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Design and performance analysis on adaptive reservation-assisted collision resolution protocol for WLANs

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Abstract In conventional IEEE 802.11 medium access control protocol, the distributed coordination function is designed for the wireless stations (WSs) to perform channel contention within the wireless local area networks (WLANs). Packet collision is considered one of the major issues within this type of contention-based scheme, which can severely degrade network performance for the WLANs. Research work has been conducted to modify the random backoff mechanism in order to alleviate the packet collision problem while the WSs are contending for channel access. However, most of the existing work can only provide limited throughput enhancement under specific number of WSs within the network. In this paper, an adaptive reservation-assisted collision resolution (ARCR) protocol is proposed to improve packet collision resulting from the random access schemes. With its adaptable reservation period, the contention-based channel access can be adaptively transformed into a reservation-based system if there are pending packets required to be transmitted between the WSs and the access point. Analytical model is derived for the proposed ARCR scheme in order to evaluate and validate its throughput performance. It can be observed from both analytical and simulation results that the proposed protocol outperforms existing schemes with enhanced channel utilization and network throughput.

Keywords Wireless local area network (WLAN) · IEEE 802.11 standards · Medium access control · Random backoff mechanism · Reservation-based algorithm

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1 Introduction

In recent years, the techniques for wireless local area networks (WLANs) have been prevailing exploited for both indoor and mobile communications. The applications for WLANs include wireless home gateways, hotspots for commercial usages, and ad-hoc networking for inter-vehicular communications. Among different techniques, IEEE 802.11 standard is considered the well-adopted suite due to its remarkable success in both design and deployment. Various amendments are contained in the IEEE 802.11 standard suite, mainly including IEEE 802.11a/b/g [1–3] and IEEE 802.11e [4] for quality-of-service (QoS) support. The medium access control (MAC) protocol within the IEEE 802.11 standard supports the distributed coordination function (DCF) to regulate the random and complex medium accessing behaviors among the wireless stations (WSs) within the same WLAN. How to alleviate the probability of packet collision has been considered a crucial issue for the enhancement of network throughput.

Different types of schemes have been proposed in order to resolve the packet collision problem within the WLAN. The adjustment of contention window (CW) size has been considered an effective scheme in most of the existing research work [1, 5–12]. The binary exponential backoff scheme [1] as described in the IEEE 802.11 MAC protocol controls the waiting time duration for channel contention. The CW size will be increased or decremented with failed or successful transmission respectively. In general, the probability of packet collision can be decreased with augmented value of CW size, especially with a larger number of WSs in the network. However, excessive idle time resulted from the enlarged CW size will consequently degrade the channel utilization. In order to enhance the throughput performance for the conventional IEEE 802.11

protocol, the algorithm proposed in [5] increases the transition rate between the backoff stages associated with decreased value of minimum CW and incremented value of maximum CW size. The hybrid algorithm proposed in [6] combines both the exponential and the linear backoff for the purpose of decreasing packet collision; while the slow CW decrease (SD) scheme in [7] either doubles or halves the CW size according to the successfulness of packet transmission. The early backoff announcement (EBA) protocol [8] proposed a WS to record its next backoff number into the MAC head while transmitting data packets. All the other WSs will select their corresponding backoff numbers excluding this value in order to avoid potential packet collisions. Similar design concept was also presented in [9]; while [10] proposed a MAC protocol with multiple-step distributed in-band channel reservation. The gentle DCF (GDCF) protocol as proposed in [11, 12] maintains a larger value of the CW size compared to the conventional backoff scheme in order to decrease the probability of packet collision. The work in [13] proposed a handshake based channel aware (HCA) MAC protocol which selects the WSs to access the channel according to its corresponding channel condition. Nevertheless, all the existing contention-based protocols suffer from the tradeoff between packet collision and transmission delay. Moreover, the throughput performance by adopting these algorithms is greatly influenced by the total number of WSs within the WLAN.

Compared to the DCF-based random access schemes, there are also polling-based algorithms proposed for WLAN in order to provide feasible performance to fulfill time-constrained requirements. Various centralized polling protocols and scheduling algorithms (e.g. [14]) have been proposed to increase the channel utilization for the IEEE 802.11 point coordination function (PCF) [1]. The operation time period for each WS is divided into cycles of contention period (CP) and contention-free period (CFP), where CFP is utilized by either the PCF for real-time packet delivery. A reservation-based MAC protocol was employed in [15] to provide support for real-time traffic. The work in [16, 17] proposed piggyback schemes by adjusting the transmission rate of WS for throughput enhancement. However, the requirement to specifically assign the designated CFP for the implementation of polling-based algorithms will lead to excessive overhead if the WSs have no packet to be delivered to the access point (AP). Moreover, these AP-initiated polling protocols can not completely fulfill the throughput requirement while the WSs are intending to conduct uplink data transmissions. Moreover, the channel reservation MAC protocol was presented in [18] to provide automatic scheduling of channel usage between the WSs. However, this scheme requires both a busy tone channel and multple antennas in order to resolve the hidden terminal problem.

It is noted that there are tradeoffs between the centralized-based and contention-based schemes under different network environments. It will be beneficial to provide a channel access mechanism that can adaptively switch between these two types of schemes. Therefore, an adaptive reservation-assisted collision resolution (ARCR) protocol is proposed in this paper in order to alleviate packet collisions within the random access scheme. The main feature of proposed ARCR scheme is that the original contention-based channel access will be adaptively transformed into a reservation-based system in the case that there are pending requests for packet transmission from the WSs. With the adaptable reservation period by exploiting the ARCR algorithm, packet collision resulting from channel contention can be effectively reduced which consequently leads to enhanced network throughput. Analytical model for throughput analysis is developed in this paper to provide feasible observations on the behaviors of proposed ARCR protocol. Numerical results are conducted via simulations both to provide validation on the analytical models and to evaluate the effectiveness of proposed scheme. It can be observed that network throughput can be enhanced by adopting the ARCR algorithm compared with other existing protocols.

The remainder of this paper is organized as follows. Section 2 briefly summarizes the IEEE 802.11, the GDCF, and the EBA protocols. The proposed ARCR scheme is described in Sect. 3 associated with its throughput analysis presented in Sect. 4. Section 5 illustrates the performance validation and evaluation for the proposed ARCR protocol; while conclusions are drawn in Sect. 6.

2 Preliminaries

2.1 IEEE 802.11 MAC protocol

The DCF is utilized as the basic access mechanism in the IEEE 802.11 MAC protocol. It is based on the carrier sensing multiple access with collision avoidance (CSMA/CA) scheme to ensure that each WS can acquire a fair chance to access the wireless medium. A WS that intends to transmit data will first sense the channel to verify if it is at the idle state. As the channel is idle for the time interval of DCF interframe space (DIFS), the random backoff process will be started which is executed in each WS for the purpose of decreasing the probability of data collision. The random number k_{dcf} at the backoff stage i is chosen within the range of a uniform distribution $U[a, b]$, i.e. $k_{dcf} = U[0,\ 2^i\ W - 1]$ where W denotes the minimum backoff window size. It is noted that the backoff stage i corresponds to the number of transmission retries. Moreover, both the request-to-send (RTS) and clear-to-send

(CTS) packets exchanged before the data transmission is exploited to resolve the potential hidden terminal problem. In order to avoid packet collision during data transmission, the virtual carrier sensing mechanism carried out by the network allocation vector (NAV) is utilize to record the duration of on-going data transmission. It is noted that the NAV information adopted within each WS will be delivered to its neighbor nodes. A nonzero NAV value recorded in a WS will consequently prohibit the surrounding neighbor nodes to initiate a new data transmission.

Unlike the contention-based DCF scheme, the PCF supported by IEEE 802.11 standard is designed to be a centralized polling protocol. Periodic occurrences of CP and CFP are designed for each WS, where CP is operated by DCF and CFP is executed by polling mechanism. The AP will broadcast a beacon message to inform all the WSs regarding the start of CFP. Based on a polling list of WSs recorded within the AP, the AP will sequentially transmit the CF-Poll control frame to the WS within the list by adopting the round-robin scheduling algorithm. If a WS that receives the CF-Poll frame has data to be delivered, the WS will transmit data packets to the AP after waiting for a short interframe space (SIFS). The AP correctly receiving data packets will send a CF-ACK frame in response to the WS after waiting for the SIFS time interval. On the other hand, in the case that the AP did not receive any data packet within the time interval of PCF interframe space (PIFS), it will continue to poll the next WS in its corresponding polling list. After all the WSs in the list have been consecutively polled, the AP will broadcast the CF-End frame as the indication for the end of CFP. Afterwards, all the WSs in the network will enter into the CP mode with the adoption of contention-based DCF scheme.

2.2 Gentle DCF (GDCF) protocol

The GDCF algorithm in [11, 12] modifies the conventional backoff scheme within the IEEE 802.11 protocol for the enhancement of network throughput. The major parameter in GDCF scheme is the design of a successful counter for recording the number of consecutive successful transmissions. The counter will be reset to zero every time a failed transmission has been occurred. Similar to the conventional DCF scheme, the CW size will be doubled if the packet for the WS is failed in transmission. On the other hand, in the case of successful packet transmission, the CW size by adopting the GDCF protocol will not be reset back to the minimal CW size as the DCF scheme. The CW size will be maintained until there exist c successful transmissions of data packets, and the size will be halved only after the c consecutive transmissions have been achieved. Consequently, the packet collision owing to the channel contention can be alleviated with the adoption of GDCF scheme. However, the network throughput can only be enhanced with the reduction of RTS packet collisions while there exists a large number of WSs within the network. In the case that there is a comparably smaller number of WSs in the considered network, the design of an enlarged CW size will degrade the network throughput, which consequently results in elongated transmission delay.

2.3 Early backoff announcement (EBA) protocol

The main concept of EBA protocol [8] is to select the next backoff counter earlier and also inform the other WSs in the current transmission. An extra field, called EBA field, is piggybacked after the MAC header in order to record the value for the WS to select in its next contention. The other WSs will hear the value of backoff counter chosen by this WS, and avoid picking the same slot for channel contention. Each WS will maintain a reservation window to record the slots occupied by other WSs according to the EBA field received from others. If a WS selects a backoff number but hears that this number will be utilized by another WS, it will choose another empty slot to avoid collision with that WS. Moreover, the authors proposed two different methods for CW selection, i.e. the EBA-1 and EBA-2 schemes. Similar to the conventional DCF protocol, the EBA-1 scheme randomly chooses a value based on the current CW. The difference is that the WS will be kept away from the occupied slot by adopting the EBA-1 scheme. On the other hand, in the EBA-2 method, the WS will calculate the number of occupied slot a to estimate the number of WSs existed in the network. The CW size will be set as $2a$ and the backoff counter will be randomly selected in this range excluding the occupied slot. Moreover, the minimum CW size (W) is assumed to be 8 in the EBA-2 method except that $W = 0$ is chosen if the WS enters the network for the first time. Intuitively, the EBA-2 scheme can adapt to the environment change faster than the EBA-1 method.

3 Proposed ARCR protocol

The design concept of proposed ARCR algorithm is to adaptively provide reservation periods for specific WSs within the contention-based channel access networks. In order to promote the network throughput without incurring excessive control overhead, the piggyback mechanism [19] is utilized to append the control messages after either the data or the acknowledge (ACK) packets. The piggybacked fields introduced by the ARCR protocol are applied in order to alleviate the RTS/CTS/ACK overheads, to regulate the backoff processes, and to schedule the transmission orders, which ultimately can achieve higher network throughput. With the enhanced channel utilization by adopting the proposed ARCR scheme, it will be illustrated in the numerical evaluation that the overheads from the piggybacked control fields are observed to be insignificant. The functional description of proposed ARCR scheme is described in Sect. 3.1 The examples of both ideal and realistic network scenarios for the proposed scheme are addressed in Sects. 3.2 and 3.3.

3.1 Functional description

As a node intends to transmit data packets within an IEEE 802.11 AP-based network, an RTS/CTS exchange process will be initiated before the transmission of data packets. In the case that there are additional data packets to be delivered, a control field called table-adding request (TAR) will be appended after the data packet for piggyback purpose, i.e. denoted as DATA+TAR. On the other hand, the conventional DCF scheme will be adopted if there is no further data packet to be dispatched. The TAR control field is defined as follows.

Definition 1 (TAR) TAR (Table-Adding Request) is defined as a control field used to inform the AP that a WS is intending to join the AP's reservation table.

After receiving the DATA+TAR packet from the WS, the AP will record the MAC address of the corresponding WS within its reservation table $\mathbf{T} = \{T_r(S), \forall\ r, S\}$ that consists a list of prioritized numbering for each WS, e.g. $T_0(A)$ indicates that WS A is recorded in the first entry (i.e. $r = 0$) of the reservation table $\mathbf{T}$. Consequently, the AP will respond with an ACK packet associated with a piggybacked field called next transmission order NTO(r), which is defined as follows.

Definition 2 (NTO(r)) NTO(r) (Next Transmission Order) is defined as a control field adopted by the AP to inform a WS that its order for the next transmission is r.

For example, $r = 0$ indicates that the WS is recorded at the top of the reservation list $\mathbf{T}$, which will be the next WS to conduct packet transmission. Therefore, each WS that are recorded in the reservation table will be informed by the AP with the ACK+NTO(r) packet. By adopting the ARCR scheme, the random backoff number k_{arcr} for the WS will be selected based on the corresponding index r as

$$k_{arcr} = \begin{cases} U[0, 2^0 W - 1], & r = 0 \\ U[2^{r-1} W, 2^r W - 1], & 1 \le r \le M \\ U[\ell \cdot 2^{M-1} W, u \cdot 2^{M-1} W - 1], & r > M \end{cases} \quad (1)$$

where $\ell = r - M + 1$, $u = r - M + 2$, and the parameter M denotes the maximum number of backoff stage. According to the transmission order r, it can be observed from (1) that each specific WS S within the table entry $T_r(S)$ will possess a distinct range of values for its corresponding random backoff number k_{arcr}. This design will assure that small value of r will result in smaller random backoff number k_{arcr}. Consequently, based on the reservation system of the ARCR scheme, the WS with the smallest value of r (i.e. at the top of the reservation table) will be ensured to acquire the channel access comparing with the other WSs within the table $\mathbf{T}$. It is also noticed that the backoff scheme is transformed from exponential to linear increase for the purpose of limiting the range of random number k_{arcr} after $r > M$.

Definition 3 (RTS-R) The RTS-R packet signifies the initiation of the reservation period, which is delivered by the WS after acquiring the ACK+NTO(r) packet from the AP.

After the WS is informed by the AP that it will be the next station to conduct packet transmission, the WS is ready to transmit its RTS-R packet in order to initiate the reservation period. The transmission of RTS-R packet will be delivered from the WS after it has succeeded in contending the channel access by adopting its random backoff number k_{arcr} as in (1). After the RTS-R/CTS handshake has been completed, either the DATA+TAR packet or the DATA packet will be transmitted from the WS to the AP. Once the data transmission has been accomplished, the table entry $T_r(S)$ will remain in or be removed from the reservation table if the DATA+TAR packet or the DATA packet is transmitted respectively. Furthermore, in the case that there are remaining table entries within $\mathbf{T}$, the AP will transmit its ACK packet appended with a request for data (RFD) field towards the WS that is recorded within the next table entry. The RFD field is defined as follows.

Definition 4 (RFD(r)) RFD(r) (Request for DATA) is defined as a control field utilized by the AP to inform the r-th WS in the reservation table that it can conduct packet transmission after waiting for a short interframe space (SIFS) duration.

The ACK+RFD(r) packet is employed to serve as the indication message from the AP to the WS for requesting the next data transmission, which is delivered within the reservation period. Without conducting the backoff process, the corresponding WS can immediately transmit its DATA+TAR (or DATA) packet to the AP after a SIFS interval. The procedures for transmitting the ACK+RFD(r) packet will be continuously conducted until all the table entries within the reservation table $\mathbf{T}$ have been processed. The ARCR algorithm will be switched from the reservation-based system back to the contention-based DCF scheme. It is especially noticed that there is only one RTS-R packet required for channel contention within the entire reservation period. With the exploration of adaptive reservation period, the proposed ARCR scheme can reduce packet collision from the RTS packets, which effectively increases the channel utilization.

Furthermore, the fairness for packet transmission between the WSs is also considered within the reservation period of proposed ARCR scheme. All WSs within the reservation table will be scheduled by the AP based on the round-robin fashion in order to maintain the fairness for packet transmission. Considering that all the WSs continuously have data packets to be delivered, i.e. the DATA+TAR packets are always transmitted by the WSs, the WS that is informed by the AP with the order r (i.e. NTO(r)) will be assigned with the order of $r-1$ for its next transmission with NTO $(r-1)$. It is noted that the WS with the order of $r=0$ will therefore be assigned with the maximum value of r for its next transmission order.

Figure 1 shows the flow chart for each WS by adopting the proposed ARCR protocol. As a WS enters the network at the first time, it will stay in the DCF mode and wait for packet arrival. In the case that the WS possesses data packets to be delivered, the WS will send out an RTS packet to contend for channel access. Assuming that the WS wins the channel contention, it will verify there exists additional packet in its queue to be delivered. If there are extra packets, the flag *DataInQueue* will be set to 1, and the DATA+TAR packet will be transmitted. Otherwise, the

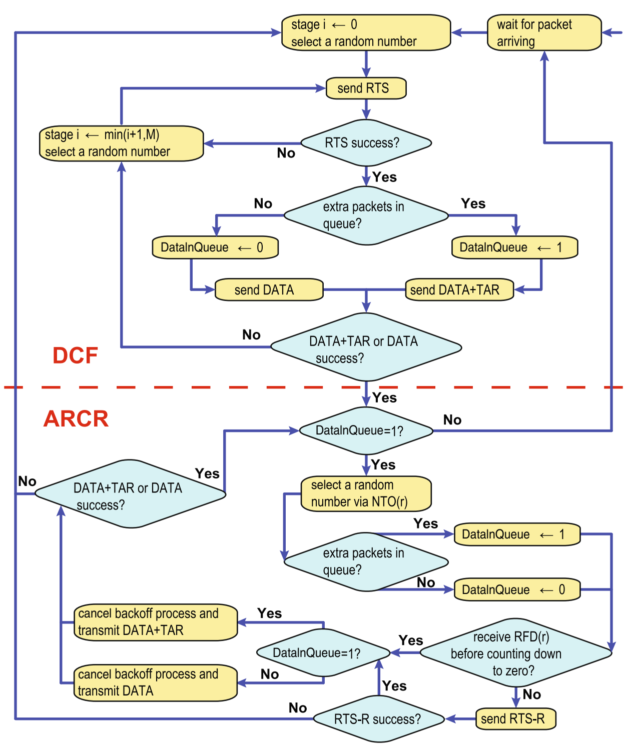


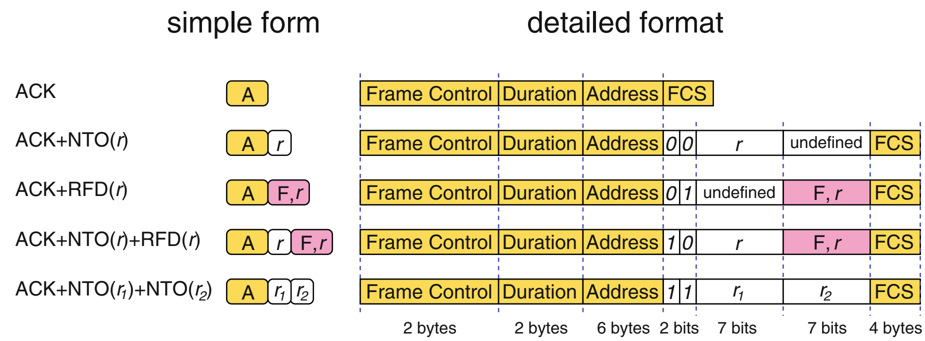
Fig. 1 The flow chart for the behavior of WS by adopting the proposed ARCR protocol

flag *DataInQueue* will be 0 and a pure DATA packet will be delivered. After successful transmission of the packet, if *DataInQueue* $=1$, the WS will select a random number in the range based on the NTO(r) value given by the AP. Afterwards, if the WS receives the RFD(r) field before the backoff counter goes down to 0, the WS will cancel its backoff process and transmit either the DATA+TAR or DATA packet after waiting for a SIFS interval. Otherwise, the WS will send out an RTS-R packet for channel contention. The transitions between the conventional DCF scheme and the ARCR algorithm are also illustrated. Either the WS failed in packet transmission or it has no further data to be delivered, the ARCR scheme will be switched back to the DCF protocol with the implementation of random backoff scheme for packet retransmission. It is noted that the AP is in charge of all the WS within the reservation table; while those WSs that are out of the reservation table will conduct the RTS/CTS handshakes with the AP. Therefore, the hidden terminal problem can be resolved in the proposed ARCR algorithm since the AP will set the NAV vector to all the WSs in the network. Moreover, several types of control fields can be piggybacked after the ACK packet, e.g. NTO(r) or RFD(r). Figure 2 shows the formats of ACK packet with different piggybacked control fields. Therefore, while receiving the ACK packet, the WS can recognize the type of ACK packet according to the value within the two-bit flag as illustrated in Fig. 2. Different types of transmission scenarios will be exemplified in the following two subsections.

3.2 Ideal network scenarios

Figure 3(a) shows an example for an ideal network scenario by exploiting the proposed ARCR algorithm. In this case, it is assumed that the channel is error-free without any packet collision occurred. Three WSs A, B, and C within the network are intending to continuously transmit data packets to the AP. At the beginning time instant t_1, no entry is recorded within the AP's reservation table $\mathbf{T}$; while the three WSs are contending for channel access by adopting the IEEE 802.11 DCF mechanism. It is assumed that WS A acquires the channel access after the contention, the conventional RTS/CTS exchange will be conducted between WS A and the AP. The DATA+TAR packet will be delivered from WS A to the AP, where the TAR field indicates the request from node A that it still possesses remaining data packet to be transmitted. After the table entry $T_0(A)$ has been added to the reservation table $\mathbf{T}$, the AP will transmit the ACK+NTO(0) packet to WS A indicating that it will be the first WS to conduct packet transmission in the next reservation period. It is noted that the

Fig. 2 The formats of ACK packets with different piggybacked control fields



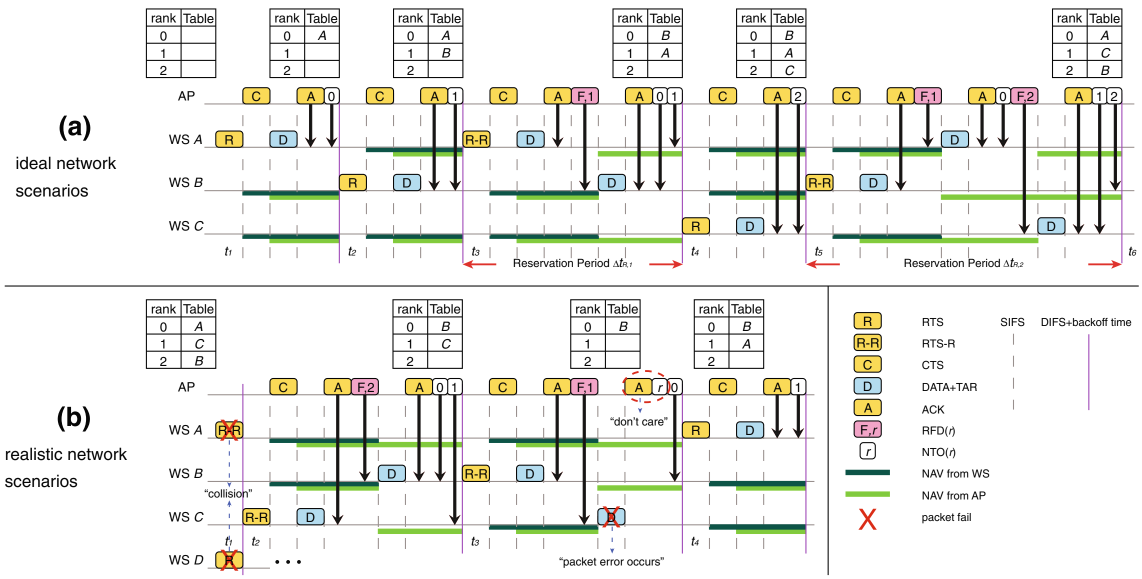


Fig. 3 The timing diagram for the proposed ARCR protocol under ideal network scenarios

NAV vector is utilized to suspend potential channel sensing and packet transmissions from both WSs *B* and *C* during the interaction time interval between WS *A* and the AP.

After WS *A* completes its first transmission with the AP, the three WSs will continue to compete for the channel access at time t_2. Since WS *A* has received the NTO(0) packet from the AP, it will employ the random backoff scheme in (1) by adopting the ARCR scheme; while the conventional backoff scheme from the DCF mechanism will be applied to both WSs *B* and *C*. Considering that WS *B* has obtained the channel access, similar procedures between WS *B* and the AP will be taken place, i.e. the transmission of RTS, CTS, DATA+TAR, and ACK+NTO(1) packets between WS *B* and the AP. The table entry $T_1(B)$ will also be included in the AP's reservation table **T**. Due to the reason that both WSs *A* and *B* have received the NTO(*r*) packets, the random backoff scheme from (1) is exploited for both nodes at time instant t_3; while the conventional DCF backoff mechanism will be adopted by WS *C*. Owing to the special design of the random backoff algorithm as in (1), the WS with the smallest *r* value (i.e. WS *A* in this case) will be ensured to have the highest opportunity to acquire the channel access among the WSs recorded in the table. Therefore, there will only be either WS *A* or *C* that will finally win the channel access after the time instant t_3.

Assuming that WS *A* acquires the channel access after t_3, the RTS-R packet will be initiated by WS *A* to start the reservation period for both WSs *A* and *B*, i.e. $\Delta t_{R,1}$ as shown in Fig. 3. After the reception of the DATA+TAR packet from WS *A*, the AP will respond with the ACK+RFD(1) packet where the ACK packet is intended for WS *A* and the RFD(1) field is targeting for WS *B*. Note that as WS *A* receives this type of ACK packet, i.e. ACK+RFD(*r*), WS *A* will know that it is the first successfully transmitted WS in this reservation period. Based on the received RFD(1) field from the AP, WS *B* will terminate its backoff process and conduct the transmission of DATA+TAR packet to the AP after a SIFS time interval. It is noted that the cancelation of the backoff process for WS B can reduce the channel idle time, and consequently promotes the network throughput. After the completion of the DATA+TAR packet from WS B, the AP will respond with an ACK+NTO(0)+NTO(1) packet where the ACK+NTO(0) packet is delivered to WS B and NTO(1) packet is intended for WS A. It is noticed that the transmission order within the reservation system has been swapped for the consideration of fairness, i.e. $\mathbf{T} = \{T_0(B), T_1(A)\}$.

Considering that WS C finally acquires the channel access at t_4, the table-adding procedures will be conducted for WS C after the completion of its data transmission, i.e. $\mathbf{T} = \{T_0(B), T_1(A), T_2(C)\}$. Consequently, at t_5, the reservation period $\Delta t_{R,2}$ will be utilized to conduct packet transmission for all the three WSs that are recorded within the reservation table $\mathbf{T}$. First of all, the AP does not have the information regarding the total number of WSs that will continue to stay in the reservation table before the end of reservation period. Therefore, the AP will not give out the NTO(r) field after WS B finished its data transmission, i.e. only the ACK+RFD(1) packet is delivered where the ACK packet is intended for WS B and the RFD(1) field is targeting for WS A. WS B will understand that it is the first successfully transmitted WS in the reservation period after receiving the ACK+RFD(1) packet where the ACK packet is targeting for itself. Next, as WS A finishes its data transmission, the AP will deliver the ACK+NTO(0)+RFD(2) packet where the ACK+NTO(0) part is for WS A to inform WS A to be the first WS in the next round's reservation table. Note that the RFD(2) part is to inform WS C that it will be the next WS for data transmission. After WS C transmits its data packet, it will receive an ACK+NTO(1)+NTO(2) packet and recognize that NTO(1) is targeting for itself since the ACK packet is specified for WS C. WS C recognizes that it will be the second item recorded in the reservation table for the next round. On the other hand, as WS B receives the same ACK+NTO(1)+NTO(2) packet, it will understand that the second NTO, i.e. NTO(2), is designated for itself since this type of ACK packet specifies the end of this reservation period. WS B will be assigned with a lower priority on the next reservation period based on the round-robin fashion. Afterwards, the transmission order will be rotated for the purpose to ensure the transmission fairness i.e. $\mathbf{T} = \{T_0(A), T_1(C), T_2(B)\}$. Therefore, with the recognition of the different types of ACK packets, it is not required for the WSs to include their station identifier in the NTO field. In the case that there exists a new WS (e.g. WS D) that joins the network at the time instant t_6, channel contention will occur between WSs A and D. Otherwise, a new reservation period $\Delta t_{R,3}$ will be initiated to continuously transmit the packets from WSs A, B, and C.

3.3 Realistic network scenarios

The examples for the proposed ARCR scheme to alleviate the packet collision problems under an realistic network scenario is shown in Fig. 3(b). First of all, the adaptive adjustment of ARCR scheme owing to the RTS-R packet collision is considered. Assuming that the AP's reservation table is recorded as $\mathbf{T} = \{T_0(A), T_1(C), T_2(B)\}$ before the time instant t_1. Since WS A is situated at the top of table $\mathbf{T}$, it will possess the smallest backoff number k_{arcr} according to (1) which results in the acquisition of channel access.

WS A will initiate the RTS-R packet to the AP, and it is assumed to be unsuccessfully transmitted due to packet collision. Without receiving the CTS packet from the AP, WS A will change its channel access mechanism from the ARCR algorithm back to the conventional DCF scheme. As shown in the flow chart from Fig. 1, the random number k_{dcf} will be selected via the original DCF scheme with backoff stage $i = 0$, i.e. within the range of $U[0,2^0W - 1]$. On the other hand, since WS C did not obtain the RFD(1) field from the AP, it will continue its random backoff process. Therefore, both WSs A and C will be involved in contending the channel access at time t_2. Considering that WS C is successful in acquiring the channel, it will start the reservation period by sending the RTS-R packet to the AP. With the reception of the RTS-R packet, the AP will notice that its first table entry $T_0(A)$ is not available for data transmission. Consequently, the entry $T_0(A)$ is removed such that the reservation table will become $\mathbf{T} = \{T_0(B), T_1(C)\}$. It can be observed that all the WSs within the reservation table are assigned with the random number k_{dcf} based on the ARCR scheme. If the RTS-R packet of the WS with NTO(0) fails, the WS with NTO(1) can continue to conduct the corresponding reservation process.

The transmission priorities that are recorded within the reservation table will be changed after the packet transmissions for both WSs B and C, i.e. $\mathbf{T} = \{T_0(B), T_1(C)\}$. For the next reservation period starting from t_3, after WS B accomplishes its packet transmission with the AP, WS C will receive the RFD(1) message from the AP and start to dispatch its DATA+TAR packet. Considering that the DATA+TAR packet failed in transmission due to channel error, the AP will wait for a period required for successful packet transmission, i.e. the AP timout period, to recognize this situation and consequently remove WS C from its reservation table as $\mathbf{T} = \{T_0(B)\}$. Moreover, if there are still other table entries recorded behind the removed table entry, the AP will continue to initiate the RFD message to the remaining WSs for packet transmissions. On the other hand, without any further acknowledgement from the AP, WS C will change its channel access mechanism from the ARCR algorithm back to the DCF scheme. At time t_4, all the three WSs will be in the process to contend for channel access, and similar procedures are implemented to conduct packet transmission.

Similar processes can be examined as above in the case that either the ACK+NTO or the ACK+RFD packet failed in its transmission from the AP to the corresponding WS. The AP will remove the table entry for the WS after waiting for the AP timeout period; while the WS will be adaptively switched back to its original DCF mode for channel contention.

4 Throughput analysis of proposed ARCR protocol

Analytical study is performed in order to explore the benefits of proposed ARCR protocol. The probability for a WS to join the reservation table is derived in Sect. 4.1 As a consequence, the analytical model of throughput performance for proposed ARCR protocol will be obtained in Sect. 4.2

4.1 Derivation of reservation probability P_t

There are existing research [20–25] establishing the analytical models for the backoff process of DCF scheme under different considerations, e.g. fading channel [21], backoff suspension [24], or retry limit [25]. The two-dimensional Markov chain model utilized in [21] is adopted as the baseline model to analyze the random backoff process in the proposed ARCR protocol. It is considered that there are N WSs and 1 AP in the wireless network. Let the probability p represent the probability of failed transmission due to packet collisions or channel noise, and τ be defined as the probability that a WS transmits a RTS packet in a randomly selected time slot. By iteratively solving the nonlinear functions for p and τ as stated in [21], these two parameters can therefore be obtained.

The major task in this subsection is to derive the parameter P_t which refers as the transition probability that a WS either is in or will join the reservation table, named as *reservation probability*. As described in Sect. 3.1, the WSs will be added into or removed from the AP's reservation table **T** according to the proposed ARCR scheme. Therefore the total number of effective WSs will vary with the transmission events that happen in the network. In the proposed ARCR protocol, the effective WSs are defined as the set which consists of (a) the WSs that adopt the DCF scheme for channel contention and (b) the WS in the first entry of the reservation table **T**. Consider that the AP has recorded several WSs in its reservation table **T**. If a WS successfully completes its transmission by applying the DCF scheme, it will be added as the last entry in **T** and the number of effective WSs will be decreased by one. On the other hand, the number of the effective WSs will be increased by one if any of the WSs recorded in **T** is forced to be removed from the table under certain network scenarios. Let $n_{e,r}$ be referred as the number of the effective WSs in the network on the condition that there are r WSs in the reservation table **T**. The relationship between the number of WSs r in the reservation table **T** and the number of effective WSs $n_{e,r}$ in the network is represented as

$$n_{e,r} = \begin{cases} N, & r = 0 \\ N - r + 1, & 1 \le r \le N \end{cases} \quad (2)$$

According to (2), if the reservation table **T** is empty (i.e. $r = 0$), $n_{e,0}$ will be equal to N and all the effective WSs will compete the channel by using the DCF scheme. In the case that there is one WS in **T**, the parameter $n_{e,1}$ will still be equal to N since the WS in **T** will need to contend for channel access with the other $N - 1$ WSs that are not in the table. Considering that there are $n_{e,r}$ effective WSs in the network, the numbers of WSs reside inside and outside the reservation table **T** will be $N - n_{e,r} + 1$ and $n_{e,r} - 1$ respectively.

A WS which joins in or departs from the reservation table **T** will affect the degree of channel contention in the wireless network. If a WS joins in the reservation table **T**, the number of effective WSs will decrease and the occurrence of packet collisions will be reduced. On the other hand, the transmitted packets will potentially suffer from more collisions when the number of effective WSs is increased owing to the departure of WSs from the reservation table **T**. To simplify the interactions among the WSs, it is assumed that whether a WS will join in or depart from the reservation table is independent to the strategies adopted by the other WSs. Figure 4 shows the transitions between the steady states according to whether a WS will be recorded in the reservation table **T**. The parameter π_t is defined as the steady state probability that a WS will reside in the reservation table **T**, which can be obtained as

$$\pi_t = \pi_t P_t + (1 - \pi_t) P_t = P_t \quad (3)$$

In order to solve the reservation probability P_t, another relationship between π_t and P_t will be required. Given that there are r WSs in the reservation table which corresponds to $n_{e,r}$ effective WSs in the network, the parameters $P_{c,r}$ and τ_r are respectively denoted as the probabilities of collisions and the events that a WS transmits its RTS

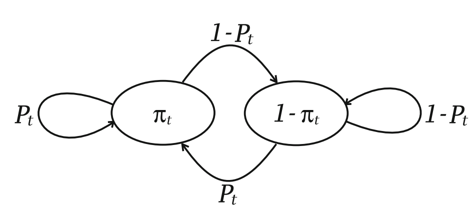


Fig. 4 The Markov model of reservation probability P_t for the proposed ARCR protocol

packet in a random slot time. Based on the iterative computation between τ and p, the set of parameters $P_{c,r}$ and τ_r can be solved from $r = 0$ to $r = N$. In other words, $P_{c,r}$ and τ_r can be calculated by replacing N with $n_{e,r}$. Moreover, the probability for a WS to be in the reservation table can be contributed to either one of the following two factors: (a) a WS is added into the reservation table **T** after successfully transmitting packets via channel contention or (b) a WS that exists in table **T** has conducted successful packet transmission. Therefore, the parameter P_t can also be regarded as the probability of successful transmission considering the situations that a WS is either inside or outside of the reservation table. Based on the value of $P_{c,r}$ as described above, the probability P_t in the steady state can consequently be derived as

$$P_t = \sum_{r=0}^{N} C_r^N \pi_t^r (1-\pi_t)^{N-r} \left[\frac{n_{e,r}}{N}(1-P_f)(1-P_{c,r}) + \frac{N-n_{e,r}}{N}(1-P_f)\right] \quad (4)$$

where P_f denotes the packet error rate due to the existence of channel noises. It is noted that $\frac{n_{e,r}}{N}$ in (4) is denoted as the probability that a WS is required to contend with the other WSs in the network. On the other hand, $\frac{N-n_{e,r}}{N}$ represents the probability that the WS resides within the reservation table to be scheduled for packet transmission. Therefore, only the packet error rate P_f is required to be addressed without the consideration of collision probability $P_{c,r}$. By substituting (3) into the (4), the parameters π_t and P_t can consequently be obtained by solving the corresponding nonlinear function.

4.2 Throughput performance of proposed ARCR protocol

Compared to conventional analytical models for DCF scheme, the analysis for throughput performance of proposed ARCR protocol is to further investigate the effect from the reservation table to the channel contention. Let $P_{tr,r}$ be the probability that there is at least one WS transmitting in a slot time while r WSs are recorded in the reservation table **T**, i.e.

$$P_{tr,r} = 1 - (1-\tau_r)^{n_{e,r}} \quad (5)$$

Moreover, the probability $P_{s,r}$ is denoted as the event that exactly one WS occupies the channel without any transmission from the other WSs given that there are r WSs in the reservation table. The probability $P_{s,r}$ can be derived as

$$P_{s,r} = \frac{n_{e,r}\tau_r(1-\tau_r)^{n_{e,r}-1}}{P_{tr,r}} \quad (6)$$

To obtain the system throughput with r WSs recorded in **T**, the average payload delivered in successful transmissions will be considered. The parameter $E[P_r]$ represents the average payload size for one transmission given that there are r ($r \neq 0$) WSs in the reservation table **T**, which can be obtained as

$$E[P_r] = \frac{n_{e,r}-1}{n_{e,r}}E[P] + \frac{1}{n_{e,r}}(N-n_{e,r}+1)E[P] = \frac{N}{n_{e,r}}E[P] \quad (7)$$

where $E[P]$ denotes the average intended transmitted payload size for each WS. It is noted that $\frac{n_{e,r}-1}{n_{e,r}}$ represents the probability that the transmitters do not reside in the reservation table **T**, and each of them has payload $E[P]$ to be delivered. On the other hand, the fraction $\frac{1}{n_{e,r}}$ stands for the transmission probability of the WS that possesses the first transmission priority among all the WSs in the reservation table **T**. The total payload issued at this case by the entire r WSs in **T** becomes $(N - n_{e,r} + 1)E[P]$. In the case that $r = 0$, all the WSs will adopt the conventional DCF scheme which results in $E[P_{r=0}] = E[P]$ that can also be verified by substituting $r = 0$ in (7).

In order to evaluate the total required time $T_{av,r}$ for packet transmission given that there are r WSs in the reservation table, the time durations owing to packet collisions T_c, successful transmissions $T_{s,r}$, and noise corruptions $T_{f,r}$ will be taken into account. Note that the required time owning to noise corruption $T_{f,r}$ is assumed to be equal to that for successful transmissions $T_{s,r}$. With the consideration of the three events mentioned before, the average required time $T_{av,r}$ can be derived as

$$T_{av,r} = (1-P_{tr,r})\sigma + P_{tr,r}(1-P_{s,r})T_c + P_{tr,r}P_{s,r}(1-P_f)T_{s,r} + P_{tr,r}P_{s,r}P_fT_{f,r} \quad (8)$$

where σ represents the slot time. The probabilities $P_{tr,r}$ and $P_{s,r}$ can be obtained from (5) and (6) respectively. The parameter T_c denotes the time for a WS to sense the occurrence of packet collisions which can be expressed as

$$T_c = T_{RTS-R} + \delta + T_{CTS} + \delta + T_{SIFS} + T_{DIFS} \quad (9)$$

where δ is the propagation delay, and the remaining parameters in (9) are indicated by their corresponding subscripts. Noted that $T_{RTS\text{-}R}$ represents the required time for either the RTS or the RTS-R packet since no additional control field is required by adopting the designed RTS-R packet. On other other hand, the required time for successful transmissions can be acquired as

$$T_{s,r} = \frac{n_{e,r}-1}{n_{e,r}}[T_{RTS-R} + T_{CTS} + T_{PHY} + T_{MAC} + T_{E[P]} + T_{ACK+NTO} + 3T_{SIFS} + 4\delta + T_{DIFS}] + \frac{1}{n_{e,r}}[T_{RTS} + T_{CTS} + T_{SIFS} + 2\delta + T_{DIFS} + (N - n_{e,r} + 1)(T_{PHY} + T_{MAC} + T_{E[P]} + T_{ACK} + 2T_{SIFS} + 2\delta)] \quad (10)$$

where $T_{E[P]}$, $T_{ACK+NTO}$, T_{PHY}, and T_{MAC} are defined as the required time intervals for transmitting payload, ACK+NTO frame, PHY header, and MAC header. Noted that the time interval for transmitting the designed RFD field is considered within the MAC header. Similar to the concept in (7), the first term in (10) that associated with probability $\frac{n_{e,r}-1}{n_{e,r}}$ denotes the successful transmission conducted by a WS that adopts the DCF scheme. The second term associated with probability $\frac{1}{n_{e,r}}$ indicates the required time for a successful transmission while the WS resides in the reservation table, which exploits the ARCR protocol to compete the channel access. Furthermore, a transmitter will need to perceive whether its transmission has completed or not according to the reception of ACK packet. Therefore, the required time owing to noise corruption will be equal to that for successful transmissions, i.e. $T_{f,r} = T_{s,r}$. Based on (7) and (8), the average system throughput S can consequently be derived as

$$S = \frac{\sum_{r=0}^{N} C_r^N \pi_t^r (1-\pi_t)^{N-r} P_{tr,r} P_{s,r} (1-P_f) E[P_r]}{\sum_{r=0}^{N} C_r^N \pi_t^r (1-\pi_t)^{N-r} T_{av,r}} \quad (11)$$

where π_t can be obtained by solving (3) and (4). It is noted the term $P_{tr,r}P_{s,r}(1-P_f)E[P_r]$ in (11) denotes the expected payload to be transmitted with r WSs in the reservation table. The term $(1-P_f)$ shown in (11) indicates that only partial payload can be successfully transmitted with the consideration of packet error rate P_f. The validation of throughput performance S in (11) for the proposed ARCR protocol will be conducted in Sect. 5.1.

5 Performance evaluation

In this section, the performance of proposed ARCR protocol will be validated and compared with existing schemes via well-known simulator (NS-2) [26]. All the simulation runs will be conducted for 100 s. Performance validation of the ARCR scheme is conducted in Sect. 5.1, and performance comparison with other schemes will be shown in Sect. 5.2.

5.1 Performance validation

In order to validate the analytical model for proposed ARCR scheme, the system throughput S as derived in (11) is compared with simulation results as shown in Figs. 5 and 6. Noted that the legends "ana" and "sim" in both figures represent the results from analytical model and simulations respectively. The system parameters and MAC configurations based on IEEE 802.11b standard are listed in Table 1, and saturation traffic is assumed for each WS to deliver its data packets. Figure 5 shows the performance validation for throughput performance versus the number of WSs (N) under BER = 0, 10^{-5}, and 10^{-4}. It can be intuitively observed that the system throughput increases as the total number of WSs in the network is augmented. Moreover,

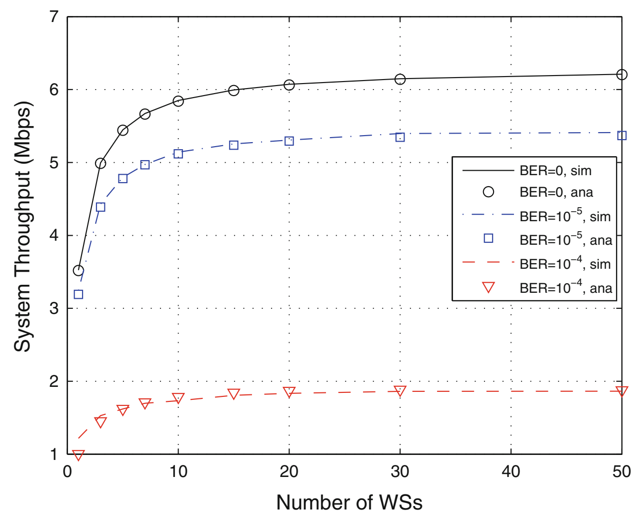


Fig. 5 Performance validation for ARCR protocol: system throughput versus number of WSs

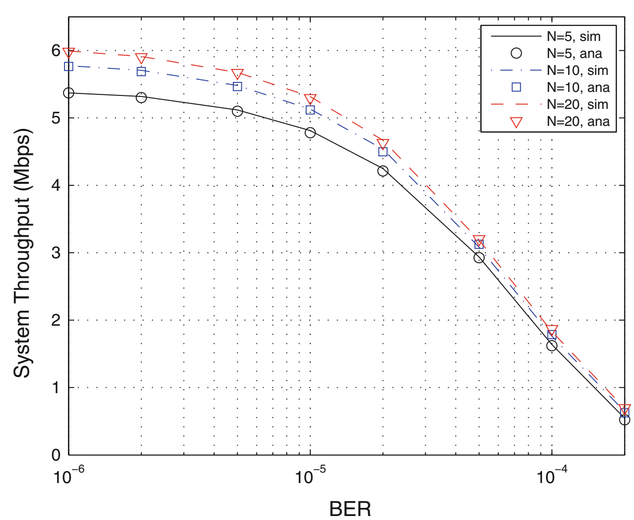


Fig. 6 Performance validation for ARCR protocol: system throughput versus BER

Table 1 System parameters

Parameter	Value
Minimum window (W)	32
Maximum backoff (M)	5
Data rate	11 Mbps
Basic rate	1 Mbps
Slot time (σ)	20 µs
T_{SIFS}	10 µs
T_{DIFS}	50 µs
PHY header	192 bits
MAC header + TAR	224 bits
Propagation delay (δ)	1 µs
Payload size ($E[P]$)	8184 bits
RTS/RTS-R	160 bits
CTS	112 bits
ACK + RFD/NTO	112 + 16 bits

Fig. 6 illustrates the throughput versus BER under $N = 5$, 10, and 20. The throughput performance decreases as the BER values are increased. It can be seen from both figures that the proposed analytical model can match with the simulation results under different numbers of WSs and BER values.

5.2 Performance comparison

As shown in Figs. 7, 8, 9 and 10, the proposed ARCR protocol is compared to the DCF, GDCF [11, 12], PCF, and EBA-2 [8] schemes through a series of simulations in terms of both the number of WSs and the BER values. The system parameters in Table 1 are utilized in performance comparison with saturation traffic considered for each WS. It is also assumed that the successful counter c of GDCF is

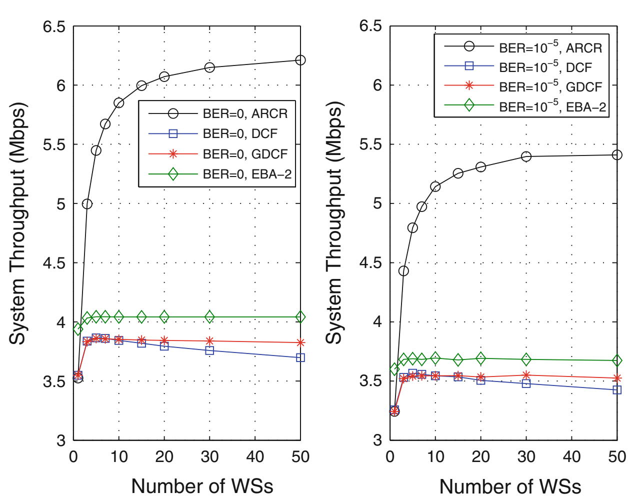


Fig. 7 Performance comparison for ARCR protocol: system throughput versus number of WSs

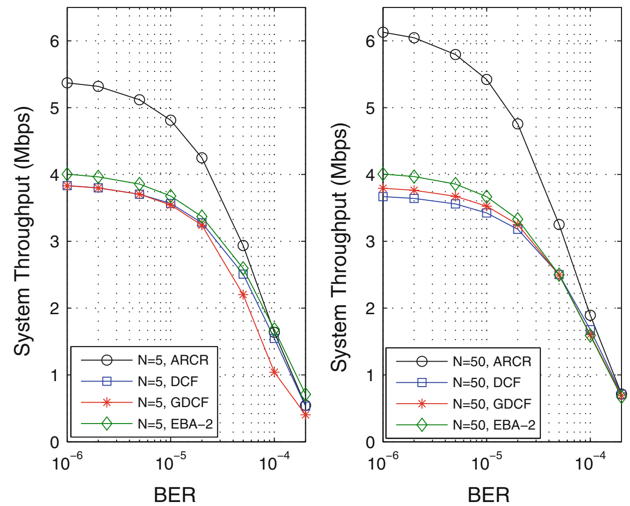


Fig. 8 Performance comparison for ARCR protocol: system throughput versus BER

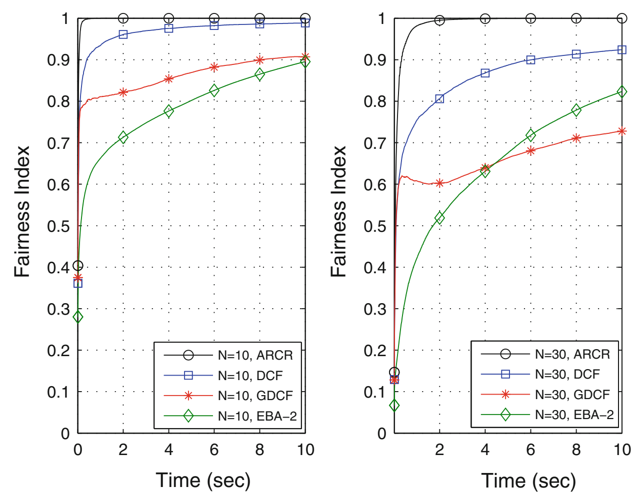


Fig. 9 Fairness comparison for ARCR protocol: fairness index versus time

set equal to 2. Figure 7 shows the performance comparison of system throughput w.r.t. different numbers of WSs under BER =0 and 10^{-5}. It can be observed that the proposed ARCR scheme possesses higher throughput performance than the other three protocols under different numbers of WSs. The only exception is at the case of $N = 1$ that the EBA-2 scheme provides better performance than the ARCR protocol mainly due to the reason that the parameter W is selected to be 8 and 32 for EBA-2 and ARCR schemes, respectively. It is intuitively that smaller W will enhance the throughput performance if there exists only one WS in the network. The EBA-2 protocol has better performance than the GDCF and DCF schemes since most of the WSs are not allowed to choose the same slot to transmit their RTS packets. Collision overhead and backoff delay can therefore be reduced. Moreover, the GDCF

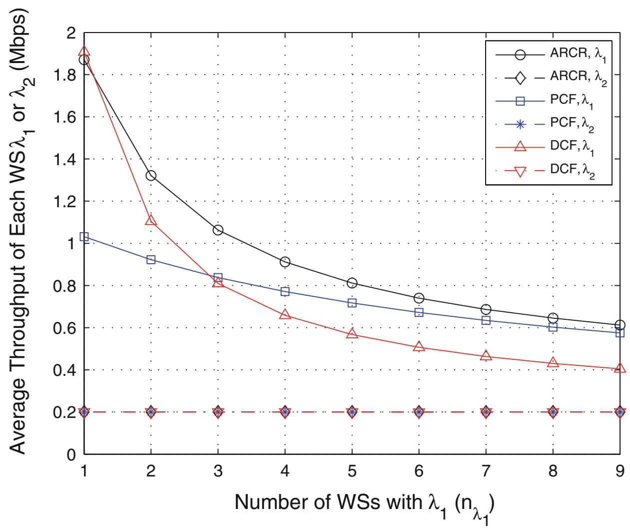


Fig. 10 Performance comparison for ARCR protocol: average throughput of each WS versus number of WSs with λ_1 (n_{λ_1}) ($n_{\lambda_2} = 10 - n_{\lambda_1}$, $\lambda_1 = 2$Mbps, $\lambda_2 = 0.2$Mbps)

method is slightly superior to the DCF scheme with larger number of WSs in the network. The reason is that the GDCF scheme has higher probability of staying at the stages with larger backoff window sizes compared to the DCF protocol. Less packet collisions will be incurred by adopting the GDCF scheme especially under larger number of WSs, which results in higher system throughput.

Figure 8 illustrates the comparison of throughput performance versus different BER values under $N = 5$ and 50. The proposed ARCR protocol still outperforms the other three schemes under various BER values. It can also be observed that the system throughput of four schemes decrease and converge with the augmentation of BER values. At higher BER values, the proposed ARCR protocol behaves similar to the DCF scheme since almost all the WSs in the network will be removed from the reservation table due to occurrence of packet error . On the other hand, with higher BER values, the GDCF method is also comparable to the DCF scheme owing to the reason that its backoff stage will eventually remain at the maximum value. Furthermore, the fairness index F [27] is introduced to estimate the fairness of each protocol, which is formulated as

$$F = \frac{\left(\sum_{i=1}^{N} S_i\right)^2}{N \cdot \sum_{i=1}^{N} S_i^2} \tag{12}$$

where S_i represents the throughput of WS i. The maximum value of F is equal to 1 which indicates the fairest situation; while minimal value $F = 1/N$ denotes the most unbalanced case. Intuitively, the value of F will be approximated to 1 for the steady state response of each protocol since every WS has equal opportunity to contend the channel. Therefore, the rates of achieving steady state for all the schemes are compared in order to determine the fairness levels. Figure 9 shows the fairness comparison F versus time under different numbers of WSs. It can be observed that the proposed ARCR protocol can quickly achieve the steady state value of the fair index, i.e. $F = 1$, compared to the other schemes. On the other hand, both the GDCF and EBA-2 schemes result in worse performance compared to that of the DCF protocol due to their inherent designs. The WS with RTS packet collision will suffer from larger backoff delay for the GDCF scheme than that for the DCF protocol since the WS will slowly return back to the minimum CW size in the GDCF scheme, which makes the GDCF scheme become more unfair between the WSs. Furthermore, the WSs that receive the EBA field from the other WS should reselect another backoff counter, which is advantageous for the WS to easily win the channel contention. Therefore, the EBA-2 scheme possesses inferior fairness compared to the DCF protocol. Note that it takes more time for the fairness index to achieve steady state with the $N = 30$ scenario compared to the $N = 10$ case.

Moreover, the proposed ARCR protocol is compared with the distributed DCF scheme and the centralized PCF protocol given the condition of non-saturated queue in each WS with M/G/1 queuing system. In order to illustrate the pure reservation-based system, the PCF scheme is implemented only with the CFP while the CP is not considered in performance comparisons. It is assumed that there are two types of WSs in the network, including the WSs with high packet-arrival rate (λ_1 bits/sec (bps)) and with low packet-arrival rate (λ_2 bps). Let n_{λ_1} and n_{λ_2} be respectively defined as the numbers of WSs with λ_1 and λ_2 as the packet-arrival rates, the corresponding average throughput for each WS with λ_1 and λ_2 is respectively denoted as μ_{λ_1} and μ_{λ_2} with the unit of bps. It is considered that there are total of 10 WSs in the network for performance comparison, i.e. $n_{\lambda_1} + n_{\lambda_2} = 10$.

The performance comparisons of average throughput for each WS (i.e. either μ_{λ_1} or μ_{λ_2}) versus the number of WSs with the packets arrive rate equal to λ_1 are shown in Fig. 10. Noted that the packet arrival rates $\lambda_1 = 2$ Mbps and $\lambda_2 = 200$ Kbps, and the number of WSs with packets arrive rate λ_2 becomes $n_{\lambda_2} = 10 - n_{\lambda_1}$. It can be observed from Fig. 10 that the average throughput for the WSs with λ_2 is approximately the same for all these three protocols, i.e. $\mu_{\lambda_2} \simeq 0.2$ Mbps. The results indicate that all three schemes can provide satisfactory services for the WSs with packet arrival rate $\lambda_2 = 0.2$ Mbps since μ_{λ_2} is around the same as the theoretically maximal throughput for each WS with λ_2. On the other hand, the effectiveness of proposed ARCR scheme can be revealed by observing the average throughput μ_{λ_1} for the WSs with λ_1. As n_{λ_1} is small, the polling-based PCF scheme becomes inefficient comparing with the ARCR and the DCF protocols since the network bandwidth is wasted as the AP is scheduled to periodically poll the larger numbers of WS with λ_2. The proposed ARCR protocol and the DCF scheme can provide higher throughput for WSs with λ_1 since there is more opportunity for these WSs to frequently transmit their data packets. Furthermore, with larger values of n_{λ_1}, the contention-based DCF scheme will spend significant amount of time to resolve for packet collisions, which results in reduced system throughput of μ_{λ_1}. The proposed ARCR protocol and the PCF scheme can provide higher throughput performance since there is greater chance for the larger amount of WSs with λ_1 to be scheduled for packet transmission. As a result, the ARCR protocol can provide better throughput performance under different arrival rates of the WSs in the network.

Figure 11 illustrates the average throughput of each WSs (μ_{λ_1} or μ_{λ_2}) versus the packet arrival rate λ_2 on the conditions that $n_{\lambda_1} = 2$, $n_{\lambda_2} = 8$, and $\lambda_1 = 2$ Mbps. As can be expected, with the augmentation of λ_2, the throughput μ_{λ_2} will be increased, however, the throughput performance μ_{λ_1} for the WSs with λ_1 is reduced for all three schemes. A saturation point will be reached by the WSs with either λ_1 or λ_2 for all three protocols due to the availability of total network bandwidth. Owing to the severe packet collision, the DCF scheme will result in the lowest throughput among the three protocols with the earliest saturation point at $\lambda_2 \simeq 400$ Kbps. Furthermore, the ARCR scheme will provide higher throughput performance with around $\mu_{\lambda_1} \simeq \mu_{\lambda_2} \simeq 0.58$ Mbps. On the other hand, the proposed ARCR scheme and DCF can outperform the PCF protocol under smaller values of packet arrival rate λ_2 owing to the polling

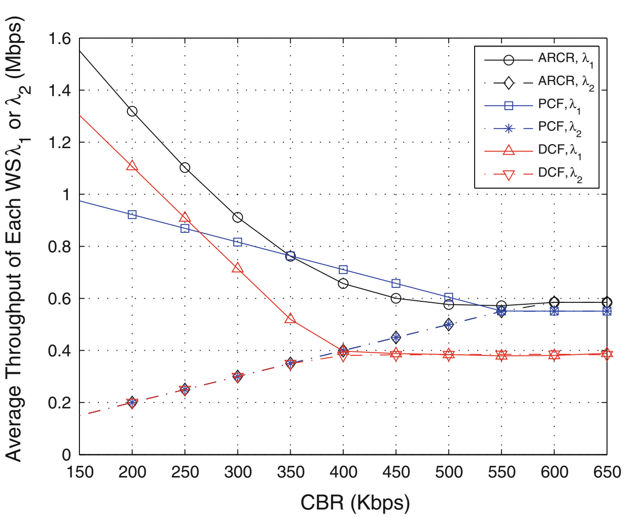


Fig. 11 Performance comparison for ARCR protocol: average throughput of each WS versus packet arrival rate λ_2 ($n_{\lambda_1} = 2$, $n_{\lambda_2} = 8$, $\lambda_1 = 2$Mbps)

overheads resulting from the centralized-based PCF scheme.

Moreover, in each channel competition, based on our proposed ARCR protocol, the first WS in the reservation table possesses the same range of CW size compared to the newly joining WSs. In other words, unsaturated WSs that may not have constant packet to be delivered will have the same level of opportunity for channel contention with the saturated WSs. As shown from Fig. 11 that the average throughput of WSs with λ_1 is around 1.32 Mbps and that with λ_2 is around 0.2 Mbps at packet arrival rate $\lambda_2 = 200$ Kbps. It can be seen that the throughput of the unsaturated WS with λ_2 will always be identical to its packet arrival rate before the saturation occurs at around 580 Kbps. That is to say, the WSs with λ_2 will not encounter large backoff timer due to packet collisions. As the packet arrival rate λ_2 is increased to 580 Kbps, it can be observed that all the WSs will achieve around the same throughput performance. Therefore, the merits of adopting the proposed ARCR scheme can be perceived.

6 Conclusion

In this paper, an adaptive reservation-assisted collision resolution (ARCR) protocol is proposed in order to enhance the network throughput for wireless local area networks. According to the ARCR scheme, adaptive reservation periods will be imposed within the conventional contention-based system by adopting the proposed piggy-back mechanisms. Based on the design of reservation table at the access point, excessive packet collision can effectively be alleviated in the network. The analytical model of system throughput for the proposed ARCR protocol is derived and validated via simulations. Numerical results show that the ARCR scheme outperforms other existing protocols with enhanced network throughput and better channel utilization.

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