Effectiveness of RTS/CTS handshake in IEEE 802.11a Wireless LANs

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The RTS/CTS reservation scheme in IEEE 802.11a Wireless LANs (WLANs) is employed to improve performance as it shortens packet collision duration and addresses the hidden station problem. An investigation has been conducted into how effective the RTS/CTS handshake is in reducing collision duration for 54 Mbit/s by extending an existing mathematical model for the particular packet overheads and delays defined in 802.11a. The study reveals, for the first time, that the RTS/CTS scheme is not beneficial in most network scenarios for the 54 Mbit/s data rate as currently specified in the 802.11a standard and that RTS/CTS effectiveness in improving throughput and average packet delay performance is uncertain.

Introduction: IEEE 802.11 Distributed Co-ordination Function (DCF) employs two techniques for packet transmission: the basic access and the RTS/CTS scheme [1]. The optional four-way handshaking RTS/CTS scheme involves the transmission of short *request-to-send* (RTS) and *clear-to-send* (CTS) control packets prior to the data packet transmission in order to shorten the collision duration. Although the RTS/CTS scheme is also employed to improve performance in the presence of hidden stations, the authors in [2] have reported several potential problems in the ability of the RTS/CTS scheme to address the hidden station problem and reduce interference. Bianchi in [3] developed a mathematical model for 802.11 DCF when no hidden stations are present and showed that RTS/CTS is effective in reducing collision duration for the 1 Mbit/s data rate. However, in [3] the difference between control rate and data rate has not been investigated and therefore the conclusions on the RTS/CTS effectiveness should be re-examined for the high data rates of IEEE 802.11a. In [4], we have extended Bianchi's model [3] and calculated the average packet delay for IEEE 802.11b, taking into consideration packet retry limits.

In this Letter, we extend the mathematical model presented in [4] for the IEEE 802.11a protocol, which provides data rates up to 54 Mbit/s. 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 evaluate precisely the effectiveness of the RTS/CTS scheme with respect to the basic access. By utilising the mathematical model for throughput and delay as 'performance metrics', we explore, for the first time, the effectiveness of RTS/CTS for collision duration decrease in high data rate IEEE 802.11a WLANs.

Analysis: Our model is based on the same discrete-time Markov chain model presented in [4]. We recall that the collision probability p is defined as the probability that a packet transmission fails due to simultaneous transmission from another station. Let τ be the probability that a station transmits in a randomly chosen slot time and n is the number of contending stations. The probabilities p and τ can be expressed as [4]:

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

$$\tau = \frac{2\cdot(1-2p)\cdot(1-p^{m+1})}{W\cdot(1-(2p)^{m'+1})\cdot(1-p) + (1-2p)\cdot[W\cdot 2^{m'} \times p^{m'+1}\cdot(1-p^{m-m'}) + 1 - p^{m+1}]} \tag{2}$$

where m is the packet retry limit, $CW_{\min} = W_0 = W$ is the minimum CW size, $CW_{\max} = W_{m'} = W\cdot 2^{m'}$ is the maximum CW size and $m' = \log_2(CW_{\max}/CW_{\min})$ is the number of backoff stages. The probabilities p and τ can be calculated by solving the nonlinear system of (1) and (2) using numerical methods.

The saturation throughput S is given by:

$$S = \frac{n\tau(1-\tau)^{n-1} l}{(1-\tau)^n \sigma + n\tau(1-\tau)^{n-1} T_s + [1-(1-\tau)^n - n\tau(1-\tau)^{n-1}]T_C} \tag{3}$$

where the denominator of (3) denotes the average length of a slot time $E[slot]$, l is the packet size, σ is the duration of an empty slot time, T_s and T_c are the average durations the medium is sensed busy due to a successful transmission and a collision, respectively. For the basic access scheme, T_s and T_c are given by:

$$T_S^{bas} = T_C^{bas} = DIFS = T_{DATA} + SIFS + T_{ACK} \tag{4}$$

and for the RTS/CTS scheme:

$$\begin{cases} T_S^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} + SIFS + T_{DATA} + SIFS + T_{ACK} \\ T_C^{RTS} = DIFS + T_{RTS} + SIFS + T_{CTS} \end{cases} \tag{5}$$

where T_{DATA}, T_{ACK}, T_{RTS} and T_{CTS} are the transmission times for a data, acknowledgment, RTS and CTS packet, respectively. According to the IEEE 802.11a standard [1]:

$$T_{DATA} = 20us + 4us\cdot\left\lceil\frac{294+l}{4\cdot C}\right\rceil$$

$$T_{RTS} = 20us + 4us\cdot\left\lceil\frac{182}{4\cdot C_{con}}\right\rceil \tag{6}$$

$$T_{ACK} = T_{CTS} = 20us + 4us\cdot\left\lceil\frac{134}{4\cdot C_{con}}\right\rceil \tag{7}$$

where C is the data rate at which data packets are transmitted (6, 9, 12, 18, 24, 36, 48 and 54 Mbit/s) and C_{con} is the control rate at which the RTS, CTS and ACK control packets are transmitted (6, 12 or 24 Mbit/s). Note that the data and control rate may not be the same. To ensure that the vital information contained in the RTS and CTS packets will be received by all stations in range and to cope with potential hidden stations, control packets are transmitted at a lower data rate, which increases reception distance.

The average delay $E[D]$ for a successfully transmitted packet given by [4] is:

$$E[D] = E[X]\cdot E[slot] = \sum_{i=0}^{m}\left[\frac{W_i+1}{2}\cdot\frac{(p^i - p^{m+1})}{1-p^{m+1}}\right]\cdot E[slot] \tag{8}$$

where $E[X]$ is the average number of slot times required for a successful packet transmission and $(p^i - p^{m+1})/(1-p^{m+1})$ is the probability that a packet that is not dropped reaches the i stage.

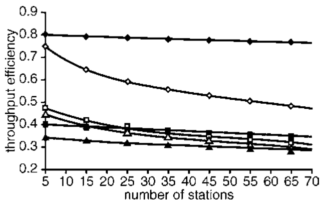

Fig. 1 *Throughput efficiency against n, for W = 16, m = m' = 6, l = 1023 bytes and various (C, C_{con})*

◇ Basic access, $C = C_{con} = 6$ Mbit/s
□ Basic access, $C = 54$ Mbit/s, $C_{con} = 24$ Mbit/s
△ Basic access, $C = 54$ Mbit/s, $C_{con} = 6$ Mbit/s
◆ RTS/CTS, $C = C_{con} = 6$ Mbit/s
■ RTS/CTS, $C = 54$ Mbit/s, $C_{con} = 24$ Mbit/s
▲ RTS/CTS, $C = 54$ Mbit/s, $C_{con} = 6$ Mbit/s

Results: Fig. 1 plots throughput efficiency against the number of contending stations for a fixed data packet size of $l = 1023$ bytes and for three different pairs of data and control rates. When the link data and control rates are the same (6 Mbit/s), the RTS/CTS reservation scheme always achieves better performance than the basic access due to the shorter collision duration, which is consistent with the conclusion derived in [3] for a data rate of 1 Mbit/s. Conversely, when the highest data rate of 54 Mbit/s is utilised combined with the lowest control rate of 6 Mbit/s, the basic access scheme outperforms RTS/CTS for any network size since the much lower control rate considerably degrades performance. Furthermore, for the 54 Mbit/s data rate and in the best-case scenario for the highest possible control rate of 24 Mbit/s, the RTS/CTS scheme attains higher throughput efficiency than the basic access scheme for network sizes $n > 35$.

Figs. 2 and 3 show further the effectiveness of the RTS/CTS scheme in high data rates by plotting throughput efficiency and average packet delay against packet size for small ($n = 5$) and large ($n = 50$) network sizes. The best-case scenario is considered where control packets are transmitted at the highest possible control rate (24 Mbit/s). The Figures demonstrate that both throughput efficiency and packet delay increase, as the data packet size increases. 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. Fig. 3 shows that even when the collision probability increases considerably 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 ($l > 800$ bytes). Similar Figures (not shown due to space limitations) for intermediate network size values $n = 20$, 30 and 40, show that the RTS/CTS scheme enhances performance only when the length of data packets exceeds 1300, 1000 and 900 bytes, respectively.

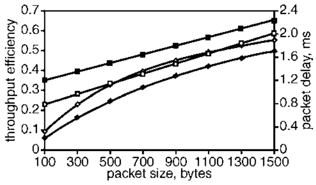

Fig. 2 *Packet delay and throughput efficiency against packet size, for $n = 5$, $W = 16$, $m = m' = 6$, $C = 54$ Mbit/s, $C_{con} = 24$ Mbit/s*

◇ Throughput efficiency, basic access
◆ Throughput efficiency, RTS/CTS
□ Packet delay, basic access
■ Packet delay, RTS/CTS

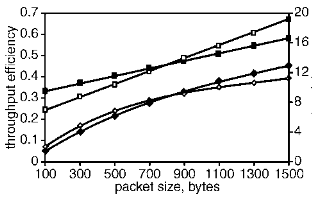

Fig. 3 *Packet delay and throughput efficiency against packet size, for $n = 50$, $W = 16$, $m = m' = 6$, $C = 54$ Mbit/s, $C_{con} = 24$ Mbit/s*

◇ Throughput efficiency, basic access
◆ Throughput efficiency, RTS/CTS
□ Packet delay, basic access
■ Packet delay, RTS/CTS

The performance results in this Letter demonstrate the deficiency of the RTS/CTS scheme for high data rates (54 Mbit/s), unlike general expectation. We find that only very large packet size values render the RTS/CTS beneficial. This result holds true even when the highest control rate (24 Mbit/s) is utilised and is due to the exchange of the RTS and CTS reservation packets at a much lower control rate, which results in a significant delay in communication.

Conclusions: In this Letter, the effectiveness of the RTS/CTS reservation scheme is examined in reducing the collision duration for IEEE 802.11a DCF. This work has studied the impact of using the RTS/CTS scheme in high data rate WLANs and for different data and control transmission rates without the presence of hidden stations. We conclude that the overall WLAN performance suffers significantly when the lower rate RTS/CTS exchange reservation scheme is combined with higher transmission data rates. The RTS/CTS scheme has a notable disadvantage for high data rates and small network scenarios and its effectiveness in improving performance is uncertain.

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References

1 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY): High-speed PHY extension in the 5 GHz band, IEEE 802.11a WG, 1999

2 Xu, K., Gerla, M., and Bae, S.: 'Effectiveness of RTS/CTS handshake in IEEE 802.11 based adhoc networks', *Ad Hoc Networks J.*, 2003, **1**, (1), pp. 107–123

3 Bianchi, G.: 'Performance analysis of the IEEE 802.11 distributed coordination function', *IEEE J. Sel. Areas Commun.*, 2000, **18**, (3), pp. 535–547

4 Chatzimisios, P., Boucouvalas, A.C., and Vitsas, V.: 'IEEE 802.11 packet delay – a finite retry limit analysis'. Proc. IEEE Global Telecommunications Conf. (GLOBECOM), San Francisco, CA, USA, 2003, Vol. 2, pp. 950–954