Extended IFS and asynchronism influence on IEEE 802.11b medium access equity

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Abstract: This article presents a theoretical modeling of an ad hoc network scenario that shows that a great inequity can appear in medium access between nodes using the IEEE 802.11 DCF mode. Numerical results confirm that both asynchronism and Extended Inter Frame Spacing (EIFS) use perturbate the equity between mobiles in wireless networks.

Key-words: IEEE 802.11b, performace evaluation, Mobile ad-hoc networks, interferences

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Modélisation de l'influence de l'asynchronisme et des interférences dans les réseaux 802.11b

Résumé : Dans ce papier nous proposons une modélisation théorique d'une configuration ad hoc qui présente une très grande inégalité dans l'accès au médium entre les mobiles lorsque le mode DCF de 802.11 est utilisé. Les résultats numériques obtenus viennent corroborer l'idée que l'asynchronisme et l'utilisation des EIFS perturbent fortement l'équité entre les mobiles dans les réseaux 802.11.

Mots-clés : IEEE 802.11b, évaluation de performace, Réseaux ad hoc, interférences

Introduction

Most of the actually used wireless interface cards implement the IEEE 802.11b standard that defines physical and medium access layers for wireless networks. The first standard (802.11) was defined in 1997 while the actual one (802.11b), widely used nowadays, was specified in 1999. This protocol can operate in two modes: PCF (Point Coordination Function) mode shall be used when mobiles communicate using a base station and DCF (Direct Coordination Function) mode is used when mobiles communicate directly without the help of any fixed infrastructure.

In order to understand and to evaluate the performance of these networks, a certain number of contributions have been written. These works can be classified in two main categories: a theoretical approach and a simulation based one. Performance evaluation of 802.11 based on a theoretical analysis mainly evaluate the characteristics (throughput, retransmissions, delay, RTS / CTS mechanism cost) of the DCF mode of the protocol [2, 9, 10, 3, 4, 7]. All these analysis are made in a configuration where all the nodes are in communication range of the others and show the same results.

Nevertheless, some works [8, 11, 5], have shown that in real ad hoc configuration, in which some mobiles compete with more nodes than others for medium access, the MAC protocol equity was not preserved. All these works are based on simulations and no theoretical analysis has been proposed yet to evaluate the performance of the mobiles in these situations.

In [5], a particular configuration showed a great inequity between the mobiles. As this scenario involves few emitters, it constitutes a good choice for a first step towards analysis of scenarios involving asymmetry. Moreover the effect of this asymmetry is accentuated by a mechanism of the 802.11 protocol that is triggered when interferences disrupt the carrier sense mechanism.

In section 1, we will describe briefly the DCF mode of 802.11, then we will present the ad hoc scenario studied. In section 2, we describe how we modeled this scenario using discrete time Markov chains. Due to the asynchronism of the system, the Markov chain is infinite. We will describe how to reduce this number of states. We will then compute the transition probabilities in Section 3. Finally, results, that confirm that a great inequity between mobiles can appear, will be presented in section 4.

1 System description

DCF mode of IEEE 802.11 [6] being part of the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) protocol family, it associates a carrier sense mechanism to a random wait (backoff) before transmission mechanism.

When a mobile wishes to transmit a frame, it first ensures that the radio medium is not occupied by another transmission by measuring the signal level on the radio channel. As long as the channel is occupied, transmission is deferred to prevent collisions. As soon as the medium becomes free, the random backoff mechanism is initiated. The emitter chooses a random number between 0 and a value of CW_{min} (initially equal to 31 in 802.11b). The emitter then waits for a constant time of $DIFS$ during which the medium shall stay idle. It the starts to decrement its backoff counter. Each time a time slot is passed without any transmission on the medium, the backoff is decremented by one. When it reaches 0, the frame is emitted. If, during this process, another transmission occupies the medium, the decrementation process is suspended and will be resumed when the medium becomes idle again and after a $DIFS$ waiting time.

In this kind of protocols, collisions can happen whenever two emitters choose the same random number. Collisions have a high cost as it is not possible to use collision detection mechanisms. Every started frame transmission will be ended. In order to limit the impact of collisions, a frame protection mechanism is provided. Before sending its frame, the source sends a RTS (Request To Send) packet to the destination that should answer by sending back a CTS (Clear To Send) packet if the transmission can happen. Protecting frames this way implies that collision mainly happen on small packets (RTS) and thus the medium is sooner freed. For more details on the protocol operation, see [6].

Some works ([2]) have been made to model the behavior of this protocol in fully connected networks (in which every mobile is in the communication range of every other mobile). These contributions try to compute the achievable throughput of one particular station in contention with others. As far as we know, no study has been made in the case of networks in which interferences can appear, disrupting the carrier sense mechanism. IEEE 802.11 standard specifies that when a frame is received with an incorrect MAC checksum (FCS) value, the waiting time before starting to decrement the backoff of the next frame to send is set to $EIFS$, which is more that 7 times $DIFS$ delay. In other words, when a mobile detects a signal level on the channel, and when it identifies that this should have been a data frame (i.e. when it understands the physical PLCP header), it defers its next frame transmission so that the acknowledgment corresponding to the actual transfer can be transmitted correctly.

The standard specifies that this PLCP header should be transmitted at a basic rate (that is much slower than the data rate) in order to be understood by any other mobile (i.e. by all 802.11 versions). But data transmitted at lower rates can reach greater distances. Therefore, for every node there is an area in which a receiver is able to decode the physical headers but not the packet contents, which triggers the long wait mechanism.

We chose to focus on the rather simple scenario depicted of Figure 1. In this configuration, three emitters try to transmit a flow to associated receivers that are nearby their corresponding source. Pairs of mobiles are distant enough, so that emitters cannot communicate but near enough so that interferences have an influence on the carrier sense mechanism, triggering the EIFS wait. Moreover, mobiles of each pair are near enough so that simultaneous emission of packets do not collide at the receivers' locations.

This scenario was designed to be unfair because the two exterior pairs do not interfere but the central pair is in the interference zone of both exterior pairs. This situation shows a certain unfairness and thus a certain asynchronism (the two exterior pairs evolve independently). This can seem to be an extreme situation but considering the size of the interference zone, it may happen quite often, especially in indoor configurations.

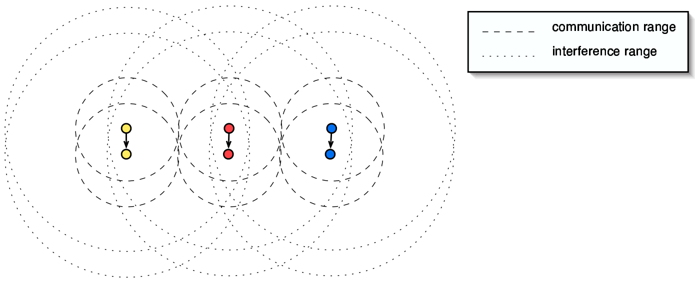

Figure 1: Scénario

As exterior pairs do not interfere together, the system can be separated in two sub-systems interacting: the first pair on one side and the two exterior pairs on the other side. In this vision, two exclusive situations only are possible: either the central pair transmits, or the two exteriors pairs transmit and the central one waits.

2 Modelling description as a Markov chain

2.1 States and transitions

The scenario will be modeled as a discrete time Markov chain. We will try to determine the proportion of packets transmitted by each sub-system, so a transition in the chain will occur each time a packet is transmitted on the channel by one of the three pairs that we will elect to be the *reference pair*. The one and only purpose of this election is to determine the pair whose emissions trigger transitions in the chain. Nevertheless, for any of the three pairs, there will be situations in which it transfers a few consecutive packets as well as situations in which it is totally silent for a more or less long period of time. In order to have meaningful transitions in our chain, we will have to change dynamically our reference pair each time it "looses" the channel access, as illustrated on Figure 2.

- At the initialization of the system, the first pair to transmit is chosen as the reference.
- When the central pair is transmitting packets, it is the reference pair as it is the only one to transmit.
- Sooner or later, when the central pair is transmitting, one of the external pairs will see its backoff reach zero and will win the channel access contention. The central pair is then forced to be silent during at least a whole packet emission. During this time, the second external pair continues to decrement its backoff counter and it is transmitting way before the first one has finished its transmission, so whenever an external pair gains access to the channel, it is the whole subsystem that does. In this situation, the

first pair to gain access to the medium is elected as the reference pair and will stay in this position until the central pair takes back the channel.

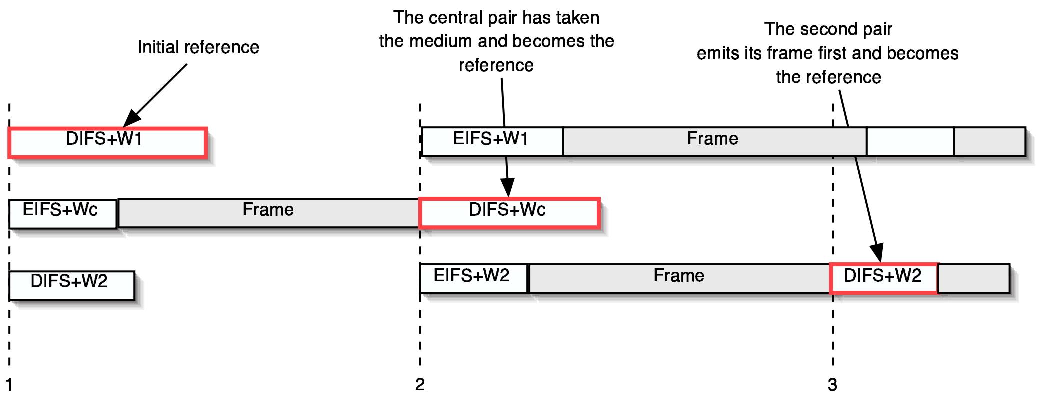

Figure 2: Changing the reference pair when the previous reference looses the access to the medium

Now, let's examine what information we need to represent a state of the system. First, we need to know which sub-system is transferring (central pair or the two external ones). We also need to know how far from gaining access the waiting sub-system is (i.e. the number of backoff slots remaining to decrement).

When the external pairs transmit, we focus on only one of the pairs because transitions in the chain occur on one pair's emissions. We need to model the influence of the second external pair on the whole system. What is important here is how well aligned the two external pairs are in order to determine the probability that the central pair has to decrement its backoff. So we will store in the states description the offset between the external reference pair and the other, as illustrated on Figure 3.

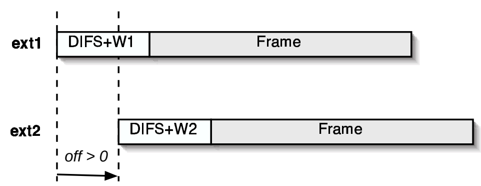

Figure 3: Offset between the reference pair and the other external pair

When the central pair transmits, we need to keep the two backoff values of the external pairs in order to compute which external pair will take the channel first and the subsequent offset between it and the other external pair when the external pairs take back the channel. This information can be stored as the two values of the backoffs or as the minimum of the two backoffs and the offset between the two values. We chose this second solution because it is analogous to the offset depicted in the latest paragraph.

One state of the system will be characterized by a triplet $(W_e; W_c; off)$ where:

- W_e equals 0 when the external pairs transmit. When the central pair transmits, it contains the number of backoff slots remaining before the external pair that has the minimum number of slots gains back access to the channel.
- W_c equals 0 when the central pair transmits. When the external pairs transmit, it contains the number of slots remaining before the central pair gains access to the channel.
- off represents the offset in microseconds between the reference pair and the other external pair. When the externals pair transmit this is used to compute the probability that the central pair has to gain access to the channel. When the central pair transmits, it is used to keep trace of the backoff difference between the two external pairs.

As long as we neglect the collisions between packets (this is quite realistic because of the ratio between the signal level over noise from other emitters), W_c and W_e are always in the interval $[0; W-1]$, i.e. $[0; 31]$. Nevertheless, the offset can vary indefinitely towards one direction or the other. So it can become infinite. We need to find a way to limit it.

2.2 Reducing the number of states

The number of states in the part of the Markov chain corresponding to the situations in which the exterior nodes are transmitting is equal to the number of possible values for the backoff of the central pair (i.e. the contention window size, i.e. 32) mutiplied by the number of possible values for the offset (which is infinite).

The same formula can be applied in the second subset of states, when the central pair is transmitting. The number of states is, in this case, equal to the number of backoff possibilities for the external pairs multiplied by the maximum offset between the two pairs.

2.2.1 Maximum remaining backoff

First of all, by making a simple observation, we can easily reduce the number of possible values for the maximum reachable backoff of every pair. This number is the number of slots remaining before the waiting subsystem gains access to the channel. Let's look at how this value is computed. This value is the consequence of an interruption in the backoff decrementation process. A node is transmitting and is waiting $DIFS + Backoff$ between each frame transmission. Meanwhile, the waiting nodes have to wait EIFS before starting to decrement their backoff. Due to the great difference between EIFS and DIFS, when one of the waiting nodes has the opportunity to decrement one backoff slot, the transmitting one has already decremented $\lfloor \frac{EIFS-DIFS}{Slot\_time} \rfloor$ slots. As the waiting nodes have at least one reamining slot to decrement, whenever a node is interrupted in its backoff decrementation process, it has already decremented at least $\lfloor \frac{EIFS-DIFS+Slot\_time}{Slottime} \rfloor = 16$ slots of backoff (as shown on Figure 4) and it has at least one slot remaining (or it would have emitted its packet).

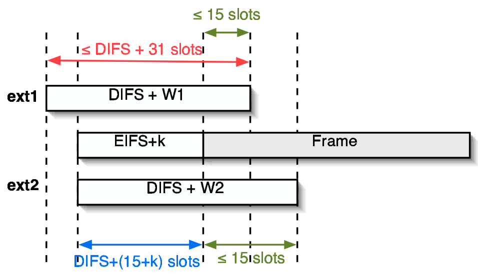

Figure 4: The residual backoff cannot be greater than 15 slots

So, the states corresponding to $W_c = 0$, $W_c \in [16; 31]$, $W_e = 0$ or, $W_e \in [16; 31]$ are unreachable, except at the initialization of the system. As we want to study the stationary properties of the system, we will consider only the cases when $W_c \in [1; 15]$ and $W_e \in [1; 15]$.

2.2.2 Limitation of the offset

First, let's look at the case when the exterior pairs transmit. To limit the offset, we need to look at what this offset really means. We have elected one of the external pairs as the reference one. This value represents the influence of the other external pair on the whole system. When the reference pair starts a waiting period, we want to know if the other pair is transmitting or making silence too in order to determine if the central pair can decrement its backoff of n slots.

When the reference pair starts a period of silence, we needn't to know the offset with the corresponding packet of the other external pair but the offset with the *nearest* period of silence of the other external pair. So, it seems possible to keep the value of the offset in an interval $[off_{min}, off_{max}]$ of values that is almost the maximum length of a packet long.

This can be done in the following way: whenever a pair becomes too far ahead of the other, it waits for the second one. There are in fact two situations: the offset becomes too large (i.e. when the reference emitter becomes too late) and when the offset becomes too small (when the second pair becomes too late).

Let's look at the first case. Whenever the offset becomes greater than a certain value off_{max}, as shown on Figure 5, the pairs are totally unaligned. The central pair has no chance to decrement its backoff (provided we have chosen the value of off_{max} such as no coincidence with the previous silence period of the second pair can happen — this is developed later in this section). We will then stop the second external pair and have only the reference one to transmit.

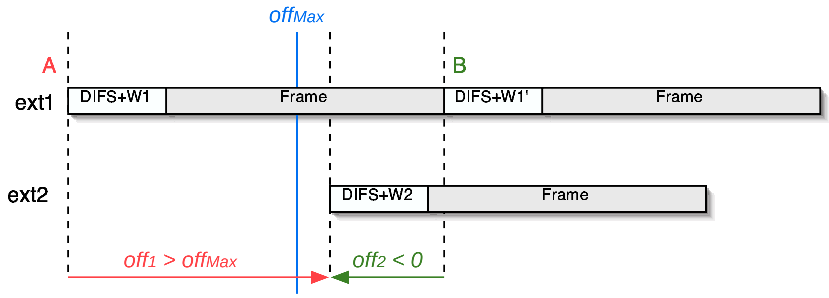

Figure 5: The second pair has to wait for the first one

This means that in the Markov Chain, when we reach a state that exceeds the maximal offset value, we will suppress some following states of this state and replace the orphaned transitions by other ones. As shown on Figure 6, the transition corresponding to an offset increase of $n\mu$s will be replaced by a transition directed to the state in which the offset is n minus one frame duration.

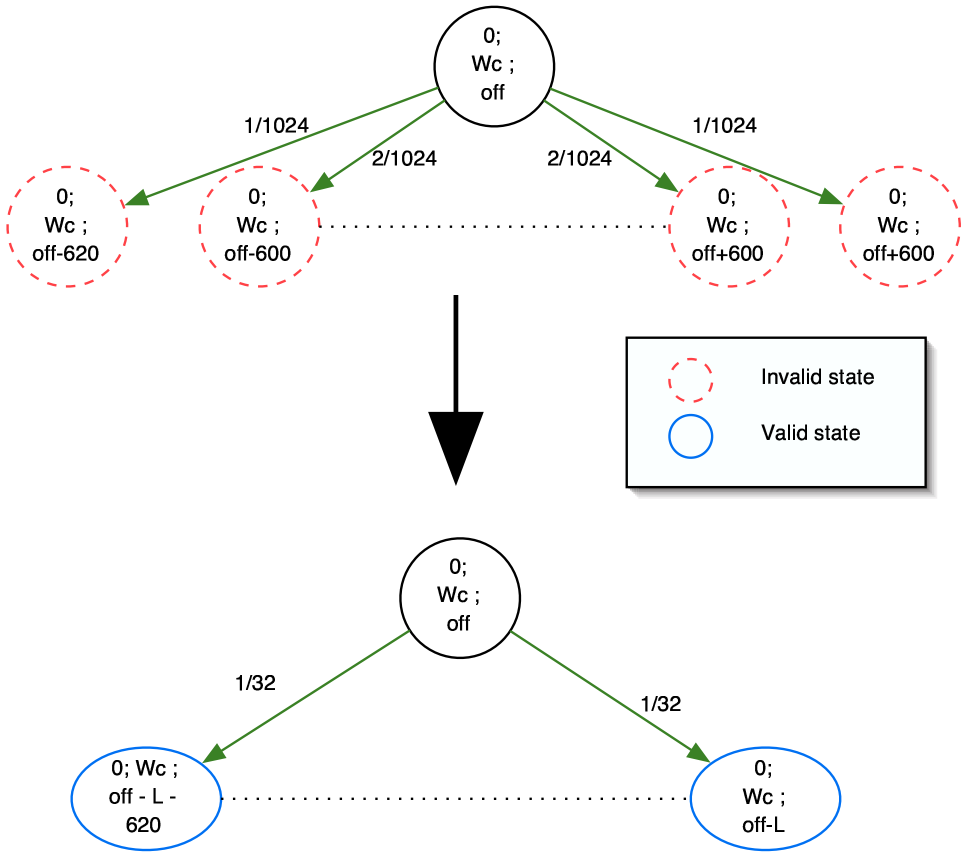

Figure 6: Transitions replacement to have the second exterior pair wait

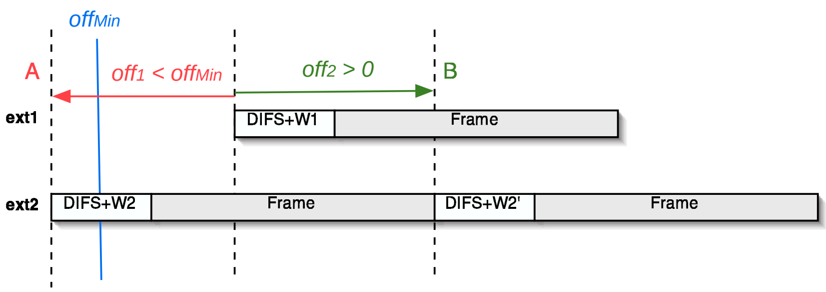

Figure 7: The reference external pair has to wait for the other one

The second case represented on Figure 7 is a little bit more tricky. Simply replacing transitions would lead to a situation where we have zero-time transitions in the chain because the reference pair waits in this case. A transition should represent one packet emission if we want our results to have a meaning. To fix this, we will aggregate two transitions in one. We will replace each transitions that leads to a too small offset (i.e. smaller than off_{min}) by another one representing the emission of *one* packet for the reference pair and the emission of *two* consecutive packets for the other external pair. We have to choose the value that triggers this mechanism wisely so that no backoff decrementation can occur in this interval of time (again, this is discussed a bit further in this section).

In order to compute the probabilities associated with each transition, we will look at what the chain would have been if we had left the zero-time transitions. What are the situations that lead to such a state and what are the possibilities to get out of it ? Then, we will suppress the states, add a transition from each start-state to each end-state and compute the associated probabilities considering that the two events are independent. This transformation is illustrated on Figure 8

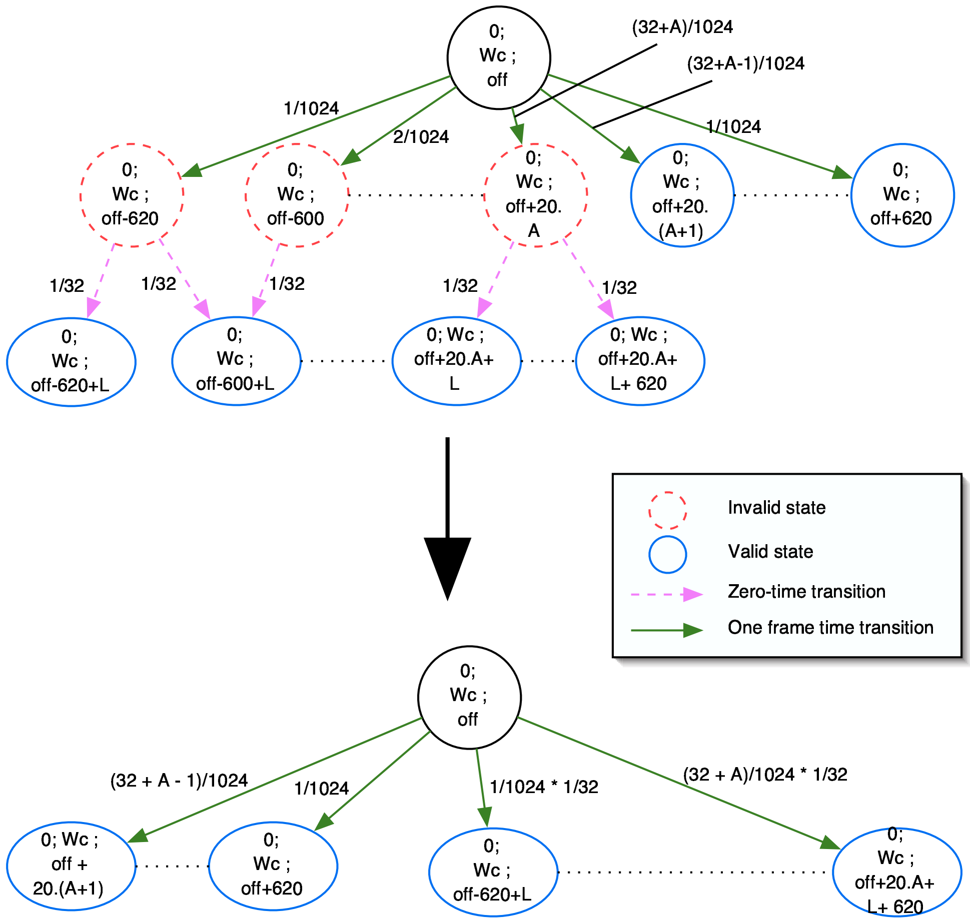

Figure 8: Transitions replacement using temporary states to have the reference pair wait

Now that we have described both offset translation mechanisms (positive and negative), we have to find good values for off_{min} and off_{max}. In order to facilitate the writing of the chain, we don't want to mix backoff decrementation and offset translation so we will try to choose these thresholds so that no translation operation is made in the interval in which the central pair has a chance to decrement its backoff.

The central pair can decrement its backoff of one slot when the two external pairs are silent together during $EIFS + Slot\_time = 384\mu s$. Each of the external pairs is silent during at most $DIFS + Max_backoff = 670\mu$s. Therefore, if the absolute value of the offset between the two pair is greater than $670 - 384 = 286\mu$s, there is no chance for the central pair to decrement its backoff at all. Therefore, the interval we want to protect from the translation operation will then be $[-286; 286]$.

In the same way, we don't want to have other values than the ones in this interval that can lead to a backoff decrementation. In particular, we don't want to have the kind of situation depicted on Figure 9, in which a period of total silence could be undetected due to a badly chosen value for off_{max}.

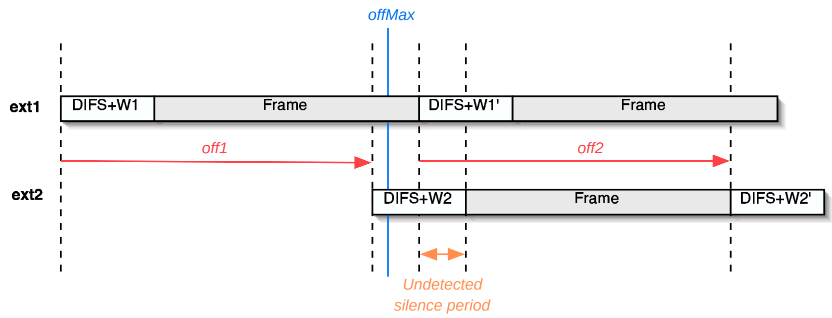

Figure 9: Undetected silence period due to a wrong off_{max} value

If we call L the minimum length of a frame transmission, i.e. the time between the start of a DIFS and the start of the next DIFS for the same emitter when the backoff is equal to 0. According to the introduction, we will take $L = 1812\mu$s. In order to avoid the situation of Figure 9, we need to choose off_{max} so that $off_{max} - L < -286 \Rightarrow off_{max} < 1526$. Thus, we will take $off_{max} = 1525$. Whenever the offset reaches a value in the interval $[1526; 1526 + 620 = 2146]$, we will execute a translation operation as described previously.

Now, let's look at the image of the interval $[1526; 2146]$ by our translation operation described in Section 2.2.2. This operation substracts from L to $L + 620$ to the offset, so the new offsets will be in the interval $[1526 - L - 620; 2146 - L] = [-906; 334]$. If we don't want to play ping-pong with the offset by having one pair wait then the other and then again the first one and so on, we need to set $off_{min} \leq -906$.

We can notice that $-906 = -286 - 620$, which means that setting the minimum offset to a value of -906 will ensure that we don't mix translations and backoff decrementations. Finally, the image by the translation operation of the interval [-906 ; -287] is the interval $[-906 - 620 + 1812; -287 + 1812 + 620] = [286; 1525]$ which fits in all of our criteria.

By setting $off_{min} = -906$ and $off_{max} = 1525$, we have $(1525 + 620) + 906 + 1 = 3052$ possible offset values for a frame length of 1028 bytes. This leads to a sub-chain composed of $15 \times 3052 = 45780$ states.

2.2.3 When the central pair emits

The other subsystem's number of states can also be reduced. First, we saw previously that there were only 15 possible values for the remaining backoff of the external pairs. Now, let's take a look at the offset in this part of the chain. Here, the offset represents the offset between the pair that has the minimum remaining backoff of the two external pairs (the next reference pair) and the other one. Yet, neither of the two pairs can have a backoff greater than 15 or less than 1, because before the central pair starts emitting, the external pairs were emitting (i.e. external pairs used DIFS whereas central pair used EIFS). Therefore, for a given W_e (the minimum remaining backoff of the external pairs), we only have a limited number of choices for the corresponding offset. The difference between the two backoffs cannot be greater than $15 - W_e$ and the corresponding offset is a multiple of 20 μs. That means that the second sub-chain is only composed of $15 + 14 + \ldots + 1 = 120$ states. This sub-chain is represented on Figure 10.

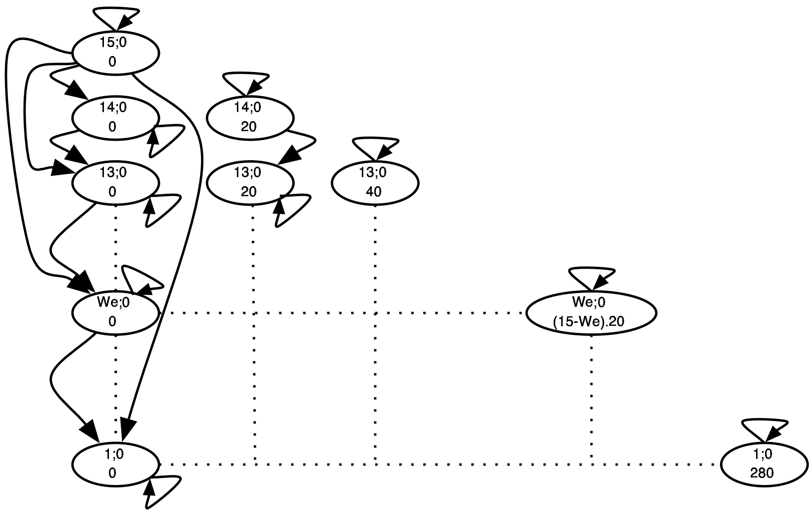

Figure 10: Sub-chain corresponding to the cases when the central pair transmits

2.2.4 Dealing with collisions

We haven't made a lot of approximations so far. We have rounded the frame minimal length from 1812.3 to 1812μs and we haven't dealt with collisions. Indeed, in our scenario, when the central pair and an external pair emit at the same time, the ratios of the distances (emitter - destination of one pair / emitter of one pair - emitter of the other one) prevents the frames from being jammed. But there is still one case that needs to be looked at. Logically, both emitters (of the central and external pairs) should get a new backoff and the third one (of the other external pair) should defer its transmission. If we examine the situation depicted on Figure 11, we see how a collision can lead to a remaining backoff of 31 slots.

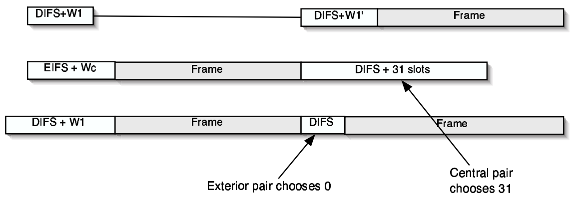

Figure 11: How a "collision" can lead to a remaining backoff of 31 slots

This situation – that is not likely to happen – makes our first approximation on the size of the remaining backoff of the central pair) wrong. The backoff is not limited to 15 anymore. Taking these cases into account would double the number of states in our chain, so we will make another approximation here. When we are in the situation described in this section, we will always give the medium access to one of the two pairs by adding one to the other one's backoff counter. We will examine separately the case in which the central pair always wins the contention (it will give an over-approximation of the used bandwidth of the central pair) and the case in which it always looses the contention (it will give an under-approximation of the used bandwidth of the central pair) and compare the two values obtained to validate our approximation later.

2.2.5 Final layout

The Markov chain representing the system has 45900 states that can be separated into separate categories (note that by translation, we mean the offset translation mechanisms described in Section 2.2.2:

1. $W_c \in [1; 15]; W_e = 0; d \in [-906; -287]$: The exterior pairs are transmitting, the central pair is waiting. The offset is too important to allow the central pair to decrement its backoff. The only possible transitions are offset increase or decrease. If the offset becomes too low, a translation operation is necessary.

2. $W_c \in [1; 15]; W_e = 0; d \in [-286; 286]$: The exterior pairs are transmitting, the central pair is waiting. The offset is small enough to allow the central pair to decrement its backoff and eventually to gain access to the medium.

3. $W_c \in [1; 15]; W_e = 0; d \in [287; 1525]$: The exterior pairs are transmitting, the central pair is waiting. The offset is too important to allow the central pair to decrement its backoff. The only possible transitions are offset increase or decrease but no translation is possible.

4. $W_c \in [1;15]; W_e = 0; d \in [1526;2145]$: The exterior pairs are transmitting, the central pair is waiting. The offset has become too large, so the only possible operation is a translation.

5. $W_e \in [1;15]; W_c = 0$: The exterior pairs are waiting, the central pair is transmitting. Depending only on the central pair's backoff, the system can remain in the same state or the backoff of the exterior pairs can decrease until they gain access to the channel.

3 Transition probabilities

3.1 First case

The external pairs are transmitting and neither backoff decrementation nor offset translation is possible. This situation, illustrated by Figure 12, arises when $W_c \in [1;15]; W_e = 0$ and $off \in [287;1525]$.

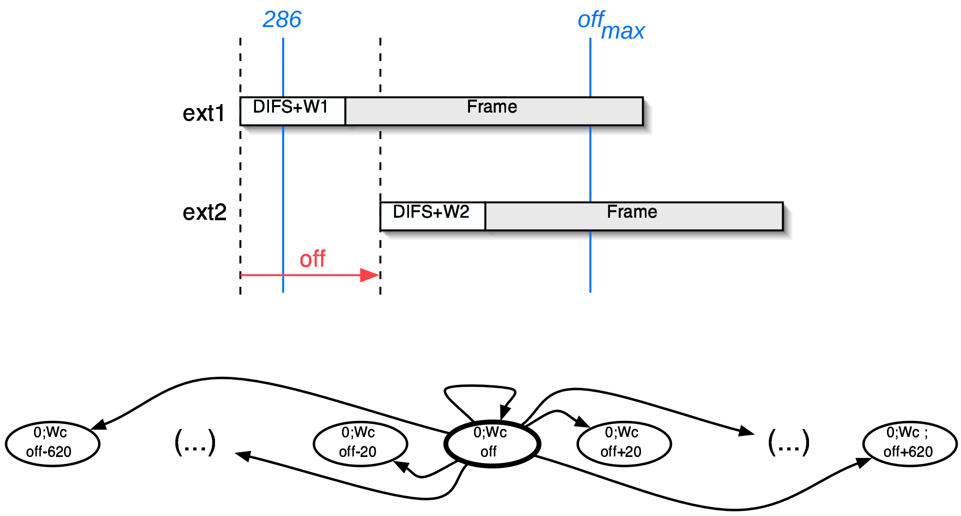

Figure 12: Offset $\in [287;1525]$ - only offset modification is possible

The only possible transition is an offset modification. The difference between the two external pairs' backoffs is a multiple of the slot duration and cannot exceed 31 slots in absolute value. Therefore, the possible transitions from these states and their associated probabilities are:

$$\forall k \in [-31;31], P\left((0;W_c;off) \rightarrow (0;W_c;off + 20 \times k)\right) = \frac{32-|k|}{1024} \qquad (1)$$

3.2 Second case

The external pairs are transmitting, backoff decrementation is not possible but offset translation is (because the offset may become too small). This situation, illustrated by Figure 13, arises when $W_c \in [1;15]; W_e = 0$ and $off \in [-906;-287]$.

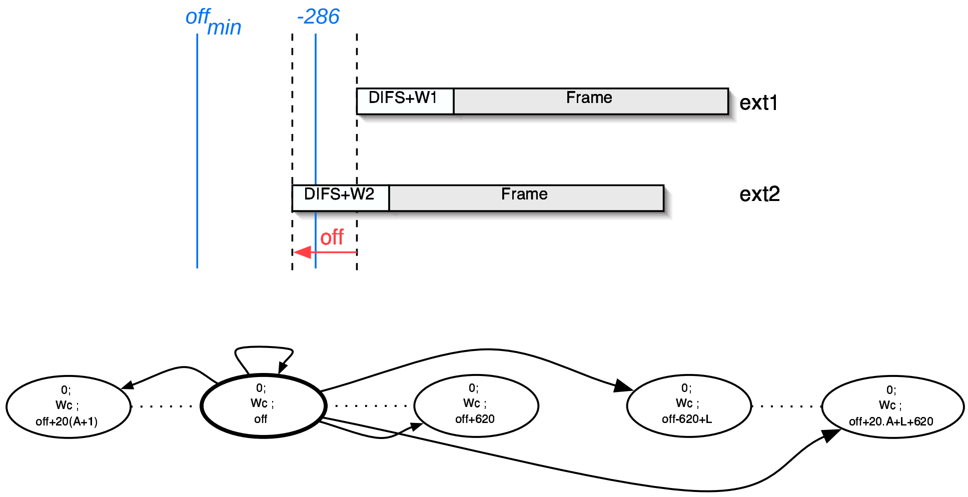

Figure 13: Offset $\in [-906;-287]$ - offset modification is possible, with a translation eventually

Whenever the transition would lead to a state with an offset value less than -906, we let the pairs advance together and then the reference pair wait for the other one. Let's define $A = \lfloor \frac{-907-off}{20} \rfloor$, the upper limit of the difference $W_{e2} - W_{e1}$. Two groups of arrival states can be separated:

$$\forall k \in [A+1;31] P\left((0;W_c;off) \rightarrow (0;W_c;off + 20 \times k)\right) = \frac{32-|k|}{1024} \qquad (2)$$

$$\forall k \in [-31; A]$$
$$P\left((0; W_c; off) \rightarrow (0; W_c; off + L + 20 \times k)\right) = \frac{1}{32^3} \times \sum_{i=-31}^{k} (32 - |i|) \quad (3)$$

3.3 Third case

The external pairs are transmitting, backoff decrementation is not possible and offset translation is mandatory. This situation, illustrated by Figure 14, arises when $W_c \in [1; 15]; W_e = 0$ and $off \in [1526; 2145]$.

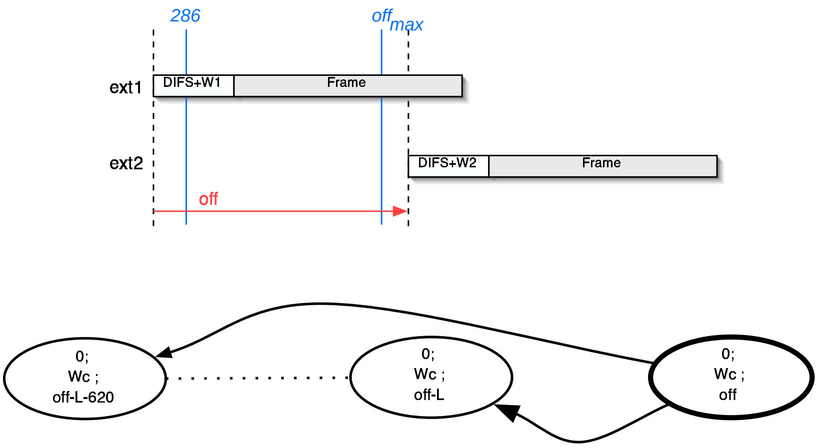

Figure 14: Offset $\in [1526; 2145]$ - offset translation only

The possible arrival states are only determined by the backoff chosen by the reference pair. There is an offset modification of at least L and at most $L + 620$. The possible transitions and their associated probabilities are:

$$\forall k \in [0; 31] P\left((0; W_c; off) \rightarrow (0; W_c; off - L - 20 \times k)\right) = \frac{1}{32} \quad (4)$$

3.4 Fourth case

The external pairs are transmitting, backoff decrementation is possible but not offset translation. This situation arises when $W_c \in [1; 15]; W_e = 0$ and $off \in [-286; 286]$. Three transition types are possible: either the central pair decrements its backoff but the number of slots is not enough to allow it to gain access to the medium, or the central pair manages to emit a packet, or only the offset is modified.

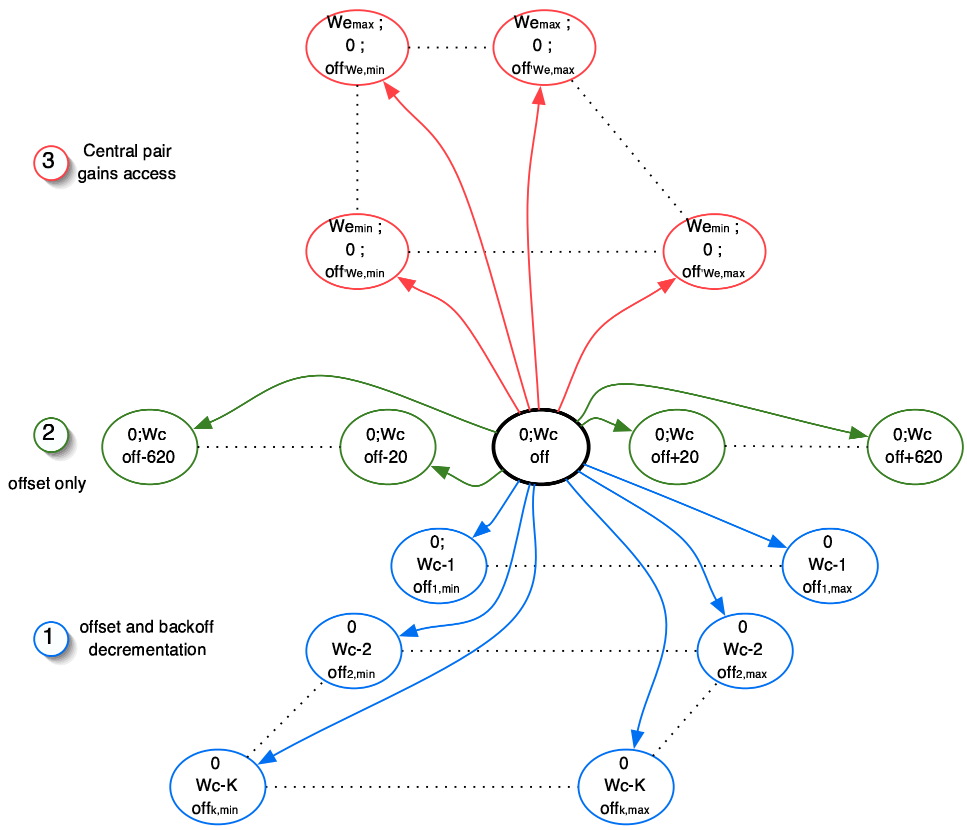

Figure 15: From a state with an offset within [-286 ; 286], many transitions are possible

Let's first look at the case where the central pair decrements its backoff of at least one slot. From the state $(0; W_c; off)$ we arrive in the state $(0; W_c'; off')$. Each arrival state corresponds to a single value of the couple of the backoffs chosen by the external pairs $(W_{e1}; W_{e2})$. Therefore, each transition has an associated probability of $1/32^2$. Now we need to find the set of reachable states.

Given an initial offset value of off, in the best case for the central pair, both external pairs choose a backoff of 31 slots. In this case, the central pair will be able to decrement its backoff of k slots, k being limited by the following constraints:

$$\begin{aligned} & 20.k \leq DIFS + 20 \times 31 - |off| - EIFS \\ \Leftrightarrow\ & 20.k \leq 306 - |off| \\ \Leftrightarrow\ & k \leq \lfloor \frac{306 - |off|}{20} \rfloor \qquad (k \in \mathbb{N}) \end{aligned} \tag{5}$$

Now let's imagine that the central pair decrements its backoff of k slots. Let's examine first the case in which $k < W_c$. The corresponding sub-chain is reprensented in green (zone 1) on Figure 15. We will separate the case in which initial offset off if negative, i.e. the reference pair is ahead and the other case.

When $off \leq 0$, in order to decrement the central pair's backoff, we have the following conditions:

$$\begin{cases} W_{e1} & \in [\lceil \frac{EIFS-DIFS}{20} \rceil + k; 31] \\ W_{e2} & \in [\lceil \frac{EIFS-DIFS+|off|}{20} \rceil + k; 31] \quad \Leftrightarrow \quad W_{e2} \in [\lceil \frac{EIFS-DIFS-off}{20} \rceil + k; 31] \end{cases}$$

By looking at the extreme cases, we can easily infer that:

$$\begin{cases} off' & \geq off + 20 \times \lceil \frac{EIFS-DIFS-off}{20} \rceil + 20.k - 620 \\ off' & \leq off - 20.k + 300 \end{cases}$$

If the initial offset was strictly positive, using the same method, we would have had the following properties:

$$\begin{cases} W_{e1} & \in [\lceil \frac{EIFS-DIFS+|off|}{20} \rceil + k; 31] \quad \Leftrightarrow \quad W_{e1} \in [\lceil \frac{EIFS-DIFS+off}{20} \rceil + k; 31] \\ W_{e2} & \in [\lceil \frac{EIFS-DIFS}{20} \rceil + k; 31] \end{cases}$$

Which leads to:

$$\begin{cases} off' & \leq off - 20 \times \lceil \frac{EIFS-DIFS+off}{20} \rceil - 20.k + 620 \\ off' & \geq off + 20.k - 300 \end{cases}$$

If the number of slots decremented had been greater than the remaining number of slots in the central pair's backoff counter, this last one would have managed to gain access to the medium. This case corresponds to the third zone (in red) on Figure 15. In this case, we need to look at the two remaining backoffs of the external pairs in order to determine which one has the minimum value and how much the new offset will be.

We can use the same formulas than above to compute the new offset. If this offset is positive, then the pair that has the minimal backoff is the previous reference pair. In the other case, it is the other one. Now, the new offset is a multiple of the slot time (i.e. 20 μs). To compute it, we should look at how much slots have been consumed by decreasing the central pair's backoff until the emission:

$$off \leq 0 \Rightarrow \begin{cases} \text{Pair 1} & \lfloor \frac{EIFS+20.k-DIFS}{20} \rfloor \\ \text{Pair 2} & \lfloor \frac{EIFS+20.k-DIFS+|off|}{20} \rfloor \end{cases}$$
$$off > 0 \Rightarrow \begin{cases} \text{Pair 1} & \lfloor \frac{EIFS+20.k-DIFS+|off|}{20} \rfloor \\ \text{Pair 2} & \lfloor \frac{EIFS+20.k-DIFS}{20} \rfloor \end{cases}$$

Considering this, we can find the new offset value (which is in fact $20 * |W_{e1} - number - slots - decremented_{pair1} - W_{e2} + number - slots - decremented_{pair2})$.

Finally, we deal with the transitions corresponding to the cases in which the two exterior pairs choose backoff values that prevent the central pair from decrementing its backoff, i.e. the zone labelled 2 on Figure 15. This happens whenever:

$$off \leq 0 \Rightarrow \begin{cases} & W_{e1} < \lceil \frac{EIFS-DIFS}{20} \rceil = 16 \\ \text{or} & W_{e2} < \lceil \frac{EIFS+|off|-DIFS}{20} \rceil = \lceil \frac{314-off}{20} \rceil \end{cases}$$
$$off > 0 \Rightarrow \begin{cases} & W_{e1} < \lceil \frac{EIFS+|off|-DIFS}{20} \rceil = \lceil \frac{314+off}{20} \rceil \\ \text{or} & W_{e2} < \lceil \frac{EIFS-DIFS}{20} \rceil = 16 \end{cases}$$

Then, $off' = off + 20(W_{e2} - W_{e1})$.

3.5 Fifth case

The central pair is transmitting and both of the external pairs are waiting. This situation arises when $W_e \in [1; 15]$ and $W_c = 0$. Each external pair is synchronized on the silence periods of the central one. The three pairs decrement their backoff together, thus no offset modification is possible.

When the central pair chooses a backoff smaller than $\lceil \frac{EIFS+Slot\_time-DIFS}{Slots\_time} \rceil = 17$, no backoff decrementation is possible for any external pair. If it chooses a backoff B_c of at least 17, both external pairs do decrement their backoff of $B_c - 16$ slots. Whenever $B_c \geq 16 + W_e$, the external reference pair manages to emit a packet and takes back access to the medium. In this case, the arrival state is $(0; B_c - 15 - W_e; off)$ with an associated probability of $1/W$.

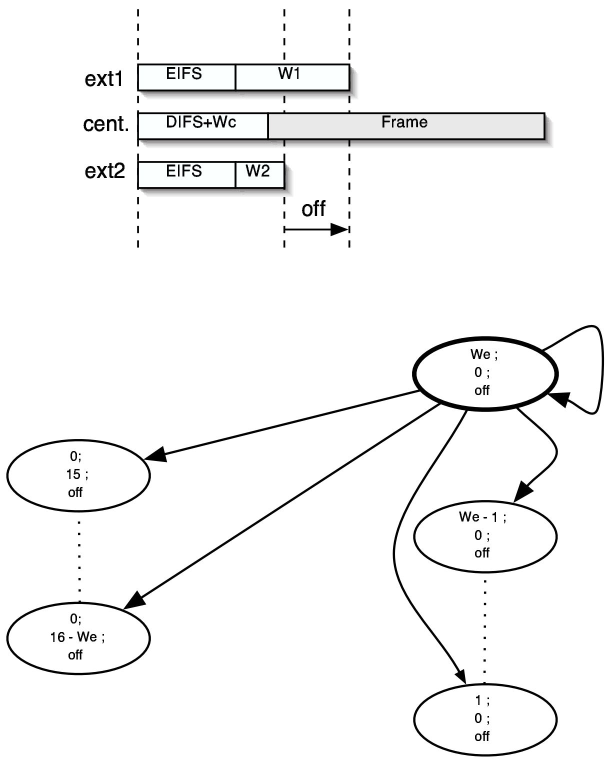

Figure 16: The central pair is transmitting

3.6 Summary

We now have the whole transition matrix for our Markov chain. The following properties can be verified:

- The system modeling is a Markov chain because the probability to be in a certain state only depends on the previous state.
- The chain is homogeneous because the transition probability does not depend on the step number.
- This chain is irreductible because there is no absorbing sub-chain in the graph (verified by construction).
- The chain is not periodical because there are some one-step long cycles.

According to this, we can infer that the limit of the probabilities vector exists and does not depend on the initial state.

4 Results

This system has been solved using the linear algebra library MUMPS [1] in the case of 1000 bytes long packets with a data rate of 11 Mb/s, with and without RTS/CTS exchanges. The characteristics of the two scenarios are summed up in this table:

	frame min. duration	matrix dim.	number of transitions
1000 bytes frames with RTS/CTS	1812 μs	45900×45900	3802223
1000 bytes frames without RTS/CTS	1272 μs	37800×37800	3329723

The results obtained for both cases are gathered in the following table:

	Time-share of central pair	time share of exterior pairs
with RTS/CTS	3,32 %	96,68%
without RTS/CTS	4,4%	95,6%

These results show that a strong inequity seems to appear between concurrent transmissions whenever emitters' tranmsissions can interfere while the nodes cannot communicate. This theoretical result confirms the observations made by simulation under NS-2 in [5].

Conclusion

This paper describes the modeling of a scenario in which inequity between contending emitters arise. The EIFS mechanism designed to avoid interferences between out of range transmissions can lead to a near-starvation situation for certain mobiles. The fact that emitters can only see their own surrounding environement and not the one of its potential receivers makes it a difficult problem to solve.

If IEEE 802.11b protocol has proven itself quite good in managed environnement, its adequation to mobile ad hoc networks could still be discussed. Performance problems that occur in this particular case make us think that ad hoc networks could benefit from dedicated lower layers.

This paper only addresses a particular scenatio, but we plan to extend this modeling method to a more general case. Plenty of scenarios can be imagined in order to describe this problem more precisely and to validate the proposed solutions.

A IEEE 802.11b timings

SIFS	$10\mu s$
DIFS	$50\mu s$
EIFS	$364\mu s$
Backoff	rand(0,CW) – uniform
PLCP Preamble + hdr	192 bits ($192\mu s$)
MAC Overhead (Data)	34o ($24{,}7\mu s$)
ACK	14o ($56\mu s$)
RTS	20o ($80\mu s$)
CTS	14o ($56\mu s$)

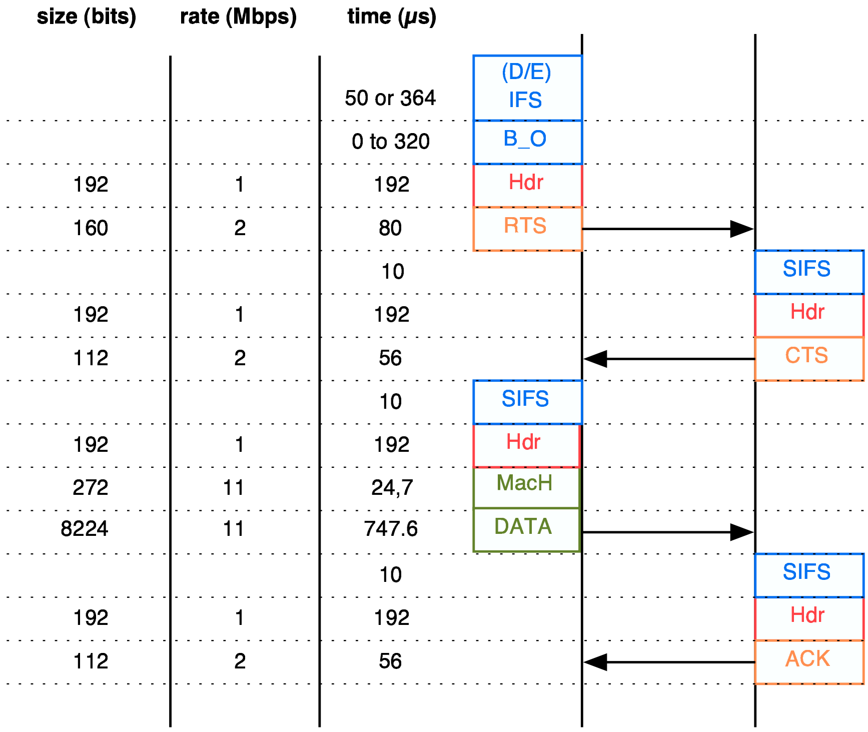

Figure 17: Transmission of a data packet using IEEE 802.11b DCF protocol

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