Optimisation of RTS/CTS handshake in IEEE 802.11 Wireless LANs for maximum performance

P. Chatzimisios[1], A. C. Boucouvalas[1] and V. Vitsas[2]

[1] Multimedia Communications Research Group, School of Design, Engineering and Computing,
Bournemouth University, Fern Barrow, Poole, UK,
{pchatzimisios, tboucouv}@bournemouth.ac.uk

[2] Department of Information Technology,
Technological Educational Institution, Thessaloniki, Greece,
vitsas@it.teithe.gr

Abstract - **IEEE 802.11 Medium Access Control (MAC) protocol employs two techniques for packet transmission; the basic access and the RTS/CTS reservation scheme. The latter is employed in order to improve performance as it a) shortens packet collision duration and b) addresses the hidden station problem. In this paper, we study how effective the RTS/CTS handshake is in reducing collision duration for high data rates and under ideal channel conditions by taking into account the particular packet overheads and delays defined in IEEE 802.11b Wireless LANs (WLANs). Furthermore, we derive an all-purpose expression for the RTS threshold value that actually maximizes performance by employing the RTS/CTS reservation scheme whenever it is beneficial for both the packet delay and throughput performance. Results indicate that the proper selection of protocol parameters such as retry limit, initial contention window and physical packet overhead is of great importance in minimizing packet delay and improving throughput performance.**

I. Introduction

Wireless Local Area Networks (WLANs) are becoming more and more popular attracting the interest of researchers, system integrators and computer manufacturers [1]. The IEEE 802.11 protocol [2] is the dominant standard for WLANs and employs the Distributed Coordination Function (DCF) as the essential Medium Access Control (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 the CTS response, the RTS/CTS scheme results in an increase on system performance by reducing the duration of collisions, especially when long data packets are transmitted. The RTS/CTS scheme is also employed to result in a better performance in the presence of hidden stations. However, authors in [3] and [4] have reported several potential difficulties in the ability of the RTS/CTS scheme to cope with the hidden station problem. On the other hand, RTS/CTS decreases efficiency since it transmits two additional control 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 the performance of wireless data protocols as well as the RTS/CTS mechanism in IEEE DCF [3]-[12]. The authors in [5] and [6] first studied the performance of the RTS/CTS mechanism in IEEE 802.11 WLANs through simulations. Although the RTS/CTS scheme is also employed to result in a better performance in the presence of hidden stations, authors in [3] and [4] pointed out that the RTS/CTS handshake does not work as well as expected in dealing with the hidden station problem and reducing interference. In particular, Bianchi in [7] proved the superiority of RTS/CTS in most cases by calculating the RTS threshold for throughput maximization but without taking into account packet retry limits [1]. In [8], we evaluated the dependency of the RTS/CTS scheme on network size, but we did not provide any general expression for the RTS threshold. Moreover, in [9] we presented a method capable of calculating the average packet delay by taking into consideration retransmission delays with or without packet retry limits. However, [7]-[9] considered the low 1 Mbit/s as being the data and control rate in their presented analysis. Ziouva in [10] demonstrated that for any data rate of IEEE 802.11b (1, 2, 5.5 and 11Mbit/s) the RTS/CTS scheme always achieves a better throughput and delay performance than the basic access scheme. However, the derived results did not take into account the fact that the physical header and preamble as well as all the control packets (RTS, CTS and ACK) are always transmitted at either 1 Mbit/s or 2 Mbit/s. Furthermore, the authors in [11] have performed a simulation study and suggested that the RTS/CTS mechanism must be employed at all times by setting the

[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.

RTS threshold equal to 0. On the other hand, results in [12] illustrated that the RTS/CTS mechanism provides very limited advantages with respect to the basic access for data rates of 11Mbit/s when no hidden stations are present.

In this work, we provide a packet delay analysis for a throughput model that considers packet retry limits. Our work takes into account all the protocol parameters and packet overheads introduced by both the Medium Access Control (MAC) and the physical (PHY) layers, in order to precisely evaluate the advantage of the RTS/CTS scheme in respect to the basic access. By utilizing the mathematical model for throughput and delay as 'performance metrics', we explore the effectiveness of RTS/CTS for collision duration decrease at high data rate IEEE 802.11b WLANs. Furthermore, we extent Bianchi's approach in [7], as well the analysis in [8], in order to derive an all-purpose expression for the RTS threshold. The proposed analysis aims at minimizing the delay for data packets in 802.11 DCF by optimally employing the RTS/CTS scheme under the hypothesis of ideal channel conditions (without the presence of hidden stations or transmission errors). The main advantage of our approach is its simplicity and that it gives insights of the RTS/CTS mechanism. We also investigate the dependency of protocol performance on packet retry limit, initial contention window, data rate as well as physical packet overhead and network size. The derived expression for the RTS threshold is essential in optimising the use of the RTS/CTS mechanism that significantly improves the performance of IEEE 802.11 WLANs.

II. Brief description of IEEE 802.11 DCF

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 for each station is uniformly chosen in the interval $[0, W_i - 1]$, where W_i is the current contention window (*CW*) size, i is the backoff stage, $i \in [0,m]$ and m represents the station's retry limit. The backoff timer is decremented in terms of slot times 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 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, $CW_{min} = W_0 = W$, where W represents the initial contention window. After each retransmission due to a packet collision, W_i is doubled up to a maximum value, $CW_{max} = W_{m'} = W \cdot 2^{m'}$,where m' identifies the maximum 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 after a time interval equal to Short Inter-Frame Space (SIFS).

III. Analytical modeling

Our analysis employs the Markov chain model of [9] and makes use of the same assumptions as in [7][8][9]; all stations always have a packet available for transmission (saturation case) in an error free channel. The probability p that a transmitted packet collides is assumed to be constant and independent of the number of collisions the station has experienced in the past and is given by:

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

where n is the number of contending stations, τ is the transmission probability of a packet given by equation (2), m is the retry limit, indicating that a packet will be discarded after an unsuccessful transmission at the m stage. Equations (1) and (2) form a non-linear system with two unknowns p and τ which can be easily solved by utilizing numerical methods.

The saturation throughput S, defined as the fraction of time the channel is used to transmit payload, is given by:

$$S = \frac{P_{tr} P_S \, l}{(1 - P_{tr})\sigma + P_{tr} P_S T_S + P_{tr}(1 - P_S) T_C} \tag{3}$$

where the denominator of equation (3) denotes the average length of a slot time $E[slot]$, l is the payload packet length, σ is the duration of an empty slot time, $P_{tr} = 1 - (1-\tau)^n$ is the probability that there is at least one packet transmission, $P_S = n\tau(1-\tau)^{n-1} / P_{tr}$ is the probability that an occurring packet transmission is successful T_C and T_S are the average durations the medium is sensed busy due to a collision and a successful transmission respectively.

$$\tau = \begin{cases} \dfrac{2(1-2p)(1-p^{m+1})}{W(1-(2p)^{m+1})(1-p) + (1-2p)(1-p^{m+1})} & , \; m \le m' \\[2ex] \dfrac{2(1-2p)(1-p^{m+1})}{W(1-(2p)^{m'+1})(1-p) + (1-2p)(1-p^{m+1}) + W\,2^{m'} p^{m'+1}(1-2p)(1-p^{m-m'})} & , \; m > m' \end{cases} \tag{2}$$

The values of T_C and T_S depend on the medium access mechanism and are given for the basic access and the RTS/CTS access mechanisms by:

$$\begin{cases} T_S^{bas} = DIFS + T_{header} + \frac{l}{C} + SIFS + T_{ACK} + 2\delta \\ T_C^{bas} = DIFS + T_{header} + \frac{l}{C} + SIFS + T_{ACK} + 2\delta \end{cases} \quad (4)$$

$$\begin{cases} T_S^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} + SIFS + T_{header} + \frac{l}{C} + SIFS + T_{ACK} + 4\delta \\ T_C^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} + 4\delta \end{cases} \quad (5)$$

where δ is the propagation delay, C is the data rate, 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. We have:

$$T_{header} = \frac{MAC_{hdr}}{C} + \frac{PHY_{hdr}}{C_{control}} \quad , \quad T_{ACK} = \frac{l_{ACK}}{C_{control}} \quad (6)$$

$$T_{RTS} = \frac{l_{RTS}}{C_{control}} \quad , \quad T_{CTS} = \frac{l_{CTS}}{C_{control}} \quad (7)$$

where $C_{control}$ is the rate that the control packets (ACK, RTS, CTS) are transmitted[2] (2 Mbit/s), l_{ACK}, l_{RTS} and l_{CTS} is the length of ACK, RTS and CTS 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}.

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. Fig.1 shows the format of the Long and Short PLCP PHY_{hdr} of a data packet.

We next provide simple equations for the average delay for a successfully transmitted packet, which is defined as the time interval from the instance a head-of-queue packet is ready for transmission until its successful reception. If a packet has reached its retry limit and it is dropped, it will not be included in the calculation of the average packet delay. The average packet delay $E[D]$ is given by:

$$E[D] = E[X]\, E[slot] \quad (8)$$

where $E[X]$ is the average number of time slots needed for a successful transmission. The values of $E[X]$ are independent of the employed access mechanism (basic access or RTS/CTS) and can be found in [9] with further details on the derivation of the packet delay.

[2] In order to ensure that all stations in range receive control packets, ACK, RTS and CTS packets are sent at a lower rate increasing reception distance. Note that the data and the control rates may not be the same.

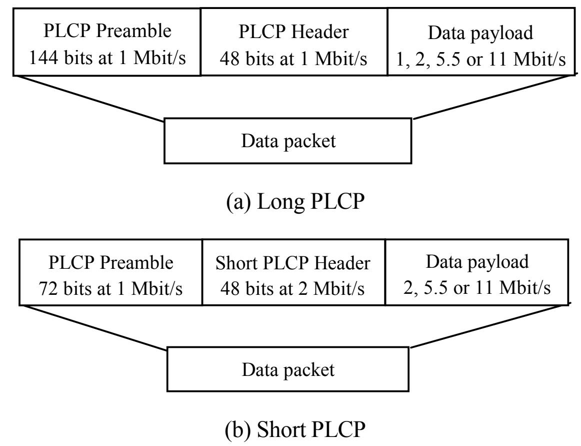

Fig. 1 Long and short PLCP data packet formats

IV. Performance evaluation of basic access and RTS/CTS schemes

The values reported in the figures of this paper have been obtained using the system parameters in table I (unless otherwise specified) and are based on the Direct Spread Sequence Spectrum (DSSS) physical layer used in 802.11b standard [2].

Parameter	Value
Packet payload, l	8184 bits
Slot time, σ	20 μs
MAC header	272 bits
PHY header (long), l_{PHY}	192 μs
PHY header (short), l_{PHY}	96 μs
RTS packet	160bits $+ l_{PHY}$
CTS packet	112bits $+ l_{PHY}$
ACK packet	112bits $+ l_{PHY}$
DIFS	50 μs
SIFS	10 μs
Data rate, C	2, 5.5, 11 Mbit/s
Control rate, $C_{control}$	2 Mbit/s
Minimum CW, W_0	32
Number of CW sizes, m'	5
Short retry limit, m	6

Table I The system parameters used to performance evaluation

Fig. 2, 3 and 4 study the effectiveness of the RTS/CTS scheme in high data rates (C=11 Mbit/s) by plotting throughput and average packet delay versus packet size for small (n=5), medium (n=25) and large (n=50) network sizes, respectively. The best-case scenario is considered where control packets (RTS, CTS and ACK) are transmitted at the highest possible control rate (2 Mbit/s) and the short PHY header is utilized. The figures demonstrate that both packet delay and throughput increase, as the data packet size increases. Note that the curves for packet delay and throughput cross in exactly the same point in both the basic access and RTS/CTS schemes.

Fig. 2 illustrates that the basic access outperforms RTS/CTS when the number of contending stations is relatively small (n=5) for all packet size values. This expected outcome confirms that the RTS/CTS reservation scheme is not beneficial for small size networks due to the low collision probability and is consistent with the conclusion derived in [7] and [8] for the data rate of 1 Mbit/s. Fig. 3 illustrates the case of a medium network size (n=25) with a much higher collision probability; the RTS/CTS scheme attains lower packet delay and higher throughput than the basic access scheme for packet sizes l >8500 bits. This RTS threshold value is large due to the much lower control rate considerably degrades performance. Furthermore, fig. 4 shows that even when the collision probability increases significantly as a result of the large number of contending stations (n=50), the RTS/CTS scheme is advantageous to basic access for relatively large packets (l> 6000 bits). Similar figures (not shown due to correspondence) for intermediate network size values of n=20, 30 and 40, show that the RTS/CTS scheme enhances performance only when the length of data packets exceeds 9500, 8000 and 6500 bits, respectively.

The presented performance results demonstrate the deficiency of the RTS/CTS scheme for high data rates (11 Mbit/s), unlike common expectation. We find that only very large packet size values render the RTS/CTS beneficial compared to the basic access scheme. This result holds true even when the highest possible control rate (2 Mbit/s) is utilized and is explained by considering that the exchange of the RTS and CTS reservation packets at a much lower control rate results in a significant delay in communication.

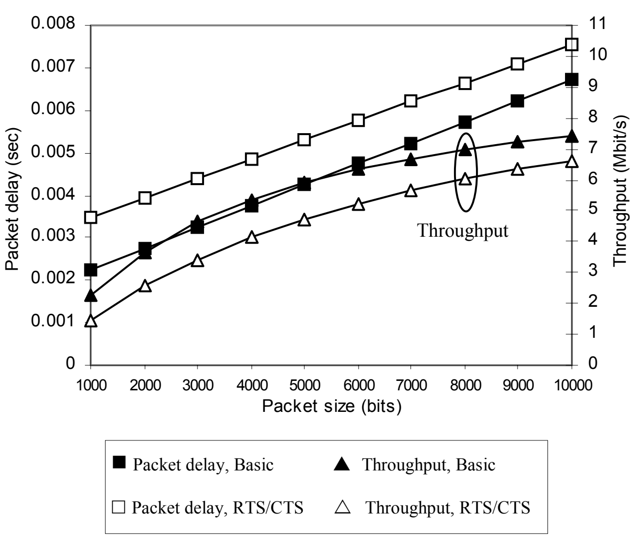

Fig. 2 Packet delay and throughput versus packet size (n=5, C= 11 Mbit/s, $C_{control}$= 2 Mbit/s)

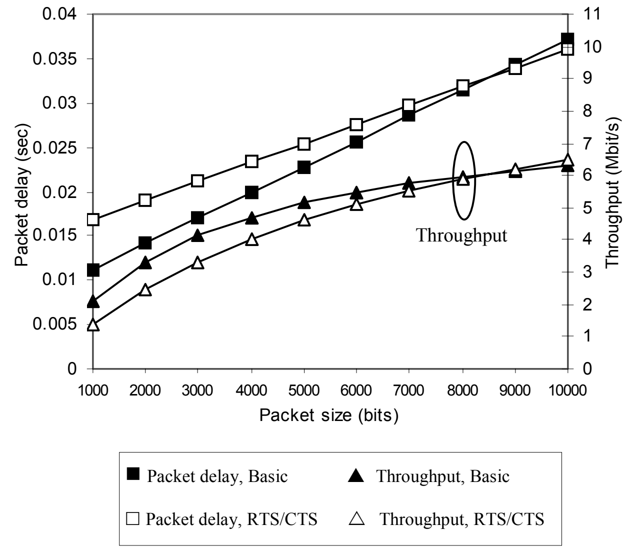

Fig. 3 Packet delay and throughput versus packet size (n=25, C= 11 Mbit/s, $C_{control}$= 2 Mbit/s)

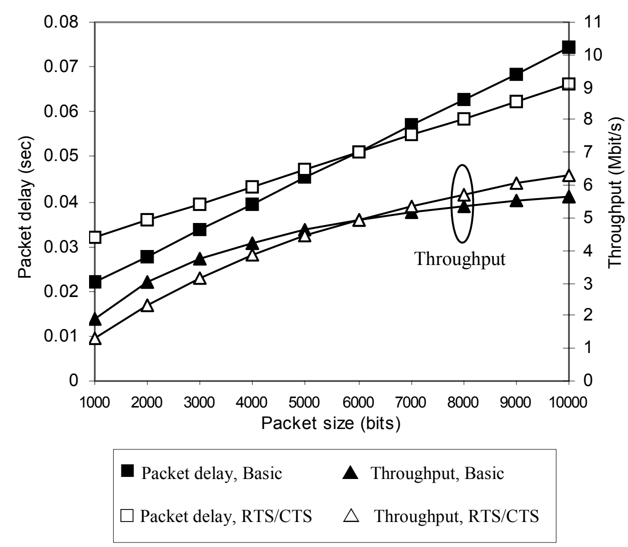

Fig. 4 Packet delay and throughput versus packet size (n=50, C= 11 Mbit/s, $C_{control}$= 2 Mbit/s)

V. Derivation of RTS threshold

Performance results presented in the previous section indicate that the use of RTS/CTS reservation scheme must balance between the reduced collision duration and the increased overhead for the transmission of the RTS and CTS control packets. Therefore, the desire for optimal use of the RTS/CTS reservation scheme makes essential the derivation of an all-purpose expression for the threshold value, which determines when the RTS/CTS reservation scheme should be employed.

We indicate with D^{BAS} and D^{RTS} the average delay of a packet transmitted by the basic access and RTS/CTS mechanism, respectively. The threshold value should satisfy the following condition[3]:

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

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

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

Let $O_{RTS} = T_S^{RTS} - T_S^{BAS} = \frac{l_{RTS}}{C_{control}} + 2\ SIFS + \frac{l_{CTS}}{C_{control}}$ be the overhead introduced by the RTS/CTS scheme and $T_C^{BAS} - T_C^{RTS} = \frac{l}{C} + O_h$ where $O_h = T_{header} - T_{RTS} = (\frac{MAC_{hdr}}{C} + \frac{PHY_{hdr}}{C_{control}}) - \frac{l_{RTS}}{C_{control}}$ is the extra length of the data packet header with respect to the RTS packet size. Thus, equation (9) becomes:

$$\frac{P_S}{1-P_S}\ O_{RTS} = O_h + \frac{l}{C}$$

$$l_{threshold} = \left(\frac{P_S}{1-P_S}\ O_{RTS} - O_h \right) C \quad (10)$$

Equation (10) gives the threshold value $l_{threshold}$ over which it is beneficial 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.

VI. Performance evaluation of the RTS threshold

We next study the effect of packet retry limit and initial contention window. Fig. 5 and 6 plot the RTS threshold versus *m* and *W*, respectively, for four representative network sizes (*n* = 5, 25, 50 and 70) and data rate of *C*=11 Mbit/s. Both figures show that when the number of the contending stations is relatively small (*n* = 5), the RTS threshold attains high values that exceed the maximum packet size (without employing the fragmentation mechanism as specified by IEEE 802.11b) so the RTS/CTS scheme should not me employed due to the low packet collision probability. When the network size increases, the RTS threshold decreases to lower values. This can be justified since large network sizes cause more packet collisions and a much lower successful transmission probability is achieved. We can see that the packet retry limit has a significant effect on RTS threshold; when retry limit increases, the RTS threshold values also increase due to the improved successful transmission probability. An interesting outcome is that for *m*>6, the RTS threshold is only marginally affected, indicating the proper choice of the retry limit value in the IEEE 802.11 standard. Furthermore, fig. 6 shows that the RTS threshold values are also highly dependent on the initial contention window. In fact, small network sizes appear to be more sensitive on the initial contention window. A small increase of *W* results in a greater increase in the RTS threshold for small networks than for large networks.

[3] Although, the derived expression is derived in order to minimize packet delay, the same approach can be followed for maximising throughput performance.

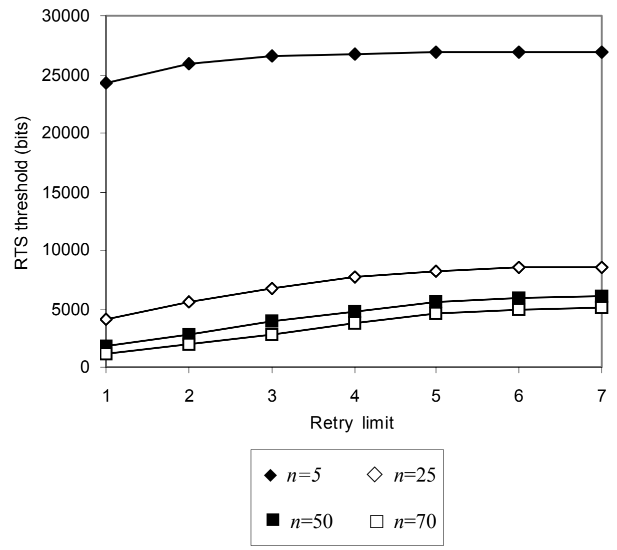

Fig. 5 RTS threshold versus packet retry limit (C= 11 Mbit/s, $C_{control}$= 2 Mbit/s)

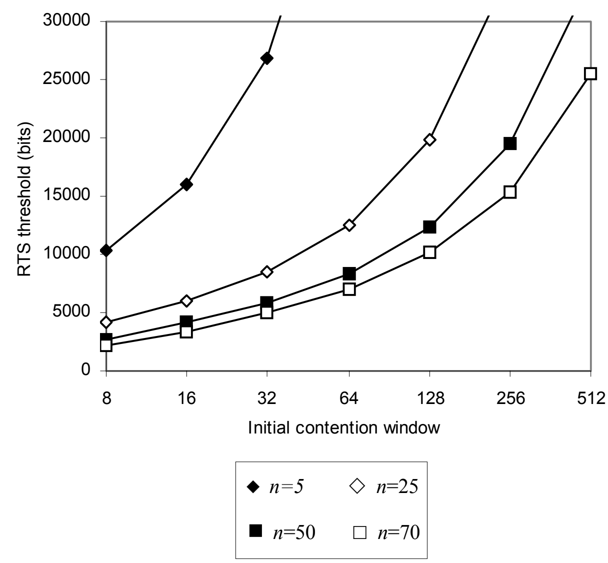

Fig. 6 RTS threshold versus initial contention window (C= 11 Mbit/s, $C_{control}$= 2 Mbit/s)

Fig. 7 plots RTS threshold versus network size for three data rates (*C* = 2, 5.5, and 11 Mbit/s) as well as for a short and long PHY packet overhead. According to fig. 7, the packet size threshold is highly dependent on the data rate. When the data rate increases, the threshold values increase significantly. 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 shorter 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 that RTS and CTS control packets introduce. Thus, the main drawback (increased overhead) of the RTS/CTS scheme is minimized denoting that it can be employed for even smaller data packets.

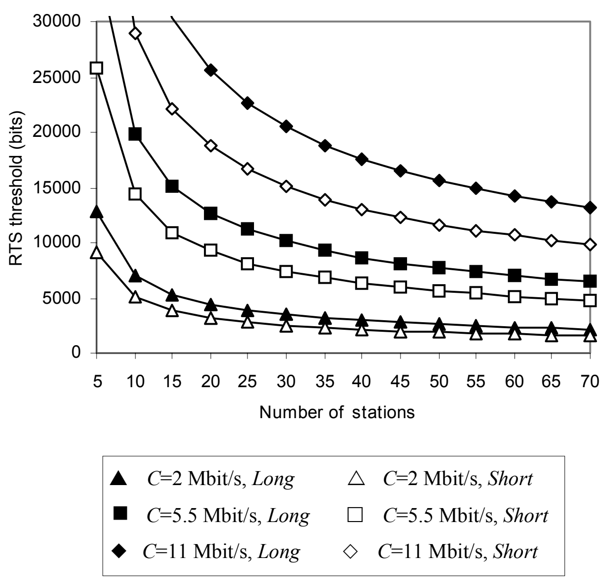

Fig. 7 Effect of data rate and PLCP header on RTS threshold

VII. Conclusions

In this paper, we reported a mathematical analysis and simple equations for packet delay of IEEE 802.11b DCF. Based on the presented analysis, we studied the effectiveness of the RTS/CTS scheme in reducing the collision duration under certain scenarios. Results have showed that the lower rate RTS/CTS exchange reservation scheme has limited utility when it is combined with higher transmission data rates and under ideal conditions.

We next have derived an all-purpose expression for the RTS threshold value, which determines when it is beneficial to switch to the RTS/CTS scheme. The proposed approach will allow any station to dynamically adjust its RTS threshold aiming to maximize performance by taking into account the transmission parameters (like data and control rates) in addition to the current congestion level. Performance results have demonstrated that the RTS threshold significantly depends on both protocol parameters and network size; high data rates as well as high packet retry limit and initial contention size values, bring about the considerable increase of RTS threshold. Moreover, the use of a short physical packet overhead minimizes the main weakness of the extra overhead of the RTS/CTS scheme and makes its employment beneficial for even smaller data packets and network sizes.

To conclude, the derived framework for the optimal use of the RTS/CTS reservation scheme could be useful for simple performance improvements, in the absence of hidden stations and in high-speed IEEE 802.11 WLANs.

References

[1] T. Zahariadis, "Evolution of the Wireless PAN and LAN standards", *Computer Standards & Interfaces*, no. 26, pp. 175-185, 2004.

[2] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification: High-Speed Physical Layer Extension in the 2.4 GHz Band*, IEEE 802.11b WG, 1999.

[3] K. Xu, M. Gerla and S. Bae, "How Effective is the IEEE 802.11 RTS/CTS Handshake in Ad Hoc Networks?", in Proc. of *IEEE Globecom '02*, vol. 1, pp. 72-76, Taipei, 2002.

[4] K. Xu, M. Gerla and S. Bae, "Effectiveness of RTS/CTS Handshake in IEEE 802.11 Based Ad Hoc Networks", *Ad Hoc Networks Journal*, vol. 1, no.1, pp. 107-123, July 2003.

[5] J. Weinmiller, H. Woesner and A. Wolisz, "Analyzing and improving the IEEE 802.11-MAC protocol for wireless LANs", in Proc. of *MASCOT*, pp.200-206, Feb.1996.

[6] J. Weinmiller, H. Woesner, JP Ebert and A. Wolisz, "Analyzing the RTS/CTS mechanism in the DFWMAC Media Access Protocol for Wireless LANs", in Proc. of *PWC*, pp. 117-130, April 1995.

[7] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function", *IEEE Journal on Selected Area in Comm.*, vol.18, no.3, pp. 535-547, Mar. 2000.

[8] P. Chatzimisios, A. C. Boucouvalas and V. Vitsas, "Packet delay analysis of the IEEE 802.11 MAC protocol", *IEE Electronic Letters*, vol. 39, no. 18, pp.1358-1359, Sep. 2003.

[9] P. Chatzimisios, A. C. Boucouvalas and V. Vitsas, "IEEE 802.11 Packet Delay - A Finite Retry Limit Analysis", in Proc. of *IEEE Globecom*, vol. 2, pp. 950-954, Dec. 2003.

[10] E. Ziouva and T. Antonakopoulos, "CSMA/CA performance under high traffic conditions: throughput and delay analysis", *Computer Communications,* vol. 25, pp. 313-321, Feb 2002.

[11] S.-T. Sheu, T.Chen, J.Chen and F.Ye, "The impact of RTS Threshold on IEEE 802.11 MAC protocol", in Proc. of *IEEE ICPADS,* pp. 267-272, Dec. 2002.

[12] R. Bruno, M.Conti and E.Gregori, "IEEE 802.11 optimal performance: RTS/CTS mechanism vs. basic access", in Proc. of *IEEE PIMRC,* vol.4, pp. 1747 -1751, Sep 2002.