being captured by the medium component.

For each scenario, the different stages of the protocol are investigated and the utilisation of the medium computed. In the first scenario, unfairness is due to the medium sharing with the other nodes. In the second scenario, because of the collisions the penalized node spends most of its time retransmitting its packets. Even if the penalized pair of the third scenario undergoes more the EIFS/DIFS mechanisms, this scenario appreared to be the best of the three scenarios. The results of the last scenario have shown that the effect of the protocol malfunctioning is more complex that it seems as they suggest that as long as a certain degree of the protocol malfunctioning is not reached the expected behaviour of the channel utilisation rate may be preserved.

In the future, we are interested in the use of the generic model as a mean to study the main interactions in the wireless environment of MANET. Because of the unfairness of 802.11, it is necessary to investigate the conception of a new medium access protocol for MANET where fairness will be supported. Our generic model will be usefull to validate the new approach.

7. REFERENCES

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