Improving performance through optimization of the RTS/CTS mechanism in IEEE 802.11 Wireless LANs

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***ABSTRACT* - IEEE 802.11 Medium Access Control (MAC) protocol employs two techniques for packet transmission; the basic access scheme and the RTS/CTS reservation scheme. In this paper, we carry out an analysis in order to derive an all-purpose expression for the threshold value, which determines when the RTS/CTS scheme should be employed, under ideal channel conditions without the presence of hidden stations or transmission errors. The main advantage of our proposed approach is that it is simple and gives insights of the RTS/CTS mechanism. Results based on the presented analysis for the IEEE 802.11b transmission rates and delays study the effect of the different protocol parameters on the RTS/CTS threshold. Moreover, results indicate that proper selection of protocol parameters such as retry limit and physical packet overhead for the specific data rate is of great importance in minimizing packet delay and improving overall performance.**

I. Introduction

Wireless Local Area Networks (WLANs) are becoming more and more popular since they provide high data rates while maintaining a relative low price. The IEEE 802.11 protocol [1] is the dominant standard for WLANs and employs Distributed Coordination Function (DCF) as the essential MAC method. DCF defines two access mechanisms to employ packet transmission; the default, two-way handshaking technique called basic access and the optional four-way handshaking RTS/CTS reservation scheme.

The RTS/CTS scheme involves the transmission of the short *request-to-send* (RTS) and *clear-to-send* (CTS) control packets prior to the transmission of the actual data packet. Since collisions may occur only on the RTS packets and are detected by the lack of CTS response, the RTS/CTS scheme results in an increase of the system performance by reducing the duration of a collision, especially when long data packets are transmitted. The RTS/CTS scheme is also employed to obtain a better performance in the presence of hidden stations. However, authors in [2] and [3] have reported several potential difficulties in the ability of the RTS/CTS scheme to eliminate the hidden stations problem and to reduce interference. On the other hand, RTS/CTS decreases efficiency since it transmits two additional packets without any payload. Hence, the 802.11 standard specifies the *RTS_Threshold* (RT), a manageable parameter that indicates the data length under which the data packets should be sent without RTS/CTS. The value of the *RT* parameter is not specified in the standard and has to be set separately by each station. The data packet size is the only parameter used for deciding whether the RTS/CTS reservation scheme should be employed or not.

There are a number of studies in the literature on performance of wireless data protocols as well as the RTS/CTS mechanism in IEEE DCF [2]-[7]. The authors in [6] first studied the RTS/CTS mechanism in the IEEE 802.11 through simulations. Work in [2] and [3] has pointed out that the RTS/CTS handshake does not work as well as expected in theory. The authors in [7] have performed a simulation study and suggested that the RTS/CTS mechanism must be employed at all times. Bianchi in [8] calculated the RTS/CTS threshold for throughput maximization but without taking into account packet retry limits[1]. In [9] we have presented a method capable of calculating packet delay by taking into consideration retransmission delays with or without packet retry limits. Moreover, in [10], we have evaluated the dependency of the RTS/CTS scheme on network size, however, without providing any general expression for the RTS/CTS threshold.

In this paper, we extent Bianchi's approach in [8], as well the analysis in [10], in order to derive an all-purpose expression for the RTS/CTS threshold. The proposed analysis takes into account packet retry limits and aims at minimizing the delay for data packets in 802.11 DCF by optimally employing the RTS/CTS scheme. Our work is carried out under the hypothesis of ideal channel conditions without the presence of hidden stations or transmission errors. The main advantage of our proposed approach is that is simple and gives insights of the RTS/CTS mechanism. We investigate the dependency of protocol performance on packet retry limit, data rates as well as physical packet overhead and network size. The derived framework in our paper can be useful and valuable for simple but effective performance improvements in WLANs, through the optimal use of the RTS/CTS reservation scheme.

The remainder of the paper is organized as follows. In section II, we briefly review the DCF mechanism used in IEEE 802.11 MAC. In section III, we carry out an analysis that gives a simple but general expression for the RTS threshold. Section IV presents performance results that examining the relationship between the RTS threshold and protocol parameters. Finally, section V concludes our paper.

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[1] Every station maintains a retry count that indicates the maximum number of retransmission attempts of a RTS packet or of a data packet when RTS/CTS is not used. When the retry count reaches the specified limit, retry attempts cease and the data packet is discarded.

II. DCF of IEEE 802.11 MAC

DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique and adopts a slotted Binary Exponential Backoff (BEB) scheme to reduce collisions due to stations transmitting simultaneously.

Each node with a packet to transmit first senses the medium to ascertain whether it is in use. If the medium is sensed to be idle for a time interval greater than the Distributed Inter-Frame Space (DIFS), the station proceeds with the packet transmission. If the medium is sensed busy, the station defers transmission and initialises its random backoff timer. The value of the backoff timer value for each station is uniformly chosen in the interval $[0,W_i-1]$, where W_i is the current contention window size, i is the backoff stage, $i \in [0,m]$ and m represents the station's retry limit. The backoff timer is decremented by one when the medium is idle, is frozen when the medium is sensed busy and resumes again only after the medium has been idle for longer than DIFS.

A station initiates a packet transmission (transmits the data packet in basic access or a short RTS packet first in the RTS/CTS scheme) when its backoff timer reaches zero. The value of W_i depends on the number of unsuccessful transmissions of a packet; at the first transmission attempt, $W_0 = CW_{min} = W$. After each retransmission due to a packet collision, W_i is doubled up to a maximum value, $W_{m'} = CW_{max} = W \cdot 2^{m'}$ where m' is the number of backoff stages. Once W_i reaches CW_{max}, it will remain at this value until it is reset to CW_{min} after the successful data packet transmission or when the retry limit for this packet is reached. After the successful reception of a data packet, the receiver sends back an acknowledgment (ACK) packet.

III. Mathematical analysis

We employ the same discrete-time Markov chain model as in [9]. Using the same assumptions with [7] and [9], we can calculate the probability p that a transmitted packet collides (independent of the number of collisions occurred in the past) as:

$$p = 1 - (1 - \tau)^{n-1} \qquad (1)$$

where n is the number of contenting stations and τ is the transmission probability of a packet. When retry limits are taken into account [9], τ is given by equation (2), where W is the minimum contention window size. Equations (1) and (2) form a non-linear system with two unknowns p and τ, which can be easily solved using numerical methods.

Our analysis in [9] has calculated the average delay $E[D]$ for a successfully transmitted packet. Packet delay is defined to be the time interval from the time a packet is at the head of its MAC queue ready for transmission, until its successful reception in the destination. $E[D]$ is given by:

$$E[D] = E[X] \cdot E[slot] \qquad (3)$$

where $E[X]$ is the average number of slot times for a successful packet transmission and $E[slot]$ is the average length of a slot time. The values of $E[X]$ are independent of the employed access mechanism (basic access or RTS/CTS) and can be found in [9]. The average length of a slot time is:

$$E[slot] = (1 - P_{tr}) \cdot \sigma + P_{tr} \cdot P_S \cdot T_S + P_{tr} \cdot (1 - P_S) \cdot T_C \qquad (4)$$

where $P_{tr} = 1 - (1-\tau)^n$ is the probability that there is at least one packet transmission in the considered slot time, $P_s = n\tau(1-\tau)^{n-1} / P_{tr}$ is the probability that an occurring packet transmission is successful, T_c , T_s and σ are the time durations the medium is sensed busy due to a collision and a successful transmission and of an empty slot time, respectively.

The values of T_s and T_c depend on the medium access mechanism and are defined for the basic access and the RTS/CTS access mechanisms as follows:

$$\begin{cases} T_S^{bas} = DIFS + T_{header} + \dfrac{l}{C} + SIFS + T_{ACK} \\ T_C^{bas} = DIFS + T_{header} + \dfrac{l}{C} + SIFS + T_{ACK} \end{cases} \qquad (5)$$

$$\begin{cases} T_S^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} + SIFS + T_{header} + \dfrac{l}{C} + SIFS + T_{ACK} \\ T_C^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} \end{cases} \qquad (6)$$

where l is the length of the transmitted packet, C is the data rate, $C_{control}$ is the rate that the control packets (ACK, RTS, CTS) are transmitted (1 Mbit/s), T_{header}, T_{ACK}, T_{RTS} and T_{CTS} are the time intervals required to transmit the packet payload header, the ACK, RTS and CTS control packets, respectively. The above time intervals are given by:

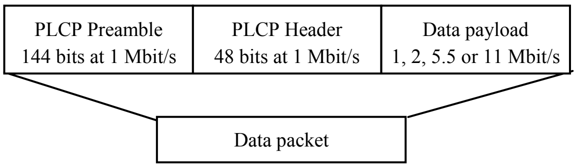
$$T_{header} = \frac{MAC_{hdr}}{C} + \frac{PHY_{hdr}}{C_{control}} \quad , \quad T_{ACK} = \frac{l_{ACK}}{C_{control}} \qquad (7)$$

$$T_{RTS} = \frac{l_{RTS}}{C_{control}} \quad , \quad T_{CTS} = \frac{l_{CTS}}{C_{control}} \qquad (8)$$

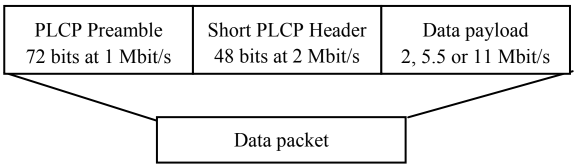
where l_{ACK}, l_{RTS} and l_{CTS} is the length of ACK, RTS and CTS control packets respectively, MAC_{hdr} is the MAC header and PHY_{hdr} is the physical header. In fact, a physical layer preamble (PLCP preamble) and a physical layer header (PLCP header) exist in both data and control frames. Hereafter, we will refer to the sum of PLCP preamble and PLCP header as PHY_{hdr}.

$$\tau = \begin{cases} \dfrac{2\cdot(1-2p)\cdot(1-p^{m+1})}{W\cdot(1-(2p)^{m+1})\cdot(1-p)+(1-2p)\cdot(1-p^{m+1})} & , \ m \le m' \\ \\ \dfrac{2\cdot(1-2p)\cdot(1-p^{m+1})}{W\cdot(1-(2p)^{m'+1})\cdot(1-p)+(1-2p)\cdot(1-p^{m+1})+W\cdot 2^{m'}\cdot p^{m'+1}\cdot(1-2p)\cdot(1-p^{m-m'})} & , \ m > m' \end{cases} \qquad (2)$$

The IEEE 802.11b protocol supports data rates of 1, 2, 5.5 and 11 Mbit/s. The standard defines two different formats for the preamble and header (PHY_{hdr}): the mandatory supported Long PLCP PHY_{hdr} which interoperates with the 1 Mbit/s and 2 Mbit/s data rates and an optional Short PLCP PHY_{hdr}. The Short PLCP PHY_{hdr} allows performance at the high rates (2, 5.5 and 11 Mbit/s) to be significantly increased. In fact, the Short PLCP PHY_{hdr} is intended for applications where maximum performance is desired and interoperability with legacy is not a consideration. Figure 1 shows the format of the Long and Short PLCP PHY_{hdr} of a data packet.



(a) Long PLCP



(b) Short PLCP

Fig. 1 Long and short PLCP data packet formats

In order to quantify the threshold value for the packet size over which it is best to switch to the RTS/CTS mechanism, we indicate with D^{RTS} and D^{BAS} the average delay of a packet transmitted by the basic access and RTS/CTS mechanism, respectively.

$$D^{RTS} < D^{BAS} \Leftrightarrow E[X]\cdot E[slot]^{RTS} < E[X]\cdot E[slot]^{BAS}$$

$$P_S \cdot T_S^{RTS} + (1-P_S)\cdot T_C^{RTS} < P_S \cdot T_S^{BAS} + (1-P_S)\cdot T_C^{BAS}$$

$$P_S \cdot (T_S^{RTS} - T_S^{BAS}) < (1-P_S)\cdot (T_C^{BAS} - T_C^{RTS}) \quad (9)$$

Let $O_{RTS} = T_S^{RTS} - T_S^{BAS} = \frac{l_{RTS}}{C_{control}} + 2SIFS + \frac{l_{CTS}}{C_{control}}$ be the overhead introduced by the RTS/CTS scheme, T_{data} be the time required to transmit the packet payload and let $O_h = T_{header} - T_{RTS} = (\frac{MAC_{hdr}}{C} + \frac{PHY_{hdr}}{C_{control}}) - \frac{l_{RTS}}{C_{control}}$ be the extra length of the data packet header with respect to the RTS packet size. After some rearrangements, equation (10) finally gives the threshold value $l_{threshold}$ over which it is convenient to switch to the RTS/CTS mechanism. The value of the threshold size depends on the probability of a successful transmission P_s, the control and the data rate as well as the packet overhead.

$$\frac{P_S}{1-P_S}\cdot O_{RTS} < O_h + T_{data}$$

$$l_{threshold} > (\frac{P_S}{1-P_S}\cdot O_{RTS} - O_h)\cdot C \quad (10)$$

IV. Performance evaluation

Fig. 2 and 3 study the effect of packet retry limit and the network size by plotting the probabilities P_s and p versus m, and the packet size threshold versus m respectively, for four representative network sizes (n = 5, 25, 50 and 70), W=32 and data rate of C=1 Mbps. Figure 2 shows that both the probability that an occurring packet transmission is successful P_s and the packet collision probability p are highly dependent on the network size; more contenting stations cause the increase on packet collisions and the decrease of successful packet transmissions. The figure also illustrates that the retry limit significantly affects the probabilities P_s and p. An important observation is that large network sizes appear to be more sensitive on retry limit. A small increase of m results in a greater increase in the successful transmission probability for large networks (equivalent decrease in the collision probability) than for small networks. In fact, for small network sizes (n = 5), both the probabilities P_s and p are independent of the retry limit.

Fig. 3 provides the threshold value above which the performance of the RTS/CTS mechanism is considerably enhanced. When the number of the contenting stations is relatively small (n = 5), it appears that it is not necessary to employ the RTS/CTS reservation scheme due to the low collision probability (fig. 2). On the contrary, when the network size increases, the RTS/CTS threshold decreases to lower values. This can be justified since large network sizes and a low retry limit cause more packet collisions and a much lower successful transmission probability (fig. 2). The figure illustrates that the packet retry limit has a significant effect; when retry limit increases, the RTS/CTS threshold values also increase due to the improved successful transmission probability and the reduced number of collisions (fig. 2). An interesting outcome in fig. 2 and 3 is that for m>6, the probabilities P_s and p as well as the RTS/CTS threshold are only marginally affected, indicating the proper choice of the retry limit value in the standard.

Fig. 4 plots packet size threshold versus network size for three data rates (C = 1, 5.5, and 11) as well as for a short and long PHY packet overhead. According to fig. 4, the packet size threshold is highly dependent on the data rate. When the data rate increases, the threshold values significantly increase. The reason is that although high data rates reduce the transmission time for data packets, the RTS and CTS control packets are still being transmitted by the low control rate, resulting in delay in communication. Moreover, the use of a short PHY header, which results in a lower transmission time comparing to the long PHY header's transmission time, considerably decreases the packet size threshold. This can easily be explained by considering that smaller packet overhead mainly reduces the overhead of RTS and CTS control packets. Thus, the main drawback the RTS/CTS scheme is minimized and it can be employed for even smaller data packets.

V. Conclusions

In this paper, we have presented a simple analysis to derive an all-purpose expression for the threshold value, which determines when the RTS/CTS reservation scheme should be employed, under ideal channel conditions without the presence of hidden stations or transmission errors. Based on our analysis, we have studied and concluded that the RTS/CTS threshold significantly depends on both protocol parameters and network size. Performance results show that high data rates and a high packet retry limit, bring about the considerable increase of RTS/CTS threshold values. Conversely, for large network sizes the RTS/CTS scheme appears to be beneficial due to the increased collision probability. The use of a short physical packet overhead minimizes the main drawback of the extra overhead for the RTS/CTS scheme and makes beneficial its employment for even smaller data packets. The derived analysis could be useful for simple performance improvements, through the optimal use of the RTS/CTS reservation scheme, however, it brings about the question of effectiveness and necessity of the RTS/CTS reservation scheme in high-speed IEEE 802.11 WLANs and in the absence of hidden stations.

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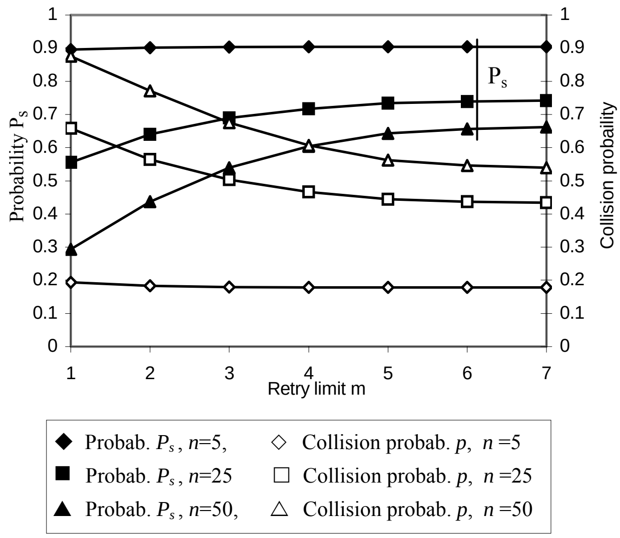

Fig. 2 Effect of retry limit on probabilities P_s and p

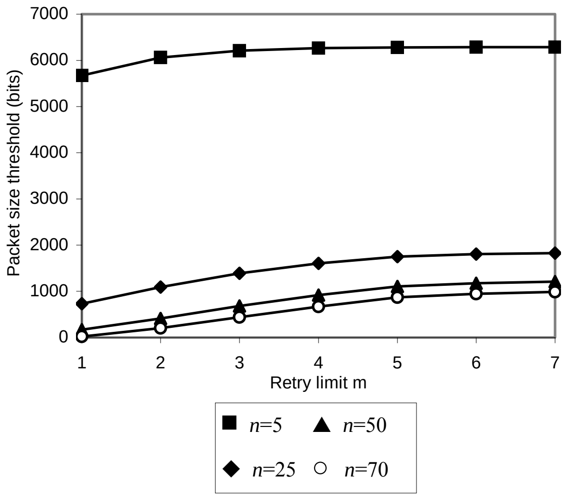

Fig. 3 Packet size threshold versus retry limit

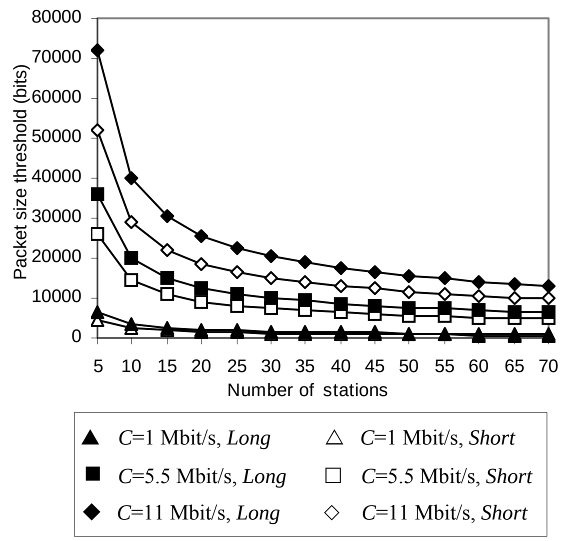

Fig. 4 Effect of data rate and physical packet overhead