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Fragmentation and Retransmission of Data Fragment, without Renewing the Channel Reservation, on IEEE 802.11b

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Abstract: In this paper, we focus on the study of the Distributed Coordination Function (DCF) protocol, which is based on the basic CSMA/CA multiple access scheme, provided with a second RTS/CTS mechanism to avoid collision effects. However, the major problem that causes the loss of frames is the internal or external signals' influences, which disturb the transmitted signal, and thus noise errors occur. This leads us to suggest a new analysis of the Saturation Throughput (ST) for IEEE 802.11b DCF protocol. We consider the Packet Fragmentation Mechanism (PFM), Data Fragment Retransmission, without Renewing the Channel Reservation Mechanism (DFR/RCRM) and the distinction between control frames lost due to noise and control frames lost due to collisions. This work provides an analytical model of 3D Markov chain. It is closer to the real IEEE 802.11b DCF protocol's functioning and calculates the ST in a very precise manner. We determined the appropriate ST for both cases where the DFR/RCRM was and was not employed. The results indicate that a wireless network installed in a noisy environment utilizing DFR/RCRM performs better than one using a simple IEEE 802.11b DCF.

Keywords: IEEE 802.11 DCF, PFM, HR-DSSS, Throughput analysis, Markov chain, Signal To Noise ratio

1. INTRODUCTION

The IEEE 802.11 standard [1] is published by the 802.11 group, and provides detailed specifications for channel access mechanisms. DCF is a medium access mechanism distributed between network stations, based on CSMA/CA. Sometimes it is coupled with another optional mechanism of reservation known as RTS/CTS, to solve the problem of hidden stations from the transmitter. When a station, in the network, wishes to send data, it starts by listening to the channel, via the physical layer convergence protocol (PLCP). If this channel is free for a time interval equals to DCF InterFrame Space (DIFS), the transmitter sends an RTS frame containing the total transmission time, and its destination's address. Any station that receives the RTS frame, updates its Network Allocation Vector (NAV) timer. After a period equals to Short IFS (SIFS), the receiver responds with a CTS frame containing (itself) the rest of the transmission time. It is sent to all stations in the same coverage area, to change their NAV timers. If the CTS frame reaches the transmitter after a time period equals to SIFS, in this case the transmitter immediately begins transmitting a data frame. When a SIFS period is expired, the receiver transmits an acknowledgment (ACK), to determine whether the transmitted data frame has been received successfully or not. In this work, we will focus on the data link layer (DLL) and the physical layer (PhyL) of the OSI system. On one hand, in the DLL, precisely the medium access control (MAC) sublayer, we will study the RTS/CTS access technique, used to distinguish between different types of packets depending on the cause of loss, collision or noise (non ideal channel). Since RTS/CTS mechanism can guarantee that the transmission channel is available at the given time, this explains why the transmitted data frames and the ACK control frames are not lost due to collisions. According to the principle of RTS/CTS mechanism, the frames lost due to collisions are only RTS or CTS control frames of stations trying to occupy the channel at the same time. On the other hand, the RTS and CTS control frames can be lost if they encounter noise on the transmission channel. In both cases, the CTS frame is not captured by the sender; it doubles its contention window (CW). On the other hand, in the physical layer, we will extract the exact probabilities of errors, of different types of frames, according to the syntax of the frame in the physical interface, and the parameters of this interface, taking into account the signal-to-noise ratio during data transmission. Many researchers have carried out

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different studied to evaluate the performance of the standard IEEE 802.11 DCF, for the two access modes (basic and RTS/CTS access). Most of these studies took into account the transmission delay, saturation and unsaturated throughput, and under the influence of different conditions of the transmission channel. In [2], the authors extended Bianchi's two dimensional Markov chain model (2D-MCM) [3], to evaluate the efficiency of the optional access mechanism, in IEEE 802.11b. In this study, the authors assumed the existence of an ideal channel, and two frame formats, long-PLCP and short-PLCP of the physical layer. The work [4] proposed a 2D-MCM, from the IEEE 802.11 DCF, to analyze the ST of the basic access mechanism in an ad-hoc mode. The authors assumed a non-ideal transmission channel, and considered the immediate freezing of back-off time, when the channel is busy. In [5], the authors produced a 3D-MCM, to estimate the transmission rate in the optional reservation mechanism, under conditions of a non-ideal transmission channel, and considered the effect of Bit Error Rate ($BER > 10^{-5}$) on different types of frames. The model [5] is based on two main counters: station minimum attempt number for the RTS/CTS and station maximum attempt number for DATA/ACK frames. The backoff stage is the sum of these two counters. In [6], the authors extended the analytical model of Bianchi [3], to evaluate the performances of the 802.11b DCF protocol, in noisy transmission channel conditions, an environment not saturated, taking into account that the number of packet retry limits and the packet length. The work [7] extended the 2D-MCM of Bianchi [3], in order to evaluate the ST, under conditions of a bad transmission environment and the effect of the received signals. The packets lost due to noise are differentiated from the ones lost due to collision, to optimize the performance of the CSMA/CA. In [8], the authors introduced a MCM, which allows the ST of an 802.11b DCF network to be analyzed, under the effect of noise and collisions in the transmission channel. The proposed model is equipped with an algorithm adaptable to the collision rate, and able to differentiate between collisions and noise errors. An extension of the analytical model of the 802.11 DCF network is presented in [9], the authors assumed an unsaturated environment, homogeneous traffic and non-ideal transmission channel. They modeled the modified DCF as a 2D-MCM in order to enhance the unsaturation throughput and reduces packet delay. In article [10], the authors improved the performance of packet loss rate and packet transmission delay, in an IEEE 802.11 DCF wireless network. To study the previous two metrics as a function of data length, non-ideal channel, retry limit access attempts, and different physical layer modes (modulation and coding mechanisms), the authors derived a 2D-MCM. In [11], the authors introduced a new wireless media access protocol named TCCW-DCF, including the same CW and under conditions of an ideal environment. The latter is modeled by a 2D-MCM, with two stages of the backoff. The proposed protocol improves the ST, effectively reduces the average time to access the channel, and in order to derive an optimal CW. The work [12] proposed a new 2D-MCM, to analyze the ST of the IEEE 802.11 DCF protocol in the presence of hidden nodes, and in an ideal transmission channel, for both access modes. In the article [13], the authors proposed a new 2D-MCM, which makes it possible to analyze the ST of the CSMA/CN (Collision Notification) protocol, of early detection of collisions, under conditions of an ideal wireless channel, for WiFi Direct networks. In [14], the authors proposed a 2D-MCM, to examine the performance of IEEE 802.11 DCF, in a vehicular network, under different CW size. This model makes it possible to analyze several performance metrics, such as: probability of channel occupancy, probability of successful transmission, probability of collision, ST and packet dropping rate under different size of CW. In article [15], the authors developed two models, to analyze the saturation(2D-MCM) and unsaturation (3D-MCM) throughput performance of the IEEE 802.11 DCF network access protocol, under different channel conditions. Before analyzing the different groups of collision probabilities of the two previous systems, the authors geometrically analyze the collision probability, with and without hidden terminals, depending on the covered area of the network.

In the models described in [2], [5], [6], [7], [9], [13], [15], when a station wants to transmit data, decrements the selected backoff successively, without taking into account that the transmission channel is occupied by another station (the transition probability that the channel is occupied $p_{busy} = 0$). When backoff time becomes zero, the station starts transmitting the packet, with success or failure. This problem is partially addressed in models [4], [10], [12], a station that is waiting to transmit, first it listens to the channel, if it has become free (idle), it decrements its backoff with a probability of $1 - P_{coll}$. However the channel might be reserved by one of the (n-1) stations in the network and without collision ($p_{coll} = 0$ but $p_{busy} \neq 0$). Further, the model [11], manages its backoff in two ways, in stage zero each station assumes that the channel is free ($p_{idle} = 1$) and decrements its backoff chosen successively, without listening to the channel. If the backoff value becomes null, the station listens to the medium, and starts transmitting data, if the channel is free, otherwise the station chooses another backoff time randomly in stage one, without doubling the CW and decrements its backoff correctly. In the same stage, and with zero backoff time, the station begins to transmit its data, but without listening to the channel ($p_{idle} = 1$).In models [6], [7], if the packet is lost due to noise, the system iteratively (without stopping) retransmits the data packet with the same CW. This malfunction in the backoff algorithm causes a loss of time equal to the backoff value multiplied by the size of a slot time on each retransmission attempt, which negatively affects the ST. The operation of the backoff in the model [12] is different from the other models, in the first stage, if there is a collision, any station whose backoff value is zero, changes its CW from stage i to stage i + 1 according to the formula $CW_{i+1} = \sqrt{2}CW_i$. This formula indicates that the value of the CW is a fractional number, therefore according to the proposed Markov chain, the decrement of the CW_i of stage i, does not reach the value zero and this shows the correct malfunction of the model. In the rest of the stages, each station uses the traditional backoff algorithm.

In the physical interface, the different parts of a data or control frame are transmitted at predefined rates. The differentiation of these rates during the transmission of any frame (RTS, CTS, DATA, ACK), shows that the BER varies from one part to another in a frame. For this reason, the works in [5], [6] do not conform to the physical layer actual functioning. Moreover, in models [4], [7], [8], [9], [10], the operating principle of the physical layer is almost satisfied, as indicated in Table 1. Furthermore, the authors in models [2], [11], [12], [13], [14] , assume that the environment is ideal (BER = 0 i.e. p_{error} = 0), and this shows that the results obtained by the models known in the literature, remain always mysterious, lacking accuracy and far from reality.

As part of this work, we are extending the previous models to deal with the formerly raised problems such the loss of different types of frames due to either collision or environmental impacts. We take into account the transmission rates of each part of these types of frames, depending on the physical interface and the correct functioning of the backoff. Finally, we add a new parameter (j: defined in subsection 3.3) to show the advantage of DFR/RCRM. Therefore, in the presence of noise, the station which reserves the channel in the network having the possibility of retransmitting its data fragments several times, without doubling the CW. None of the previous works takes into account the modeling of the DCF protocol, with the DFR/RCRM, in a noisy environment, i.e. by considering retransmissions of a data fragment without channel reservation renewal in the MCM.

The rest of this paper is arranged into four parts as follows: in second part, we present the physical layer of 802.11b HR-DSSS and the computation of different probabilities of errors. Then, in third part, we describe our proposed model and extract the ST. In fourth part , we comment the obtained numerical results. Finally, we conclude the work on the last part.

2. 802.11*b* PHYSICAL LAYER

The following is an example of the 802.11b physical layer and is based on one of two transmission techniques: frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS). In our model, we use the High Rate-DSSS (HR-DSSS) transmission method, which divides the 2.4 GHz band, 83.5 MHz wide(2.4 to 2.4835 GHz), into 14 interfered sub-channels, each 22 MHz wide [1]. It has two frame formats, in the physical interface(PLPC-PPDU), and each of them has predefined values in the 802.11b standard, as shown in Table I. Generally, any frame in the physical layer is the concatenation of three parameters: Pr, He and frag. Where Pr is the preamble, transmitted with a rate PR, He is the physical header, transmitted with a rate MR and finally, frag = MPDU (MAC header + fragIV + CRC) is the information coming from the MAC layer. It transmits the MAC header plus the CRC with a rate MR, and body of the data fragment (fragBody) with its initialization vector (IV) with a rate DR. The control frames (RTS, CTS and Ack) are generated at the MAC layer and transmitted at a rate MR [2].

Now, we determine the two probabilities of errors Pe and Pe_{RC} of erroneous transmission of a data frame and an RTS control frame respectively. $BER_{1Mb/s}$, $BER_{2Mb/s}$, $BER_{5.5Mb/s}$ and $BER_{11Mb/s}$ are the error rates per bit according to the transmission rate corresponding to each of them. Thus, the different BERs in the 802.11b HR-DSSS physical interface calculated using the formulas described in [16], as follows:

$$\begin{cases} BER_{1Mb/s} = Q(\sqrt{11E_c/N_c}) \\ BER_{2Mb/s} = Q(\sqrt{5.5E_c/N_c}) \\ BER_{5.5Mb/s} = \frac{8}{15}[14Q(\sqrt{8E_c/N_c}) + Q(\sqrt{16E_c/N_c})] \\ BER_{11Mb/s} = \frac{128}{255}[24Q(\sqrt{4E_c/N_c}) + 16Q(\sqrt{6E_c/N_c}) + \\ \qquad 174Q(\sqrt{8E_c/N_c}) + 16Q(\sqrt{10E_c/N_c}) + \\ \qquad 24Q(\sqrt{12E_c/N_c}) + Q(\sqrt{16E_c/N_c})] \end{cases} \tag{1}$$

Where: $E_c/N_c = 2 \times SINR$, represents the signal to noise ratio per chip. SINR is the signal to noise ratio plus interference.

First, we calculate the error probability Pe, let G1 be the first group of transmission events of a data packet, defined as follows:
E_1: the event that a transmission fails on a preamble Pr occurs due to noise.
E_2: the event that a transmission fails on the physical header He, the MAC header and CRC (He + Mc) occurs due to noise.
E_3: the event that a transmission fails while broadcasting the fragment body with its IV (fragIV) occurs due to noise. These three events are compatible, if and only if they are joined to each other, then:

$$Pe(G1) = p(E_1 \cup E_2 \cup E_3) = p(E_1) + p(E_2) + p(E_3) - p(E_1)p(E_2) - p(E_1)p(E_3) - p(E_2)p(E_3) + p(E_1)p(E_2)p(E_3) \tag{2}$$

$$Pe(G1) = \begin{cases} 1 - (1 - BER_{PR})^{Pr}(1 - BER_{MR})^{He+Mc}(1 - BER_{DR})^{fragIV}, \\ \qquad short\ preamble \\ 1 - (1 - BER_{PR})^{Pr+He+Mc}(1 - BER_{DR})^{fragIV},\ long \\ \qquad preamble \end{cases} \tag{3}$$

Let G2 be the second group of acknowledgment of event reception defined as follows:
B_1: the event that a reception fails on the preamble Pr occurs due to noise.
B_2: the event that a reception fails on the physical header He occurs due to noise.

TABLE I. Frame Structure in the 802.11b HR-DSSS physical interface

Parameters	Size (Bits)	Modulation	Rate (Mb/s)
	Long PLCP-PPDU format		
Pr	144	DBPSK	PR =1
He	48	DBPSK	MR=1
MC= MAC header+CRC	272	DBPSK	MR=1
fragIV=fragBody+IV	[0,18432]+64	DBPSK	DR=1
		DQPSK	DR=2
		CCK-4	DR=5.5
		CCK-8	DR=11
	Short PLCP-PPDU format		
Pr	72	DBPSK	PR =1
He	48	DQPSK	MR=2
MC= MAC header +CRC	272	DQPSK	MR=2
fragIV=fragBody+IV	[0,18432]+64	DQPSK	DR=2
		CCK-4	DR=5.5
		CCK-8	DR=11

B_3: the event that a reception fails on acknowledgment Ack occurs due to noise.
Since these events are compatible, therefore the error probability is:

$$Pe(G2) = p(B_1 \cup B_2 \cup B_3) \tag{4}$$

$$Pe(G2) = \begin{cases} 1-(1-BER_{PR})^{Pr}(1-BER_{MR})^{He+Ack}, & short\ preamble \\ 1-(1-BER_{PR})^{Pr+He+Ack}, & long\ preamble \end{cases} \tag{5}$$

Since the error happens during the time of transmission (G1) or on reception (G2) and because the two groups are compatible with each other, so by definition we obtain:

$$Pe = P(G1 \cup G2) = P(G1) + P(G2) - P(G1)P(G2) \tag{6}$$

Thus:

$$Pe = 1 - \begin{cases} (1-BER_{PR})^{2Pr}(1-BER_{MR})^{2He+Mc+Ack}(1-BER_{DR})^{fragIV} & short\ preamble \\ (1-BER_{PR})^{2(Pr+He)+Mc+Ack}(1-BER_{DR})^{fragIV}, & long\ preamble \end{cases} \tag{7}$$

In a similar way, we calculate the error probability Pe_{RC}, on one of the frames RTS or CTS. Let the two events C_1 and C_1 be defined as follow:
C_1: The event of a transmission failure on the RTS frame occurs due to noise.
C_2: The event of a transmission failure on the CTS frame occurs due to noise.

In the physical interface, the system transmits the preamble Pr, followed by the physical header He and the RTS or CTS frame:

$$Pe(C_1) = \begin{cases} 1-(1-BER_{PR})^{Pr}(1-BER_{MR})^{He+RTS}, & short\ preamble \\ 1-(1-BER_{PR})^{Pr+He+RTS}, & long\ preamble \end{cases} \tag{8}$$

$$Pe(C_2) = \begin{cases} 1-(1-BER_{PR})^{Pr}(1-BER_{MR})^{He+CTS}, & short\ preamble \\ 1-(1-BER_{PR})^{Pr+He+CTS}, & long\ preamble \end{cases} \tag{9}$$

Since the two events C_1 and C_2 are compatible with each other, therefore:

$$Pe_{RC} = P(C_1 \cup C_2) = P(C_1) + P(C_2) - P(C_1)P(C_2) \tag{10}$$

$$Pe_{RC} = 1 - \begin{cases} (1-BER_{PR})^{2Pr}(1-BER_{MR})^{2He+RTS+CTS}, & short\ preamble \\ (1-BER_{PR})^{2(Pr+He)+RTS+CTS}, & long\ preamble \end{cases} \tag{11}$$

Where $L_{RTS} = Pr + He + RTS$ and $L_{CTS} = Pr + He + CTS$. L_{RTS} and L_{CTS} represent the size of the RTS and CTS control frame, respectively, in the physical interface.

3. Markov model for DCF with DFR/RCRM

In our analysis, we define the set of hypotheses, parameters and probabilities of the proposed model.

A. Hypotheses

1) The transmission channel is not ideal (noisy environment, the error probability of a set of bits varies according to the BER used)
2) The number of wireless stations in an ad-hoc network is n.
3) All stations use the RTS/CTS reservation mechanism to access a shared transmission channel.
4) A collision occurs only at the RTS control frame level.

5) An RTS or CTS control frame can be lost due to errors on the frame itself.
6) A data frame or acknowledgment ACK frame can be lost only if there is an error on the frame itself.
7) All waiting queues of stations must contain at least one packet available to send (taking into account saturation conditions).
8) All stations use the same structure of the physical interface.
9) In the case of a transmission error, each data fragment frag will only be retransmitted after a delay $T_{e.frag}$, given by equation (42), without renewing the channel reservation.
10) The propagation time γ of a signal is taken into consideration in our model.

B. Model input parameters

We add the following input parameters, which are essential for our proposed model functionality.

1) m' : the maximum backoff stage, in which we make the last attempt to double the size of CW
2) m : the maximum backoff stage, in which we make the last attempt to transmit an RTS frame without doubling the size of CW.
3) $h = m–m'$: number of retransmission, with the channel renewed reservation using the RTS/CTS mechanism without doubling the size of CW.
4) r : Maximum Number of the same Data Fragment Retransmission, without Renewing the Channel Reservation (Maximum_NDFR/RCR).

C. Model states

To study such an operating mechanism, it is first necessary to model its behavior correctly. In our case, we model the behavior of our proposed system (defined by a set of characteristics) by a MCM (see Figure 1). This model enables us to extract the stationary probability τ of data packet transmission (N data fragment), to calculate the ST in different situations. Let us consider the following stochastic processes:

1) B(t): representing the backoff time counter k of a particular station at a specific moment t, defined by a random, uniform probability.
$$k = random(0, CW).Slotime$$
Where CW is the contention window in the current backoff stage, given by:
$$CW_i = \begin{cases} 2^i\, CW_0 & i \leq m' \\ 2^{m'}\, CW_0 & m' + 1 \leq i \leq m \end{cases} \quad (12)$$
Where i the backoff stage ($1 \leq i \leq m$) and CW_0 the initial CW.
2) S(t): representing the backoff stage of a particular station at a specific moment t, and its values in the set $\{0, 1, 2, 3, ...m', ..., m\}$.
3) N(t): representing the number of non-transmitted fragments plus one RTS frame of a particular station at a specific moment t, and its values are from the set $\{N_0 + 1, N_j, (N - 1)_j, \ldots, 1_j, 0_0\}$. Where j: represents the attempts to retransmit a data fragment, without renewing the reservation of the channel (NDFR/RCR), and its values are from the set $\{0, 1, 2, \ldots, r\}$, and the one "R = 1" added in "N_0+1", indicates that the RTS control frame is not yet sent (R = 1). If the station transmits the RTS frame, after receiving the corresponding CTS frame correctly, it sets R to zero (R = 0).

Thus, we can model the three processes B(t), S(t) and N(t) by the 3D process {B(t), N(t), S(t)} , with discrete-time Markov chain. Figure 1 shows our proposed MCM of IEEE 802.11 with RTS/CTS access mechanism, PFM, and the DFR/RCRM." .

D. Probabilities Calculation

To obtain accurate results, we define the different elementary probabilities of our proposed model as follows:

1) Probability of an occupied channel(Pb)

In this case, during listening, the transmission channel is found busy, by at least one of the $(n-1)$ waiting stations, over a specified period. We assume x a random variable, which represents the number of stations currently transmitting, where $k \in x = \{0, 1, 2\ldots, n-1\}$ and every station emits successfully with a probability τ, specified by equation (35), otherwise $(1-\tau)$ on failure.So, $x \xrightarrow[follows]{} B(n-1, \tau)$, knowing that:
$$p(x = k) = C_n^k \tau^k (1 - \tau)^{n-k} \quad (13)$$
By definition:
$$Pb = p(x \geq 1) = 1 - (1 - \tau)^{n-1} \quad (14)$$

2) Collision probability occurring at the transmission channel (Pc)

A collision occurs, during a given slot time, when at least two of the n stations emit simultaneously (they have chosen the same backoff). We assume x a random variable that represents the number of stations, which want to start the transmission, where $k \in x = \{0, 1, 2\ldots, n\}$. Each station transmits successfully with a probability τ, otherwise $(1 - \tau)$ in case of failure. So $x \xrightarrow[follows]{} B(n, \tau)$, knowing that: $x \xrightarrow[follows]{} B(n - 1, \tau)$, knowing that:
$$p(x = k) = C_{n-1}^k \tau^k (1 - \tau)^{n-k} \quad (15)$$
By definition:
$$Pc = p(x \geq 2) = 1 - [1 + (n - 1)\tau](1 - \tau)^{n-1} \quad (16)$$

3) Probability of unsuccessful transmission (P)

A retransmission involves a new reservation of the transmission channel, which happens in two cases. Case 1: a transmission failure of one of the control frames

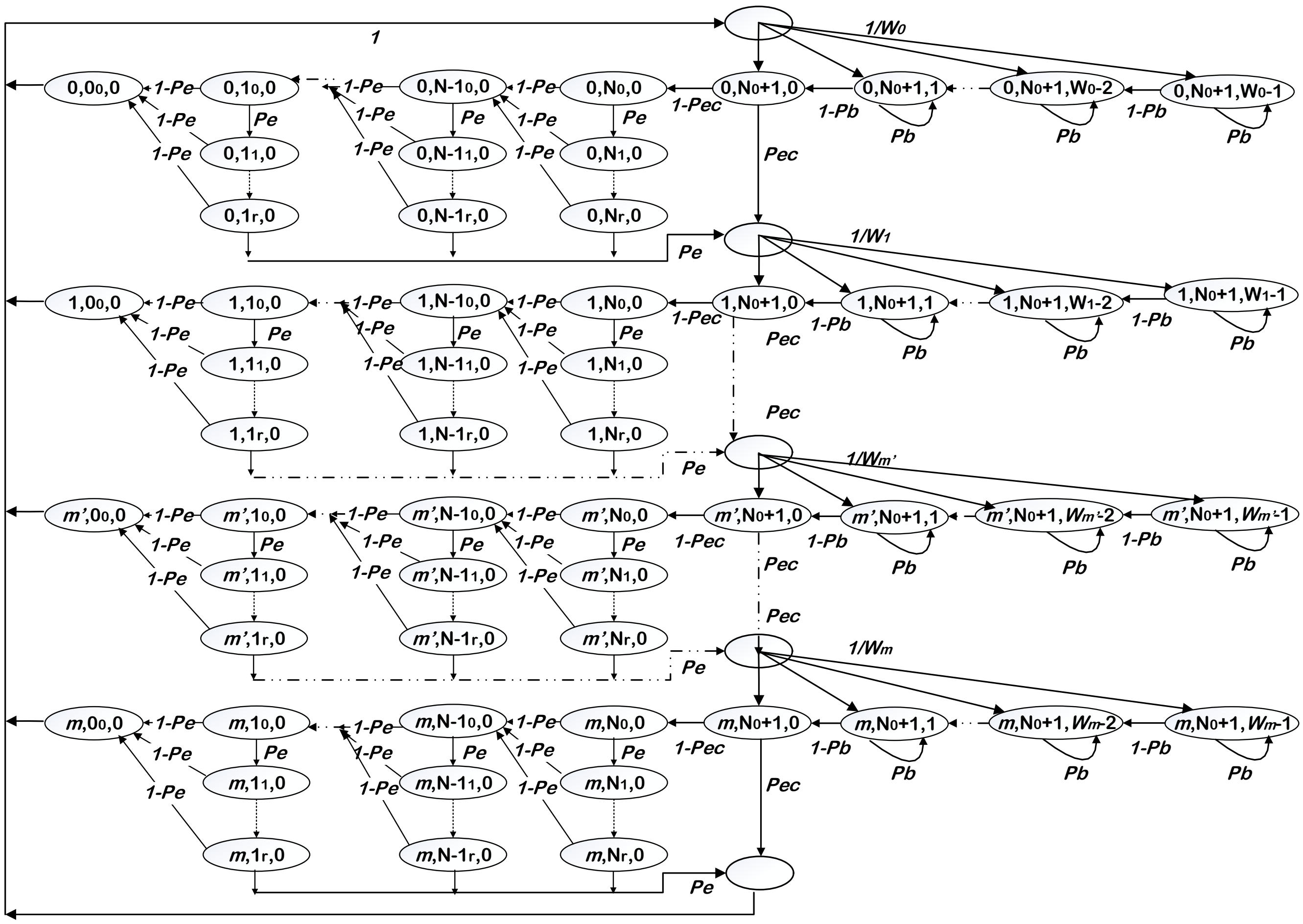

Figure 1. IEEE 802.11 MCM with RTS / CTS, PFM and the DFR/RCRM

RTS or CTS. Case 2:a transmission failure of one of the frames: data fragment or Ack control. Let *Pec* be the first probability of unsuccessful transmission caused by the following three events:
E_1: The event of a transmission failure on the RTS frame occurs due to noise.
E_2: The event of a transmission failure on the CTS frame occurs due to noise.
E_3: The event of a transmission failure on the RTS frame occurs due to a collision.

By definition:

$$Pec = P(E_1 \cup E_2 \cup E_3) = P(E_1 \cup E_2) + P(E_3) - P(E_1 \cup E_2)P(E_2) \quad (17)$$

Where $P(E_1 \cup E_2) = Pe_{RC}$ and $P(E_3) = Pc$ Thus:

$$Pec = 1 - (1 - Pe_{RC})(1 - Pc) \quad (18)$$

Let *Perr* be the second probability of unsuccessful transmission caused the following two events:
D: the event, that the channel is booked via the RTS/CTS mechanism.
E: the event, that the channel is lost after $(r + 1)$ retransmission of a data fragment, occurs due to environmental noise.

By definition and since events A and B are independent of each other, then:

$$Perr = P(D \cap E) = P(D)P(E) = (1 - Pec)(1 - \alpha^N) \quad (19)$$

Where $\alpha = 1 - Pe^{r+1}$ Thus, we can conclude:

$$P = Pec + Perr = 1 - (1 - Pec)\alpha^N \quad (20)$$

4) Probabilities of transitions

Based on Figure 1, we can extract the general formulas, from the conditional probabilities of the transitions as:

$$P(i, N_0 + 1, k - 1 | i, N_0 + 1, k) = 1 - Pb, i \in \{0, 1, ..m\} \text{ and } k \in \{1, 2, ..W_i - 1\} \quad (21)$$

The station listens to the channel, if it is free, during a DIFS period, it decrements its backoff counter from k to

$(k-1)$ in the i^{th} stage.

$$P(i, N_0+1, k|i, N_0+1, k) = Pb,\ i \in \{0, 1, ..m\}\ and\ k \in \{1, 2, ..W_i - 1\} \quad (22)$$

The station listens to the channel, if it is found to be busy, for a DIFS time, it freezes its backoff counter at k in the i^{th} stage.

$$P(i, N_0+1, k|i-1, N_0+1, 0) = Pec/W_i, i \in \{1, 2, ..m\}\ and\ k \in \{0, 1, ..W_i - 1\} \quad (23)$$

Once the backoff time becomes zero, the station tries to send an RTS frame, but with unsuccessful transmission (without CTS in return). Thus, the station increments its backoff stage from $(i-1)$ to i (it doubles the size of its CW) and selects randomly a new backoff time k in the i^{th} stage.

$$P(i, N_0+1, k|i-1, N-L_r, 0) = Pe/W_i, i \in \{1, 2, ..m\},\ k \in \{0, 1, ..W_i - 1\}\ and L \in \{0, 1, ..N-1\} \quad (24)$$

Every station reserves the channel using the RTS/CTS mechanism, having the right to retransmit a data fragment r times, each of its L fragments in its waiting queue. If the number of retransmissions exceeds r failed attempts (due to noise), the station increments its backoff stage from $(i-1)$ to i and selects randomly a novel backoff time k in the i^{th} stage.

$$P(i, N_0, 0|i, N_0+1, 0) = 1 - Pec, i \in \{0, 1, ..m\} \quad (25)$$

If the backoff time is zero and the channel is free during a DIFS period, the station sends an RTS control frame and receives the corresponding CTS, finally sets R to zero (i.e. from N_0+1 to N_0+0 frames not transmitted).

$$P(i, N-L_j, 0|i, N-L_{j-1}, 0) = Pe, i \in \{0, 1, ..m\}, j \in \{1, 2, ..r\}\ and\ L \in \{0, 1, ..N-1\} \quad (26)$$

In the i^{th} stage, and due to the environment noise, which prevents the data transmission, the station tries to send the current fragment and in case of failure it increments j (the number of retransmission).

$$P(i, N-1-L_0, 0|i, N-L_j, 0) = 1 - Pe,\ i \in \{0, 1, ..m\},\ j \in \{0, 1, ..r\}\ and\ L \in \{0, 1, ..N\} \quad (27)$$

While in the i^{th} stage, and in the j^{th} attempt the station correctly transmits the fragment after receiving the acknowledgment ACK, and decrements the number of fragments in the waiting queue from $(N-L)_j$ to $(N-1-L)_0$, where zero indicates that the new fragment has not been retransmitted yet.

$$P(0, N_0+1, k|i, 0_0, 0) = 1/W_0,\ i \in \{0, 1, ..m\}\ and\ k \in \{0, 1, ..W_0 - 1\} \quad (28)$$

The station can successfully transmit all of its fragments, in any backoff stage $(i, 0_0, 0)$, and initializes its backoff stage to zero, so it randomly chooses the new backoff time k.

$$P(0, N_0+1, k|m, N-L_r, 0) = Pe/W_0,\ k \in \{0, 1, ..W_0-1\}\ and\ L \in \{0, 1, ..N-1\} \quad (29)$$

Because of the high noises, the station tries r times to retransmit a data fragment, up to the m^{th} backoff stage, but with unsuccessful transmission of the packet completely $(m, N-L_r, 0)$, where L represents the number of fragments transmitted. In all cases of unsuccessful transmission, the station restarts its backoff stage to zero and randomly chooses the corresponding backoff time k.

$$P(0, N_0+1, k|m, N_0+1, 0) = Pec/W_0, k \in \{0, 1, ..W_0 - 1\} \quad (30)$$

In the m^{th} backoff stage, the station failed to reserve the transmission channel again $(R = 1)$, either because of noise or collision in the control frames. The station restarts its backoff stage to zero and randomly chooses the corresponding backoff time k.

5) Probabilities of stationary states

Let $\pi_{i,(N-L)_j+R,k} = \lim_{t\to\infty} p\{S(t) = i, N(t) = (N-L)_j + R, B(t) = k\}$, such that: $i \in \{0, 1, ..m\}, L \in \{0, 1, ..N\}, j \in \{0, 1, ..r\}, R \in \{0, 1\} and\ k \in \{0, 1, ..W_0 - 1\}$, the stationary distribution of our proposed model. In stationary states, the equations representing this model, are given with respect to the initial state $\pi_{0,N_0+1,0}$,by the following five formulas:

$$\pi_{i,(N-L)_j+R,k} = \pi_{0,N_0+1,0} \begin{cases} \frac{(W_i-k)P^i}{(1-Pb)W_i}, & R=1,\ L=j=0,\ 0 \le i \le m'\ and\ 1 \le k \le W_i - 1 \\ \frac{(W_{m'}-k)P^i}{(1-Pb)W_{m'}}, & R=1,\ L=j=0,\ m'+1 \le i \le m\ and\ 1 \le k \le W_i - 1 \\ P^i, & R=1,\ L=j=0,\ 0 \le i \le m\ and\ k=0 \\ Pe^j\alpha^L(1-Pec)P^i, & R=0,\ 0 \le L \le N-1,\ 0 \le j \le r,\ 0 \le i \le m\ and\ k=0 \\ (1-P)P^i, & R=j=0,\ L=N,\ 0 \le i \le m\ and\ k=0 \end{cases} \quad (31)$$

Where $\alpha = 1 - Pe^{r+1}$ and $P = 1 - (1 - Pec)\alpha^N$

6) Transmission Probability (τ)

In the proposed Markov model (Figure 1), the probability of transmission (τ), of a data packet, is equal to the sum of all the stationary probabilities, whose backoff value is zero ($\pi_{i,(N-L)_j+R,0}$). These stationary probabilities expressed as a function of the initial stationary state $\pi_{0,N_0+1,0}$ and the probability of unsuccessful transmission P, see equations (31)and(20). Based on the normalization condition we obtain the probability of the initial stationary state, as follows:

$$1 = \pi_{0,N_0+1,0} \sum_{x=1}^{5} S_x \tag{32}$$

Where

$$\begin{cases} S_1 = \sum_{i=0}^{m'} \sum_{k=1}^{W_i-1} \frac{(W_i-k)P^i}{(1-Pb)W_i} = \frac{1}{2(1-Pb)}\left[\frac{W_0(1-(2P)^{m'+1})}{1-2P} - \frac{1-P^{m'+1}}{1-P}\right] \\ S_2 = \sum_{i=m'+1}^{m} \sum_{k=1}^{W_i-1} \frac{(W_{m'}-k)P^i}{(1-Pb)W_{m'}} = \frac{(W_{m'}-1)(P^{m'+1}-P^{m+1})}{2(1-Pb)(1-P)} \\ S_3 = \sum_{i=0}^{m} P^i = \frac{1-P^{m+1}}{1-P} \\ S_4 = (1-Pec)\sum_{i=0}^{m}\sum_{L=0}^{N-1}\sum_{j=0}^{r} Pe^j \alpha^L P^i = \frac{(\alpha-\alpha^{N+1})(1-P^{m+1})}{(1-Pe)(1-\alpha)\alpha^N} \\ S_5 = (1-P)\sum_{i=0}^{m} P^i = 1 - P^{m+1} \end{cases} \tag{33}$$

Where equation (32) implies that:

$$\pi_{0,N_0+1,0} = \frac{1}{\sum_{x=1}^{5} S_x} \tag{34}$$

After assigning values to the input parameters, and calculating the elementary probabilities, we can extract the expression for the transmission probability (τ) of a data packet as:

$$\tau = (S_3 + S_4 + S_5)\pi_{0,N_0+1,0} = \frac{S_3 + S_4 + S_5}{\sum_{x=1}^{5} S_x} \tag{35}$$

To find the numerical values of the transmission probability τ corresponding to the different values of the input parameters, we solved the nonlinear system of equations (14), (20), and (35). The probability P in equation (20) is depending on the transmission probability τ and vice versa. Therefore, the transmission probability τ represents a recursive nonlinear system of equations, provided by the relation: $\tau = f(\tau)$ and solved using a numerical method and accepting only one solution.

E. Saturation Throughput (ST)

The normalized saturation throughput ST, corresponding to our proposed model, can be given by:

$$ST = \frac{E(Packet)}{E(T)} \tag{36}$$

Where $E(Packet)$: represents the average quantity of information successfully transmitted on the transmission channel.$E(T)$: represents the average transmission time of a data packet. First, we express the general expression of the numerator in equation (36):

$$E(Paquet) = p(x=1)(1-Pe_{RC})E(N_{S.frag})fragBody \tag{37}$$

Where $p(x = 1)$ is calculated using equation (15) and $E(N_{S.frag})$ represents the average number of successfully transmitted fragments. If there is a data fragment that is lost, the station starts retransmission from that fragment.

$$E(N_{S.frag}) = Pe^{r+1}\sum_{i=0}^{N-1} i\alpha^i + N\alpha^N = \frac{\alpha - \alpha^{N+1}}{1-\alpha} \tag{38}$$

The general expression of the denominator is presented as:

$$\begin{aligned} E(T) = {} & p(x=0)\sigma + p(x=1)(1-Pe_{RC})[E(T_{S.RC}) + \\ & E(T_{S.packet}) + E(T_{e.packet})] + p(x=1)Pe_{RC}T_{e.RC} + \\ & p(X \geq 2)(1-Pe_{RC})T_{C.RC} \end{aligned} \tag{39}$$

Where σ is the length of an empty timeslot, $E(T_{S.RC})$ is the mean time of RTS frame successfully transmitted, $E(T_{S.packet})$ is the average time of data packet successfully transmitted, and $E(T_{e.packet})$ is the average time of data packet unsuccessfully transmitted due to channel errors. We express them in a precise way as:

$$\begin{cases} E(T_{S.RC}) & = T_{S.RC}(Pe^{r+1}\sum_{i=0}^{N-1}\alpha^i + \alpha^N) \\ & = T_{S.RC} \\ E(T_{S.packet}) & = T_{S.frag}(Pe^{r+1}\sum_{i=1}^{N-1} i\alpha^i + N\alpha^N) \\ & = T_{S.frag}E(N_{S.frag}) \\ E(T_{e.packet}) & = T_{e.frag}[Pe^{r+1}((r+1)\sum_{i=0}^{N-1}\alpha^i + \beta\sum_{i=1}^{N-1} i\alpha^{i-1}) \\ & \quad + \beta N\alpha^{N-1}] \\ & = T_{e.frag}\frac{Pe}{1-Pe}E(N_{S.frag}) \end{cases} \tag{40}$$

Where $\beta = \alpha\frac{Pe}{1-Pe} - (r+1)(1-\alpha)$

Now to obtain the equation (41), we substitute $E(T_{S.RC})$,$E(T_{S.packet})$,and $E(T_{e.packet})$ in equation (39) by their values as expressed in equation (40).

$$\begin{aligned} E(T) = {} & p(x=0)\sigma + p(x=1)(1-Pe_{RC}[T_{S.RC} + T_{S.frag} \\ & E(N_{S.frag}) + T_{e.frag}\frac{Pe}{1-Pe}E(N_{S.frag})] + p(x=1) \\ & Pe_{RC}T_{e.RC} + p(x \geq 2)(1-Pe_{RC})T_{C.RC} \end{aligned} \tag{41}$$

Where $T_{S.RC}$ is the time needed to send an RTS frame successfully. $T_{S.frag}$is the successful transmission time of a data fragment. $T_{e.frag}$ is the time required to send a data fragment without success occurs due to a transmission error. $T_{e.RC}$ and $T_{C.RC}$ are the unsuccessful transmission times of an RTS frame, which occur due to a transmission error and a collision respectively. These terms can be expressed (see equations (42)), according to the frame format used at the PLCP-PPDU physical interface.

$$\begin{cases} T_{S.RC} = DIFS + \frac{Pr}{PR} + \frac{He+RTS}{MR} + SIFS + 2\gamma + \frac{Pr}{PR} + \frac{He+CTS}{MR} \\ T_{e.RC} = T_{C.RC} = T_{S.RC} - \gamma \\ T_{S.frag} = SIFS + \frac{Pr}{PR} + \frac{He+MC}{MR} + \frac{fragIV}{DR} + SIFS + 2\gamma + \frac{Pr}{PR} \\ \quad + \frac{He+Ack}{MR} \\ T_{e.frag} = T_{S.frag} - \gamma \end{cases} \tag{42}$$

Where, $p(x = 0) = (1-\tau)^n$ is the probability that the transmission channel is free (idle), $p(x = 1) = n\tau(1-\tau)^{n-1}$ is the successful transmission probability and $p(x \geq 2) = Pc$ is the unsuccessful transmission probability, which occurs due to collision.

4. Discussion of results

In this part, we introduce the numerical results that show the influence of the environment, the fragment length and the Maximum_NDFR/RCR, on the efficiency of the system. The data fragment retransmission process, represented by NDFR/RCD, is closely related to the DFR/RCRM mechanism. The activation of this mechanism gives each station the possibility of retransmitting each data fragment several times (r >=one retransmission, i.e. at least two transmissions) without renewing the reservation of the transmission channel. Otherwise (when DFR/RCRM is disabled), each data fragment is only transmitted once ($r = 0$ i.e. Maximum_NDFR/RCR equals zero). This last case (when r = zero) represents a simple IEEE 802.11b DCF.

In the remaining part of this section, we take into account the practical considerations identified in Tables I and II.

A. Environment influence on errors probabilities

The three equations (1), (7) and (11) indicate the impact of environmental noise on different types of frames when transmitting. The numerical results are illustrated in Figures 2 and 3, which show the error probabilities of Pe_{RC} and Pe, for the HR-DSSS system in terms of E_c/N_c ratio, respectively for the two structures of the physical interface, long and short frame format. From the results shown in Figures 2 and 3, the error probability on the control frames (RTS and CTS) varies according to the structure of the frame at the level of the physical interface (the preamble and the bit rate used) and according to the E_c/N_c) ratio. On one hand, we note that a short preamble control frame is more sensitive to noise than a long preamble control frame for any value of the E_c/N_c ratio. On the other hand, the error probability of the same frames (RTS and CTS) decreases when the E_c/N_c ratio increases.

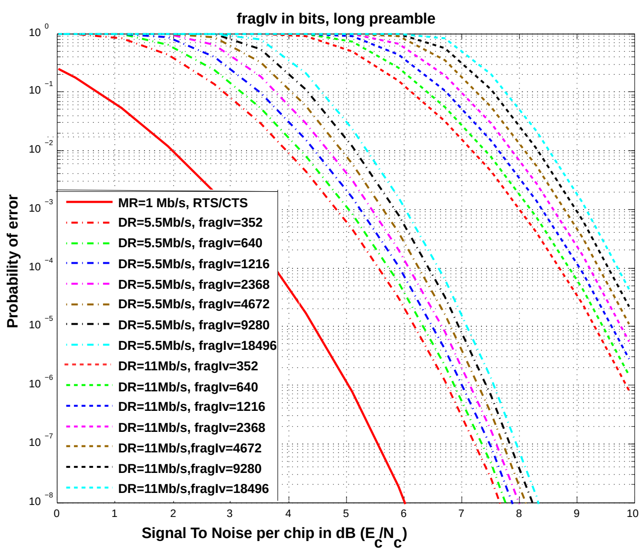

Figure 2. Error probability of a long preamble frame, depending to the E_c/N_c ratio

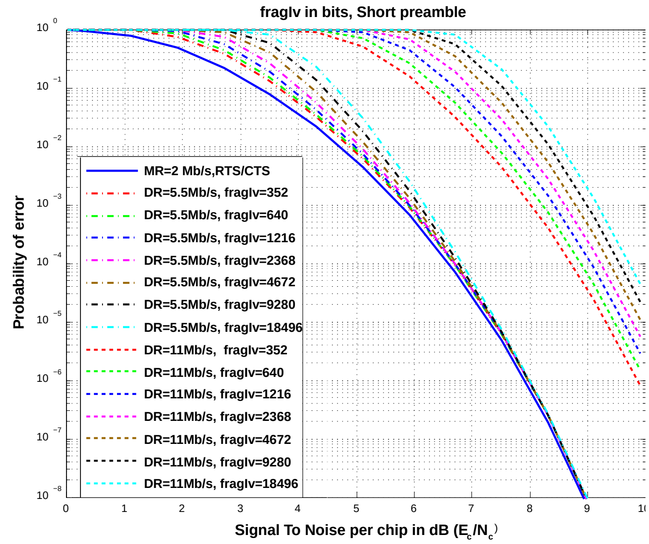

Figure 3. Error probability of a short preamble frame, as a function of E_c/N_c ratio

In addition, we also observe that the probability of error on the data frames is similar for the short and long preamble frames, in the case of a transmission rate of 11Mb/s. When the transmission rate is 5.5Mb/s, the probability of error on frames with a long preamble is lower than that on frames with a short preamble. On one hand, from results the error probability increases as the length of the data fragment (frag) increases, and decreases when the E_c/N_c ratio increases. On the other hand, to ensure efficient data transmission, the error probability must be strictly less than one ($Pe < 1$). This implication shows the importance of the PFM on the noise of the environment. For example long frame format, if the size of the data fragment ($frag = MC + fragIV$) to transmit: 624 bits, 1488 bits and 9552 bits, respectively, we need at least a signal to noise ratio per chip of approximately 4 dB, 5 dB and 6 dB.

Finally, we conclude that the structure of the frame at the level of the physical interface (PLPC-PPDU format), the PFM and the degradation of the transmission rate (Variable rate shifting) have an important effect on the error probability in a more or less noisy environment.

B. Influence of the NDFR/RCR on the ST

In this part, we have used the numerical results, shown in Figures 2 and 3, to classify the noise strength in three different environments, according to the interval of change of the signal to noise ratio per chip (E_c/N_c) corresponding to the error level (probability of error). Approximately, the environment is classified as: weakly noisy when $E_c/N_c > 7.5dB$, noisy when $4dB < E_c/N_c \leq 7.5dB$, and highly noisy when $E_c/N_c \leq 4dB$.

TABLE II. System parameters

Parameters 1		Parameters 2		Parameters 3	
Parameter	Value	Parameter	Value	Parameter	Value
MPDU	2346 bytes	σ	20 μs	n	20
RTS	160 bits	SIFS	10 μs	W_0	31
CTS	112 bits	DIFS	50 μs	$\acute{m}$	5
Ack	112 bits	γ	1 μs	m	6

Figures 4, 5 and 6 show the saturation throughputs depending on the Maximum_NDFR/RCR, different fragment lengths and different noise strength. The ST varies according to the fragment length, the characteristics of the environment (E_c/N_c), and the Maximum_NDFR/RCR. In

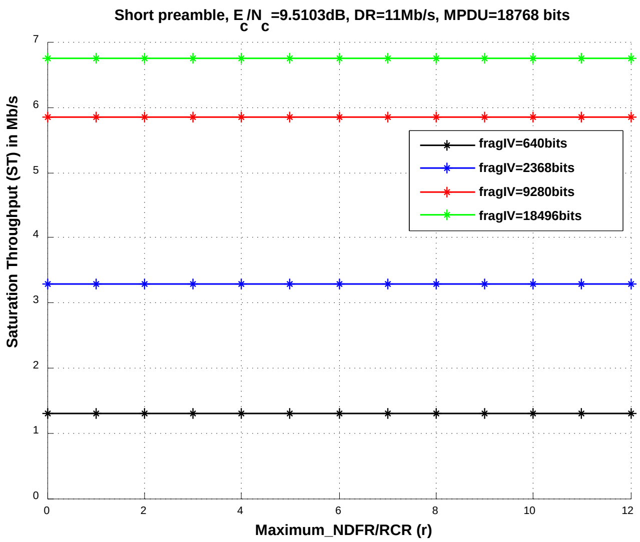

Figure 4. ST, according to Maximum_NDFR/RCR, in a low-noise environment

the case of a weakly noisy environment ($E_c/N_c = 9.51dB$), as shown in Figure 4, the ST increases when the fragment (or packet) length increases, and for each fragment, records stable values for any number of retransmission of the same data fragment (same length). In this situation, it is preferable to choose the longest fragment possible, which corresponds to the packet length (MPDU= 2346 bytes), with 0 retransmission, to get a better ST (about 6.76 Mb/s). In the case of a noisy environment ($E_c/N_c = 6.01dB$), the curves depicted in Figure 5, show that there is a shift between them because of the noise. The order of the maximum saturation throughputs from top to bottom is directly related respectively to the lengths of the fragments ($frag$), which are 2640 bits, 912 bits, 9552 bits and 18768 bits. We note that the ST increases logarithmically, depending on the Maximum_NDFR/RCR from 0 to 9 approximately. However, if this number is equal to or greater than nine successive retransmissions, the saturation throughputs of the preceding fragments stabilize respectively towards the maximum values 1.40 Mb/s, 1.02

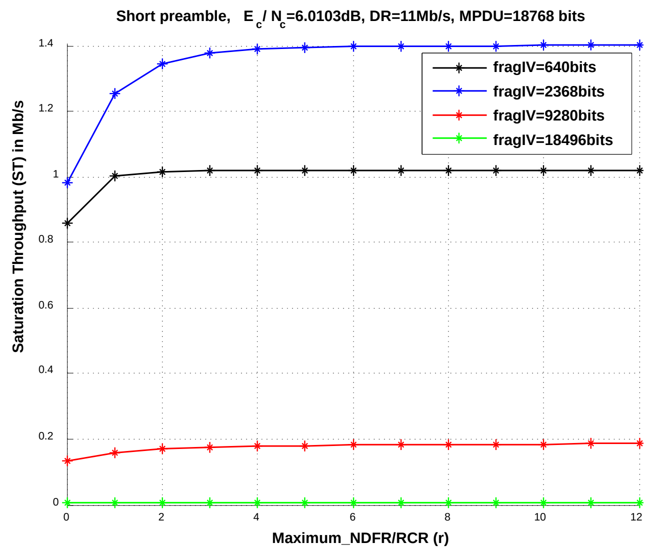

Figure 5. ST, according to Maximum_NDFR/RCR, in a noisy environment

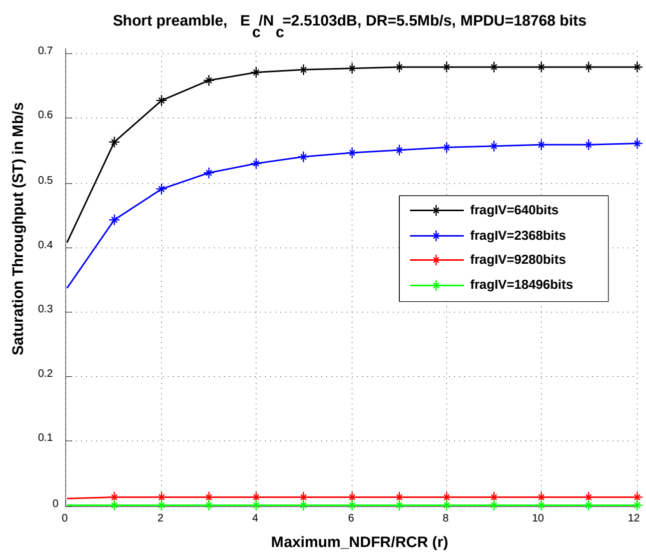

Figure 6. ST, in terms of the Maximum_NDFR/RCR, in a highly noisy environment

Mb/s, 186 Kb/s and 6 Kb/s. Finally, in the case of a highly noisy environment ($E_c/N_c = 2.51dB$), the curves in Figure

6 show that a new shift in the saturation throughputs is achieved, from top to bottom respectively according to the fragments lengths ($frag$) (912 bits, 2640 bits, 9552 bits and 18768 bits). The throughputs increase logarithmically, according to the Maximum_NDFR/RCR from 0 to 9. Then they stabilize when they reach these maximum values: 680 Kb/s, 561 Kb/s, 14 Kb/s and 0.07 Kb/s. The data, in Figure

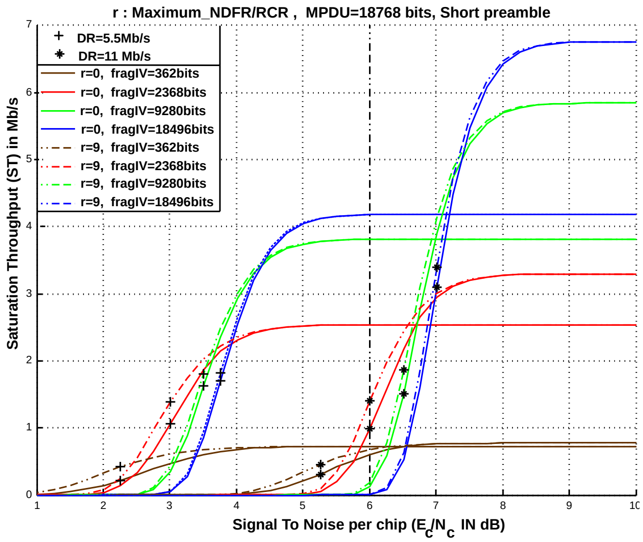

Figure 7. ST versus E_c/N_c ratio and Maximum_NDFR/RCR

7, shows that the ST varies according to the environment nature (weakly noisy, noisy and highly noisy), the fragment length and the transmission rate DR. In this case, to obtain efficient results, it is preferable to decrease the length of the fragment according to the increase in noise level in the environment. We also note that the successive retransmission without renewing the channel reservation (r = 9 i.e. Maximum_NDFR/RCR equals nine) and the degradation of the transmission rate DR (Variable rate shifting), improves the ST dropped by various effects

C. Influence of contender stations with and without DFR/RCRM on ST

We calculate the ST with respect to the number of stations in the network, taking into account a fixed size of (frag=2368 + 272 = 2640) bits of the data fragment, in short preamble format, data transmission of 5.5 Mb/s and 11 Mb/s corresponding respectively to the E_c/N_c ratio 3.103dB and 6.269dB. In the case where the DFR/RCRM is disabled (r = 0 i.e. Maximum_NDFR/RCR equals zero), Figure 8 demonstrates that the ST increases when the number of stations in the network increases (up 30 stations). Moreover, if the number of stations in the network exceeds 30 ($n > 30$), the variation of the ST is inversely proportional to the number of stations in the network. In the case where the DFR/RCRM is active(r = 9 i.e. Maximum_NDFR/RCR equals nine), the obtained results (Figure 8) show that the ST is reduced when the number of stations in the network increases. The best ST is obtained when the number of

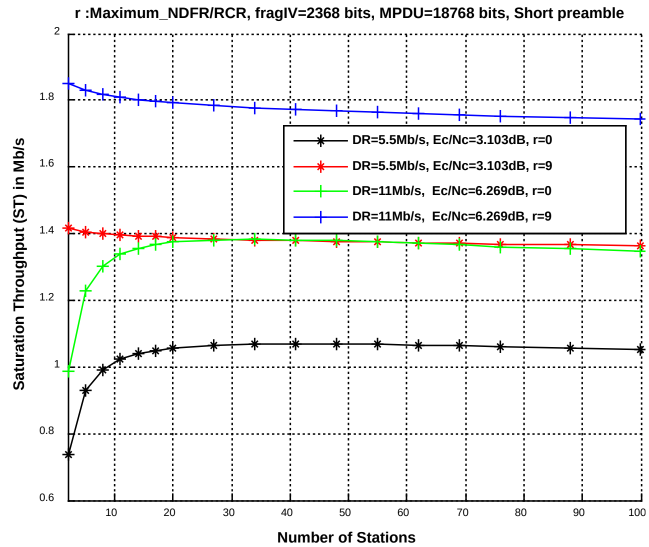

Figure 8. Presents the effect of the Maximum_NDFR/RCR and the number of stations on the ST

stations is two. The comparison between these two results shows the importance of activating the DFR/RCRM.

5. Conclusion

In this paper,we constructed a new analytical 3D-MCM to estimate the importance of DFR/RCRM on IEEE802.11b DCF performance, under non-ideal channel conditions. The noise influence, on data transmission, decreases the saturation throughput (ST) digressively, depending on the degradation of the strength of the E_c/N_c ratio. The performance analysis of the proposed model shows the importance of the combination of the mechanisms, fragmentation of data packets (PFM) and retransmission of these data fragments without renewing the reservation of the transmission channel (DFR/RCRM), in a highly noisy environment, on the saturation throughput (ST). The effectiveness of these mechanisms on the saturation throughput (ST), is significant specially in low load coverage area and a noisy environment, with a low E_c/N_c ratio.

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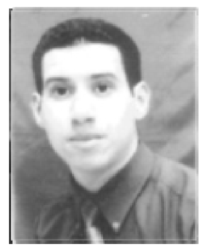

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