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PERFORMANCE STUDY OF DISTRIBUTED COORDINATION FUNCTION OVER IEEE 802.11A PHYSICAL LAYER

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Abstract

IEEE 802.11a is one of the latest standards to be released by the IEEE Project 802 for wireless LANs. It has specified an additional physical layer (PHY) to support higher data rates, and is termed as the orthogonal frequency division multiplexing (OFDM). In order to exploit its benefits, one of the medium access control (MAC) protocols specified in the IEEE 802.11 specification is called distributed coordination function (DCF). DCF is a carrier sense multiple access with collision avoidance (CSMA/CA) scheme with slotted binary exponential backoff. The frames can be transmitted using the basic access scheme or the RTS/CTS scheme in DCF. It was demonstrated previously that the RTS/CTS mechanism works well in most scenarios for the previously specified PHYs. In this work, a simple simulator is developed to verify the scalability of the RTS/CTS mechanism over OFDM PHY, which supports much higher data rates.

Keywords: 802.11, DCF, MAC protocol, Ad hoc, Simulation.
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1. Introduction

One of the most promising developments in the computer communications is the widespread deployment of wireless end systems. These untethered end systems already includes portable PCs within wireless LAN's (WLAN's), and PDA's and handhelds that connect to the Internet using existing and emerging wireless telephony infrastructures. WLAN's are enjoying wide deployment in university campuses, business offices, cafes, airports and even homes.

As many traditional network vendors are beginning to enter this market, interoperability among them becomes crucial. The Study Group 802.11 was formed under IEEE Project 802 to develop standards for WLAN's. The first IEEE standard was introduced in 1999 [1], which meant for systems operating in the ISM band of 980 MHz and uses spread spectrum or undirected infrared for access. This standard was followed by 802.11b standard (also known as wireless Ethernet and Wi-Fi), which uses either direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS) in the ISM 2.4 GHz band, and supports data rate of 11 Mbps [2]. 802.11a, which represents the third generation of wireless networking standard, followed through with data rates up to 54 Mbps and operates in the 5 GHz band [3], [4]. It may use DSSS, FHSS or orthogonal frequency-division multiplexing (OFDM). These standards provide detailed MAC and physical layer (PHY) specification for WLAN's.

The media access approaches supported in 802.11 are distributed coordination function (DCF) and point coordination function (PCF). DCF is a random access scheme based on carrier sense multiple access with collision avoidance (CSMA/CA). PCF supports collision free access mediated by an access point (AP) in an 802.11 *architecture* network. This paper considers DCF operation in an 802.11 *ad hoc* formation. The fundamental building block of the 802.11 architecture is the cell known as the basic service set (BSS) in 802.11 parlance.

DCF is specified with two techniques to govern data transmission. The first scheme is known as the basic access, where a node wishing to transmit data on finding the channel idle, transmits a data frame and then waits for an positive acknowledgement (ACK) frame from the destination. The second scheme is known as the request-to-transmit/clear-to-transmit (RTS/CTS) mechanism. Before transmitting a data frame, a node indicates its intention to use the channel by sending a control frame known as the RTS frame. This frame contains the duration the source wishes to use the channel. Upon reception by the destination, it responds with the CTS control frame to confirm the channel availability. Since collisions may occur during RTS transmission, and is detected by lack of CTS response, the RTS/CTS mechanism allows to increase the system performance by reducing the duration spent in collision. This mechanism is also found to overcome the Hidden Terminal problem [5].

Theoretical analysis of the basic access scheme was carried in [6]. It established the general behaviour of CSMA/CA protocol in terms of delay and throughput. Real test-bed implementation was carried out in [7]. It was found that there is less than 1% of packet loss in an environment with minimal interfering noises. In [8], the saturation throughput performance of 802.11 DCF for both standardised access mechanisms were studied. It was shown that basic access method strongly depends on the contention window and the number of stations. Also, the RTS/CTS mechanism was found to be more stable with limited frame sizes. However, with the new PHY specified in the standard for wireless networking, namely OFDM, it needs to be verified whether the RTS/CTS mechanism is also suitable and scalable at data rates up to 54 Mbps.

In this paper, the performance of both DCF access schemes is investigated by means of a discrete-event simulator. Our model assumes a finite number of stations and ideal channel conditions. The performance of CSMA/CA over OFDM PHY is studied for the optimum frame size and the number of nodes in an ad hoc network. The performance is quantified by mean frame transmission delay and network throughput metrics.

The rest of this paper is organised as follows. Section II discusses the system operation of both DCF schemes. The discrete-event simulator used to study this system is presented in Section III. Section IV describes the results obtained from the experiments. Finally, a concluding remark is given in Section V.

2. The IEEE 802.11 MAC Operation

This section briefly outlines the DCF in two modes, i.e. the basic scheme and the RTS/CTS mechanism, as standardized by the 802.11 protocol. For a more complete and detailed presentation, refer to the 802.11 standard [2].

For a node to transmit, it shall sense the medium to determine if another node is transmitting. If the medium is not determined to be busy, the transmission may proceed. The CSMA/CA distributed algorithm mandates that a gap of a minimum specified duration exist between contiguous frame sequences. This is known as distributed interframe space (DIFS). A transmitting node shall ensure that the medium is idle for this duration before attempting to transmit. If the medium is determined to be busy, the node shall defer until the end of the current transmission. After deferral, or prior to attempting to transmit again immediately after a successful transmission, the node shall select a random backoff interval and shall decrement the backoff interval counter while the medium is idle.

DCF adopts an exponential backoff scheme. At each packet transmission, the backoff time is uniformly chosen in the range (0, cw-1). The value cw is called contention window, and depends on the number of transmissions failed for the frame. At the first transmission attempt, cw is set equal to a value CW_{min} called minimum contention window. After each unsuccessful transmission, cw is doubled, up to a maximum value CW_{max}. The values are PHY-specific and are summarised in Table 1.

Table 1. OFDM PHY related specification

Slot Time	9 μs
CW_{min}	15
CW_{max}	1023

Let us consider only two stations A and B sharing the same wireless channel with other stations. Assuming station A has found the channel idle first, it transmits its data frame. On hearing this transmission, all other stations will defer their own access based on the value specified in the frame header (i.e. duration field). This value is recorded in a counter known as the network allocation vector (NAV). Upon receiving the complete frame, the particular destination waits for short interframe space (SIFS) before replying to station A with an ACK frame. Since the CSMA/CA does not rely on the capability of the stations to detect a collision by hearing their own transmission, an ACK is required to signal the successful reception. As the SIFS (plus the propagation delay) is shorter than a DIFS, no other station is able to detect the channel idle for a DIFS until the end of the ACK. If the transmitting station does not receive the ACK within a specified timeout, or it detects the transmission of a different frame on the channel, it reschedules the frame transmission according to the given backoff rules. In the case of successful ACK transmission, this backoff procedure shall begin at the end of the received ACK frame.

The above technique for the frame transmission is called the basic access mechanism. DCF defines an additional technique to be optionally used for a frame transmission. This mechanism, known as the RTS/CTS scheme, is shown in Fig. 1. A station that wants to transmit a frame, waits until the channel is sensed idle for a DIFS, follows the backoff rules explained above. Then, instead of the data frame, it preliminarily transmits a special control frame called request to send (RTS). When the receiving station detects an RTS frame, it responds, after a SIFS, with a clear to send (CTS) frame. The transmitting station is allowed to transmit its data frame only if the CTS frame is correctly received.

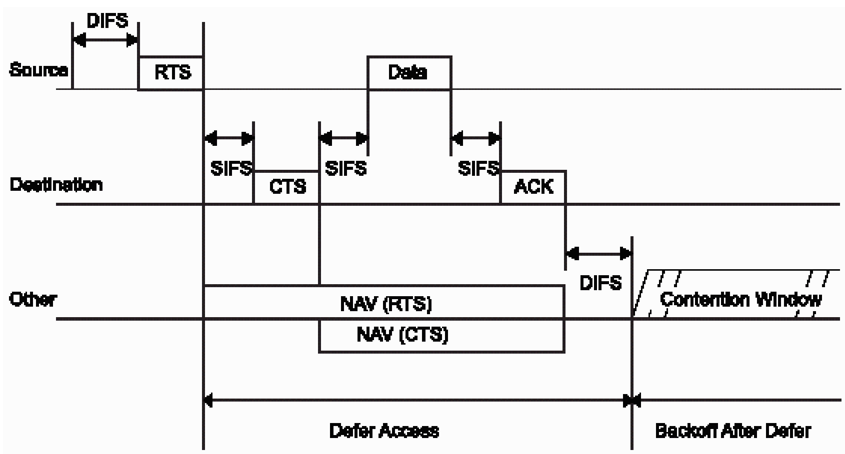

Fig.1. The RTS/CTS access mechanism (adapted from [1])

The frames RTS and CTS carry the information of the duration the intending station needs to occupy the channel. This information can be read by any listening station, which is then able to update its NAV counter. Therefore, when a station is hidden from either the transmitting or the receiving station, by detecting just one frame among the RTS and CTS frames, it can suitably delay further transmission, and thus avoid collision.

The RTS/CTS mechanism is very effective in terms of system performance, especially when large data frames are considered, as it reduces the length of the frames involved in the contention process. In fact, in the assumption of perfect channel sensing by every station, collision may occur only when two (or more) frames are transmitted within the same slot time. If both transmitting stations employ the RTS/CTS mechanism, collision occurs only on the RTS frames, and it is early detected by the transmitting stations by the lack of CTS responses.

Based on the above description, we have developed suitable simulators to evaluate these schemes. Brief description about the approach is given next.

3. The Discrete-Event Simulator

The system configuration presented above was modelled with the discrete-event simulation technique. The simulator is developed using the object-oriented development approach. The overall simulator's architecture is given in Fig. 2 as a simplified class diagram.

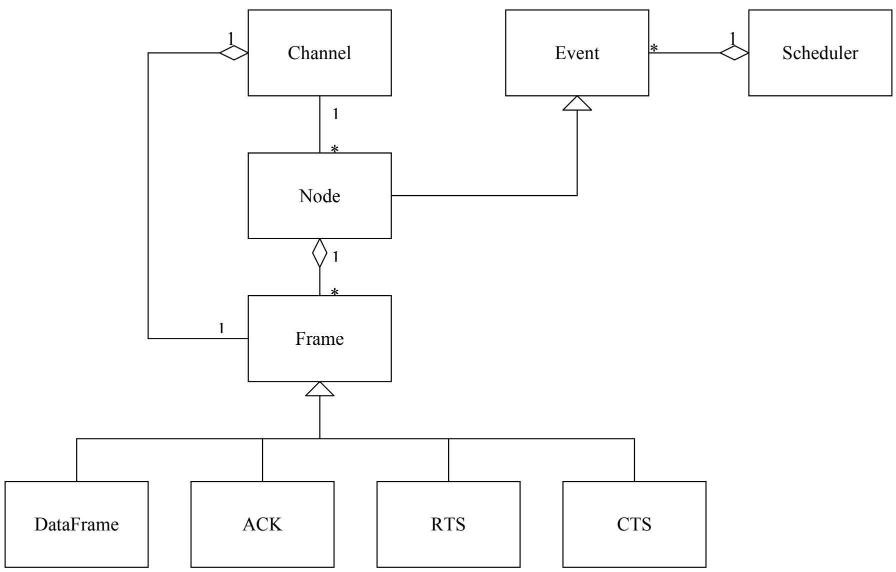

Fig. 2. The class diagram for the RTS-CTS simulator

The active entity in the real system, i.e. a mobile station (represented by the Node class), also represents the most complicated object in this simulator. The Channel object represents the spectrum resource. The passive objects in the system are made the subclass of the Frame class. The resulting architecture is highly cohesive and loosely coupled enabling easy extension for many other future works. The simulator is implemented in C++. For most of the considered scenarios, the simulator is able to give results within a minute on a Pentium III 2 GHz processor. Only for large networks (> 20 nodes), it requires not more than 5 minutes. For the case of the basic access scheme, the architecture is similar as in Fig. 2 with some changes in the Node class.

Using these simulators, experiments were carried out on a few cases of investigation and are discussed next.

4. Results and Discussion

Two cases of investigation are considered in this paper for the evaluation of CSMA/CA over OFDM PHY specified in 802.11a. They are the frame size optimisation case and the performance comparison of the basic scheme to the RTS/CTS mechanism case. The second case in carried out against the packet arrival rate at each station (λ) as well as the number of stations (N) in the network. These parameters are varied as follows:

N = 2, 4, 8, 10, 12, 16, 20, 30, 40, 50 stations

λ = 10, 50, 100, 200, 500, 750, 1000 packets per second

Unless otherwise stated, the rest of results have been obtained assuming the parameters given in Table 2.

Table 2. OFDM System parameters

MAC Frame size (with MAC header)	2346 octets
PHY header	6 octets
ACK (with PHY header)	30 octets
RTS (with PHY header)	30 octets
CTS (with PHY header)	30 octets
Channel bit rate	54 Mbps
Propagation delay	10 ns
Slot time	9 μs
SIFS	16 μs
DIFS	34 μs

Figures 3-4 show the results obtained for the first case using the basic access scheme. It is expected that the results would be similar to that of the RTS/CTS mechanism, and thus they are not shown here. While varying the data frame size, it is assumed that the average data arrival rate is fixed at 3.75 Mbps at each station according to the Poisson distribution. In Fig. 3, it is seen that frames with the largest payload results in the lowest mean delay, as expected. This size is also the maximum allowable size (S_{MAX}) at the MAC level for CSMS/CA. However, frames with larger than 1000 octets experienced delays that is not far from the minimum delay.

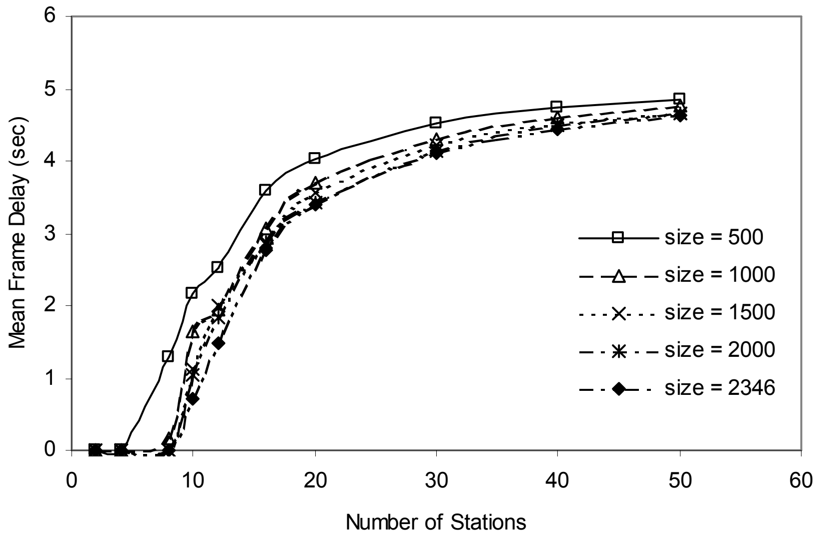

Fig. 3. Mean frame transmission delay versus the number of stations for different frame sizes.

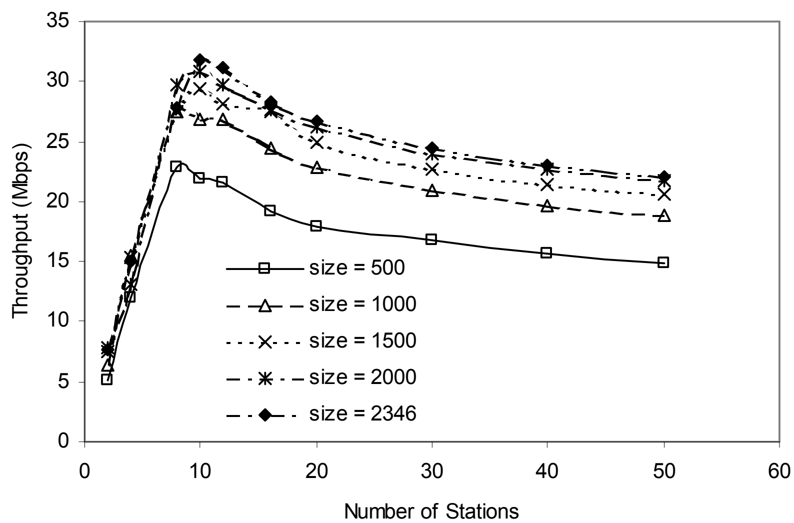

Fig. 4. Throughput versus the number of stations for different frame sizes

In Fig. 4, a consistent pattern of results is obtained for the throughput. Again, data sent in frames with S_{MAX} size achieved the highest throughput. As the ratio of data to overhead increases, we are able to maximise the utilisation. It is also deducible from

Figs. 3-4 that data sent in frames larger than 1500 octets is able to achieve close to optimal performance in terms of mean delay and throughput. Thus, whenever possible, to conserve the scarce spectrum resource, the transport layer should buffer data up to at least about 85% of maximum transmission unit (MTU) of PHY in the case of local delivery prior to handing over to the lower layers and further transmission.

For the second case of investigation, where the basic access scheme is compared to the RTS/CTS scheme, the frame size will be fixed to S_{MAX}. This would allow us to study the scalability of an ad hoc BSS under both the basic and RTS/CTS DCF schemes in its saturation condition. Such a condition will represent the maximum performance achievable while the system is in stable conditions [8]. The two access schemes are initially compared against the packet arrival rate (λ), and then followed by comparison against the number of nodes (N).

For the study against traffic arrival rate, N is fixed to 10 stations. In Fig. 5, it can be seen that the RTS/CTS mechanism performs better the basic scheme. The disparity of in their performance becomes more evident in Fig. 6, which shows the throughput curves. As λ at each station is increased uniformly, the throughput increases linearly initially for both schemes. However, when λ is increased beyond 100 packets/sec, the RTS/CTS scheme's throughput saturates at about 20% higher than the basic scheme. The basic scheme does not only have a lower achievable throughput but also unable to maintain it. As each station generate traffic beyond its share of the bandwidth, the throughput deteriorates linearly. As such, the basic scheme for an ad hoc BSS is not recommended for stations with high exchange of data.

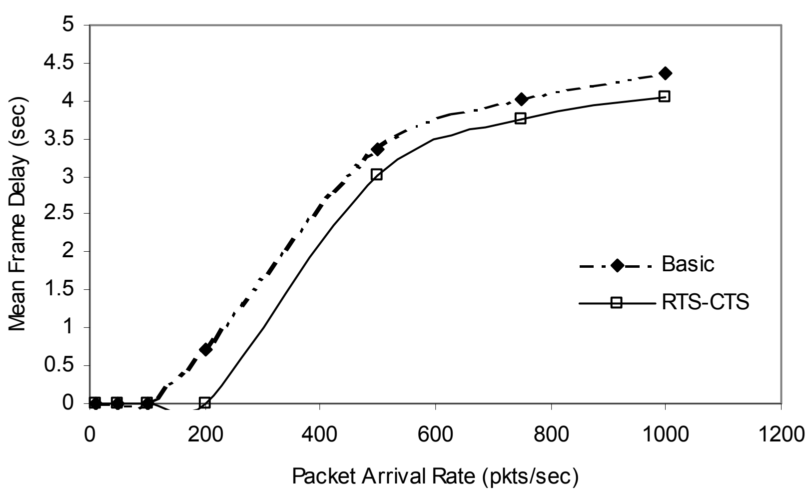

Fig. 5. Mean frame transmission delay versus the packet arrival rate for both access schemes

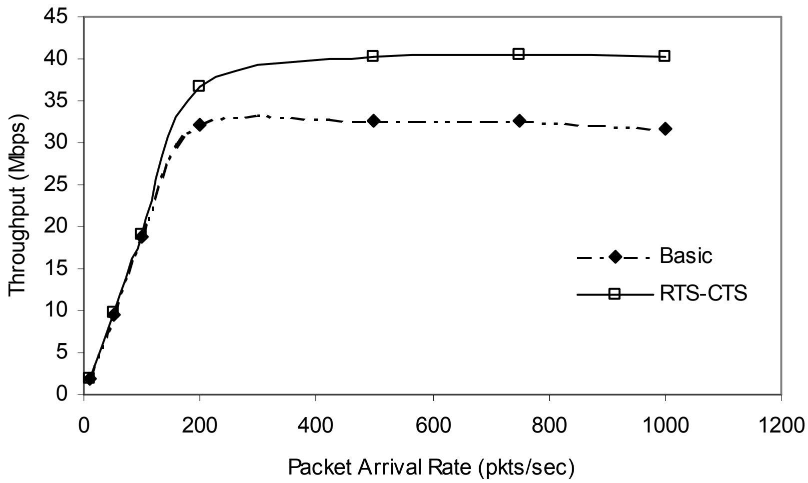

Fig. 6. Throughput versus the packet arrival rate for both access schemes

In Figs. 7 and 8, the comparison of the basic and RTS/CTS schemes are made against the number of stations in the network. In lightly loaded network, they behave with negligible difference as seen from Fig. 7. However, it is obvious that when *N* grows larger than 8, there is significant difference between both curves. For example when *N* = 20 stations, there is almost 43% higher delays faced by the stations running the basic scheme. It is also noticeable in both curves that as N is increased, the mean delay increases as well, but not in an exponential fashion as one would expect in a random access scheme. This is primarily due to the random exponential backoff scheme adopted in CSMA/CA with dynamic contention window value.

The throughput metric for the same case of investigation shows some interesting outcomes. In Fig. 8, the throughput grows linearly in the beginning as expected. Again when *N* is larger than 8, the difference between both schemes becomes evident. The basic scheme reaches a lower peak, and thereafter the throughput begins to drop steeply initially and later with lesser gradient. This is due to more time spent in deferring access and backoff as many collisions take place. As for the RTS/CTS mechanism, the highest throughput is obtained later (when *N* = 12), and then the throughput saturates around its maximum point for larger networks. This is equivalent to almost 75% utilisation by data frames. This surely suggests that the RTS/CTS mechanism is very scalable with a rather moderate penalty on the mean delay. This scheme should find use in short irregular gatherings such as, one-day conferences or expositions, where only minimal infrastructure setup is required.

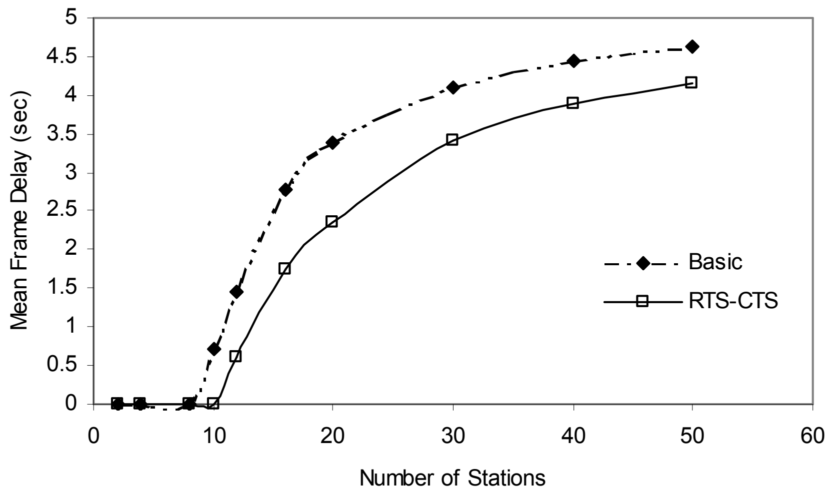

Fig. 7. Mean frame transmission delay versus the number of stations for both access schemes

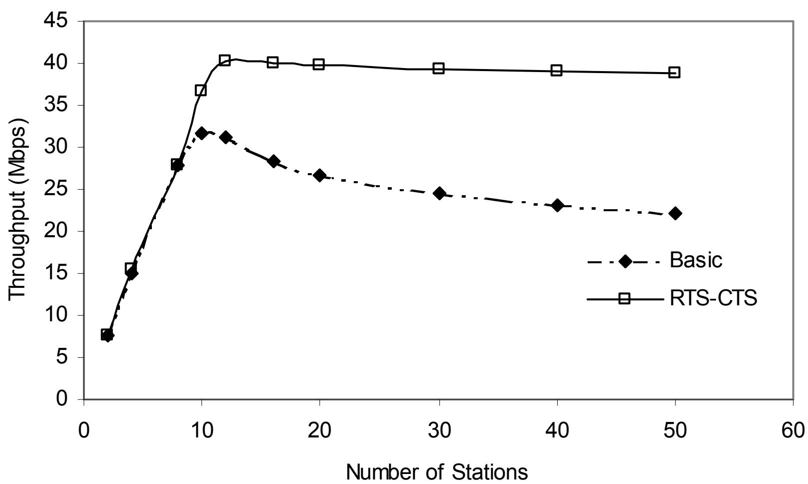

Fig. 8. **Throughput versus the number of stations for both access schemes**

5. Conclusions

In this paper, we have presented a simple discrete-event simulator used to evaluate the performance of the basic access scheme of CSMA/CA Distributed Coordination

Function (DCF) over 802.11a OFDM PHY. Our model assumes a finite number of stations and ideal channel conditions. This simulator was then extended to study the RTS/CTS mechanism for the same scenarios.

In the frame size optimisation experiment, it is found that when data is sent in frames of at least 85% of the maximum frame size, the network is able to realise the best mean delay and throughput performance. This is observed in both schemes. Using the proposed model, we have shown that the RTS/CTS mechanism has proven its superiority especially in larger networks over the basic access scheme. The results are consistent with the analytical results presented in [8] for the evaluation of the RTS/CTS mechanism over non-directed infrared, FHSS and DSSS PHYs with lower data rate specified in 802.11 (at 1 Mbps). This verifies the claim that this scheme is highly suitable and scalable over all the specified PHYs, and should be adopted in all scenarios.

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