Fairness issues in a chain of IEEE 802.11 emitters

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Abstract— **We study a simple general scenario of ad hoc networks based on IEEE 802.11 wireless communications, consisting in a chain of emitters, each of them being in the carrier sense area of its neighbors. Each emitter always attempts to send some data frames to one receiver in its transmission area, forming a pair emitter-receiver. This scenario encompass the three pairs fairness problem introduced in [1], and allows to study some fairness issues of the IEEE 802.11 medium access mechanism.**

We show by simulation that interesting phenomena appear, depending on the number n of pairs in the chain and of its parity. We also point out a notable asymptotic behavior. We introduce a powerful modeling, by simply considering the probability for a transmitter to send data while its neighbors are waiting. This model leads to a non-linear system of equations, which matches very well the simulations, and which allows to study both small and very large chains.

We then analyze the fairness issue in the chain regarding some parameters, as well as the asymptotic behavior. By studying very long chains, we notice very good asymptotic fairness of the IEEE 802.11 medium sharing mechanism.

I. Introduction

A. Motivations

Recently, wireless networks have increasingly received attention from the networking community. Although several wireless communication standards have been proposed, the IEEE 802.11 protocol [2] is the most widely used, and constitutes the de facto solution for practical network connection offering mobility, flexibility, low cost of deployment and use. This success leads to many studies of the protocol, in various situations (either ad hoc or with access point) and by different means (experimentation, simulation, modeling). It remains that, besides its qualities, the 802.11 protocol, and particularly its medium access control mechanism, suffers from some imperfections in terms of global throughput and fairness between nodes. Our work deals with some fairness issues with 802.11 protocol in ad hoc mode.

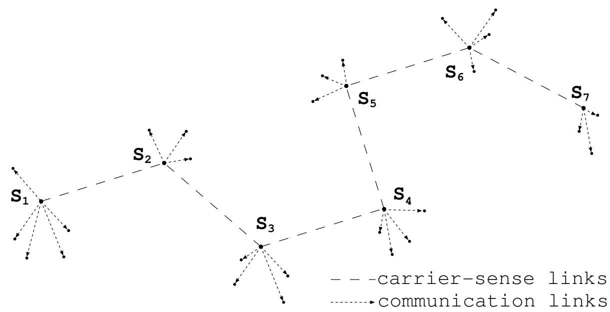

Fig. 1. A chain of emitters.

Since it is not practicable to detect a collision in wireless communications (to the contrary of wired networks with 802.3 Ethernet for instance), the 802.11 *Medium Access Control* (MAC) layer implements a *Carrier Sense Multiple Access/Collision Avoidance* (CSMA/CA) method in the *Distributed Control Function* (DCF). Instead of waiting after a collision has occurred (as in Ethernet), any emitter waits preventively before any sending. The waiting is composed of a fixed *Inter-Frame Space* (IFS) and a random delay. Both are decreased only when the medium is idle (which means that no neighbor is sending). The fixed delay depends on the situation, for instance: Short IFS (SIFS) between a frame and its acknowledgment, DCF IFS (DIFS) before any new data frame and Extended IFS (EIFS) if a station receives a communication that it cannot understand because of the distance (more details can be found in [3]).

We study a simple but general scenario, where some nodes (hereby called *emitters*) try to continuously send some data to one of their neighbors (hereby called *receivers*), not necessarily always the same. The emitters form a chain, each of which being in the carrier sense area of its neighbors (Figure 1).

Thanks to this scenario, we exhibit and study some interesting fairness issues in the DCF function of the 802.11 MAC layer. For a given pair, the probability to

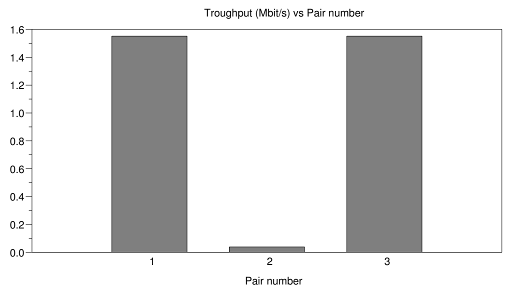

Fig. 2. Fairness problem with three pairs.

gain access to the channel depends on the order number of a pair in the chain, on the length of the chain, and on the probability to send a packet while the neighbors are idle (which is not 1 because of preventive waiting in the CSMA/CA based DCF function). Moreover, while the fairness is poor with few nodes, it appears that it tends to a kind of optimality when the length of the chain increases, which is a quite surprising result.

B. Related works

There is a large amount of literature dealing with the performances of the IEEE 802.11 DCF function responsible of the radio medium sharing (see [3] and the references herein). Due to space limitation, we only focus on previous works related to the chain of pairs.

In [1], the authors study a scenario composed of three pairs placed in such a way that the emitters can detect an emission in a neighbor pair without fully understanding the packet. They show that the central pair obtains a very poor throughput compared to the border pairs (Figure 2). For instance, with a sending rate of 2 Mbits/s, the central pair has only a throughput of 0.04 Mbits/s compared to 1.55 Mbits/s for the external ones (the throughput of a single alone pair is 1.59 Mbits/s in this situation).

This is a particular case of the chain of emitters scenario we study in this paper. It combines both EIFS delay mechanism and asymmetry of the chain in terms of number of neighbor emitters. To explain these results, one can remark that the central pair has to compete with two neighbors to access the channel, and then a smaller throughput than the border pairs (which have only to compete with one neighbor) is expected. Moreover, here the EIFS delay is used when a neighbor is sending, and this happens more frequently for the central pair.

In [4], a mathematical modeling has been proposed for the three pairs configuration, by means of discrete time Markov chains. Such a modeling gives numerical results close to the simulations obtained with the ns-2 network simulator, and not so far from real experiments of [1].

C. Contributions and outlines

We show that interesting phenomena appear when the number of pairs increases in the chain. We provide a powerful modeling which leads, among others, to interesting conclusions in terms of fairness both for small and large chains. This analysis allows us to better understand the DCF properties and to optimize the fairness in a chain by means of packet size tuning.

In Section II, we exhibit interesting results by simulation using Network Simulator when varying the number n of pairs: i) chance to gain access to the medium for the ith emitter-receiver pair depends on the parity of i, ii) the fairness increases with n especially for central pairs and iii) the system has an asymptotic behavior when n increases.

In Section III, we introduce a new modeling of such a phenomenon. Although it is quite simple, it allows to match results of simulations both for small and large values of n, depending on a α coefficient. This coefficient corresponds to the probability of emission when the neighbor emitters are waiting.

In Section IV, we prove that a stationary state exists for each pair for any length of the chain. Moreover, this stationary state converge to an asymptotic stationary state when n increases. This confirms the simulations. We also show that some values of α allows to maximize the fairness, expressed as entropy [5].

In Section V, we comment these results, and we show that when n is large, the fairness is almost optimal near the center of the chain. We also show that the simulation results tend to this ideal case when n increases, which mean that the fairness in the chain tends to a kind of optimality when its length increases. This is an interesting result. Finally, we sketch the relationship between α and the IEEE 802.11 protocol.

Concluding remarks as well as applications of this work are given in Section VI.

II. SIMULATION OF A CHAIN OF EMITTERS

A. Configuration and parameters

Our simulations have been done using Network Simulator v2.28 [6], with parameters described previously and corresponding to a Lucent Orinoco 802.11b device [7], [3]. Without loss of generality, we assume a single receiver per emitter and a chain arranged as in Fig. 3.

The data rate has been fixed to 2 Mbits/s, leading to the use of the EIFS delay with the configuration of

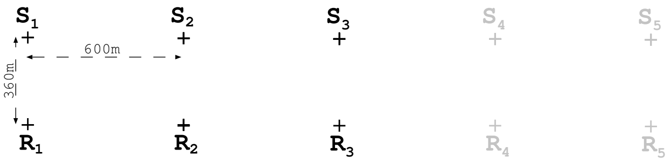

Fig. 3. Chain of emitter-receiver used for the simulations with the parameters of a Lucent Orinoco 802.11b device at 2 Mbits/s in outdoor environment (carrier sense: 670m, transmis. range: 400m).

Fig. 3. Each emitter always tries to send some UDP packets corresponding to a 1500 bytes MAC frame, using the RTS/CTS mechanism. Note that we did not notice a significant influence of RTS/CTS mechanism. The propagation model is the *two-ray ground*, corresponding to an outdoor environment with a single reflection on the ground. Others parameters are: transmission power (15 dBm), antenna height (0.9 m), receiving threshold (-91dBm), carrier sense threshold (-100dBm) [7]. The next sections summarizes some results when the number of pairs is varying [3].

B. Simulations results in the chain

For four pairs (Fig. 4), the external pairs have a throughput around 1.06 Mbits/s, whereas the two central ones reach only 0.53 Mbits/s. However, fairness is better than with three pairs. Indeed, when the pair 1 acquires the channel, pair 2 is waiting and then pairs 3 and 4 have both a single competitor. By comparison with the three pairs chain, when the pair 1 acquires the channel, the other border pair always gains access to the channel. Hence, with four pairs, the central pairs can have a more frequent access to the channel than the central pair in a chain of three pairs.

With five pairs, pairs 1, 3 and 5 have throughputs close to the maximum, whereas pairs 1 and 2 have very low throughputs. Indeed, when the pair 1 gains access to the channel, the pair two is waiting and the pairs 3, 4 and 5 have a similar behavior than a three pair chain. We observed a similar phenomenon with 7, 9 and 11 pairs.

With 6 pairs, pairs 2 and 5 have less bandwidth than central pairs 3 and 4, and that central pairs in the chain of four pairs. Here, even if the border pair 6 acquires the channel, pair 2 could have more than one competitor, which is not the case in a chain of four pairs. Note that the pattern can also be seen as two neighbors chains of three pairs. Similar behaviors are observed with 8 pairs.

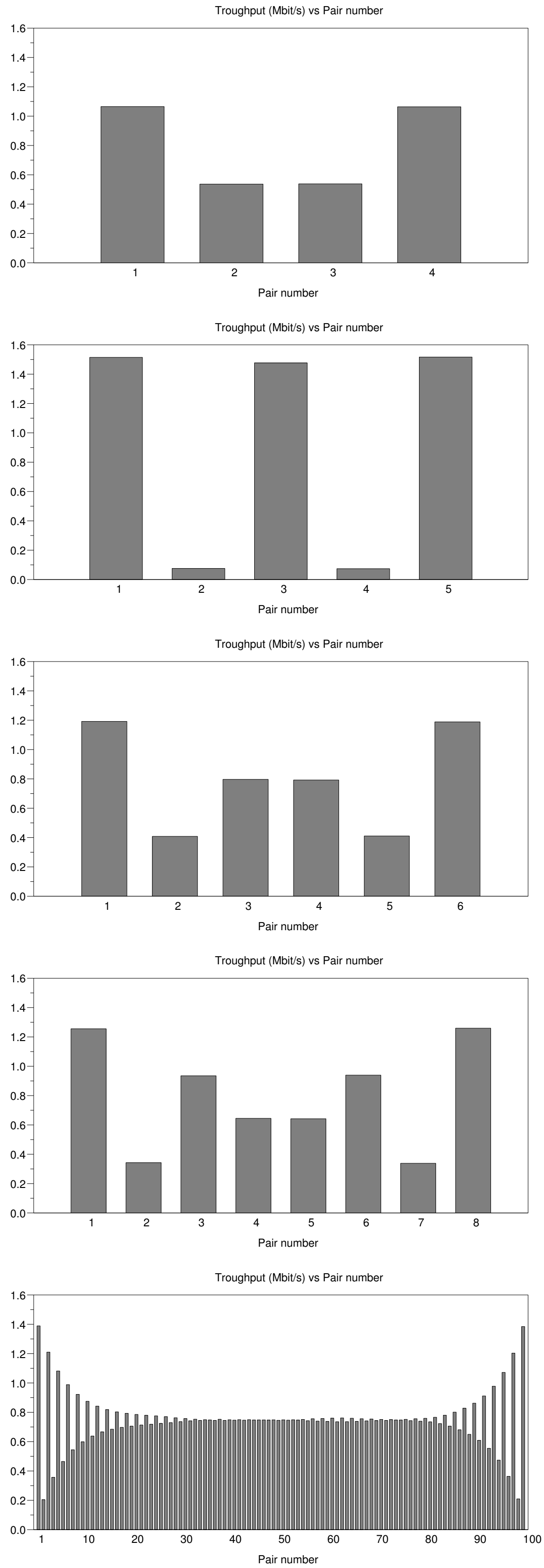

Fig. 4. Fairness in a chain of 4, 5, 6, 8 and 100 pairs.

C. Asymptotical results

Hence, the fairness pattern in a chain of n pairs depends on the parity of n. However we observed some evolutions of these patterns when n increases. We then simulated a very large chain, in order to have an idea of the asymptotic behavior (Fig. 4-bottom). Similar results are obtained with a chain of 101 pairs, which confirms that the influence of the parity of n tends to decrease when n increases. Moreover, for a chain of 101 pairs, one can see that the closer is an even pair from the middle, the larger is its throughput. This is explained by the fact that the influence of the border pairs is less important. As a consequence, the closer is an even pair from a border, the smaller is its throughput. In this chain, the throughput of external pairs (1.39 Mbits/s) is very close to the maximum (1.59 Mbits/s), measured in a single pair in the same conditions. In the central flat area, the throughput of the pairs is close to 0.75 Mbits/s (about half of the throughput of the external pairs). As a consequence of the existence of this flat area, the insertion of a new pair has less influence on the throughput of other pairs when n is large, and when the new pair is inserted near the middle of the chain.

III. Mathematical modeling

A. Modeling with a non-linear system of equations

In the previous section, we have shown that a chain of emitters presents some interesting phenomena, depending on the number n of pairs in the chain, and on the parity of n. The three pairs fairness problem introduced in [1] appear as a sub-case of our scenario. In order to study this phenomena, we propose a simple modeling.

In [4], a mathematical modeling has been proposed for the three pairs configuration, by means of discrete time Markov chains. Such a modeling gives numerical results close to the simulations obtained with the ns-2 network simulator, and not so far from real experiments of [1]. Moreover, it allows to study the influence of some parameters variations on the fairness. However, it is not easily generalizable when the number of pairs increases. Indeed, a state of the Markov chain needs to capture the relative remaining backoff delays of the pairs, which leads to many states. Moreover, transitions are more complex when the number of pairs (and then interactions) increases.

We propose a new modeling, based on a non-linear systems of n equations whose solution gives the probabilities of emission of each pair. It allows an analytical study both for small and large values of the number n of pairs. Intuitively, our model can be explained as follows. A communication can be done in a given pair only if its neighbor pairs are idle. However, the pair will only communicate during a portion of this idle time, because both the emitter and the receiver wait for some delays.

We consider a chain of n pairs numbered from 1 to n. For the purpose of the modeling, we admit that there are two border pairs (pair 0 and $n+1$), which never send data. We consider the random process $y_i(t)$ taking value 1 if the i^{th} pair is sending data at time t and 0 if the pair is idle. In fact for any t, the random variable $y_i(t)$ follows a Bernouilli's law. We now make a simple analysis of the communication mechanism in order to obtain some relationships between the variables $y_i(t)$, for $i = 1 \ldots n$.

Some data can be sent in a given pair i only if its neighbor pairs are idle, but before emitting, the emitter first waits after delays and CTS frames. To take this into account, we introduce a new random process $z_i(t)$ such that

$$P\left(z_i(t) = 1 \,|y_{i-1}(t) = y_{i+1}(t) = 0\right) = \alpha, \qquad (1)$$

where $0 < \alpha < 1$ and we consider that data can be sent in pair i at time t if neighbor pairs are idle and $z_i(t) = 1$. Thus we can write the algebraic relationship

$$y_i(t) = z_i(t)\left(1 - y_{i-1}(t)\right)\left(1 - y_{i+1}(t)\right), \; i = 1 \ldots n. \qquad (2)$$

Since we want to describe some average behavior, we consider the rate of emission as the limit when $T \to \infty$ of the time elapsed in the emitting state between $t = 0$ and $t = T$ divided by T

$$x_i = \lim_{T\to\infty} \frac{1}{T}\int_0^T y_i(t)\, dt.$$

In virtue of the Central Limit Theorem (assuming the $y_i(t)$ are independent when t evolves) we have $x_i = E[y_i(t)]$, where $E[.]$ denotes the mathematical expectation, and we have of course $E[y_i(t)] = P(i \text{ is emitting at time } t)$, since $y_i(t)$ follows a Bernouilli's law. The $z_i(t)$ process is not independent of $y_{i-1}(t)$ and $y_{i+1}(t)$ but according to Equation (1) the random variable (for clarity, we omit the dependence on the t variable) $E[z_i\left(1 - y_{i-1}\right)\left(1 - y_{i+1}\right)|(y_{i-1}, y_{i+1})]$, is a Bernoulli variable taking the value $E[z_i] = \alpha$ with probability $p = P(y_{i-1} = y_{i+1} = 0)$ and taking the value 0 with probability $1-p$. Hence, we have

$$\begin{aligned} &E[z_i\,(1-y_{i-1})\,(1-y_{i+1})] \\ &= E[E[z_i\,(1-y_{i-1})\,(1-y_{i+1})\,|(y_{i-1},y_{i+1})]], \\ &= \alpha P\,(y_{i-1}=y_{i+1}=0)\,. \end{aligned}$$

Hence, we can take the mathematical expectation on both sides of (2), and we obtain, by neglecting the correlation between pairs $i-1$ and $i+1$

$$x_i = \alpha(1-x_{i-1})(1-x_{i+1}),\ i=1\dots n. \tag{3}$$

The modeling introduced above allows to obtain, by substitution of unknowns and by using symmetry relationships, a closed form of probabilities of emission for $n<9$ (the formulas are given in [3]) but for greater n, there is no analytical formula and the solution of (3) has to be computed with numerical iterative methods.

B. Validation of the modeling with ns-2 results

In order to compare the analytical results with those given by the ns-2 network simulator, we normalize both results by the value of the first external pair and we compare the throughputs of each pair divided by the throughput of the first one (r_i/r_1) with the probability of emission of each pair divided by the probability of emission of the first one (x_i/x_1) (see [3]).

A least squares fitting with respect to α allows to approximate the ns-2 results. For instance, for $n=3$ and $n=7$, we obtain values of α respectively equal to 0.862 and 0.812. These values lead to numerical results very close to those obtained with ns-2, as seen in Figure 5 (a discussion of these values is given in Section V). The slightly differences are insignificant compared to the unavoidable approximations of the network simulator. Nevertheless, this first observation is only a rough validation of our modeling, and a precise analysis of the model itself is necessary.

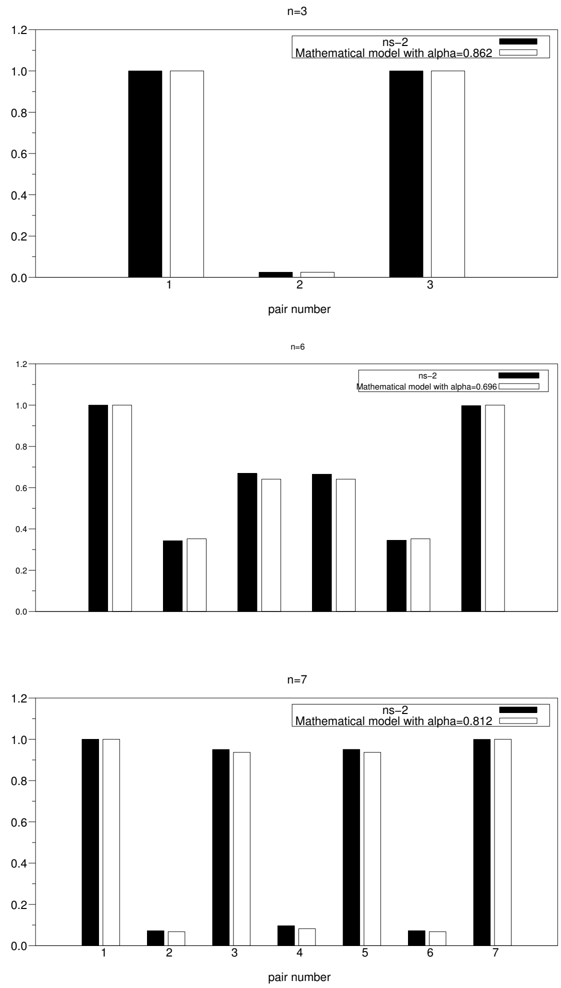

Fig. 5. Comparison of ns-2 results and mathematical modeling for $n=3$, $n=6$ and $n=7$.

IV. Analysis of the model

In this section, we use the modeling introduced above to determine the asymptotic behavior of the chain, as well as to establish the relationship between α and the fairness.

A. Proving the existence of a solution

Let us consider the n values $x_1^k \dots x_n^k$ as the components of the vector $x^{(k)} \in \mathbb{R}^n$, and the iterative process by means of a function F_α defined on vectors:

$$x^{(k+1)} = F_\alpha(x^{(k)}). \tag{4}$$

We have:

$$F_\alpha(x) = \alpha \begin{pmatrix} 1-x_2 \\ (1-x_1)(1-x_3) \\ \vdots \\ (1-x_{n-2})(1-x_n) \\ (1-x_{n-1}) \end{pmatrix}. \tag{5}$$

The sequence (4) is nothing but the so-called *successive approximation method* to determine iteratively a solution of the equation $x=F_\alpha(x)$. If we consider the derivative of F_α (or Jacobian matrix) F'_α and the supremum norm, i.e. $\|x\| = \max_{1\le i\le n}|x_i|$, we can show that $\|F'_\alpha(x)\|<1$, provided that $|x_k-1|<\frac{1}{2\alpha}$, $1\le k\le n$, i.e. F_α is a contraction on the subspace $\mathbb{S}$ defined by $\mathbb{S}=\{x\in\mathbb{R}^n,\ \|x-\mathbf{1}\|<\frac{1}{2\alpha}\}$, where $\mathbf{1}=(1,\dots,1)$. Hence by the contraction mapping theorem (see [8]) the convergence toward a unique solution $\hat{x}\in\mathbb{S}$ is guaranteed.

A direct application of this result is that the algorithm (4) converges to the unique solution of $x = F_\alpha(x)$ e.g. by taking $x^{(0)} = (1, \ldots, 1)$.

B. *Asymptotic behavior*

As for the simulations, we observe the convergence to an asymptotic behavior. Moreover the different behavior between odd and even values of n tend to disappear when n increases (see Figure 6 and [3]). Thus, without loss of generality, we will continue our study by considering only even values of n in the simulations.

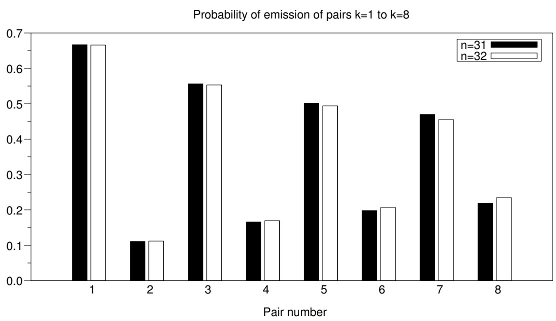

Fig. 6. Simulation of probabilities of emission of pairs $k = 1$ to 8 for $n = 31$ and $n = 32$ ($\alpha = 0.75$)

C. *Maximization of fairness with respect to* α

Among other possible criteria (see [9] and [10]), one way of maximizing the fairness between all pairs is to maximize the entropy (see [5]) of the distribution of probability of emission $\{x_i\}_{i=1\ldots n}$, i.e. the function

$$\mathcal{E}(x) = -\sum_{k=1}^{n} x_i \log x_i.$$

Hence, we consider the function $J(\alpha) = \frac{1}{n}\mathcal{E}(x(\alpha))$ where $x(\alpha)$ is the unique solution of the equation $x = F_\alpha(x)$ and the factor $\frac{1}{n}$ is used to allow some comparisons of results between different values of n, and we look for the value $\hat{\alpha}$ such that $J(\hat{\alpha}) \geq J(\alpha), \forall \alpha \in [0, 1]$.

The computation of $x(\alpha)$ is done with a Newton type method, much faster than the simple fixed point method suggested by Equation (4), and the optimization is performed by the Quasi Newton BFGS method available in Scilab (see [11]).

V. Discussion

In the previous section, the chain of senders scenario has been analyzed on the basis of the modeling introduced in Section III. Note that as far as the mathematical model is concerned, the non-linear systems of equations (3) is obtained by assuming that the emission states of pairs i and $i + 1$ are independent from a probabilistic point of view. While this assumption (also assumed in [12]) may be questionable, it is relevant because our modeling considers the stationary behavior of the chain.

In this section, we discuss the asymptotic values obtained in the analysis before interpreting α in a practical point of view.

A. *Asymptotic flat area*

If we study the asymptotic behavior of results, we see that for large values of n and the optimal value $\alpha = \hat{\alpha}$, the optimal probabilities of emission (see Fig. 7) exhibit a large flat area with a value very close to $\frac{1}{3}$ (the $\frac{1}{3}$ value will be discussed below). This flat area ensures that the insertion of a new pair will not disturb the rate for close neighbors.

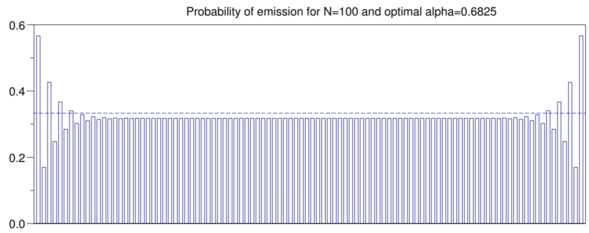

Fig. 7. Probabilities of emission for $n = 100$ and optimal α. The dotted line is at probability $1/3$.

Moreover, for $n = 100, 500, 1000$ and 2000 the value of the optimal probability corresponding to this flat area is respectively equal to 0.3177, 0.3290, 0.3313 and 0.3325.

To understand the convergence of this value to $1/3$, we must consider the idealized situation where there is an infinite number of pairs, or equivalently, the situation where the number of pairs is large enough to allow to form a circle, where the last pair numbered $k = n$ has the pairs $k = n - 1$ and $k = 1$ as neighbors. Hence, there is no border effect since all pairs have two neighbor pairs.

So let us consider the i^{th} pair and its neighbors pairs numbered $i - 1$ an $i + 1$, and a very simple model of channel acquirement: each sender of each pair generates a realization of a random variable u_i (uniformly distributed in the interval $[a, b]$). We consider that the i^{th} pair will acquire the channel if $u_i < u_{i+1}$ and $u_i < u_{i-1}$. Straightforward computations (see [3] for the details) show that the probability of this event is equal to $\frac{1}{3}$, which can be understood as a limiting value exhibiting the maximum fairness that can be obtained. This value of $\frac{1}{3}$ is asymptotically obtained in our model, by maximizing the entropy of the distribution of probabilities: this is a very interesting behavior.

B. Asymptotic optimal alpha

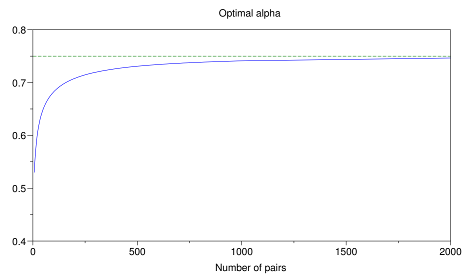

Fig. 8. Optimal α with respect to n.

Another interesting phenomenon is the apparent convergence of the optimal value $\hat{\alpha}$ to 0.75 when n tends to the infinity, as it can be seen on Fig. 8.

This is not so surprising, as we will show it in the following analysis. Consider the same idealized situation as before, where the pairs are arranged to form a circle: the probabilities of emission $\{x_k\}_{k=1\ldots n}$ are necessarily invariant with respect to a shift of indices, since all pairs will always have two neighbors. Hence we have $x_k = x_1$, $\forall k$, and the system of n equations $x = F_\alpha(x)$ giving the probabilities is equivalent to the scalar equation $x_1 = \alpha(1-x_1)^2$. In this case the entropy is already maximized since all values are equal. Then, if we are looking for the value of α giving the maximum probability of emission in such a configuration, i.e. $x_1 = \frac{1}{3}$, we obtain $\alpha = \frac{x_1}{(1-x_1)^2} = 0.75$. This value is in fact completely determined by the topology of the neighborhood.

C. Asymptotic comparison of modeling and simulation

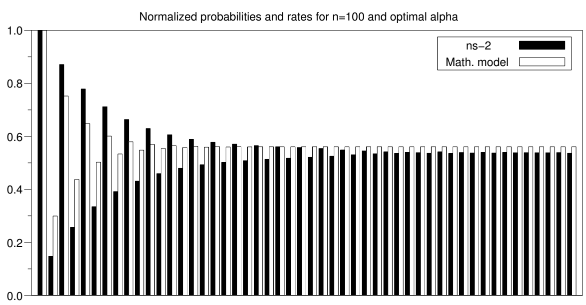

Fig. 9. Probability of emission of the first 50 pairs of 100 obtained by ns-2 and mathematical model for optimal $\alpha = 0.6825$.

We have compared the normalized rates obtained via ns-2 and via the mathematical model for $n = 100$ pairs (the rates and probabilities are normalized with respect to the pair exhibiting the maximum value, as explained in Section III-B). While some small difference remain at the border of the chain, we can see in Fig. 9 that the mathematical model with $\alpha = 0.6825$ (corresponding to the maximum entropy) gives an excellent approximation of ns-2 results.

Hence, it appears that the asymptotic behavior of the chain of n IEEE 802.11 senders-receivers (as defined in Section II) tends to the maximum entropy when n tends to the infinity. This is a surprising result.

D. Interpretation of the α coefficient

We defined α as the probability of sending for a given pair when its neighbors are not sending. Interpreting α implies to determine whether a pair is sending or not when its neighbors are not sending. In the configuration of Fig. 3, a sender can only hear (but not understand) a transmission of a neighbor sender, and not of a neighbor receiver. A neighbor pair is then considering as sending only when the sender (and not the receiver) is sending, and waiting in other cases.

Before any transmission, a sender has to wait for a delay, and in many cases this is an EIFS delay instead of a DIFS one. During this delay, chances are large that its neighbors are sending. This means that this delay is not part of the time wasting by a pair while it could send because its neighbors are not sending. To the contrary, neighbor senders are not sending during the backoff delay.

Fig. 10 summarizes a complete transmission of a s bytes MAC frame between a sender S_i and a receiver R_i (see [3] for the explanation of the numerical values); d denotes the sending rate, and 0.5 represents the mathematical expectation of a random variable on $[0, 1]$.

sender S_i		receiver R_i	
DIFS or EIFS	50 or 364 μs		
aSlotTime $\times$ CW $\times 0.5$	310μs		
RTS	304 μs		
		SIFS	10 μs
		CTS	352 μs
SIFS	10 μs		
header and preamble (PHY)	192 μs		
s data bytes (MAC)	$8 \times s/d$ μs		
		SIFS	10 μs
		ACK	304 μs

Fig. 10. Complete transmission of a s bytes MAC data frame at dMbits/s.

We suppose that CW = 31, leading to an average backoff time of 310 μs (we indeed rarely observed a contention window larger than 31 in our simulations). Based on the previous considerations, the waiting time T_w while the neighbors are waiting corresponds to the backoff (310 μs), the SIFS delays (3×10 μs), the CTS (352 μs) and ACK (304 μs) frames sent by the receiver: $T_w = 996$. The sending time T_s while the neighbors are waiting corresponds to the RTS (304 μs) and data frame (192 + $8s/d$ μs): $T_s = 496 + 8s/d$. Since $T_s = \alpha(T_s + T_w)$, we have

$$\alpha = \frac{496 + \frac{8s}{d}}{1492 + \frac{8s}{d}} \tag{6}$$

In our simulations, the sending rate has been fixed to 2Mbits/s ($d = 2$) and a data MAC frame is equal to 1500 bytes ($s = 1500$). We then find $\alpha = 0.867$. This value is very close to those found in Section III-B.

VI. Conclusion

In this paper, we developed a scenario for ad hoc networks relying on IEEE 802.11 wireless communications composed of a chain of senders, such that each of them is in the carrier sense area of its neighbors. This scenario combines the EIFS mechanism with the asymmetry of a chain, where two senders have only one neighbor while the others have two. This scenario includes the three pairs fairness problem [1].

We show that interesting patterns appear when the number n of sender-receiver pairs in the chain increases. These phenomena depend on the parity of n. For small values of n, the fairness is better if n is even than if n is odd. We also point out an asymptotic behavior when n increases, with a large central flat area. By means of a simple modeling, we provide an analytical study of this scenario, which explains the phenomena observed by simulation.

Besides the curious fairness phenomena we pointed out in the chain of senders, it is interesting to notice that this simple modeling relying on a single coefficient α is able to render the complex situation of concurrent transmissions using the IEEE 802.11 standard. Previous modeling were based on Markov chains and were not really adapted for n larger than 3. This coefficient expresses the probability for a sender to transmit a frame while its neighbors are waiting. Indeed, a sender does not fully use the channel, even when its neighbors are waiting.

Another interesting contribution is the asymptotic results. When the number of pairs is large, the probability of emission for a sender near the middle of the chain is very close to the optimal value (1/3). This optimal probability corresponds to $\alpha = 3/4$. Moreover this value gives also the maximal fairness (expressed by means of entropy) when n tends to infinity. The consequence is that, to reach the optimal case, a sender should waste 1/4 of the time it is granted for sending. We should also notice that when n increases, the chain of IEEE 802.11 senders-receivers tends to this ideal case.

We know point out a practical application of our study. The ideal value of α we mentioned above is correct for very large values of n, which does not correspond to real cases (short chains). However, our modeling highlights a link between the fairness and the packet size (Equation 6). Hence, for a given n, the modeling is able to give the optimal α, allowing to deduce the (approximative) optimal packet size. Our first results confirm that, by using such an optimal packet size, we are indeed able to maximize the fairness in a given chain.

Among possible further works, we would like to mention fairness optimization in a chain of IEEE 802.11 stations, as well as other uses of such a simple modeling, for more complex scenario.

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