Integrated Performance Analysis of PCF and DCF Schemes over IEEE 802.11a Physical Layer

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Abstract—IEEE 802.11a is one of the latest physical layer (PHY) standards to be released by the IEEE 802.11 working group. Currently, it offers the highest data rate for the wireless LAN. Even though the channel bandwidth has significantly increased with this standard, the mechanism used to govern media access is still based on the IEEE 802.11 MAC protocol. The standard caters for random access through distributed coordinated function (DCF) as well as centralised mediated access through point coordination function (PCF). The messages may be transmitted using the basic access scheme or the RTS/CTS scheme in DCF. Various works had been done based on previous PHY standards. However, only few had considered the latest PHY. In this work, we carry out an integrated performance investigation of standard PCF and DCF over the IEEE 802.11a PHY. The performance of this configuration is compared against DCF only systems. The maximum utilisation achievable by each system is also investigated when the wireless stations operate at the saturation level.

1. INTRODUCTION

At the end of 1999, the IEEE 802.11 working group ratified a new high-speed standard for wireless LAN (WLAN), namely the IEEE 802.11a [1]. This standard overtook the 1-2 Mbps and 11 Mbps direct sequence and frequency hopping spread spectrum physical layer (PHY) transmission standards to reach up to 54 Mbps with orthogonal frequency division multiplexed (OFDM) PHY. Even though the channel bandwidth is significantly increased with this standard, the mechanism used to govern media access is still based on the IEEE 802.11 MAC protocol that uses CSMA/CA. There are two types of possible arrangement of wireless stations as a network, namely ad hoc network and infrastructure network configurations. The fundamental building block of these networks is the cell known as the basic service set (BSS) in IEEE 802.11 parlance.

The IEEE 802.11 standard MAC protocol supports two kinds of access methods: distributed coordination function (DCF) and point coordination function (PCF). DCF is designed for asynchronous data transmission by using CSMA/CA. The standard for DCF specified two random access mechanisms namely the basic scheme and the RTS/CTS scheme. PCF is intended for transmission of real-time traffic as well as best effort data traffic. This access method is based on a centralized polling-based access which requires the presence of an access point (AP) that acts as a point coordinator (PC). PCF supports collision free access mediated by the PC in an infrastructure wireless network, where the uplink of the AP is further connected to a distribution system. When the PCF is supported, both PCF and DCF coexist, and the access time is divided into superframes.

Many researchers have already studied the performance of DCF [2]-[8]. Most of these studies were done based on the PHY with data rates up to 2 Mbps. In [4] and [9] only the basic access scheme were analysed through analytical models, whereas in [10] the RTS/CTS access mechanism was studied with the simplified assumptions of fixed length messages. In [11], the authors derived the theoretical upper bound for the throughput performance of the basic scheme as well as the RTS/CTS scheme over the IEEE 802.11b PHY. They found that this limit could be achieved through the dynamic backoff tuning strategy for bi-modal message length distribution. In [12], the performance of PCF over the IEEE 802.11b PHY with different polling schemes was investigated through simulation. The authors found that to achieve the maximum throughput in a BSS, the standard PCF polling scheme with poll order based upon the PC’s frame queue is the best option. An integrated performance of data transmission with DCF and voice transmission with PCF has been evaluated in [2], and video transmission with PCF can be found in [13] over non-standard PHY and [14] over the 2 Mbps PHY. The performance analysis of data transmission over both random access mechanisms in DCF over OFDM was carried out in [15]. It was reported that the RTS/CTS mechanism should always be used except for very short messages while using DCF.

The IEEE 802.11 standard MAC is a hybrid protocol of random access and polling when both PCF and DCF are used. That is, in this protocol, a wireless channel is divided into superframes; each superframe comprises a contention free period (CFP) when PCF is in effect and a contention period (CP) when DCF is used. To enable a
complete analysis of this MAC protocol, an integrated study is necessary. Thus, an integrated performance investigation of this protocol taking into consideration the channel structure is needed to know how the system parameters control the system behaviour and consequently, its performance.

This paper focuses on a single BSS in an infrastructure network and investigates the performance of the IEEE 802.11 MAC protocol taking into account data transmission using both PCF and DCF methods over the IEEE 802.11a PHY. The performance of the system in study is quantified in terms of network throughput and mean message delay. The network is also studied for the wireless stations operating in saturation conditions, i.e. they always have a frame waiting to be transmitted. This investigation would allow us to determine the protocol capacity, i.e. the maximum channel utilisation [11].

The rest of this paper is organized as follows. Section II discusses the system configuration and operation. Section III presents the assumptions made for the models. Section IV describes the results obtained from the simulation. Finally, a concluding remark is given in Section V.

2. SYSTEM CONFIGURATION

Figure 1 illustrates a typical example of a single BSS in an infrastructure network configuration. The network includes some wireless stations and connection to a distribution system through an access point (AP) that acts as the PC during CFP. A station may send data frames to other stations or to the AP itself.

![Diagram of wireless network configuration](image)

Fig. 1. Wireless network configuration.

A wireless channel is divided into superframes where each superframe comprises a CFP and a CP [1]. As mentioned above, this paper considers only best-effort data transmission during both CFP as well as CP. In CP, the stations exchange data using either the basic scheme or the RTS/CTS mechanism of DCF to access the media, which are contention-based schemes with carrier sense. On the contrary, PCF is based on polling and adopted during CFP. A CFP begins when the PC gains access to the medium by transmitting a Beacon frame after an interval known as PCF interframe space (PIFS). This is a shorter interval than the interval used in CP, which allows the PC to gain control of the channel. During a CFP, the PC polls the stations on its polling list and enables them to transmit frame without contentions. If a station has more frames to transmit, it will indicate by setting the more flag in the current frame prior to its response to the poll. If time remains in the CFP after the first round of polling, the PC can poll these stations. If a station does not have a frame when polled, it will transmit a null frame. Subsequent polling within this CFP will exclude such stations.

In CP, DCF can operate using one of two modes, either the basic scheme or the RTS/CTS mechanism. For a station to transmit, it shall sense the medium to determine if another station is transmitting. If the medium is not determined to be busy, the transmission may proceed after a gap of a minimum specified duration exists between contiguous frame sequences. This is known as distributed interframe space (DIFS). A transmitting station shall ensure that the medium is idle for this duration before attempting to transmit. If the medium is determined to be busy, the station shall defer until the end of the current transmission. After deferral, or prior to attempting to transmit again immediately after a successful transmission, the station shall select a random backoff interval and decrement the backoff interval counter while the medium is idle. While decrementing the counter if the channel becomes busy, the backoff counter is frozen allowing this station to be given higher privilege to access the media when the channel becomes idle again. To minimize collisions when the stations wake up from backoff period, DCF adopts an exponential backoff scheme.

Let us consider 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 CSMA/CA protocol 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
schemes. The adopted assumptions for the models of the duration the intending station needs to avoid collision.

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 is known as the RTS/CTS scheme. A station that wants to transmit a frame waits until the channel is sensed idle at least for a DIFS. Then, instead of transmitting the data frame, it initially 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.

The frames RTS and CTS carry the information of the duration the intending station needs to occupy the channel. Any listening station can read this information, 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.

Based on the above description, we have developed suitable simulators to evaluate these schemes. The adopted assumptions for the models are presented further.

3. ASSUMPTIONS FOR SIMULATION

In our simulation, we make the following assumptions:

• There is a finite number of stations with ideal channel conditions.
• All the stations in the BSS are pollable, and each station make only one association request during the first CP to be part of the PC’s polling list.
• The PC’s poll sequence is according to the ascending order of the stations address, a form of round robin scheme [12].
• All the generated messages are one-frame long and arrive according to Poisson distribution with mean λ frames per second.
• Each station has an unlimited buffer capacity to allow the network to operate at the saturation level, especially for the study of protocol capacity.
• When a station is polled during CFP, it will set the more flag of its current frame if it has at least one more frame in its buffer.
• If a station transmits a null frame when polled, it is temporarily not considered for the next polling rounds within the same CFP.

Based upon these assumptions and the standard IEEE 802.11 MAC operation, a discrete-event simulator is developed for the considered system configuration and extended based on the model presented in [15]. The simulator is implemented in C++. Using the simulator, an integrated study of both PCF and DCF over IEEE 802.11a PHY is carried out and the results are reported further.

4. RESULTS AND DISCUSSIONS

To fully understand the behaviour of IEEE 802.11 protocol over OFDM PHY, the following investigations are carried out:
i. Integrated performance of data transmission using PCF and DCF for different ratio of CFP to CP;
ii. Study of the IEEE 802.11 protocol capacity of the basic scheme only system, the RTS/CTS mechanism only system and the integrated system of PCF and DCF (with the RTS/CTS mechanism used in DCF), and;
iii. Comparison of the three systems in (ii) when the offered load is below as well as slightly above the saturation level.

The common parameters used in all simulations are given Table I.

<table>
<thead>
<tr>
<th>TABLE I. OFDM system and simulator parameters.</th>
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<tr>
<td>Maximum MAC Frame size</td>
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<tr>
<td>PHY header</td>
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<tr>
<td>ACK (with PHY header)</td>
</tr>
<tr>
<td>RTS (with PHY header)</td>
</tr>
<tr>
<td>CTS (with PHY header)</td>
</tr>
<tr>
<td>Beacon (with PHY header)</td>
</tr>
<tr>
<td>CF-Poll only (with PHY header)</td>
</tr>
<tr>
<td>Null frame (with PHY header)</td>
</tr>
<tr>
<td>CF-End (with PHY header)</td>
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<tr>
<td>Channel bit rate</td>
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<tr>
<td>Propagation delay</td>
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<tr>
<td>Slot time</td>
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<tr>
<td>SIFS</td>
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<tr>
<td>PIFS</td>
</tr>
<tr>
<td>DIFS</td>
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<tr>
<td>CFP Repetition Interval</td>
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<tr>
<td>Total simulation duration</td>
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For the first study where an integrated behavioural study of PCF and DCF is intended, the following parameters are fixed: λ is 200 frames/sec and message length is set at maximum MAC protocol data unit size (MPDU) of 2346 octets. The inputs parameters to be varied are the offered load in the form of number of stations from 2 to 20 stations and the CFP maximum duration (CFP_max) as a ratio of CFP repetition interval (CFPprep). The results from this study are shown in Figs. 2-4.
In Fig. 2, the plots of mean message delay against different offered loads and $\text{CFP}_{\text{max}}$ values are shown. It is evident that the increase in delay becomes significant only when the loads go beyond 75% of network bandwidth. The highest delay is experienced when $\text{CFP}_{\text{max}}$ is the smallest. Generally, as $\text{CFP}_{\text{max}}$ gets smaller, the percentage of time spent in CP is higher. When the offered load is increased, there will be more media contentions resulting in more collisions and backoffs. On the contrary, when more time is spent in CFP where the PC coordinates media access, the delay is lesser as depicted in Fig. 2 for the largest $\text{CFP}_{\text{max}}$. Thus, when operating under light loads, DCF’s random scheme is sufficient to enable faster access by the stations. However, at higher loads, PCF with its centralised mechanism prevails to provide better performance.

Figure 3 displays the network throughput against various offered loads and $\text{CFP}_{\text{max}}$ values. This result is consistent with the previous result on mean message delay. Initially, the throughput grows linearly as the network bandwidth is significantly larger than the offered loads. However, when the loads climb beyond 75% of bandwidth, the throughput growth starts to drop, and eventually, the throughput saturates at a certain level. The highest throughput level is obtained for the largest $\text{CFP}_{\text{max}}$. As more time is spent in CFP with mediated access, the network is able to realise higher throughput as lesser time is wasted in deferring access due to collisions.

In order to observe the behavioural difference while the system alternates between CFP and CP, the plots of the ratio of number of messages transmitted in CFP to CP are presented in Fig. 4. A ratio of one signifies equal success rate in both periods. When the ratio is less than one, the number of messages transmitted in CP is larger than in CFP, and when the ratio is larger than one, it is vice-versa. As anticipated, when the load is below 75%, most messages are transmitted using the DCF method evident from ratios close to zero. When operating under light loads, the average time spent in CFP is lesser as the PC ends this period earlier as most stations will have no messages to transmit when polled. Thus, the stations mostly end up in CP. As the network traffic increases, the number of messages in CFP climbs and exceeds that of CP’s under heavy loads except for the smallest $\text{CFP}_{\text{max}}$. It is interesting to note in Fig. 4 that when equal time is allotted to CP and CFP (i.e. $\text{CFP}_{\text{max}}=0.5 \times \text{CFP}_{\text{prep}}$), the number of messages transmitted in CFP is more than CP (ratio > 1) as some time is wasted in CP due to collisions. From this investigation, it is apparent that the standard PCF’s significant contribution is noticeable when the network is operating under heavy loads. For the rest of the intended studies, we will assume $\text{CFP}_{\text{max}}=0.8 \times \text{CFP}_{\text{prep}}$ for the integrated system.

For the second case of investigation of protocol capacity, the fixed system parameters are: the number of stations is 10 and the offered load is 54 Mbps (i.e. OFDM maximum data rate), which allows the network to achieve its maximum utilisation. As an input parameter, we vary the message length from 600 to 2346 octets. This study will enable us to compare the IEEE 802.11 MAC protocol capacity when operating under these mechanisms: i) DCF using the basic scheme only; ii) DCF using the RTS/CTS scheme only, and; iii) the integrated system of PCF and DCF. The results of this investigation are presented in Figs. 5-6.

Figure 5 shows the plots of mean message delay against the message length. For all three systems, they face the highest delay when the message length is the shortest. This is intuitive as the smallest message has the highest overhead to
payload ratio. As the message length is increased, the delay drops logarithmically. The basic scheme only system experiences the highest delay as it spends significantly more time in collisions and backoffs [15]. The integrated PCF and DCF system enjoys the lowest delay of the three especially when the message length is small. When the message is longer, the RTS/CTS scheme only system has delay performance reaching that of the integrated system. For the same load level when the message length gets larger, besides reduced overhead to payload ratio the number of generated messages drops and consequently, reducing the number of collisions in random access. However, similar delay reduction is not experienced by the integrated system as it spends similar amount of overhead in CFP through centralised polling, and is not affected by the message length.

Maximum throughput achievable by each system against the message length is depicted in Fig. 6. The basic scheme only system has the lowest throughput as expected, consistent with the above results. Again the integrated system achieves the highest throughput of them all. Since the network is exercised with loads equivalent to its bandwidth, the random access mechanisms of DCF obviously suffer with numerous collisions and backoffs. However, the integrated system is able to realise substantially higher throughput as it occupies CFP to its maximum. Again, the performance difference is most significant when the message length is the smallest. Throughput improvement of more than 42% is obtained for message length of 600 octets as opposed to 12% for length of 2346 octets when the integrated system is compared against the RTS/CTS scheme only system. Therefore, it is evident that even for data transmission, adopting PCF results in much improved performance, which capitalises on the OFDM physical layer capability.

For the third case of investigation, the following parameters are fixed: $\lambda$ is 200 frames/sec and the message length is 2346 octets. The considered systems are exercised against the offered load in the form of number of stations varied from 2 to 20. Figures 7-8 depict the results from this study.

In Fig. 7, it can be noticed that the delay difference is only significant when the offered load increases beyond 75% of the network bandwidth. As anticipated, the integrated system offers the lowest delay as more messages are served in CFP using PCF resulting in lesser time being spent in deferrals. Furthermore, it only faces exponential increase in delay when the network traffic goes beyond 83% of its bandwidth. As for the random access systems, they suffer under heavy loads due to their contention-based access.

As for the throughput metric, the results are consistent with delay metric as shown in Fig. 8. The integrated system has substantial advantage especially when operating under heavy loads. As it spends more time in CFP, it is able to provide more controlled access to the stations resulting in higher throughput.

Therefore, from the above three investigations, we can discern that in order to realise the full potential of the IEEE 802.11a PHY, we should adopt PCF with DCF employing the RTS/CTS mechanism to content for channel as opposed to the basic scheme when best-effort traffic are in concern. PCF provides significant performance improvements especially when the network is under heavy utilisation. As for DCF, due to its random access nature, it is very suitable in low and medium loads to enable asynchronous and minimal delayed access by the wireless stations. However, PCF will falter when considering delay-sensitive traffic. IEEE 802.11 task group E is currently tackling this issue in the upcoming 802.11e standard. Here, applications are classified into eight categories and each has a different IFS and backoff interval to enable differentiated service, known as enhanced DCF. And in an infrastructure network, each request undergoes admission control to receive contention free access in hybrid CF (HCF).
5. CONCLUSION

This paper has evaluated the integrated performance of PCF and DCF of the IEEE 802.11 MAC protocol over the IEEE 802.11a physical layer by means of simulation. The simulation included data transmission with both PCF and DCF. The results of this investigation are compared against the systems using only the basic scheme and the RTS/CTS mechanism of DCF. It is found that the integrated system of PCF and DCF offers the largest protocol capacity for the considered network configuration and is highly desirable for short message lengths when considering only the best-effort data transmission. PCF is also able to offer lower delays and higher utilisation especially under heavy loads. However, PCF may falter when considering overlapping BSSs where centralised polling is more difficult to implement. Some issues are being tackled in the upcoming IEEE 802.11e.

REFERENCES


