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Modeling and enhancement of the IEEE 802.11 RTS/CTS scheme in an error-prone channel

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Abstract. In this paper, we present a new discrete time Markov chain model to estimate the packet transmission probability τ, in order to develop mathematical models to derive the saturation throughput and the average packet delay of a 802.11 wireless LAN based on the RTS/CTS access method in the presence of noise, which distorts transmitted frames. Besides the standard backoff rule of the 802.11, Distributed Coordination Function assumes that each loss in the network is caused only by collision and acts to treat this situation by delaying the retransmission of the lost packet. We propose an enhancement of the IEEE 802.11 RTS/CTS scheme to recognize the reason of a transmission failure (collision or noise errors). Thus, the data packet is immediately retransmitted with zero-waiting time if a failure happens due to distortion by noise. This retransmission continues until the data packet is successfully transmitted or it is dropped when the number of packet transmission retries attains its limit. After that, we model the enhanced RTS/CTS scheme using a four-dimensional Markov model and we compare its performance with the actual RTS/CTS scheme.

Keywords: IEEE 802.11, RTS/CTS, Noisy channel, Modeling, Enhancement, Markov chains, Performance comparison

1. Introduction

In recent years, wireless data communication networks have become one of the major trends of the network industry developments. Wireless LANs can be considered as an extension of the wired networks with wireless links for connecting a large number of mobile terminals. The obvious merit of wireless LANs is the simplicity of implementation, LAN topology can be dynamically changed with connection, movement, and disconnection of mobile users without much loss of time [Lya05]. The IEEE 802.11 is an international standard (ISO/IEC 8802-11) for Wireless Local Area Networks. It was first released in 1999 [Iee99] and reissued later in 2007 [Iee07] grouping some of the subsequent amendments. The IEEE 802.11 standard includes detailed specifications for both Medium Access Control (MAC) and Physical Layer (PHY). In the MAC layer, the standard includes the DCF and the optional Point Coordination Function (PCF). DCF is an asynchronous data transmission function. It is available in ad hoc or infrastructure network configurations. PCF is used for real time services and it is only available in infrastructure environments.

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The performance analysis of IEEE 802.11 DCF can be achieved by either simulation and experiment (see [Cho03, Pha05, Szc08, Gen12, Abu12, Abd12]) or by mathematical modeling (see [Bia00, Hei01, Ray05, Ozd06, Bur07, Zak08, Rap09, Pen09, Mas09, Sen10, Zai11, Kum11, Pra11, Sen12, Cal13]). Mathematical modeling is an abstract representation of the system behavior, frequently in steady state [Pui03]. The analytical solutions of the mathematical models provide exact results for system performance metrics [Mol10]. The main existing mathematical modeling techniques are Markov chains, and the related high level modeling formalisms: Queues and Queuing Networks, Petri Nets and stochastic Process Algebras [Cas11]. These techniques are used according to analysis types (quantitative or qualitative), objectives, needed level of detail, etc. A discrete event system, modeled with one of these formalisms, may be mapped onto a Markov chain through a process known as state space generation [Nar07]. Hence, Markov chains provide the most general modeling technique and give a low abstraction level [Lef07]. Specifically, discrete time Markov chains can be used to model a wide class of concurrent and stochastic computer systems [Bol06]. Furthermore, Markov chains provide very flexible, powerful, and efficient means for the description and the analysis of dynamic IEEE 802.11 network properties. Indeed, the global state space of the IEEE 802.11 can be easily represented as a graph whose directed arcs are the transitions between its states [Bia00]. Thus, performance and dependability measures (particularly throughput and delay) can be easily derived.

Bianchi in [Bia00] was the first author in the literature who used a Markov chain model to analyze DCF operation and calculated the saturated throughput of 802.11 protocol. However, the performance index called saturation throughput was evaluated in the assumption of ideal channel conditions. Consequently, the calculated throughput may be overestimated, since electromagnetic noise in large cities is inevitable, it worsens the throughput due to data distortion. Some recent papers address the performance of DCF under error-prone channel, where unsuccessful transmission can be caused either by collision or noise errors. Chatzimisios et al. [Cha04] extended the work in [Bia00] by taking into account transmission errors for the basic access method of IEEE 802.11a protocol. Calculating the throughput metric, Wang et al. [Wan05] evaluated the impact of transmission errors rate on both basic and RTS/CTS access methods of 802.11 MAC protocol. However, the probability of bits errors, appearing on the transmission channel [Wan05], is considered the same in both Basic and RTS/CTS access methods. Alsabbagh et al. [Als08] presented an analytical model to evaluate the performance of the DCF in case of bits errors appearing on the transition channel and took into account the type of the access method. However, in the case of RTS/CTS access method, the Markov chain model developed by Alsabbagh et al. considers only one transmission state for both RTS control packet and data packet. Yet, retransmission probabilities of RTS control packet and data packet are different, because the RTS control packet can encounter a collision or undergo noise errors. Whereas, the data packet can only be lost due to noise errors since the channel is reserved after the RTS/CTS exchange sequence. In this paper, we focus on the modeling of the IEEE 802.11 RTS/CTS scheme in an error-prone channel, and on the enhancement of its performance in such situation. The actual MAC layer has no mechanism to differentiate noise related losses from collision induced losses. Therefore, it treats all losses as collision. So, as another part of our work, we propose and study a modification of the IEEE 802.11 RTS/CTS scheme to provide the wireless station the means to differentiate between collision and noise errors. Thereby, the wireless station does not increase the mean backoff interval if a loss happens due to noise errors.

The remainder of this paper is organized as follow: an overview of the IEEE 802.11 DCF function is presented in Sect. 2. We propose a new analytical model for the standard IEEE 802.11 RTS/CTS scheme in Sect. 3. We propose an enhancement of the IEEE 802.11 RTS/CTS scheme in Sect. 4. We propose an analytical model for the enhanced IEEE 802.11 RTS/CTS scheme in Sect. 5. We present the performance evaluation and comparison in Sect. 6. Section 7 concludes the paper.

2. IEEE 802.11 DCF function overview

The DCF is based on the Carrier Sense Multiple Access with Collision Avoidance. Retransmission of collided packets, is managed according to Binary Exponential Backoff (BEB) rules. DCF describes two methods for packet transmission. The essential method used in DCF is called Basic Access Method, and the optional method is called Request to Send/Clear to Send (RTS/CTS) method. A comprehensive description of DCF can be found in [Iee07].

2.1. Basic access method

Priority of access to the wireless medium is controlled by the use of the Inter Frame Space (IFS) time period between the transmissions of frames. A small IFS gives a higher priority for access to the medium of a mobile station. The two major IFSs used in DCF scheme are Short IFS (SIFS) and Distributed IFS (DIFS). SIFS is the shortest IFS. After a SIFS, only ACKnowledgement (ACK), CTS or fragment may be sent. DIFS is used before any packet transmission. Under the basic access mechanism, a ready station to transmit a new data packet, senses the channel status before transmission. If the channel is idle for a period of time equal to a DIFS, the station transmits. Otherwise, the station defers its transmission (deferring period) and continues to sense the channel until it is idle for a DIFS. At this point, the station chooses a random number as backoff time (see Fig. 1). This time is immediately decreased after the DIFS period while the channel is sensed idle, stopped if the channel is sensed busy and resumed if the channel is idle again, for a DIFS time duration. When the backoff timer reaches zero, the data packet is transmitted.

2.2. Binary Exponential Backoff

The choice of the backoff time value is based on the BEB algorithm. A station randomly chooses a number in an interval of time, called Contention Window (CW), between 0 and $CW - 1$. CW is set to be CW_{min} for every new data packet transmission. CW is doubled each time the transmission is unsuccessful, until it reaches CW_{max}, and then it remains at CW_{max} (see Fig. 2). If the data packet transmission is successful, a positive ACK is transmitted by the destination station to the source after a SIFS period. If the source station does not receive an ACK, the data packet is assumed to have been lost, and a retransmission is required. If the number of retransmission attempts exceeds its maximum, the data packet is dropped and CW is set to CW_{min}.

2.3. RTS/CTS access method

RTS/CTS is an optional access method initially conceived to resolve the hidden nodes problem, and to protect data packets against collisions. It introduces an additional operation on the top of the basic access mechanism, before a data packet transmission is taken place (see Fig. 3). When the backoff timer reaches zero, instead of transmitting a data packet, the source station transmits a RTS frame to request a transmission. The destination station may reply with a CTS frame after a SIFS period. Once the RTS/CTS is exchanged successfully, the source station starts transmitting its data packet after a SIFS period. If the RTS/CTS transmission is unsuccessful or the ACK is absent, the RTS/CTS operation must be resumed. To enhance the RTS/CTS access method, an additional mechanism Network Allocation Vector (NAV), is introduced. RTS and CTS frames include time fields, indicating to other stations the duration of the current transmission. All neighbor stations that receive the RTS or CTS frames update their NAV field to the value of the duration field in these frames and they do not access to the medium until the NAV reaches 0.

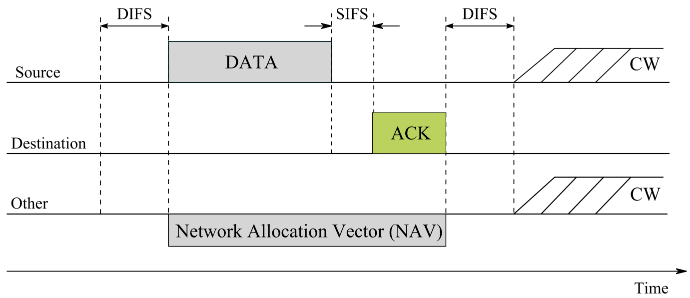

Fig. 1. Basic access method

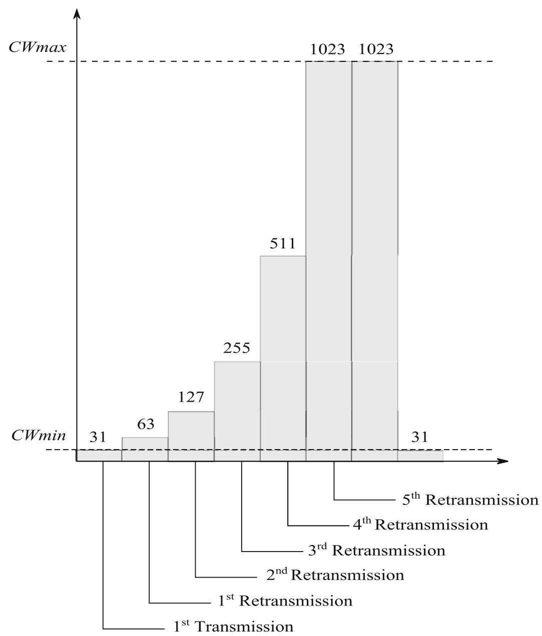

Fig. 2. Binary Exponential Backoff

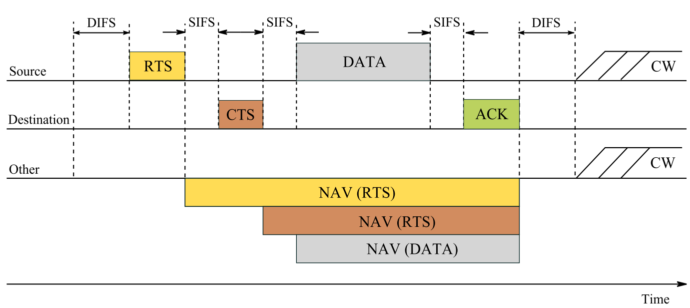

Fig. 3. RTS/CTS access method

3. Modeling of the IEEE 802.11 RTS/CTS scheme

In this section, we describe a new four-dimensional discrete time Markov chain model for the IEEE 802.11 RTS/CTS scheme in an error-prone channel. The resolution of the stationary probabilities equations of this Markov chain model allows us to compute the packet transmission probability τ. This probability will be used to develop mathematical models to derive the overall throughput and the average packet delay.

3.1. Assumptions of the IEEE 802.11 RTS/CTS scheme analytical model

The following is a list of assumptions of our analytical model for IEEE 802.11 RTS/CTS scheme. The couple of lists of parameters and probabilities are provided respectively in Tables 1 and 2.

1. We assume a fixed number of stations, each always have a packet available for transmission. In other words, we operate in saturation conditions, i.e., the transmission queue of each station is assumed to be non-empty.
2. All the data packets are of the same size. RTS/CTS frames are exchanged before the beginning of the data packet transmission, in order to differentiate between the reasons of a transmission failure (collision or noise errors).
3. The collision probability of a RTS control packet is constant and is independent of the number of retransmissions.
4. The channel is not ideal and the errors can occur on the transmitted data packets, i.e., the effect of the BER is considered and data packets can be lost due to the disturbed channel.

Table 1. Parameters of the 802.11 RTS/CTS analytical model

Parameter	Description
n	Number of stations in the network
m	Maximum backoff stage
m'	The number of backoff stages after which the CW reaches its maximum value CW_{max}
w_0	Minimum contention window
$2^{m'}w_0$	Maximum contention window
P	Data packet length (header+payload)
$\bar{P}$	Data packet payload length
ACK	The length of an acknowledgment
$T_R^{\bar{P}}$	Time of a packet payload transmission with data rate R
T_{MAC}	Time of a MAC layer header transmission
T_{PHY}	Time of a PHY layer header transmission
T_{ACK}	Time of an acknowledgment transmission
T_{RTS}	Time of a RTS control packet transmission
T_{CTS}	Time of a CTS control packet transmission
$DIFS$	Time interval of DIFS
$SIFS$	Time interval of SIFS
δ	Time of a signal propagation
σ	An empty slot time

Table 2. Probabilities of the 802.11 RTS/CTS analytical model

Probability	Definition
τ	Packet transmission probability
P_c	Packet collision probability
P_e	Packet error probability
P_b	Probability that the station finds the channel busy for any time slot

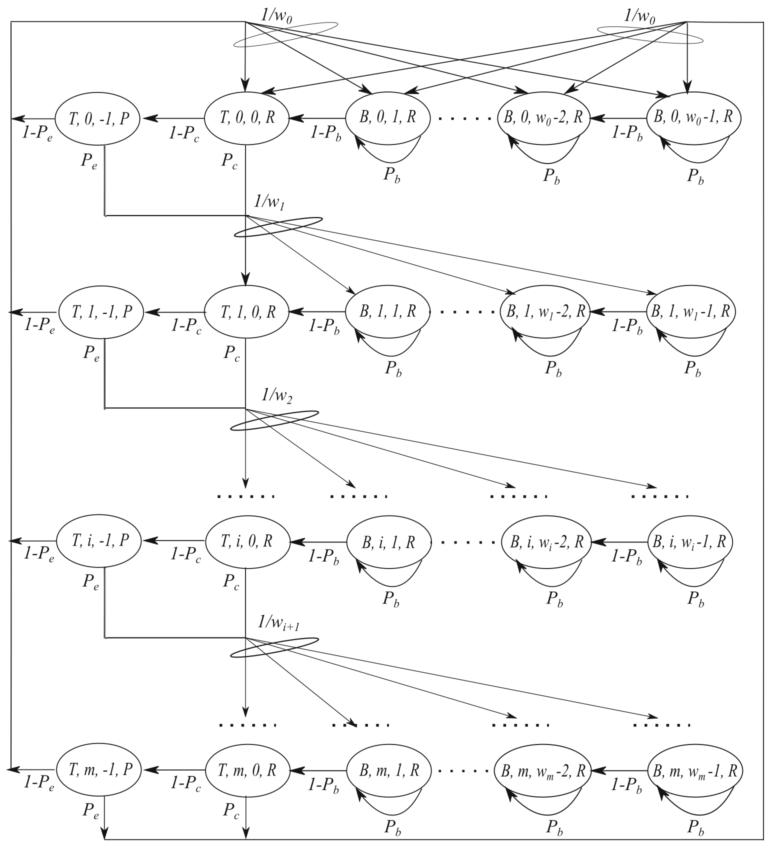

Fig. 4. Markov chain model of a single source station running the standard version of IEEE 802.11 RTS/CTS scheme.

3.2. Packet transmission probability

We study the behavior of a single station with a Markov chain model to obtain the stationary probability τ. It is the probability that a station transmits a packet in a generic slot time. This probability will be used to determine the performance metrics of 802.11 RTS/CTS scheme.

Let $y(t)$ be the stochastic process representing, at the time t, the state of the station, namely: (*B*) the station decrements its backoff time slots and (*T*) the station transmits its packet. Let $b(t)$ be the stochastic process representing the backoff time counter for a given station. Let $s(t)$ be the stochastic process representing the backoff stage $(0, \dots, m', \dots, m)$ of the station at the time t. Let $c(t)$ be the stochastic process representing the type of the transmitted packet namely: RTS control packet (*R*) or data packet (*P*).

For a station in backoff stage i, the backoff window size w_i is:

$$w_i = \begin{cases} 2^i w_0 & i \le m', \\ 2^{m'} w_0 & i \in [m'+1, m]. \end{cases} \tag{1}$$

Once the key approximation in Bianchi's analytical model is assumed [Bia00] (which means that, at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant and independent probability P_c), it is possible to model the four-dimensional process $\{y(t), s(t), b(t), c(t)\}$ with the discrete-time Markov chain depicted in Fig. 4.

In this Markov chain model, we have two transmission states: $(T, i, 0, R)$ and $(T, i, -1, P)$, the first state represents the RTS control packet transmission and the second state represents the data packet transmission; in RTS/CTS access method, the RTS control packet can encounter a collision or undergo noise errors, but the data packet can only undergo noise errors, since the channel is reserved after RTS/CTS exchange sequence. In the proposed Markov chain, we have neglected the noise errors on the RTS control packet, since its length is very small compared to average length of the data packet.

The non null one-step transition probabilities of this Markov chain are given from Eq. (2a) until Eq. (2n).

$$\begin{cases}
P\{B, i, j-1, R \mid B, i, j, R\} = 1 - P_b, \quad i \in (0, m), j \in (2, w_i - 1). & \text{(2a)}\\
P\{T, i, 0, R \mid B, i, 1, R\} = 1 - P_b, \quad i \in (0, m). & \text{(2b)}\\
P\{B, i, j, R \mid B, i, j, R\} = P_b, \quad i \in (0, m), j \in (1, w_i - 1). & \text{(2c)}\\
P\{B, i+1, j, R \mid T, i, 0, R\} = \dfrac{P_c}{w_{i+1}}, \quad i \in (0, m-1), j \in (1, w_{i+1} - 1). & \text{(2d)}\\
P\{T, i+1, 0, R \mid T, i, 0, R\} = \dfrac{P_c}{w_{i+1}}, \quad i \in (0, m-1). & \text{(2e)}\\
P\{T, 0, 0, R \mid T, m, 0, R\} = \dfrac{P_c}{w_0}. & \text{(2f)}\\
P\{B, 0, j, R \mid T, m, 0, R\} = \dfrac{P_c}{w_0}, \quad j \in (1, w_0 - 1). & \text{(2g)}\\
P\{T, i, -1, P \mid T, i, 0, R\} = 1 - P_c, \quad i \in (0, m). & \text{(2h)}\\
P\{B, 0, j, R \mid T, i, -1, P\} = \dfrac{1 - P_e}{w_0}, \quad i \in (0, m-1), j \in (1, w_0 - 1). & \text{(2i)}\\
P\{T, 0, 0, R \mid T, i, -1, P\} = \dfrac{1 - P_e}{w_0}, \quad i \in (0, m-1). & \text{(2j)}\\
P\{B, 0, j, R \mid T, m, -1, P\} = \dfrac{1 - P_e}{w_0} + \dfrac{P_e}{w_0}, \quad j \in (1, w_0 - 1). & \text{(2k)}\\
P\{T, 0, 0, R \mid T, m, -1, P\} = \dfrac{1 - P_e}{w_0} + \dfrac{P_e}{w_0}. & \text{(2l)}\\
P\{B, i+1, j, R \mid T, i, -1, P\} = \dfrac{P_e}{w_{i+1}}, \quad i \in (0, m-1), j \in (1, w_{i+1} - 1). & \text{(2m)}\\
P\{T, i+1, 0, R \mid T, i, -1, P\} = \dfrac{P_e}{w_{i+1}}, \quad i \in (0, m-1). & \text{(2n)}
\end{cases}$$

Let $\pi_{k,i,j,h} = lim_{t\to\infty} P\{y(t) = k, s(t) = i, b(t) = j, c(t) = h\}$, $k \in (B, T)$, $i \in (0, m)$, $j \in (0, w_i - 1)$, $h \in (R, P)$ be the stationary distribution of the chain. The closed-form solution for this Markov chain is:

$$\pi_{k,i,j,h} = \begin{cases}
\alpha^i \cdot \pi_{T,0,0,R} & k = T, \quad i \in (0, m), \quad j = 0, \quad h = R,\\
(1 - P_c)\alpha^i \cdot \pi_{T,0,0,R} & k = T, \quad i \in (0, m), \quad j = -1, \quad h = P,\\
\frac{\beta}{1-P_b} \cdot \frac{w_0 - j}{w_0} \cdot \pi_{T,0,0,R} & k = B, \quad i = 0, \quad j \in (1, w_i - 1), \quad h = R,\\
\frac{\alpha^i}{1-P_b} \cdot \frac{w_i - j}{w_i} \cdot \pi_{T,0,0,R} & k = B, \quad i \in (1, m), \quad j \in (1, w_i - 1), \quad h = R.
\end{cases} \quad (3)$$

Where,

- $\alpha = P_c + P_e(1 - P_c)$.
- $\beta = (1 - P_e)(1 - P_c) \cdot \frac{1-\alpha^{m+1}}{1-\alpha} + \alpha^{m+1}$.

Thus, by relation (3), all the values $\pi_{k,i,j,h}$ are expressed as a function of the value $\pi_{T,0,0,R}$ and the probabilities which are defined in Table 2. $\pi_{T,0,0,R}$ is finally determined by imposing the normalization condition, which can be simplified as follow:

$$1 = \sum_{i=0}^{m} \pi_{T,i,0,R} + \sum_{i=0}^{m} \pi_{T,i,-1,P} + \sum_{j=1}^{w_0-1} \pi_{B,0,j,R} + \sum_{i=1}^{m} \sum_{j=1}^{w_i-1} \pi_{B,i,j,R}. \tag{4}$$

Hence, we have:

$$\pi_{T,0,0,R} = \frac{2(1-\alpha)(1-2\alpha)(1-P_b)}{\lambda_1 + \lambda_2 + \lambda_3 - \lambda_4 + \beta \cdot \lambda_5}. \tag{5}$$

Where,

- $\lambda_1 = 2(1-\alpha^{m+1})(2-P_c)(1-P_b)$.
- $\lambda_2 = 2w_0\alpha(1-\alpha)(1-(2\alpha)^{m'})$.
- $\lambda_3 = 2^{m'} w_0(1-\alpha^{m-m'})(1-2.\alpha)\alpha^{m'+1}$.
- $\lambda_4 = \alpha(1-\alpha^m)(1-2\alpha)$.
- $\lambda_5 = (w_0-1)(1-\alpha)(1-2.\alpha)$.

We can now express the probability τ that a station transmits in a random chosen slot time. As any transmission occurs when the backoff time counter is equal to 0, regardless of the backoff stage, it is:

$$\tau = \sum_{i=0}^{m} \pi_{T,i,0,R} = \sum_{i=0}^{m} \alpha^i \pi_{T,0,0,R} = \frac{1-\alpha^{m+1}}{1-\alpha} \cdot \pi_{T,0,0,R}. \tag{6}$$

However, τ depends on the following probabilities:

- P_c (*packet collision probability*): the probability that a transmitted packet encounters a collision, is the probability that, in a time slot, at least one of the $n-1$ remaining stations transmits:

$$P_c = 1 - (1-\tau)^{n-1}. \tag{7}$$

- P_b (*probability that the channel is busy*): for a given station, the channel is busy in a time slot, if at least one of the $n-1$ remaining stations transmits:

$$P_b = 1 - (1-\tau)^{n-1}. \tag{8}$$

- P_e (*packet error probability*): the probability that a transmitted packet undergoes an error, depends on the bit error rate (BER), and on the packet length (P):

$$P_e = 1 - (1-BER)^P. \tag{9}$$

Equations (29) and (7) represent a non linear system in the two unknown τ and P_c, which can be solved using numerical techniques.

3.3. Overall throughput (TH_R)

We study the events that can occur within a generic slot time, and we express the overall throughput as a function of the computed value τ.

We express the elementary parameters of TH_R:

- Let P_{tr} be the probability that there is at least a transmission in the considered slot time:

$$P_{tr} = 1 - (1 - \tau)^n. \tag{10}$$

- Let P_s be the probability that the transmission occurring on the channel is successful. It is given by the probability that exactly one station transmits on the channel without noise errors on the transmitted data packet, which is conditioned by the fact that at least one station transmits:

$$P_s = \frac{n\tau(1-\tau)^{n-1}(1-P_e)}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}(1-BER)^P}{1-(1-\tau)^n}. \tag{11}$$

- Let P_{col} be the probability that an occurring transmission collides because two or more stations simultaneously transmit:

$$P_{col} = 1 - \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{12}$$

- Let P_{er} be the probability that a data packet is received in error:

$$P_{er} = \frac{n\tau(1-\tau)^{n-1}(1-(1-BER)^P)}{1-(1-\tau)^n}. \tag{13}$$

- Let T_s be the time that the channel is sensed busy by a successful transmission:

$$T_s = T_{RTS} + \delta + SIFS + T_{CTS} + \delta + SIFS + T_{PHY} + T_{MAC} + T_R^{\bar{P}} + \delta + SIFS + T_{ACK} \\ +\delta + DIFS. \tag{14}$$

- Let T_{col} be the time that the channel is sensed busy by a collision:

$$T_{col} = T_{RTS} + \delta + SIFS + T_{CTS} + DIFS. \tag{15}$$

- Let T_{er} be the time that the channel is sensed busy by a transmission error on the data packet:

$$T_{er} = T_s - \delta. \tag{16}$$

We define $E[d]$, as the average delay of packet payload successfully transmitted in a slot time, since a successful transmission occurs in a slot time with probability $P_{tr}P_s$:

$$E[d] = P_{tr}P_sT_R^{\bar{P}}. \tag{17}$$

The average length of a slot time $E[\sigma]$, is obtained by considering that, with $(1 - P_{tr})$ the slot time is empty, with $P_{tr}P_s$ it contains a successful transmission, with $P_{tr}P_{col}$ it contains a collision, and with $P_{tr}P_{er}$ it contains a transmission error on the data packet. This yields:

$$E[\sigma] = (1 - P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}P_{col}T_{col} + P_{tr}P_{er}T_{er}. \tag{18}$$

Now, we are able to express the overall throughput (TH_R) as the fraction of time (S) in which the channel is used to transmit successfully the packet payload, multiplied by the data rate (R):

$$TH_R = S \times R = \frac{E[d]}{E[\sigma]} \times R. \tag{19}$$

3.4. Average packet delay ($E[D]$)

Let $E[D_j]$ be the average delay of successfully transmitted packet from the j backoff stage, it is defined as the sum of the delay times that a packet experiences at $0, 1, \ldots, j$ stages, and it is calculated as follow:

$$E[D_j] = T_s + j.T_m + E[\sigma] \sum_{i=0}^{j} \left(\frac{w_i - 1}{2} \right), \quad 0 \leq j \leq m. \tag{20}$$

Where, T_s is the time to transmit successfully from the j stage, T_m is the time that the channel is sensed busy by a missed transmission, jT_m is the time that the packet undergoes j missed transmissions at $0, 1, \ldots, j-1$ stages, $E[\sigma]$ is the average time that a station defers its transmission (it is calculated here by considering only $n-1$ stations) and $(w_i - 1)/2$ is the average number of slot times that the station decrements in the i stage. T_s and $E[\sigma]$ are given respectively by the relations (14) and (18), and T_m has the following expression:

$$T_m = P_c \cdot T_{col} + (1 - P_c) \cdot T_{er}. \tag{21}$$

Let Q_j be the probability that a successfully transmitted packet is transmitted successfully from the j stage. So, we obtain:

$$Q_j = \frac{(1 - \hat{P})(\hat{P})^j}{1 - (\hat{P})^{m+1}}, \quad 0 \leq j \leq m. \tag{22}$$

Where, $(1 - \hat{P})$ is the probability that a packet is successfully transmitted after the packet reached the j stage (after j missed transmissions) with probability $(\hat{P})^j$, provided that the packet is not dropped $(1 - (\hat{P})^{m+1})$. $\hat{P}$ has the following expression:

$$\hat{P} = P_c + P_e. \tag{23}$$

Using the developed analytical model for the average packet delay per stage $E[D_j]$ and the probability per stage Q_j, we can compute the average packet delay $E[D]$ by:

$$\begin{aligned} E[D] &= \sum_{j=0}^{m} (E[D_j.Q_j]), \\ &= \sum_{j=0}^{m} \left[T_s + j.T_m + E[\sigma] \sum_{i=0}^{j} \frac{w_i - 1}{2} \right] \cdot \left[\frac{(1 - \hat{P})(\hat{P})^j}{1 - (\hat{P})^{m+1}} \right]. \end{aligned} \tag{24}$$

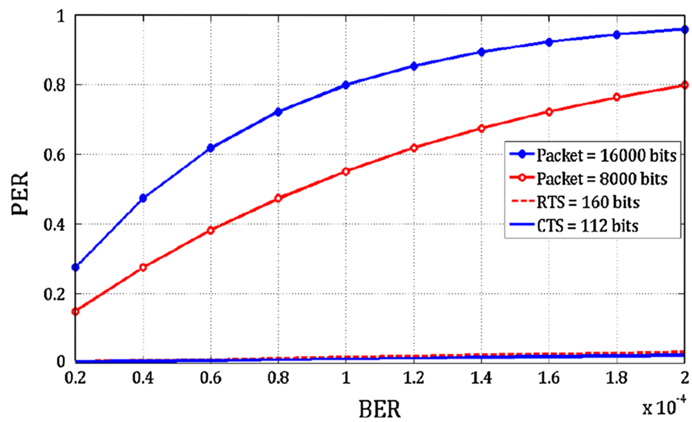

Fig. 5. PER versus BER and Packet length

4. Enhancement of the IEEE 802.11 RTS/CTS scheme

To improve the performance of the IEEE 802.11 MAC protocol in an error-prone channel, we propose to enhance the RTS/CTS mechanism. RTS/CTS is a collision avoidance (CA) mechanism, it can be established between source and destination before the actual transmission of data. This CA mechanism guarantees that all stations in the range of either the sender and the receiver know that a data packet will be transmitted. So, stations initiate their NAV variables to the duration of the ongoing transmission, and remain silent during the entire transmission. Consequently, it is evident that the RTS/CTS control packets are the only packets which collide and the data packets are spared of collision related losses.

Otherwise, in Fig. 5, where we have studied the Packet Error Rate (PER) of both RTS/CTS control packets and data packets according to the BER values by using the Eq. (9). We note that the error probability of RTS or CTS control packet is very negligible compared to the error probability of data packets, whatever the BER value. Therefore, we can affirm that when the channel is disturbed, the RTS/CTS control packets can be lost due to collision with other RTS/CTS control packets. However, the data packets can be lost due to noise errors introduced by the channel.

In other words, with the RTS/CTS mechanism, a station starts its transmission sequence by transmitting RTS control packet. When the station receives the CTS control packet, it means that the wireless channel is reserved for its data packet transmission. Then it transmits the data packet and waits for an ACK to verify a successful transmission. Since RTS and CTS are very short frames, the probability of corrupting these packets due to noise errors is very small and the only reason for their corruptions is because of a collision. On the other hand, once a station receives CTS, the probability of a collision corruption of the data packet is negligible.

Based on these two observations, we can propose an enhancement of the IEEE 802.11 RTS/CTS scheme to recognize the reason of a transmission failure (collision or noise errors). So, if no CTS control packet is received after sending RTS control packet, the RTS loss is due to collision. In this situation, the sender calls the RTS retransmission routine and increases the CW value, this value is increased only when the collision occurs. However, after a successful RTS/CTS exchange sequence, and when the sender does not receive the ACK of the transmitted data packet, it indicates that the data packet is lost due to noise errors. In this condition, instead of increasing the current CW value as in standard rules of IEEE 802.11 MAC protocol, we propose that the sender retransmits its data packet immediately with zero-waiting backoff time. This retransmission shall continue until the data packet is successfully transmitted or is dropped when the number of packet transmission retries i attains its limit m.

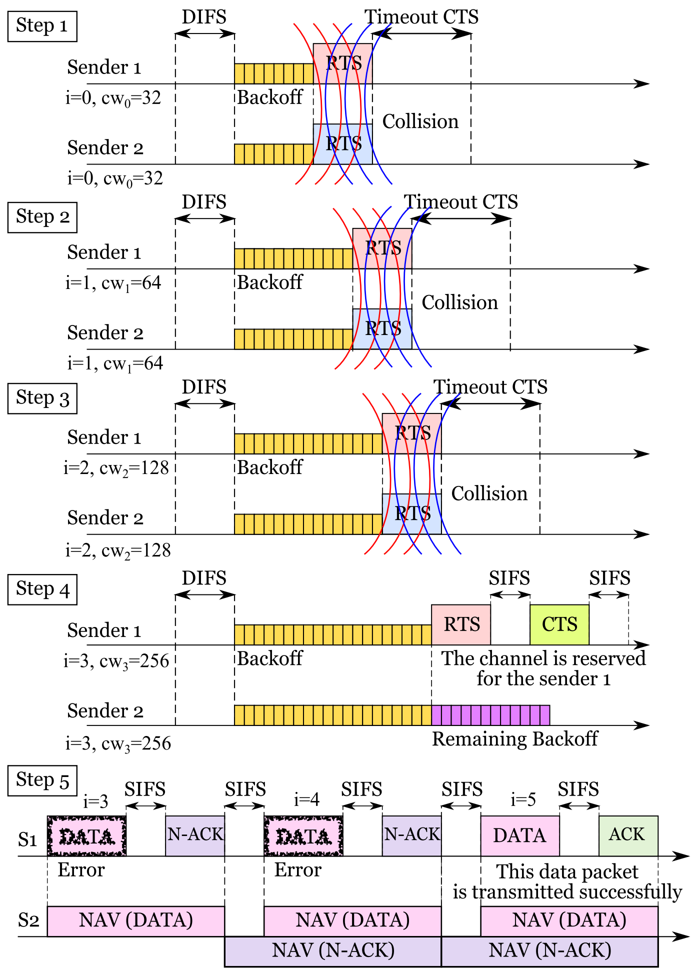

Fig. 6. Enhanced IEEE 802.11 RTS/CTS scheme (Example: part 1)

When the receiver station receives an erroneous data packet, we propose that the receiver station sends a particular acknowledgment that we call Negative-ACKnowledgment (N-ACK) to request the immediate sender's data packet retransmission with zero-waiting backoff time. The N-ACK contains the total retransmission period, which will be used to set the NAV variables of the other stations, in order to maintain the wireless channel reservation between the source station and the destination station without repeating the RTS/CTS exchange sequence. The negative reply (N-ACK) is conditioned by the maximum retry limit m.

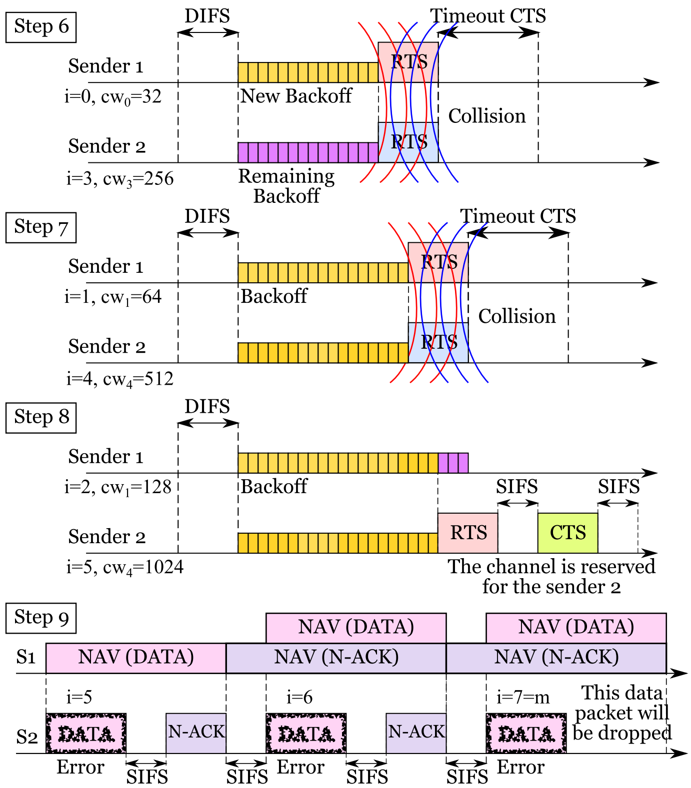

Fig. 7. Enhanced IEEE 802.11 RTS/CTS scheme (Example: part 2)

To understand more our enhanced version of RTS/CTS scheme, a detailed example is given in Figs. 6 and 7. In these figures, we have illustrated a scenario with two senders, which perform the enhanced version of RTS/CTS scheme to get the access to wireless channel, in order to transmit their data packets respectively. Firstly, our enhanced version of RTS/CTS scheme consists to solve the contention access between the two senders, by transmitting and receiving the RTS/CTS control packets (see steps from 1 to 4 in Fig. 6, and steps from 6 to 8 in Fig. 7). Secondly, Once the wireless channel is reserved by one of the two senders, our enhanced version of RTS/CTS scheme consists to transmit the data packet. The sender, first having the access to wireless channel, transmits its data packet. If the transmitted data packet is correctly received (without noise errors), the receiver acknowledges this data packet using the ACK frame. Otherwise, if noise errors happen on the transmitted data packet, the receiver station uses the N-ACK to request the immediate senders's data packet retransmission. This retransmission continues until the data packet is successfully transmitted, or is dropped when the number of attempts reaches its maximum limit. See step 5 Fig. 6 and step 9 Fig. 7, respectively.

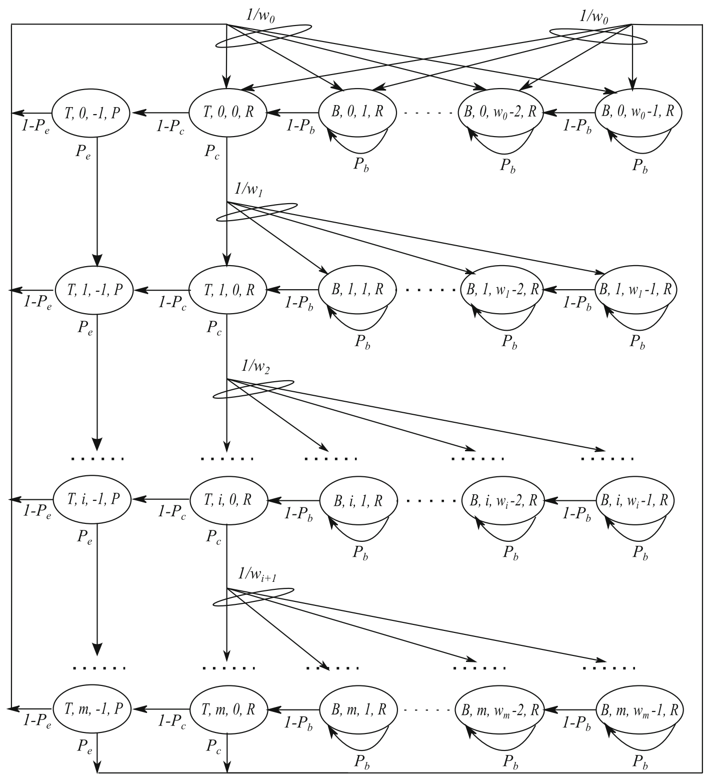

Fig. 8. Markov chain model of a single source station running the enhanced version of IEEE 802.11 RTS/CTS scheme

5. Modeling of the enhanced IEEE 802.11 RTS/CTS scheme

In this section, we propose a four-dimensional discrete time Markov chain model for the enhanced IEEE 802.11 RTS/CTS scheme, and based on the computed packet transmission probability τ, we develop mathematical models to compute the overall throughput and the average packet delay. All the parameters used in this section are the same of those defined in Sect. 3.

5.1. Markov chain model for the enhanced IEEE 802.11 RTS/CTS scheme

The Markov chain model proposed for the enhanced IEEE 802.11 RTS/CTS scheme is depicted in Fig. 8. In this Markov chain, when the RTS control packet encounters a collision, the CW value is increased. While, the data packet is retransmitted immediately with zero-waiting backoff time, when it undergoes an error.

The non null one-step transition probabilities of this Markov chain are:

$$\begin{cases} P\{B,i,j-1,R \mid B,i,j,R\} = 1-P_b, \quad i \in (0,m), j \in (2, w_i - 1). & (25a) \\ P\{T,i,0,R \mid B,i,1,R\} = 1-P_b, \quad i \in (0,m). & (25b) \\ P\{B,i,j,R \mid B,i,j,R\} = P_b, \quad i \in (0,m), j \in (1, w_i - 1). & (25c) \\ P\{B,i+1,j,R \mid T,i,0,R\} = \dfrac{P_c}{w_{i+1}}, \quad i \in (0,m-1), j \in (1, w_{i+1} - 1). & (25d) \\ P\{T,i+1,0,R \mid T,i,0,R\} = \dfrac{P_c}{w_{i+1}}, \quad i \in (0,m-1). & (25e) \\ P\{T,0,0,R \mid T,m,0,R\} = \dfrac{P_c}{w_0}. & (25f) \\ P\{B,0,j,R \mid T,m,0,R\} = \dfrac{P_c}{w_0}, \quad j \in (1, w_0 - 1). & (25g) \\ P\{T,i,-1,P \mid T,i,0,R\} = 1-P_c, \quad i \in (0,m). & (25h) \\ P\{B,0,j,R \mid T,i,-1,P\} = \dfrac{1-P_e}{w_0}, \quad i \in (0,m-1), j \in (1, w_0 - 1). & (25i) \\ P\{T,0,0,R \mid T,i,-1,P\} = \dfrac{1-P_e}{w_0}, \quad i \in (0,m-1). & (25j) \\ P\{B,0,j,R \mid T,m,-1,P\} = \dfrac{1-P_e}{w_0} + \dfrac{P_e}{w_0}, \quad j \in (1, w_0 - 1). & (25k) \\ P\{T,0,0,R \mid T,m,-1,P\} = \dfrac{1-P_e}{w_0} + \dfrac{P_e}{w_0}. & (25l) \\ P\{T,i+1,-1,P \mid T,i,-1,P\} = P_e, \quad i \in (0,m-1). & (25m) \end{cases}$$

The stationary probabilities of this Markov chain are:

$$\pi_{k,i,j,h} = \begin{cases} P_c^i \cdot \pi_{T,0,0,R} & k=T, \quad i \in (0,m), \quad j=0, \quad h=R, \\ (1-P_c)\cdot\alpha\cdot\pi_{T,0,0,R} & k=T, \quad i \in (0,m), \quad j=-1, \quad h=P, \\ \frac{\theta}{1-P_b}\cdot\frac{w_0-j}{w_0}\cdot\pi_{T,0,0,R} & k=B, \quad i=0, \quad j \in (1, w_i-1), \quad h=R, \\ \frac{P_c^i}{1-P_b}\cdot\frac{w_i-j}{w_i}\cdot\pi_{T,0,0,R} & k=B, \quad i \in (1,m), \quad j \in (1, w_i-1), \quad h=R. \end{cases} \tag{26}$$

where,

- $\alpha = \sum_{l=0}^{i} P_c^l P_e^{i-l} = \frac{P_e^{i+1}-P_c^{i+1}}{P_e-P_c}$.
- $\theta = (1-P_e)(1-P_c) + P_c^m + \frac{(1-P_e)(1-P_r)}{P_e-P_r}\left[\beta + P_e^{m+1} - P_c^{m+1}\right]$.
- $\beta = \frac{P_e^2(1-P_e^m)}{1-P_e} - \frac{P_c^2(1-P_c^m)}{1-P_c}$.

Thus, by relation (26), all the values $\pi_{k,i,j,h}$ are expressed as a function of the value $\pi_{T,0,0,R}$ which is determined by imposing the normalization condition, which can be simplified as follow:

$$1 = \sum_{i=0}^{m} \pi_{T,i,0,R} + \sum_{i=0}^{m} \pi_{T,i,-1,P} + \sum_{j=1}^{w_0-1} \pi_{B,0,j,R} + \sum_{i=1}^{m}\sum_{j=1}^{w_i-1} \pi_{B,i,j,R}. \tag{27}$$

Hence, we have:

$$\pi_{T,0,0,R} = \frac{2(1-P_c)(1-2P_c)(1-P_b)(P_e-P_c)}{\lambda_1+\lambda_2+\lambda_3\cdot\beta-\lambda_4+\lambda_5\cdot\theta+\lambda_6}. \tag{28}$$

where,

- $\lambda_1 = 2w_0 P_c(1 - P_c)(P_e - P_c)(1 - (2P_c)^{m'})$.
- $\lambda_2 = 2^{m'} w_0(1 - 2P_c)(P_e - P_c)(1 - P_c^{m-m'})P_c^{m'+1}$.
- $\lambda_3 = 2(1 - 2P_c)(1 - P_b)(1 - P_c)^2$.
- $\lambda_4 = P_c(1 - 2P_c)(P_e - P_c)(1 - P_c^m)$.
- $\lambda_5 = (w_0 - 1)(1 - P_c)(1 - 2P_c)(P_e - P_c)$.
- $\lambda_6 = 2(1 - 2P_c)(1 - P_b)(P_e - P_c)(1 - P_c)^2$.

Now, we express the packet transmission probability τ as:

$$\tau = \sum_{i=0}^{m} \pi_{T,i,0,R} = \sum_{i=0}^{m} P_c^i \pi_{T,0,0,R} = \frac{1 - P_c^{m+1}}{1 - P_c} \cdot \pi_{T,0,0,R}. \tag{29}$$

5.2. Overall throughput (TH_R)

The overall throughput mathematical model of the enhanced IEEE 802.11 RTS/CTS scheme has the following expression:

$$TH_R = \frac{P_{tr} P_s T_R^{\bar{P}}}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr} P_{col} T_{col} + P_{tr} P_{er} T_{er}} \times R. \tag{30}$$

This expression is the same of that obtained in Sect. 3, except for the T_{er} parameter which is given as:

$$T_{er} = T_{PHY} + T_{MAC} + T_R^{\bar{P}} + \delta + SIFS + T_{ACK} + \delta + SIFS. \tag{31}$$

5.3. Average packet delay ($E[D]$)

The average packet delay is obtained as:

$$E[D] = \sum_{j=0}^{m} (E[D_j . Q_j]). \tag{32}$$

where,

$$E[D_j] = T_s + \sum_{i=0}^{j} \left[(j - i) T_{col} + i T_{er} + E[\sigma] \sum_{k=0}^{j-i} \frac{w_k - 1}{2} \right] \cdot \frac{P_c^{j-i} P_e^i}{\sum_{i=0}^{j} P_c^{j-i} P_e^i}. \tag{33}$$

$$Q_j = \frac{(1 - P_c)(1 - P_e)\left[\frac{P_e^{j+1} - P_c^{j+1}}{P_e - P_c}\right]}{1 - \left[\frac{P_e^{m+2} - P_c^{m+2}}{P_e - P_c} - P_e P_c \cdot \frac{P_e^{m+1} - P_c^{m+1}}{P_e - P_c}\right]}. \tag{34}$$

$E[D_j]$ and Q_j are defined in Sect. 3.

Table 3. 802.11b PHY and MAC parameters

Parameter	Numerical value
Signal propagation delay	1 μs
DIFS	50 μs
SIFS	10 μs
Slot time	20 μs
Physical basic rate (PHY header)	1 Mbits/s
Physical basic rate (MAC header)	2 Mbits/s
Physical data rate	11 Mbits/s
Minimum contention window	32
Maximum contention window	1,024
PHY header length	192 bits
MAC header length	34 bytes
ACK length	14 bytes
RTS frame length	20 bytes
CTS frame length	14 bytes
Maximum length of MAC frame	2,312 bytes

6. Results and comparison

The results presented in this section are generated by solving the analytical models described in Sects. 3 and 5. Table 3 lists all the parameters used in this section.

Figure 9 represents a comparison between the overall throughput of the standard and the enhanced version of the IEEE 802.11 RTS/CTS scheme. In this figure, we study the overall throughput according to the number of stations with different packet lengths in an error-prone channel ($BER = 5 \times 10^{-5}$, this value of BER is moderate). In one hand, we note on this figure that, the overall throughput of the standard RTS/CTS scheme increases with the increase of the number of stations. Since, the data packets are protected from collision induced losses after the RTS/CTS exchange sequence, more the number of stations increases in the network, more the number of data packets transmitted in the network increases. Consequently, the overall throughput is increased. However, we note a highly decrease of the overall throughput when the length of data packets is doubled (packet = 16,000 bits). This degradation is due to the packet error rate, because more the data packet is great, more the packet error rate is important. In other hand, we note on Fig. 9 that, the enhanced version of RTS/CTS scheme improves the overall throughput of IEEE 802.11 network. This improvement level is due to the immediate retransmission of data packets which have undergone noise errors. These data packets are retransmitted without repeating the RTS/CTS exchange sequence. So, our enhanced version of RTS/CTS scheme allows to reduce the overhead of RTS/CTS control packets, and consequently increases the useful use of the wireless channel.

In Fig. 10, we make a comparison between the average packet delay of the standard and the enhanced version of the IEEE 802.11 RTS/CTS scheme. In this figure, we observe that the average packet delay of the standard IEEE 802.11 RTS/CTS scheme increases with the increase of the number of stations in the network. The high increase of the average packet delay is due to the contention window which is doubled every time the RTS/CTS exchange sequence is failed, because of repetitive collisions on the RTS/CTS control packets. We note on Fig. 10 that the average packet delay is extremely higher when the length of data packets is doubled (packet = 16,000 bits). These high delays are due to the packet error rate which causes distortion of data packets. Since the standard

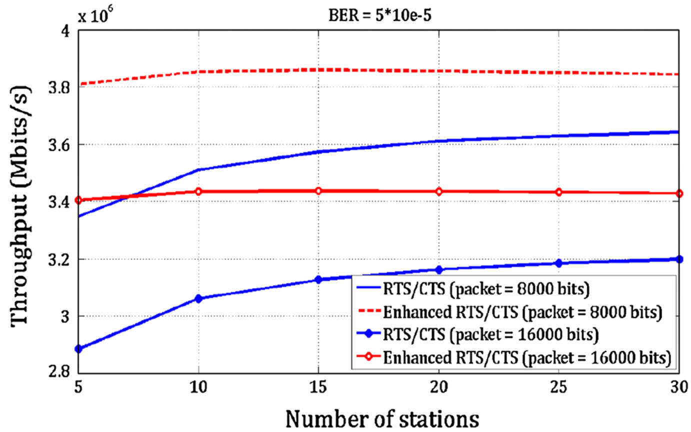

Fig. 9. Overall throughput evolution according to the number of stations

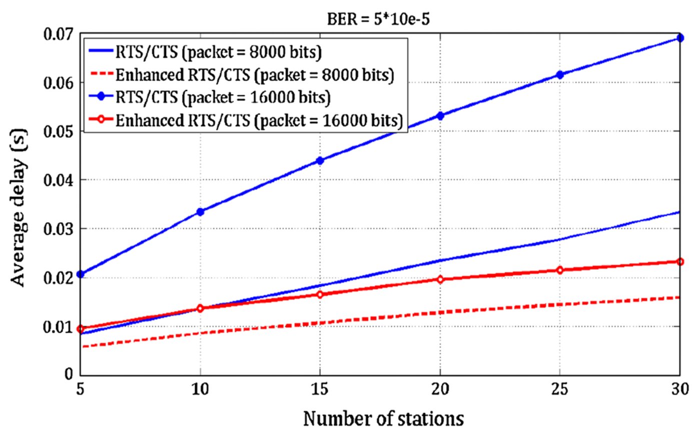

Fig. 10. Average packet delay evolution according to the number of stations

RTS/CTS scheme can not distinguish the noise related losses from the collision induced losses, the contention window is then increased at each time a data distortion happens due to noise errors. With our enhanced version of RTS/CTS scheme, we note on Fig. 10 that, the average packet delay is significatively improved. This average packet delay is acceptable whatever the data packet length. Although noise errors happen on the transmitted data packet, the CW value is never increased since the enhanced version of RTS/CTS scheme is able to recognize the reason of failure transmission. Therefore, the data packet is immediately retransmitted with zero-waiting backoff time. Consequently, the average packet delay is considerably reduced compared to the standard version of RTS/CTS scheme.

7. Conclusion

In this paper, we have interested to model and enhance the IEEE 802.11 RTS/CTS scheme in an error-prone channel. So, to address the void in existing analytical models of the IEEE 802.11 RTS/CTS scheme, we have proposed a new discrete time Markov chain model to estimate the packet transmission probability (τ). Based on the packet transmission probability, we have developed mathematical models to compute the overall throughput and the average packet delay of the RTS/CTS access method of IEEE 802.11 network. Since the IEEE 802.11 MAC protocol can not differentiate between the collision related losses and the noise induced losses, the CW value is increased at every failure transmission due either to collision or noise errors. Based on this observation, we have proposed an enhanced version of IEEE 802.11 RTS/CTS scheme to recognize the reason of a transmission failure. So, when a data packet is lost due to noise errors, instead of increasing the CW value, the data packet is retransmitted immediately with zero-waiting backoff time. The performance evaluation of the enhanced IEEE 802.11 RTS/CTS scheme in an error-prone channel proves the efficiency of this new version compared to the standard version, whatever the data packet length.

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