Adaptive Probabilistic NAV to Increase Fairness in Ad Hoc 802.11 MAC Layer

Claude Chaudet* Guillaume Chelius† Hervé Meunier‡
David Simplot-Ryl‡

* ENST / GET – Infres department – 37/39, rue Darreau, 75014 Paris, FRANCE – Claude.Chaudet@enst.fr

† CITI/INRIA ARES – INSA de Lyon – Bât L. de Vinci – 21, avenue J. Capelle – 69621 Villeurbanne, FRANCE – guillaume.chelius@inria.fr

‡ IRCICA/LIFL, Univ. Lille 1, CNRS UMR 8022 – INRIA Futurs, POPS research group – Bât. M3, Cité Scientifique – 59655 Villeneuve d'Ascq Cedex, FRANCE – {meunier,simplot}@lifl.fr

Abstract

The IEEE 802.11 MAC layer is known for its low performances in wireless ad hoc networks. For instance, it was shown in the litterature that two independent emitters nodes can easily monopolize the medium, preventing other nodes to send packets. The protocol we introduce in this article is a simple variation of the original 802.11 MAC layer which significantly increases the fairness while maintaining a high effective bandwidth. Its principle consists in avoiding systematic successive transmissions by the same emitter through the probabilistic introduction of a waiting time, a virtual NAV, after each emission. The probability to set a NAV is adaptively computed depending on the perceived utility of the previous virtual NAV. This protocol, called PNAV (*Probabilistic NAV*), is shown to be efficient by simulation and is compared to another 802.11 adaptation.

1 Introduction

Medium-access control (MAC) protocols for wireless networks have received a considerable attention over the past few years with the aim to reduce the number of collisions while maximizing the bandwidth use. Collisions occur when a node is in the neighborhood of two simultaneous transmitters. If the transmitting stations are neighboring nodes, the collision probability can be reduced through the use of a simple random backoff algorithm and a carrier sense mechanism. These principles are the basics of the widely-used CSMA protocol family. If the transmitting stations cannot communicate directly, the collision risk is increased due to the absence of carrier sense. This problem was first introduced by Tobagi and Kleinrock in [13] and is known as the "hidden terminal problem". Several solutions have been proposed to resolve this problem. For instance, communicating nodes can exchange short control messages to inform their neighborhood of the forthcoming data frame. In the IEEE 802.11 *Dis-*

tributed Coordination Function (DCF), a node initiating a communication first sends a request-to-send (RTS) frame to the receiver. If the intended receiver correctly receives the RTS frame and if the medium is free in its vicinity, this latest answers with a clear-to-send (CTS). Upon reception of the CTS frame, the sender transmits its data frame. The RTS and CTS control frames contain the duration of the subsequent data exchange, which gives the opportunity to all neighboring nodes to be aware of the medium occupation induced by the communication. More precisely, nodes that receive RTS and/or CTS frames set a "Network Allocation Vector" (NAV) for the duration of the exchange and will restrain from transmitting during this period.

In addition to collisions, the hidden terminal situation is responsible for several issues. Ng and Liew have showed that along a node string in a multi-hop network, all nodes do not have the same medium access [14]. The unfairness of the MAC protocol is also clearly exhibited by Chaudet *et al.* [10]. They propose a simple scenario with three pairs of emitters and receivers where two pairs capture the totality of the medium while the third one has no opportunity to compete for the medium access. Such typical scenarios appear when the medium is saturated. There have been some proposals to solve these issues and they usually lead to a traffic limitation. In this paper, we address the fairness problem while ensuring an efficient use of the channel bandwidth. We propose a simple modification of the MAC layer where nodes can probabilistically set a virtual NAV after each sent frame. The probability to introduce such a NAV is adaptively computed according to its observed utility. We show that our approach is efficient compared to already existing solutions. This MAC protocol is called PNAV for Probabilistic NAV and is fully compatible with the IEEE 802.11 standard.

The remaining of the paper is organized as follows. The next section is dedicated to the IEEE 802.11 MAC layer and a literature review of related works. We describe our proposal in Section 3. Sections 4 and 5 are dedicated to evaluations. In Section 4, we describe the simulation environment and results are given in Section 5. The Section 6 concludes the paper and presents the future works.

2 Related Works

2.1 Description of IEEE 802.11

The IEEE 802.11 [12] distributed medium access, the *Distributed Coordination Function* (DCF), is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) principles. Before emitting a frame, nodes sense the channel to determine whether the medium is free or not. If the medium is free, the frame is emitted after a constant period of time called $DIFS$.

When the medium is busy, the frame transmission is deferred until the medium becomes free again. To prevent collisions between multiple waiting emitters, in addition to $DIFS$, nodes have to wait during a random time called *backoff* – an integer number of constant duration time-slots – during which the medium shall stay idle. The backoff is decremented slot by slot. As soon as this counter reaches a null value, the frame is emitted. If the medium becomes busy during this waiting process, the process is suspended and will be resumed as soon as the medium is freed again, with the remaining number of slots as the new backoff value.

When an emitter gains access to the medium, the whole frame is transmitted. Collisions can happen, for instance when two emitters draw the same backoff. Collision detection is impossible in radio networks and nodes can only be aware of the proper reception of a frame by the reception of the corresponding MAC-level acknowledgment.

To address the hidden nodes situation, an optional RTS-CTS mechanism can be triggered. RTS-CTS exchange prior to transmission forces a medium reservation in a one-hop neighborhood of both of the communicating peers. Upon reception of such a message, a node will consider the medium busy for the duration of the subsequent transmission. This process is called *virtual carrier sense*. For more details on this protocol, the reader shall refer directly to the standard [12].

This protocol has been originally designed for infrastructure-based networks, operating under a base station authority. Nevertheless, its distributed operation seemed suited for ad hoc networking. Since then, numerous works have put into light performance and fairness issues with this standard in a multi-hop context. Only a few solutions have been proposed to address these problems.

2.2 Literature Review

The *binary exponential backoff* (BEB) procedure used by the IEEE 802.11 DCF has been questioned regarding fairness and performance for a long time. In MACAW [2], Bharghavan *et al.* compare the performances of a Multiplicative Increase Linear Decrease backoff algorithm and show that this mechanism achieves better overall throughput and fairness that the classical BEB algorithm.

Ozugur *et al.*, in [15] study a per-link $p_{i,j}$-persistent backoff algorithm based on a fairness index computed as the ratio between the maximum link throughput over the minimum link throughput, and on the number of connexions on each link. In this scheme, each user shall regularly broadcast information on the number of logical connexions or the average contention time to all of its neighbors.

In [16], the P-Mac protocol intends on finding the optimal contention window to enhance overall performances and enforce weighted fairness among stations. The contention window is determined dynamically, based on the time passed to wait for the channel, on the idle time and on the estimated number of stations in the contention area.

In [1] Bensaou *et al.* present an algorithm aiming to enforce weighted fairness among stations. For each emitter i, they define a channel proportion the emitter should try to obtain, ϕ_i and its achieved throughput W_i. The ϕ_i proportion can be tuned for instance to reflect the number of flows routed by the terminals. The goal of the algorithm is to adjust contention widows sizes in order to equalize the ratios W_i/ϕ_i in the network, for any couple of stations. Practically, the stations tune their contention windows by considering their whole set of neighbors as a single emitter. [17] takes into account variable packet sizes and treats the case in which RTS-CTS exchange is not used. Nevertheless, this schemes only takes into account frames that can be decoded to update statistics.

[3] have introduced DCC, a lightweight modification of the transmission mode of the IEEE 802.11 protocol. Each station regularly computes a value called *Slot_Utilization*, *i.e.* the ratio between the number of busy slots over the number of available slots during a period of time. This value reflects the level of usage of the radio channel. Whenever a backoff expires and a frame is ready to be transmitted, a transmission probability is computed according to the *Slot_Utilization* value and to the number of unsuccessful previous transmission attempts. An emitter transmits the frame according to this probability. This additional contention level makes emitters restrain from transmitting when-

ever the medium becomes overloaded, preventing collisions and therefore enhancing the protocol performances. [4] enhances this mechanism whenever the optimal *Slot_Utilization* is known, i.e. the slot utilization representing the best compromise between time spent in collisions and time spent refraining from transmitting. In this case, the probability of transmission can be tuned to aim reaching this *Slot_Utilization*.

In [8], Cal *et al.* have computed the performance of a p-persistent IEEE 802.11. They show that this protocol exhibits similar performances, in terms of throughput, as the regular BEB-based IEEE 802.11. Based on this modeling, a backoff tuning scheme has been designed in [5, 9] but it requires an estimation of the number of stations to reach its optimal performance. [6] shows that the product of the number of stations by the p value leading to the optimal performance is asymptotically constant and [4] uses this result to derive the optimal *Slot_Utilization* value, called *Asymptic Contention Limit* (ACL) which is only dependent on the average frame size. The resulting scheme, *Asymptotic Optimal Backoff* (AOB) exhibits performances close to the theoretical optimal capacity of the IEEE 802.11 protocol. [7] solves the fairness issue appearing when regular 802.11 stations contend with AOB-enhanced stations by introducing a *credits* mechanism. A station refraining from transmitting because of the probability of transmission will be granted later on backoff-free transmissions to compensate its time loss. This article also provides an ACL value computed according to HR-DSSS, the high rate transmission layer of IEEE 802.11b.

3 Probabilistic NAV

Under certain circumstances, the 802.11 DCF function leads to an unbalanced bandwidth repartition or different medium access probabilities between different radio links. For example, let us consider the three pairs topology intensively studied in [10, 11] and showed on Figure 1. In this scenario, three emitters contend for medium access. The topology is unbalanced and one emitter compete with the two others while the other ones only have to deal with the central emitter. Neighbor emitters are in mutual carrier-sense range but cannot directly communicate.

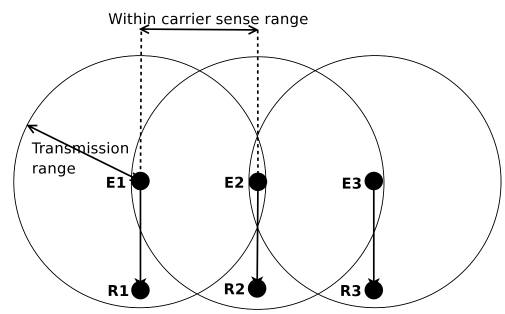

Figure 1: 3-pair topology.

the pair in the middle never gains access to the medium which is monopolized by the exterior pairs. In this configuration, the exterior pairs do not even get knowledge of the middle one trying to access the medium. In consequence, 802.11 DCF adaptations such as AOB [4] which estimates the medium occupation using the emitters' perception of the state of the medium, only slighlty increase the fairness of 802.11 in this situation. As the middle pair is dumb, exterior pairs do not hear any other communications, do not delay transmission through the classical backoff or NAV mechanisms and thus consider an unoccupied medium which in turns reduce the efficiency of the AOB protocol.

In the presence of dumb radio links, the only way to increase the fairness is to give these links an opportunity to express themselves. This may be done through the introduction of NAV in the 802.11 layer of nodes which frequently access the medium. These silence periods may give the opportunity to dumb radio links to transmit packets and to notify their presence to all surrounding nodes which could in turn activate mechanisms to increase fairness.

Our proposal, PNAV – for *Probabilistic NAV* –, follows this strategy. According to a varying probability, a node sets a NAV of duration δ after a transmission in order to give other nodes the possibility to gain access to the medium. The NAV probability, p_{nav}, is a function of both the node and other nodes' use of the medium. Qualitatively, it helps emitters answer questions such as "*am I monopolizing the medium?*" or "*did my last NAV give an opportunity to another node's communication?*". We describe the protocol in this section.

3.1 Event-Driven System

In order to estimate the medium occupancy induced by a particular node, we identify three different events. These events will be used by the PNAV automaton to adapt the node probability to introduce a NAV after each of its emissions. The events are the followings and are depicted in Figure 2:

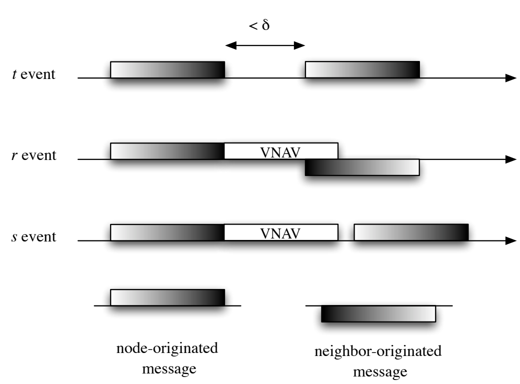

Figure 2: Events descriptions

- ***t* event**: the *t* event occurs when the considered emitter acquires the medium for two successive transmissions with an inter-emission period inferior to the NAV duration, δ.
- ***r* event**: the *r* event occurs under two conditions. First, the considered mobile has set a probabilistic NAV after its last emission; second, the medium has been acquired by another node before the NAV expiration.
- ***s* event**: the *s* event occurs under two conditions. First, the considered node has introduced a probabilistic NAV after its last emission; second, the medium has been reacquired by the considered node after expiration of the NAV.

These three events may be easily interpreted in term of a node's medium occupancy. If a node u only keeps on experiencing *t* events, it means that it is monopolizing the medium. Occurrence of an *r* transmission means that the introduction of the NAV has been successful in term of medium fairness as this silence period has been used by another node to access the medium. Finally, occurrence of the *s* event signifies that the introduced PNAV was not necessary as the associated silence period has not been successfully used by another node to access the medium. We will see in the following sections how these events can be used to efficiently adapt the probability to introduce a NAV after one's emission.

3.2 Automaton description

As described at the beginning of the section, the PNAV mechanism adapts the probability to introduce a NAV depending on the medium occupation that can be observed from one node. Three events have been identified in the previous subsection and we will now describe how the observation of one identified event impact on the NAV probability. Initially, the NAV probability, p_{nav} is set to 0. Upon observation of a *t* event, this probability is increased by p_{step}. A *t* event signifies that the considered node is consecutively acquiring the medium without giving the opportunity to dumb nodes to express themselves. In consequence, we increase the probability to introduce a NAV after the node's next emission in order to give other nodes a chance to acquire the medium.

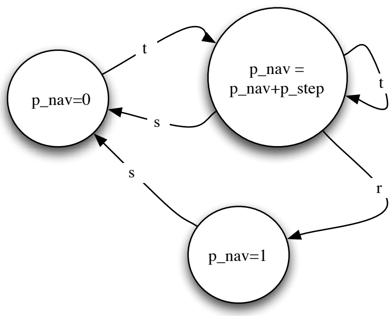

Figure 3: PNAV automaton

Upon an *r* event, p_{nav} is set to 1 and a NAV is systematically set as long as no *s* event occurs. An *r* event indicates that the previously introduced NAV has been an opportunity for other nodes to transmit packets. As a consequence, the node should keep on introducing NAV in order to keep on providing other nodes the opportunity to acquire the medium. Finally, upon a *s* event, p_{nav} is reinitialized to 0. The previously introduced NAV having remained useless, we reinitialize the probability to 0 so that NAV will be introduced only after observation of new t events. The automaton determining p_{nav} in function of the different events is depicted on Figure 3. The main concerns behind the automaton functioning are to introduce NAV as soon as a node is monopolizing the medium (*t* event), to keep on introducing NAV if they are useful (*r* event) and finally not to introduce a NAV if it is useless. The last point is important as it is the one ensuring a low bandwidth waste if the considered node is the only one competing to access the medium.

The PNAV mechanism depends on two parameters p_{step} and δ. We will see in Section 5 how they can affect the performances of the protocol, its fairness as well as the bandwidth decrease it induces.

4 Evaluations

This section focuses on introducing the simulation environment and the scenarios we used in order to study some equity issues observed in IEEE 802.11 DCF.

4.1 Environnement

Simulations in this study basically involve several parallel pairs of nodes, each pair having an emitter node trying to transmit its traffic to a receiver node. For example, figure 1 illustrates this topology considering 3 parallel pairs. We will first consider that parameters are set in such a way that an emitter node only senses and can communicate with its two closest neighbors (inter-pair distance: 150 m, radio range: 160 m, carrier sense: 160 m). Then we will increase the carrier sense distance and finally fall to the scenarios depicted earlier. Beside the basic parallel pairs, we evaluate the impact of our proposition on chained nodes and random network topologies. These experiments are conducted as follows: given a topology of nodes (couples of emitter/receiver nodes), we basically generate a saturated traffic from the emitters to their respective receivers and we log the amount of data successfully received during the simulation process.

The main parameters for these simulations are given in the table 1.

The MAC protocols considered in this study have been implemented into the widely used

Table 1: Simulation parameters.

Inter-node distance	150 m
Carrier sensing range	400 m or 160 m
Traffic generator	CBR saturated
Frame size	1000 bytes
Simulation duration	30 s
Channel bandwidth	11 Mb/s

network simulator NS-2[1], including the AOB flavor prensented in [4] with the correct ACL and our proposition PNAV.

4.2 Scenarios

4.2.1 Parallel pair scenarios

The simplest scenario, a single emitter and a single receiver with a saturated traffic, provides the opportunity to rate the maximum bandwidth provided in no-competition conditions.

The 2-pair saturated traffic scenario will also be evaluated in order to rate the maximum bandwidth over a shared channel, and thus, to rate the synchronization ability of the MAC protocol.

The 3-pair scenario enlightens the typical issue about the fairness of most ad hoc MAC protocols. The middle emitter node has to compete for medium access, with emitters from both sides, which themselves do not have to compete with each other. IEEE 802.11 DCF equity issues typically arise in this topology.

Further increasing the number of pairs then leads to similar fairness issues, whose characteristics depend on the number of pairs.

4.2.2 Chain

Besides parallel flows, we will evaluate the impact of chained flows. This topology is illustrated on figure 4. One traffic flow runs from A to B, another one from B to C, *etc*. Note that this situation is different from the one in which a flow is routed through the whole string of nodes. In this situation, we evaluate the routing capacity of each hop independently.

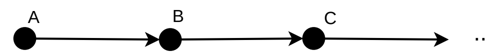

Figure 4: Chain topology.

4.2.3 Random topology

Finally, we will simulate the different MAC adaptations in a pseudo real world network topology: a uniformly randomly located set of nodes where a given number of flows is transmitted between random nodes.

5 Performance evaluation

In this section, we present an analytical evaluation of the loss of bandwidth that can be expected on a single link and simulation results for the larger scenarios described above. Simulations were performed using the network simulator NS-2 in version 2.27 with MAC and physical parameters tuned to reflect the HR-DSSS 11 Mb/s physical layer of IEEE 802.11b. Simulation results presented in this section are the average of the throughput mean and standard deviation of each flow, computed over 20 simulations. To evaluate the performance of the sole MAC protocol, we used a static routing agent for NS-2 developed by T. Razafindralambo, computing offline shortest-paths between any pairs of nodes. Other sources of traffic such as ARP have been disabled. Results presented here only concern transmissions without RTS-CTS exchange. Simulations also have been

[1] http://www.isi.edu/nsnam/ns/index.html

performed with RTS-CTS activated and the conclusions are similar in each of these situations, even though the overall performance is different.

5.1 Single pair

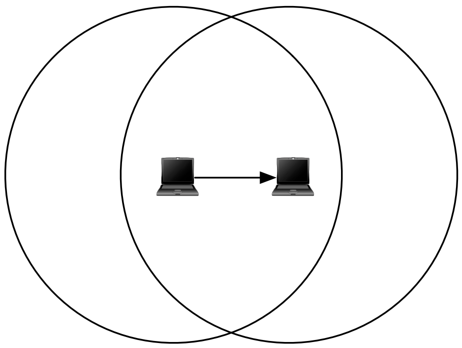

Figure 5: The single pair topology

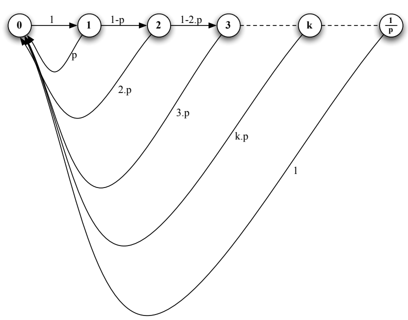

Figure 6: A markov chain describing the automaton behavior in the single pair case

To begin with the performance analysis of the PNAV mechanism, we consider a single communicating pair. This configuration is illustrated in figure 5. The aim of this first study is to evaluate the waste of bandwidth introduced by the probabilistic NAV when there is no contention on the medium. Indeed, PNAV decreases the maximum bandwidth that can be achieved by a lone communication. Consider node u communicating with node v at a packet rate such that the inter-emission period is inferior to δ. Node u will observe consecutive *t* transitions until it sets a NAV. This NAV will not be used by any other communication as u is the only transmitting node and a *s* transition will occur, reinitializing p_{nav} to zero. The phenomenon will be repeated periodically, introducing NAVs which are periods that can not be used by u to transmit packets and thus decreasing the effective bandwidth of the communication between u and v. We will now try to evaluate this bandwidth waste as a function of the parameters δ and p_{step}.

Let N_{nav} be the random variable associated to the number of emissions between two probabilistic NAV. As there is only one pair communicating, the only possible transitions are *t* and *r* depending on wether or not a NAV has been introduced after the preceding emission. The automaton behavior can be modeled with a simple markov chain described by Figure 6. In consequence, it is quite simple to compute the expected number of emissions $\mathrm{E(N_{nav})}$ between two NAV.

$$p(N_{nav} = k) = k.p_{step}.\Pi_{i=0}^{k-1}(1 - i.p_{step})$$

$$\mathrm{E}(N_{nav}) = \sum_{k=1}^{\frac{1}{p_{step}}} k^2.p_{step}.\Pi_{i=0}^{k-1}(1 - i.p_{step})$$

Given $\mathrm{E(N_{nav})}$ and depending on δ, we can also deduce the decrease of effective bandwidth in the case of a single communicating pair. It is illustrated by figure 8. As we can see on the picture, the effective bandwidth of PNAV is close to the maximum available bandwidh (3600 kb/s) even with large values for δ if we consider small values for p_{step}.

5.2 Other topologies

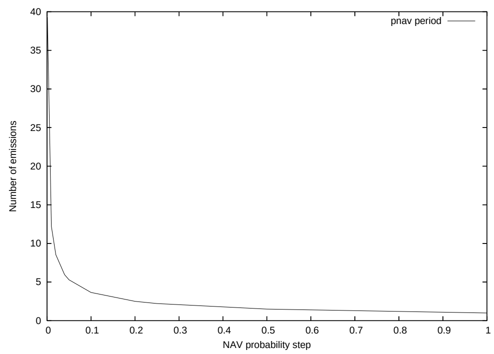

Figure 7: NAV frequency for a single pair

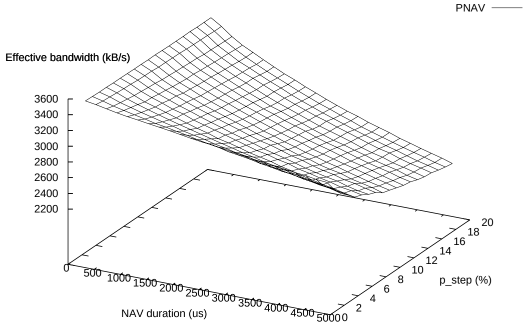

Figure 8: Effective bandwidth of a single pair using PNAV

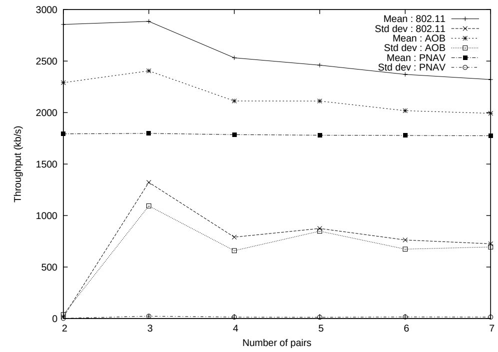

Figure 9: Throughput means and standard deviations for different configurations - carrier sense range identical to transmission range.

We first simulated two to seven parallel pairs separated by a distance close to the transmission range with a carrier sense area equal to the transmission area. Emitters only compete with their direct neighbors and no collision occurs because the receivers are near enough of their associate emitters to prevent signal jamming. This kind of scenario can happen in an indoor context, for instance. Its purpose is to give basic evaluation of the performance of the different solutions, without signal-level concerns.

Figure 9 presents the achieved throughput means and standard deviations in function of the number of parallel pairs. A first observation is that using PNAV leads to an almost null standard deviation, improving fairness, but at the cost of overall performance. AOB also presents a mean throughput decrease and leads to a fairness only a little better than the one achieved by IEEE 802.11.

Increasing the carrier sense range so that emitters compete for medium access with two-hops neighbors leads to the results presented on Figure 10. On this figure, AOB and PNAV result

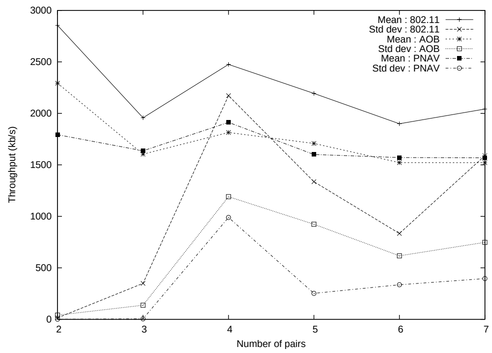

Figure 10: Throughput means and standard deviations for different configurations - large carrier sense

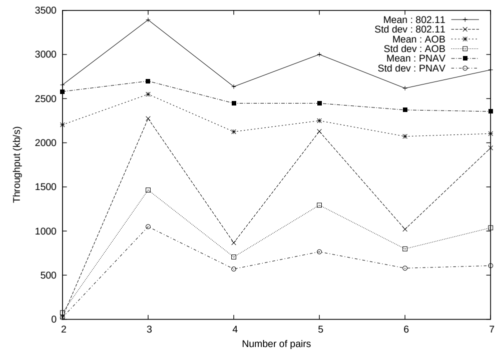

Figure 11: Throughput means and standard deviations for different configurations - neighbor pairs cannot communicate

in similar mean throughput but PNAV improves fairness. The standard deviation peaks for 4-pairs and 7-pairs configurations are due to the particularities of the topology. Let's consider, for instance the 4-pairs scenario. In this situation the central emitters have to compete with all three other emitters for medium access while the exterior ones only compete with two others. This unbalance tends to prevent central nodes from transmitting, leaving a greater share of the medium to the exterior nodes. The 7-pairs situation is indeed the aggregation of two times the 4-pairs situations. Exterior pairs and the very central pair are favored.

Finally, let us consider the three-pairs scenario as it was presented in [10, 11] and its generalizations. Neighbor emitters are now no more able to communicate with each other, but they still share the medium though. Figure 11 presents the corresponding simulation results. In these situations, PNAV leads to a channel use between regular 802.11 and AOB and achieves the best fairness among the three protocols.

These results on parallel pairs show that the additional waiting time introduced by PNAV is useful in the situations in which a node takes the whole medium and a neighbor is starved.

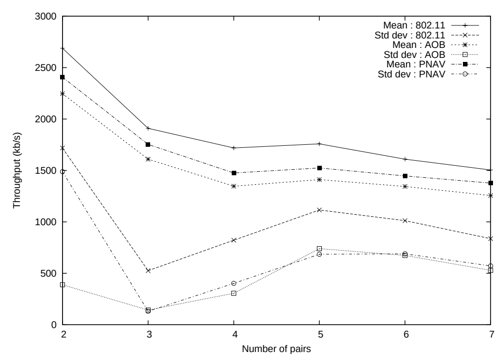

Figure 12: Throughput means and standard deviations for different chains configurations

The simulation results for chains topologies are presented on Figure 12. In these topologies, PNAV achieves good channel utilization for a fairness level similar to the one achieved by AOB.

Finally, simulations have been performed on different random topologies. Examples of these results, for 15 and 30 nodes networks in a 500 m square area with 2 to 15 active flows are presented on Figure 13. Results are similar regardless of the parameters of the simulation, statistically, PNAV improves the fairness of the medium access and does not cost a high amount of bandwidth. AOB usually leads to a better fairness but also more reduces the channel use.

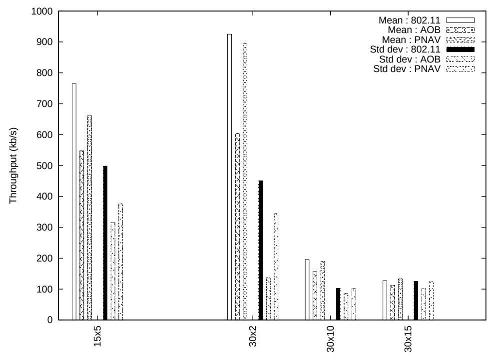

Figure 13: Throughput means and standard deviations for some random configurations

6 Conclusion

In this paper, we have presented PNAV, an adaptation of the IEEE 802.11 DCF protocol in order to increase its fairness in an ad hoc environment. Contrarily to other proposals using the medium occupation – the slot utilization metric for AOB – as an input to the system, our protocol is event-driven. It consists in introducing probabilistic NAV depending on events observed on the radio medium. These events can be qualitatively described as "*I am monopolizing the medium*" or "*my PNAV has been useful for someone's else communication*". The probability to introduce a NAV evolves depending on these events. PNAV has been simulated in several topologies known for their 802.11 DCF fairness issues, the pairs and the chain topologies, as well as pseudo-realistic topologies. It has shown very satisfying performances, inducing more fairness between the different flows than a classical IEEE 802.11 DCF and AOB as well depending on the considered topology, while maintaining a high overall throughput, lower than a classical IEEE 802.11 DCF but higher than AOB.

If the results observed by simulations are promising, several works remain to be done. A theoretical analysis of the PNAV automaton and the NAV probability function is an interesting perspective as it may enlighten the existence of an optimal NAV probability as a function of the network topology. A similar work as been done in [4] in the AOB context. Other radio medium events can also be considered in order to refine the PNAV automaton with the aim to continue on increasing the MAC protocol fairness while maintaining a high achieved throughput. We also plan on sudying the behavior of the proposed protocol when used in networks called *heterogeneous* by [7], i.e. network composed of emitters using different MAC strategies.

Finally, an interesting point is that the PNAV protocol is not incompatible with other 802.11 DCF adaptations such as AOB. They present two different approaches that could be combined. While AOB monitors the radio occupation to adapt its deferring probability, PNAV uses different events such as successive transmissions to decide to relinquish the medium. The consequence is that both protocols show their best performances in different topologies. An interesting study would be to combine both of them in order to see whether the resulting adaptation would inherit from both good performances.

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