Revisit of RTS/CTS Exchange in High-Speed IEEE 802.11 Networks *

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Abstract

*IEEE 802.11 Medium Access Control (MAC) called Distributed Coordination Function (DCF) provides two different access modes, namely, 2-way (*basic access*) and 4-way (*RTS/CTS*) handshaking. The 4-way handshaking has been introduced in order to combat the hidden terminal phenomenon. It has been also proved that such a mechanism can be beneficial even in the absence of hidden terminals, because of the collision time reduction. In this paper, we analyze the effectiveness of the RTS/CTS access mode, in current 802.11b and 802.11a networks. Since the rates employed for control frame transmissions can be much lower than the rate employed for data frames, the assumption on the basis of the 4-way handshaking introduction, i.e., the short transmission time of the RTS control frame, is no more valid. As a consequence, the basic access mode results in the optimal access solution in most cases, even in heavy load conditions with hidden nodes. We compare the 2-way and 4-way access performances through both analytical and simulation tools. We also discuss the operating conditions at which the switch from an access mode to another is desired in both the cases of uniform and heterogeneous data rates among the stations. We conclude that, for the heterogeneous data rate environments, the RTS/CTS threshold should be redefined as a frame transmission time rather than as a frame size.*

1 Introduction

IEEE 802.11 Medium Access Control (MAC) called Distributed Coordination Function (DCF) provides two different channel access modes based on 2-way (*basic access*) and 4-way (*RTS/CTS*) handshaking. The 4-way access mode has been introduced in order to combat the hidden terminal problem. By preceding the data frame transmission with the exchange of two short control frames between transmitter and receiver, the access vulnerability time, i.e., the time interval in which hidden stations can originate interfering transmissions, is reduced to the time required to transmit the first RTS frame. The mechanism works under the assumption that the hidden node is able to decode the CTS frame, and this assumption, as shown in [3, 2], is not always true. However, the RTS/CTS can be advantageous not only for the hidden node phenomenon. Since in each channel access only the first frame can experience a collision, despite of the higher per-access overhead, the 4-way access mode allows to reduce the collision times down to the RTS transmission time. It has been proved [1] that this operation can lead to a significant performance enhancement, in comparison with the basic access mode, in the case of heavy loaded networks or very long data frame.

Today's 802.11 wireless LANs (WLANs) provide multiple rates for data transmissions by employing different sets of modulation and channel coding schemes. For example, the popular 802.11b physical (PHY) layer provides 1, 2, 5.5, and 11 Mbps [11], while the emerging 802.11a and 802.11g provide 6 to 54 Mbps. These multiple transmission rates can be used for frame transmissions in an adaptive manner depending on the underlying channel conditions [13, 8]. Specifically, high data rates can be exploited only by stations which perceive good channel conditions. Since different stations, in general, use different data rates, control frames are transmitted at a rate supported by all the stations, i.e., at one of the rates in the *basic rate set*, while the physical header transmission time is fixed. In such conditions, the concept of long/short frame is no more uniquely related to the frame size and also the RTS/CTS rationale has to be revised. In fact, as the data rate increases, control packets waste proportionally more and more resources and their temporal length (i.e., transmission time) can be comparable to that of the data frames.

The impact of RTS/CTS exchange in high-speed WLAN was first analyzed in [4] in absence of hidden terminals. The authors observe that the collision time reduction is practically vanished whenever the control rate is lower than the data rate and conclude that the RTS/CTS effectiveness in improving performance is re-

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ally uncertain. In this paper, we basically deal with the same problem. We extended previous results in the case of multi-rate networks (i.e., networks in which different stations employ different data rates) and hidden terminals. In particular, we face the problem of the RTS threshold setting in practical situations, in which station frames have different sizes and/or different transmission rates.

The rest of the paper is organized as follows: In Section II, we briefly describe the motivations of RTS/CTS exchange. Then, we in Section III introduce an analytical framework, which allows us to derive the system performance when different stations employ heterogeneous access modes and data rates. We discuss some numerical results and the temporal definition of the RTS/CTS threshold in Section IV. Finally, we conclude the paper in Section V.

2 Two Access Modes of DCF

IEEE 802.11 DCF operates on the basis of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. At each packet arrival, if the channel has been sensed idle for a Distributed Inter-Frame Space (DIFS), stations can access the channel immediately. Otherwise, stations persist to monitor the channel activity until it is measured idle for a DIFS and then generates a random slotted delay (backoff) before transmitting, in order to minimize the probability of synchronization among different station transmissions. Whenever two or more stations access the channel simultaneously, a collision occurs, and receivers are not able to correctly decode their data. Since in the case of wireless medium the transmitting stations cannot detect a collision by listening the medium, an explicit ACK transmitted by the receiver is required for each frame transmission. The ACK is transmitted after a Short Inter-Frame Space (SIFS), shorter than DIFS, in order to have priority over other stations transmissions. The frame transmission followed by the corresponding ACK constitutes the 2-way handshake access mode, called *basic access*. The main difference from the wired equivalent protocols is represented by the time needed to reveal a collision. In fact, the lack of the collision detection function implies that a transmitting station holds the channel during the entire frame transmission time irrespective of the transmission outcome. Therefore, in the case of collision, the amount of channel waste depends on the frame transmission time.

DCF also defines an optional 4-way handshaking technique for packet transmissions. According to this access mechanism, whenever a channel access is granted, due to a DIFS or a random backoff delay expiration, stations preliminarily transmit a special Request-To-Send (RTS) short frame, which is acknowledged with a Clear-To-Send (CTS) frame by the destination. After a further SIFS from the CTS reception, the station can send the data frame, which in turns is acknowledged with a normal ACK frame. The usage of the RTS/CTS exchange is determined based on the length of the pending frame (or more exactly, MAC Protocol Data Unit or MPDU) size. When the MPDU size is larger than *RTS_Threshold*, a configurable parameter, the 4-way handshaking is used, i.e., the RTS/CTS exchange precedes a data transmission. We in this paper basically study the optimal *RTS_Threshold* value, which maximizes the system throughput, in different environments.

Originally, this access mechanism has been introduced in order to combat the hidden node problem. Whenever the carrier sense function is not perfect, i.e., some nodes do not sense the transmission originated by other nodes, a frame transmission can occur while the previously started transmission is not completed. This causes a collision if the receiver station is in the coverage range of the node which failed the carrier sense. In this case, the node is defined as a hidden node to the first transmitter. The interference probability among hidden nodes is obviously related to the frame transmission time. Since hidden nodes cannot hear each other, but can hear the corresponding receiver transmissions,[1] the CTS transmission allows to advertise hidden nodes among the channel occupation status, even if the physical carrier sensing does not reveal the following data frame transmission. In other words, in the case of 4-way handshaking, the vulnerability time of each channel access is reduced to the time required to transmit the RTS frame.

The 4-way access has also another important benefit. No other station can access the channel during the 4 frames exchange, since the inter-frame space is shorten than DIFS. Therefore, whenever the RTS transmission is successful, all the other frames cannot experience collisions. Then, the channel waste due to the collisions is reduced to the RTS transmission time, which is shorter than the data frame transmission time. However, since a further overhead, due to the RTS/CTS exchange, is introduced per each channel access, it is intuitive to understand that the optimal access mode depends on the frame length and on the collision probability.

Both of the advantages discussed for the use of the 4-way access mode, i.e., the vulnerability and collision time reductions, are based on the evidence that the short RTS frame requires a transmission time much shorter than the data frame one. This common statement is no more valid in today's 802.11b and 802.11a multi-rate networks. In fact, since the data frame transmission

[1] Note that the interference do not disturb the correct frame reception otherwise.

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rates can be much higher than the control frame rates, the frame transmission times are no more simply related to the frame length. Therefore, the role of RTS/CTS has to be also revisited.

3 Analytical Framework

In the following, we consider an infrastructure Basic Service Set (BSS), composed of N contending stations. We assume that all the stations generate the traffic of the same priority, and hence have the same probability to win the contention. We also consider that all the stations work in the saturation condition, i.e., data bursts are always available in the transmission queue.

It is easy to understand that the network performance is affected by two different figures: (1) the probability to have a successful channel access, and (2) the channel utilization efficiency. The first figure depends on the number of competing stations and on the contention window setting. The second figure depends on the overhead, in terms of PHY/MAC headers, control frames, and collision times, required for the data transmissions, and it is a function of the access mode (i.e., basic or RTS/CTS), the employed PHY (i.e., 802.11b or 802.11a), and the rates used for data and control frame transmissions. Given the probability P_s to have a successful channel access, the average per-access utilization time $E[slot]$, and payload bits $E[P]$, the system throughput S can be easily expressed as [1]:

$$S = \frac{P_s E[P]}{E[slot]} \tag{1}$$

Note that $E[slot]$ is given by the sum of two components: the channel inactivity time due to backoff count-down, and the channel occupancy time due to successful transmissions or collisions, i.e.,

$$E[slot] = \sigma E[bk] + P_s E[T_s] + (1 - P_s) E[T_c]$$

where σ is the backoff slot duration, $E[bk]$ is the average number of inter-transmission backoff slots, $E[T_s]$ is the average successful channel occupancy time, and $E[T_c]$ is the average collision time, respectively. Note that P_s and $E[bk]$ are functions of the number of competing stations, while $E[P_T]$, $E[T_s]$, and $E[T_c]$ depend on the employed access mode and PHY data rate. We deal with the computation of these latter parameters, while the former ones (P_s and $E[bk]$) are derived based on the well-known results given in [1].[2]

3.1 Channel Occupancy Times and Payloads

In the 802.11b and 802.11a WLANs, different modulation schemes with corresponding data rates, namely, 1, 2, 5.5, 11 Mbps for 802.11b, and 6, 9, 12, 18, 24, 36, 48, 54 Mbps for 802.11a, are available. Let r be the employed data rate and r^* the corresponding control frame rate (i.e., the maximum BSS basic rate equal to or lower than the data rate). We denote the channel occupancy time of RTS/CTS exchange, ACK, and data frames, respectively, with RTS, CTS, ACK, and $DATA$. Each frame includes a common physical header, whose transmission time H_{PHY} has to be added to the PHY payload time. Given the data frame payload P, all the time durations (in μs) are summarized in Table 1. Note that, for the 802.11a case, we have to account for the padding bits, which can be added to the PHY payload in order to make the frame composed of an integer number of Orthogonal Frequency Division Multiplexing (OFDM) symbols. Since each symbol occupies 4 μs, the resulting transmission times are multiple of 4 μs. Fig. 3.1 shows the 802.11a frame format. Since a fraction of the PLCP header (namely, the 24 bits of the SIGNAL field) ad 6 tail bits are sent at the data rate, further 24 bits have to be included for the computation of the variable number of OFDM symbols related to the payload transmission. Finally, note that we consider frame corruption due to collisions only, thus avoiding the consideration of any channel error impairment.

	RTS	CTS	ACK	DATA	H_{PHY}
b	$\frac{160}{r^*}$	$\frac{112}{r^*}$	$\frac{112}{r^*}$	$\frac{224+P}{r}$	192
a	$4\left\lceil\frac{160}{4r^*}\right\rceil$	$4\left\lceil\frac{112}{4r^*}\right\rceil$	$4\left\lceil\frac{112}{4r^*}\right\rceil$	$4\left\lceil\frac{248+P}{r}\right\rceil$	20

Table 1. PHY payload and header transmission times for 802.11b and 802.11a (in μs)

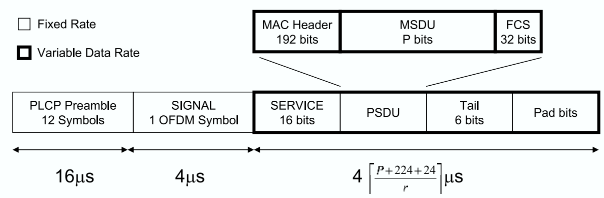

Figure 1. PPDU Format of 802.11a PHY and partial transmission times

3.2 Uniform Data Rate Case

Consider preliminarily the case in which all the stations employ the same data rate. Under the assumption of fixed packet sizes, T_s and T_c become constant, and easily expressed as.

$$\begin{aligned} E[T_s] &= O + DATA + SIFS + ACK + \\ &\quad 2H_{PHY} + DIFS \\ E[T_c] &= H + H_{PHY} + DIFS \end{aligned} \tag{2}$$

[2]We use the same notation given in [1] in the case of P_s, while $E[bk]$ is a function of the P_{tr} parameter defined in [1] and corresponds to $(1 - P_{tr})/P_{tr}$.

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where O represents the overhead introduced by the control frames in order to access the channel (which is $O_{bas} = 0$ for the basic access mode and $O_{rts} = RTS + CTS + 2H_{PHY} + 2SIFS$ for the RTS/CTS access mode), and H represents the duration of the first frame transmitted in each channel access, hereafter referred as head frame. The head frame duration is equal to $DATA$ for the basic access mode and to RTS for the RTS/CTS mode. Only the head frame can be involved in a collision, since once the channel is accessed, no random access can be performed before the channel is idle for a DIFS interval.

Whenever a general payload distribution is considered, the collision time computation is more complex, since we have to derive the distribution of the maximum duration of the frames involved in the collision. This distribution, as given in [1], depends on the transmission time cumulative distribution $F(x)$ of the head frame duration as well as on the probability τ that a given station access the channel. In fact, the maximum frame distribution for a given collision depends on the number k of colliding frames:

$$E[H] = E[E[H|k]] = \sum_{k=2}^{N} Pr(k)E[H|k]$$

where $Pr(k)$ represents the probability to have k colliding frames:

$$Pr(k) = \frac{\binom{N}{k}\tau^k(1-\tau)^{N-k}}{1-(1-\tau)^N - N\tau(1-\tau)^{N-1}}$$

and the average conditional value of the head frame duration is:

$$E[H|k] = \int_0^{\infty} \left[1 - F(x)^k\right] \, dx$$

For a given $RTS\_Threshold$, different access modes can be used on a per-frame basis. Therefore, the head frame size distribution $f(x)$ is different from the frame size distribution $g(x)$, and depends on both the frame distribution and the $RTS\_Threshold$ setting (see Fig. 2). The probability $Pr(RTS)$ to have a 4-way handshaking access is given by:

$$Pr(RTS) = \int_{RTS\_Threshold}^{\infty} g(x)\, dx$$

In practical situations, the head frame size distribution is discrete, since the frame size can assume only integer values. In such cases, the $RTS\_Threshold$ value should be also specified as a discrete value, to discriminate between frames which have to be sent via the 2-way access and frames which require the 4-way access. Moreover, most frames in many practical situations assume

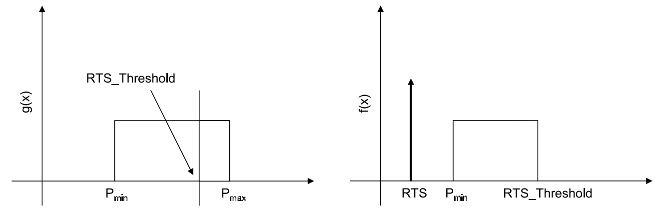

Figure 2. Example of payload size and head frame size distribution, for a given RTS_Threshold

just few different sizes, and the frame size distribution can be assumed non-zero in a few points. Let H_i be the head frame duration corresponding to the i-th head frame size x_i, which occurs with probability $f(x_i)$. Assume that the head frames are ordered from the shortest to the longest (i.e., $x_i < x_{i+1}$) and that m is the total number of different head frames. The collision time is determined by the longest H_i involved in each collision and can consequently assume m different values:

$$E[H] = \sum_{i=1}^{m} p_i H_i \tag{3}$$

where p_i is the probability that the longest frame involved in the collision is the i-th one, which for a discrete distribution results in:

$$p_i = \frac{\sum_{k=2}^{N}[F(x_{i+1})^k - F(x_i)^k]\tau^k(1-\tau^k)}{1-(1-\tau)^N - N\tau(1-\tau)^{N-1}}$$

Finally, we can express the success and collision times as:

$$\begin{aligned} E[T_s] &= E[O] + E[DATA] + SIFS + ACK \quad (4)\\ &\quad +2H_{PHY} + DIFS \\ E[T_c] &= E[H] + H_{PHY} + DIFS \end{aligned}$$

where $E[DATA]$ is obtained by simply considering the average frame size and $E[O]$ is:

$$E[O] = Pr(RTS)O_{rts}$$

3.3 Heterogeneous Data Rate Case

Let c be the total number of transmission rates. We grouped the contending stations in c transmission classes, according to the employed data rate. Let n_i be the total number of stations belonging to transmission class i, and $N = n_1 + \cdots + n_c$ the total number of contending stations in the network. Let $F_i(x)$ be the cumulative distribution of the time required to transmit the head frame, at the beginning of a transmission attempt, for transmission class i. Note that, also under

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the assumption of fixed frame size distribution among the stations, the distributions of the frame transmission times are different because of the different transmission rates. The collision duration is a random variable, which depends on the *longest duration frame*, i.e., the frame requiring the longest transmission time among those involved in the collision, due to long payload size and/or low transmission rate. Let k_i be the number of class-i stations, which access the channel in the current slot, and $K = k_1 + \cdots + k_c$ the total number of stations accessing in the current slot. Whenever K is greater than 1, a collision occurs. Considering the conditional expectation on the number of stations belonging to each transmission class, we can express the average head of access period $E[H]$ as follows:

$$E[H] = E[E[H|k_1, \cdots, k_c]|K > 1] =$$
$$= \sum_{\substack{k_1=0 \\ k_1+\cdots+k_c>1}}^{n_1} \cdots \sum_{k_c=0}^{n_c} Pr(k_1, \cdots, k_c) E[H|k_1, \cdots, k_c]$$

The probability to have $k_1, \cdots, k_c$ stations of rates $r_1, \cdots, r_c$, involved in the collision, respectively, is

$$Pr(k_1, \cdots, k_c) = \frac{\binom{n_1}{k_1} \cdots \binom{n_c}{k_c} \tau^K (1-\tau)^{N-K}}{1 - (1-\tau)^N - N\tau(1-\tau)^{N-1}}$$

The average conditional value of the head frame duration is given by:

$$E[H|k_1, \cdots, k_c] = \int_0^\infty \left[1 - F_1(x)^{k_1} \cdots F_c(x)^{k_c}\right] dx$$

Whenever a single station accesses the channel, a successful transmission is originated. Given the average payload transmission $E[DATA_i]$ of each station employing the data rate r_i, we have:

$$E[DATA] = \sum_{i=1}^{c} \frac{n_i}{N} E[DATA_i]$$

Under the assumption that the head frame is fixed for all the stations belonging to a given transmission class (i.e., they access the channel through RTS/CTS or they have fixed payload size P), the average collision time can be obtained with the simplified expressions given in (3). In this case the collision time can assume only c different values, according to the longest frame involved in the collision. Let p_i be the probability that the longest frame is H_i. If we order the stations from the longest to the shortest head frame (i.e., n_1 is the number of stations with the longest H and n_c the number of stations with the shortest), we can express such a probability as:

$$p_i = \frac{\sum_{k=2}^{N} \left[\binom{\sum_{j=i}^{c} n_l}{k} - \binom{\sum_{j=i+1}^{c} n_l}{k}\right] \tau^k (1-\tau)^{N-k}}{1 - (1-\tau)^N - N\tau(1-\tau)^{N-1}} \quad (5)$$

4 RTS/CTS Performance Evaluation

In this section, we compare the performance of the 2-way and 4-way access modes in different network scenarios. In particular, we investigate the effects of the data frame sizes, the number of contenting stations, the hidden node probability, and the data transmission rates. We also discuss the usefulness of defining the 4-way switching threshold in terms of data frame transmission time rather than in terms of data frame size. The results have been mainly from our analytical framework and extended, where specified, with the simulations. We consider the 802.11b and 802.11a as the underlying PHY. The BSS basic rate set is assumed to include 1 and 2 Mbps for the 802.11b case, and from 6 up to 24 Mbps for the 802.11a case. They are typical configurations in today's 802.11b and 802.11a networks, respectively.

4.1 Homogeneous Data Rate

As we intuitively introduced in the previous section, the 4-way access allows to reduce the collision times, but introduces some additional overhead in each successful access. Then, it results advantageous on the 4-way access for large payloads or very loaded networks, because in these cases the channel time saving overcomes the additional access overheads. Under the assumption of fixed MPDU size P, it is very easy to quantify the threshold value of the frame size over which it is desirable to switch to the 4-way access. Since the successful probability does not depend on the access mode, the 4-way access' throughput is higher than the 2-way access' throughput whenever it results in:

$$E[slot]_{rts} < E[slot]_{bas}$$

where $E[slot]_{rts}$ and $E[slot]_{bas}$ are the average slot time durations experienced in the case of 4-way and 2-way accesses, respectively. This condition is a function of the frame transmission time $DATA$ and of the successful access probability P_s, and is equivalent to:

$$P_s \cdot O_{rts} + (1 - P_s)(RTS - DATA) < 0$$

For a given P_s, the constraint on the $DATA$ transmission time can be expressed as:

$$DATA > \frac{P_s}{1 - P_s} O_{rts} + RTS \quad (6)$$

The threshold depends on the number of contending stations, since the probability to have a successful transmission P_s depends on such a number. Note that this constraint is expressed in terms of transmission times, and corresponds to different values of the payload size P,

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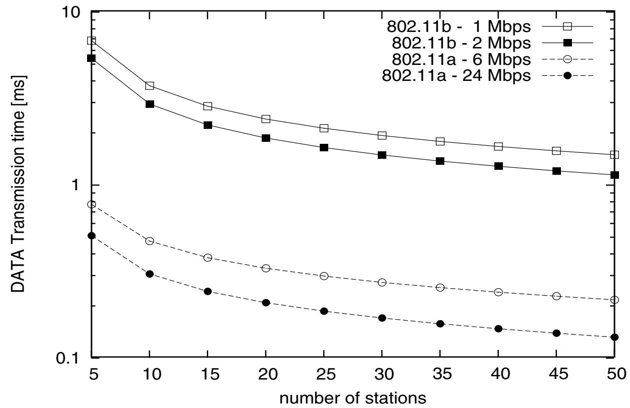

Figure 3. Data Transmission time over which the RTS/CTS access is better than the basic access vs. the number of competing stations

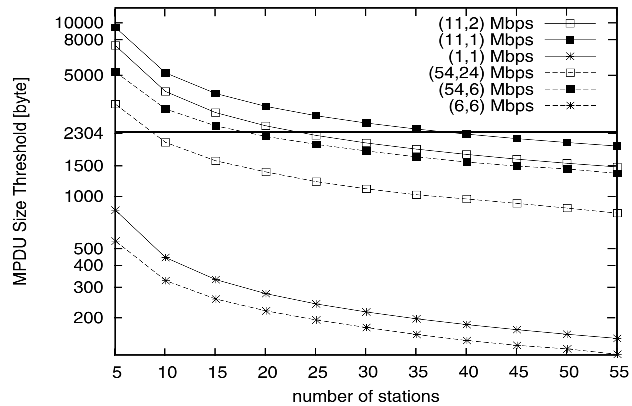

Figure 4. MPDU Payload Threshold over which the RTS/CTS access is better than the basic access vs. the number of competing stations

according to the rates r and r^*. In the case of 802.11b, the P threshold is:

$$P > \left(\frac{P_s}{1-P_s}O_{rts} + \frac{160}{r^*}\right) \cdot r - 224$$

In the case of 802.11a, because the frame transmission times are discretized to an integer multiple of $4\mu s$, the minimum P which satisfies the temporal constraint is obtained considering the maximum number of padding bits:

$$P > \left(\left\lceil \frac{P_s O_{rts}}{4(1-P_s)} \right\rceil 4 + \left\lceil \frac{160}{4r^*} \right\rceil 4\right) \cdot r - 4r - 248$$

Fig. 3 plots the $DATA$ transmission time over which the RTS/CTS access mode is advantageous, in both the cases of 802.11b and 802.11a, for the most common situation of maximum basic rates. As shown in Fig. 4 this temporal threshold corresponds to different payload threshold according to the employed data rate.
As the data rate increases, the payload size which allows to reach the constraint on the data transmission time $DATA$, grows almost proportionally. For example, for $N = 50$ and 802.11b, since P_s is 66%, the temporal constraint on the data transmission time results $DATA > 1024\mu s$. This constraint corresponds to a payload of 156 bytes in the case of $r = r^* = 1$ Mbps, and to a payload of 1518 bytes in the case of $r = 11$ Mbps and $r^* = 2$ Mbps. For lower N, since the $DATA$ threshold is higher, the payload threshold for high-speed networks is likely to be out of the maximum MPDU value (which is 2034 bytes). This implies that only in heavy load conditions the 4-way access gives advantage in high-speed networks. For example, in the case of $r = 11$ Mbps and $r^* = 2$ Mbps, the RTS/CTS access mode is beneficial only when the number of stations is larger than

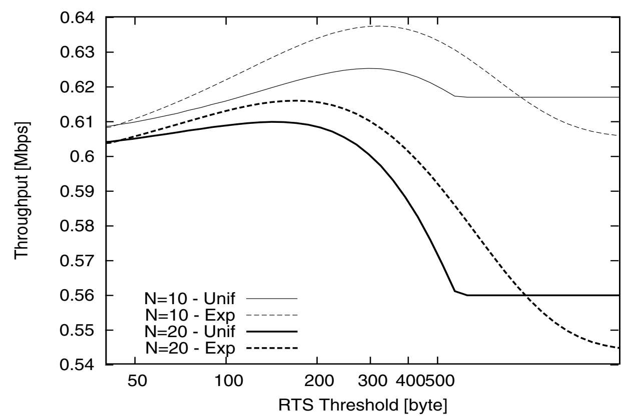

Figure 5. Throughput vs. the RTS_Threshold, in the case of 10 and 20 competing stations, with uniform and exponential frame size distribution

23. Note that, for the same ratio among r and r^*, (i.e. for the case $r = r^* = 1$ Mbps and $r = r^* = 6$ Mbps), the 802.11a thresholds are lower than the corresponding 802.11b, because of the lower P_s probability, due to the lower CW_{min} setting (namely, CW_{min} is equal to 15 for the 802.11a case and equal to 31 for the 802.11b case). The thresholds do not depend on the physical layer overhead H_{PHY}, since the overhead is fixed for both the access modes and it does not affect the difference among the collision times.

4.1.1 General Packet Distribution

The previous equation 6 gives and indication about the switching among basic access and RTS/CTS access mode, in the case of fixed packet size. However, in most practical situation, the frame sizes are not fixed. In

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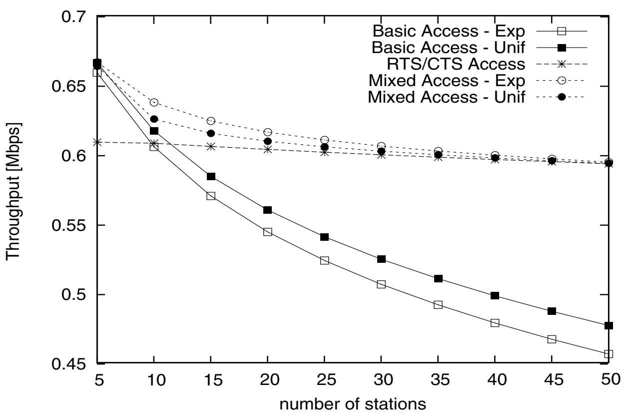

Figure 6. Throughput vs. the number of competing stations for different access modes (fixed and dynamic RTS_Thresholds) and frame size distributions (uniform and exponential)

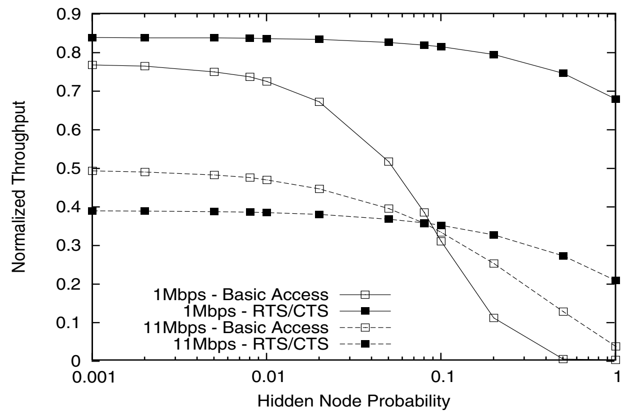

Figure 7. Normalized throughput vs. the hidden node probability h for two different data rates (1 Mbps, 11 Mbps) and $N = 10$ stations

these cases, the access mode is defined on a per-frame basis, according to the $RTS\_Threshold$ value. If the payload size distribution assumes values in the range $[P_{min}, P_{max}]$, all the frames are sent via the 2-way access whenever the $RTS\_Threshold$ is equal or higher than P_{max}, and are sent via the 4-way access whenever the $RTS\_Threshold$ is equal or lower than $P_{min} - 1$. Whenever the $RTS\_Threshold$ assumes a value in the range $[P_{min}, P_{max}]$, the channel access is different frame by frame (mixed case). It is intuitive to understand that also in this case the system performance are maximized for a given $RTS\_Threshold$ value in the range $[P_{min} - 1, P_{max}]$, as a tradeoff among collision time reduction and access overhead increment. The optimal setting corresponds to the minimization of the average slot duration and depends on the frame size distribution and on the number of contending stations. An example is shown in Fig. 5, in which the overall throughput is plotted as a function of the $RTS\_Threshold$, for two different frame size distributions and load conditions (namely, 10 and 20 stations). The uniform case refers to frame sizes uniformly distributed in the range $[40, 576]$ bytes, while the exponential case refers to frame sizes distributed according to a truncated exponential distribution in the range $[40, 2304]$ bytes, with average value equal to 308 bytes in both the cases. As the threshold grows we move from a situation in which all the frames are sent via the 4-way access to the opposite situation in which all frames are sent via the 2-way access. For the uniform distribution case, this happens whenever the threshold is higher or equal to 576, while for the exponential case is happens only when the threshold is set to 2304. Note that, whenever all the frames have a fixed size (Fig. 4), the optimal threshold P value for switching to the 4-way access is 432 bytes for $N = 10$ and 267 bytes for $N = 20$. However, from the figure we see that the performance maxima are obtained for lower thresholds.

In Fig. 6 we plot the throughput versus the number of competing stations, for the two different frame size distributions (namely, the uniform and the exponential one) and for different access mode strategies. The basic access curves refer to the situation in which all the packets are sent via the 2-way access mode. The RTS/CTS curve refers to the opposite situation, in which all the packets are sent via the 4-way access. Note that in this case the performance does not depend on the frame size distribution, since the collision times are fixed to RTS and the average payload is the same for both the distributions. The mixed access curves refer to the case in which the $RTS\_threshold$ is set, for each N, to the values plotted in Fig. 4 (which, as discussed, are not the optimal). From the figure, we see that the best access mode among basic access and RTS/CTS depends on the number of competing stations. For example, in the uniform size distribution case, the basic access is more convenient whenever it results $N < 10$. However, if we change the access mode according to the frame size and to our not-optimal threshold (mixed access case), we can always approaches the best performance among the two uniform access modes.

4.2 Performance with Hidden Terminals

Whenever the basic rates are much lower than the data rates, the RTS/CTS access mode loses its effectiveness to combat the hidden node problem, since the RTS transmission time becomes comparable with the data frame transmission time. Consider a single infrastructure 802.11 BSS, in which all the stations transmit

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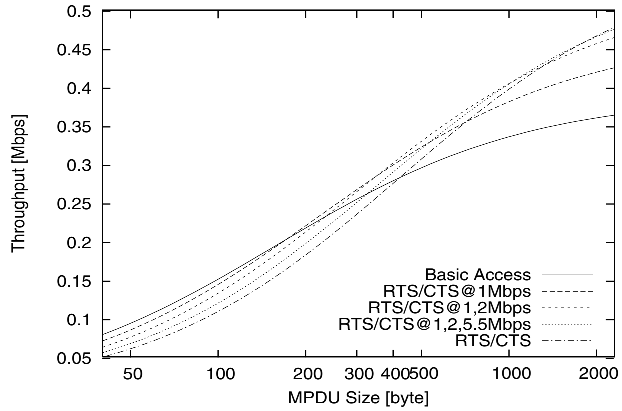

Figure 8. Throughput vs. the MPDU payload size, for different access modes policies, for heterogeneous transmission rates

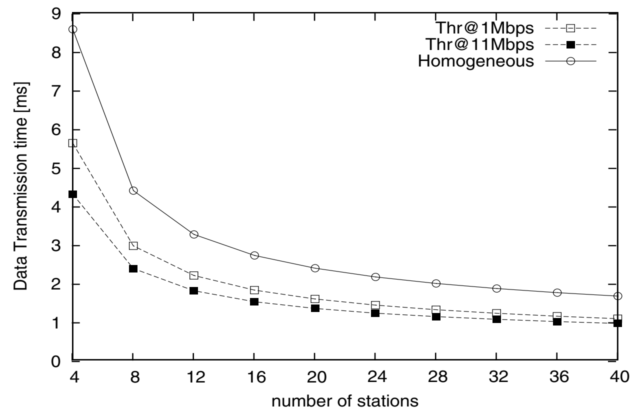

Figure 9. Data transmission times over which the RTS/CTS access should be active vs the number of contending stations, in homogeneous and heterogeneous data rate environments

to the AP. The AP is visible to all the nodes, but contenting nodes can be hidden to each other, on a per-frame basis, with probability h. We evaluated the normalized throughput perceived for two different extreme data rates (1 Mbps, 11 Mbps), in the case of 10 contenting stations, $P = 1024$ bytes, and for different values of h. The evaluation has been carried out by means of simulation only.

From Fig. 7, we observe that for the 11 Mbps case, the basic access performance degrade more slowly as the hidden probability increases. Accordingly, even if the RTS/CTS access is less sensitive to this phenomenon, whenever the hidden probability is not too high ($h < 10\%$), the basic access mode still results more advantageous than the RTS/CTS one.

4.3 Heterogeneous Data Rate

Whenever multiple data rates are simultaneously employed in the network, the optimal 4-way switching condition is not uniform among the stations. Consider the simple case of a fixed packet size. As the MPDU size P increases, the switching between the basic access and the RTS/CTS access mode should be ordered according to the employed transmission rate. In other words, the lowest rate stations have to switch the first and the highest rate stations the last. Fig. 8 shows an example of the overall system performance in a scenario in which 20 stations share the channel. Four different rates, i.e., 1, 2, 5.5, and 11 Mbps, are employed by 5 stations each. In the figure, we show 5 different curves, corresponding to 5 different access modes combinations, namely, (1) basic access for all, (2) RTS/CTS only for the 1 Mbps stations, (3) RTS/CTS for 1 and 2 Mbps stations, (4) RTS/CTS for 1, 2 and 5.5 Mbps, and (5) RTS/CTS for all. We assume a control rate equal to 1 Mbps. From the figure, we see that each access mode combination is the best possible strategy, for a given range of P values. Since the payload size P is fixed, by using the $E[T_c]$ expression as a function of the $E[H_i]$ values, and considering that in the general case of different n_i values, the stations have to be re-ordered after each 4-way access switch, the switch threshold P_i for stations belonging to class $i = 1, 2, \cdots 4$ is given by:

$$P_i > \frac{\frac{P_s n_i}{(1-P_s)N} O_{rts} + \sum_{k=0}^{i} (p'_{c-k} - p_{c-k+1}) RTS}{\sum_{k=i}^{c} \frac{p_k - p'_{k-1}}{r_k}} - 224$$

where p_i and p'_i represent the coefficients given in (5) before and after the 4-way switching for class i stations.

Fig. 9 plots the per-class thresholds as temporal intervals. For sake of presentation, the figure plots only the $DATA$ transmission times corresponding to to the extreme thresholds P_1 and P_4, regarding 1 Mbps and 11 Mbps stations. For the other classes, the thresholds are obviously located between these two curves. Each point refers to a different load scenario, in terms of number of competing stations, in which the data rates are uniformly employed among the stations (i.e., $n_i = N/4$ for each i). The figure also plots the $DATA$ threshold time obtained, according to (6), in the case of homogeneous data rate among all the contending stations N.

From the figure, we see that, as the number of contending stations increases, the 4-way temporal threshold tends to be the same value for all the contending stations. We also observe that, for each load condition, the thresholds obtained for the heterogeneous rate case maintain almost the same proportional relation with the homogeneous rate case. Therefore, we can conclude that a good heuristic solution for the 4-way threshold settings in heterogeneous rate environment is the use of a single temporal threshold for all the stations, obtained from (6) and reduced by a correction factor.

5 Conclusions

In this paper, we analyze the performance of the 2-way and 4-way access modes in IEEE 802.11 multi-rate networks. We describe an analytical framework able to account for different frame size distributions and data transmission rates among the stations and we evaluate the impact of different RTS/CTS thresholds on the overall system performance. We show that, as the data transmission times increase, since in most practical situations the maximum basic rates are constrained to lower rates, the 4-way access is less and less advantageous. In fact, whenever the $DATA$ transmission time approaches the RTS transmission time, the rationale on the basis of the 4-way access definition, i.e. the use of a short probe frame for collision times or vulnerability times reduction, is no more valid.

We provide some results in order to quantify the frame size threshold over which the 4-way access is advantageous, in both the cases of homogeneous and heterogeneous rates among the stations. We show that, expressing this threshold in temporal terms, i.e. in terms of data frame transmission times, as a function of the number of competing stations in the network, allows to define a threshold which is almost independent on the data rate. This independence is exact whenever all the competing stations employ the same data rate, and is a good approximation in the case of uniform data rate distribution among the stations. The definition of a unique temporal 4-way switching threshold is a very interesting operative result.

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