QoS-Based Adaptive Contention/Reservation Medium Access Control Protocols for Wireless Local Area Networks

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Abstract—In the 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). 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 both improve packet collision and reduce the backoff delays from the random access scheme. 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. Moreover, in order to support quality-of-service requirements, the enhanced-ARCR (E-ARCR) protocol is further proposed to provide adaptation for multiple prioritized traffic in the WLAN. Analytical models are derived for both proposed schemes to evaluate their throughput performance. It can be observed from both analytical and simulation results that the proposed protocols outperform existing schemes with enhanced channel utilization and network throughput.

Index Terms—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 extensively utilized for both indoor and mobile communications. The applications for WLANs include wireless home gateways, hotspots for commercial usages, and ad hoc networking for intervehicular 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], [2], [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 is considered a crucial issue to enhance the network throughput for this type of random access schemes. Furthermore, the point coordination function (PCF) initiated by the access point (AP) provides centralized polling-based schemes to support time-constrained traffic for the WSs.

There are trade-offs 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 the packet collisions and reduce the backoff delays within the random access scheme. The main feature of the 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. Furthermore, with the consideration of four prioritized access categories (ACs) within a WS, the enhanced-ARCR (E-ARCR) protocol is further proposed in order to fulfill the QoS requirements. Analytical models for throughput analysis are developed in this paper to provide feasible observations on the behaviors of the proposed ARCR and E-ARCR protocols. Numerical results are conducted via simulations both to provide validation on the analytical models and to evaluate the effectiveness of the proposed schemes. Compared with other existing protocols, the network throughput can be enhanced by adopting the ARCR algorithm, e.g., around 50 percent performance gain with 10 WSs under error-free channel scenario. Moreover, QoS requirements can also be fulfilled with the exploitation of the E-ARCR scheme.

The remainder of this paper is organized as follows: Section 2 provides the related work, and Section 3 briefly summarizes the IEEE 802.11 MAC protocol and the gentle DCF (GDCF) scheme [5], [6]. The proposed ARCR scheme is described in Section 4 associated with its throughput analysis presented in Section 5. The proposed E-ARCR

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protocol and its performance analysis are explained in Sections 6 and 7. Section 8 presents the performance validation and evaluation for both the proposed ARCR and E-ARCR protocols; while conclusions are drawn in Section 9.

2 RELATED WORK

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], [6], [7], [8], [9], [10]. 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 the CW size, especially with a larger number of WSs in the network. However, enlarged CW size can incur excessive idle time which will consequently degrade the channel utilization. In order to enhance the throughput performance for the conventional IEEE 802.11 protocol, the algorithm proposed in [7] increases the transition rate between the backoff stages associated with decreased value of the minimum CW and incremented value of the maximum CW size. The hybrid algorithm proposed in [8] combines both the exponential and the linear backoff for the purpose of decreasing packet collision, while the slow CW decrease (SD) scheme in [9] either doubles or halves the CW size according to the success of packet transmission. The early backoff announcement (EBA) protocol [10] 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. The GDCF protocol as proposed in [5], [6] maintains a larger value of the CW size compared to the conventional backoff scheme in order to decrease the probability of packet collision.

Furthermore, in order to provide reliable services for multimedia applications, IEEE 802.11e standard [4] has been proposed to fulfill QoS requirements. For achieving prioritized channel access, the enhanced distributed channel access (EDCA) mechanism defines four ACs in a WS associated with their distinct arbitration interframe spaces (AIFSs) and CW sizes. In order to provide higher throughput performance comparing with the conventional EDCA scheme, research work has been proposed in [11], [12] by providing adjustment on the four CW sizes for their corresponding ACs in a WS. Adaptation of AIFS has been studied in [13] for achieving stable capacity ratios between the ACs; while random AIFS algorithm was proposed in [14] to both decrease packet collisions and increase throughput performance. With the adjustment of CW size and randomized AIFS values, the work proposed in [15] improves channel utilization and fairness by preventing starvation on lower priority classes under higher traffic loads. The piggyback method [16] is utilized by inserting additional fields in order to further enhance network throughput. Nevertheless, all the existing contention-based protocols suffer from the trade-off 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., [17]) have been proposed to increase the channel utilization for the IEEE 802.11 PCF [1] and the IEEE 802.11e HCF controlled channel access (HCCA) [4]. 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 PCF or HCCA for real-time packet delivery. The work in [18], [19] proposed piggyback schemes for HCCA 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 AP. Moreover, it is considered difficult to determine the ratio of CFP to CP in order to both fulfill the QoS requirement for the WSs and enhance system throughput.

3 PRELIMINARIES

In this section, both the IEEE 802.11 MAC protocols and the GDCF scheme are summarized which will be utilized for performance comparison with the proposed schemes in Section 8. The IEEE 802.11 MAC protocols, which include both the contention-based and the reservation-based mechanisms, are utilized as the baseline schemes for performance comparison. As described in the previous section, most of the existing research [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15] considers the adjustment of the CW size within their backoff algorithm in order to alleviate packet collision in the network. The delay coming from the backoff process has not been explicitly considered and reduced in the existing schemes. On the other hand, one of the major design objectives of the proposed ARCR scheme is to reduce the backoff delay by introducing the adaptive reservation table in the AP. Therefore, it is intuitively feasible to consider that the proposed ARCR scheme can outperform the existing schemes with higher system throughput.

In order to quantitatively evaluate the proposed ARCR scheme, the GDCF algorithm [5], [6] is selected from these existing schemes as an enhanced version of the IEEE 802.11 MAC protocol. The reason for selecting the GDCF algorithm as a comparison scheme is as follows: According to the design concept of the proposed ARCR scheme, its benefit will be revealed under larger number of WSs in the network owing to its adaptive scheme for table reservation. The GDCF scheme possesses higher probability of staying at the stages with larger CW sizes compared to the other existing schemes. With this design, the GDCF is capable of allowing a larger number of WSs within the network to contend for the channel access. Therefore, the GDCF protocol is selected for performance comparison with the proposed ARCR scheme.

3.1 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 the 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 utilized to record the duration of ongoing 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 the 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 the 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 the contention-based DCF scheme.

In order to support QoS requirements, the contention-based EDCA and centralized-based HCCA protocols are proposed in the IEEE 802.11e standard. The EDCA protocol inherits the conventional DCF's CSMA/CA scheme with the enhanced RTS/CTS handshaking process. Furthermore, four prioritized ACs are defined in EDCA in order to support different types of network traffic. The QoS requirements for each AC is defined by selecting feasible values of the CW size and AIFS length. It is intuitive to observe that higher priority AC should possess smaller values of CW and AIFS sizes. Each AC will wait for its AIFS length and independently select its own backoff number. Until the backoff number for a specific AC has been decremented to zero, the corresponding AC can initiate a RTS frame for channel contention. Each AC within a WS is considered as a stand-alone entity to contend with the ACs both in the same WS and the other WSs for channel access in the network. Furthermore, HCCA is designed to be a modified version of PCF which provides prioritized ACs to conduct centralized polling-based channel access.

3.2 Gentle DCF Protocol

The GDCF algorithm in [5], [6] modifies the conventional backoff scheme within the IEEE 802.11 protocol for the enhancement of network throughput. The major parameter in the 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 occurs. 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 the 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.

4 PROPOSED ARCR PROTOCOL

The design concept of the 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 [16] 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 detailed functionalities of the proposed ARCR scheme is described in Section 4.1. The examples of both ideal and realistic network scenarios for the proposed scheme are addressed in Sections 4.2 and 4.3.

4.1 Functional Description

As a node intends to transmit data packets within an IEEE 802.11 AP-based network, a 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 to perform piggyback, 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 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 $\mathrm{DATA}{+}\mathrm{TAR}$ 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 $\mathrm{NTO}(r)$, which is defined as follows:

Definition 2 ($\mathrm{NTO}(r)$). *Next Transmission Order ($\mathrm{NTO}(r)$) 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 $\mathrm{ACK}{+}\mathrm{NTO}(r)$ 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

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

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 $\mathrm{ACK}{+}\mathrm{NTO}(r)$ 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 $\mathrm{DATA}{+}\mathrm{TAR}$ 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 $\mathrm{DATA}{+}\mathrm{TAR}$ 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 toward the WS that is recorded within the next table entry. The RFD field is defined as follows:

Definition 4 ($\mathrm{RFD}(r)$). *$\mathrm{RFD}(r)$ is defined as a control field utilized by the AP to inform the rth WS in the reservation table that it can conduct packet transmission after waiting for a SIFS duration.*

The $\mathrm{ACK}{+}\mathrm{RFD}(r)$ 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 $\mathrm{DATA}{+}\mathrm{TAR}$ (or DATA) packet to the AP after a SIFS interval. The procedures for transmitting the $\mathrm{ACK} + \mathrm{RFD}(r)$ 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 the 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 $\mathrm{DATA}{+}\mathrm{TAR}$ packets are always transmitted by the WSs, the WS that is informed by the AP with the order r (i.e., $\mathrm{NTO}(r)$) will be assigned with the order of $r - 1$ for its next transmission with $\mathrm{NTO}(r - 1)$. 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.

Fig. 1 shows the flowchart for each WS by adopting the proposed ARCR protocol. The transitions between the conventional DCF scheme and the ARCR algorithm is 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. Different types of transmission scenarios will be exemplified in the following two sections.

4.2 Ideal Network Scenarios

Fig. 2a 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 the occurrence of packet collision. 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 $\mathrm{DATA}{+}\mathrm{TAR}$ packet will be delivered from WS A to the AP, where the TAR field indicates the request from node A

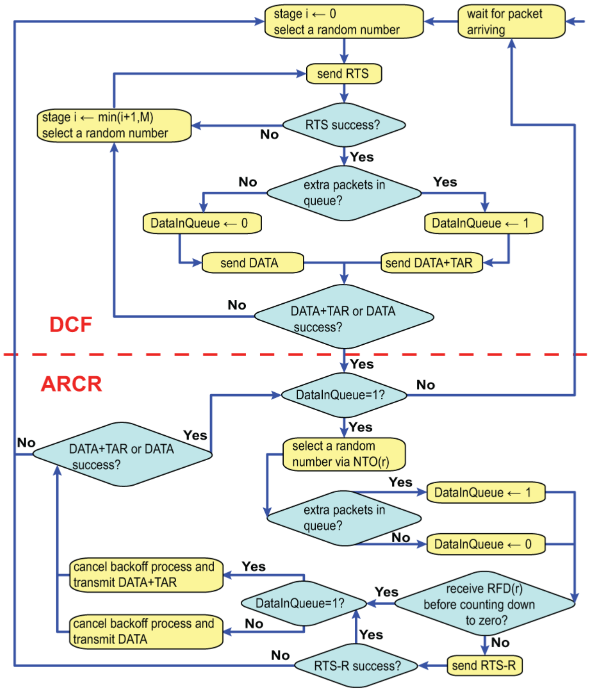

Fig. 1. The flowchart for the behavior of WS by adopting the proposed ARCR protocol.

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 $\mathrm{ACK}+\mathrm{NTO}(0)$ 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 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 $\mathrm{NTO}(0)$ 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, $\mathrm{DATA}+\mathrm{TAR}$, and $\mathrm{ACK}+\mathrm{NTO}(1)$ packets between WS B and the AP. The table entry $T_1(B)$ will also be included in the AP's reservation table $\mathbf{T}$. Due to the reason that both WSs A and B have received the $\mathrm{NTO}(r)$ 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. 2. After the reception of the $\mathrm{DATA}+\mathrm{TAR}$ packet from WS A, the AP will respond with the $\mathrm{ACK}+\mathrm{RFD}(1)$ packet where the ACK packet is intended for WS A and the $\mathrm{RFD}(1)$ field is targeting for WS B. Based on the received $\mathrm{RFD}(1)$ message from the AP, WS B will terminate its backoff process and conduct the transmission of $\mathrm{DATA}+\mathrm{TAR}$ 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 $\mathrm{DATA}+\mathrm{TAR}$ packet from WS B,

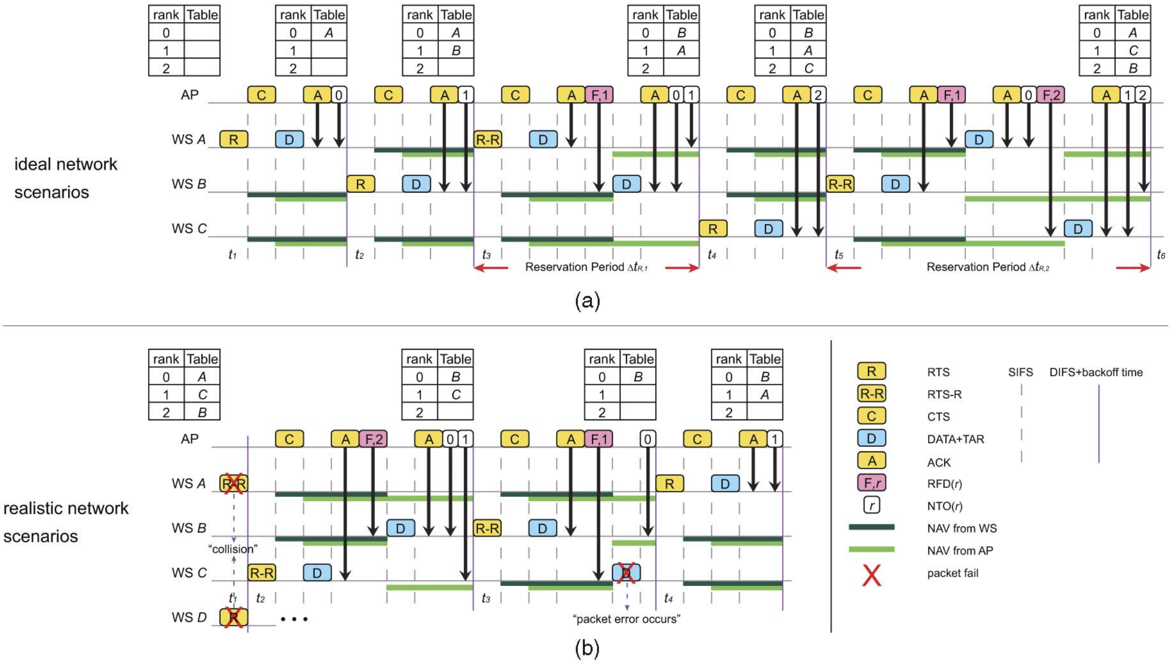

Fig. 2. The timing diagram for the proposed ARCR protocol under (a) ideal network scenarios and (b) realistic network scenarios.

the AP will respond with an $\mathrm{ACK{+}NTO}(0) + \mathrm{NTO}(1)$ packet where the $\mathrm{ACK{+}NTO}(0)$ 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., $\mathbf{T} = \{T_0(B), T_1(A)\}$.

Assuming 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 $\mathbf{T}$. Afterwards, the transmission order will be rotated for the purpose to ensure the transmission fairness, i.e., $\mathbf{T} = \{T_0(A), T_1(C), T_2(B)\}$. 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.

4.3 Realistic Network Scenarios

Fig. 2b shows the examples for the proposed ARCR scheme to alleviate the packet collision under a realistic network scenario. In this case, it is assumed that the channel is error-prone with the occurrence of RTS/RTS-R packet collision. First of all, the adaptive adjustment of the 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 with WS D. 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 flowchart 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 $\mathrm{RFD}(1)$ 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 $\mathbf{T} = \{T_0(B), T_1(C)\}$.

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 $\mathrm{RFD}(1)$ message from the AP and start to dispatch its $\mathrm{DATA{+}TAR}$ packet. Considering that the $\mathrm{DATA{+}TAR}$ packet failed in transmission due to the occurrence of packet error, the AP will wait for a period required for successful packet transmission, i.e., the AP time-out period, to recognize this situation and consequently remove WS C from its reservation table as $\mathbf{T} = \{T_0(B)\}$. It is noted that 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 acknowledgment 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 time-out period; while the WS will be adaptively switched back to its original DCF mode for channel contention.

5 THROUGHPUT ANALYSIS OF THE PROPOSED ARCR PROTOCOL

Analytical study is performed in order to explore the benefits of the proposed ARCR protocol. The backoff process of the DCF scheme is first modeled by the Markov chain model in Section 5.1. The probability for a WS to join the reservation table is derived in Section 5.2. As a consequence, the analytical model of throughput performance for the proposed ARCR protocol will be obtained in Section 5.3.

5.1 Backoff Process of the DCF Scheme

There are existing research [20], [21], [22], [23], [24], [25] establishing the analytical models for the backoff process of the 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. As shown in Fig. 3, the parameter p represents the probability of failed transmission due to packet collisions or channel noise. $W_i = 2^iW$ is defined as the backoff window size at the stage i for $0 \leq i \leq M$, where W denotes the minimum backoff window size. $s(t)$ and $b(t)$ are defined as the stochastic processes representing the backoff stage and the backoff time counter of a WS at time t, respectively. It is noted that discrete and integral timescale for the decrements of backoff time counter is adopted in the analysis. The backoff time counter will decrease by one in a slot time σ as the channel is sensed idle.

Let $b_{i,k}$ denotes the stationary distribution of the two-dimensional stochastic process $\{s(t), b(t)\}$ as a WS lies at the ith backoff stage with its counter equal to k. As shown in Fig. 3, a WS in backoff stage i will randomly select a number within $[0, W_i - 1]$ and start to count down if the channel is sensed to be idle. The WS will successfully transmit with probability $1 - p$ after the counter k decreases to zero. It will consequently be reset to the minimum window size, i.e., $i = 0$, for the next channel contention. On the other hand, the WS will be at the $(i + 1)$th backoff stage if collision happens for packet transmission. In the case that the current backoff stage is M and the transmission fails, the next

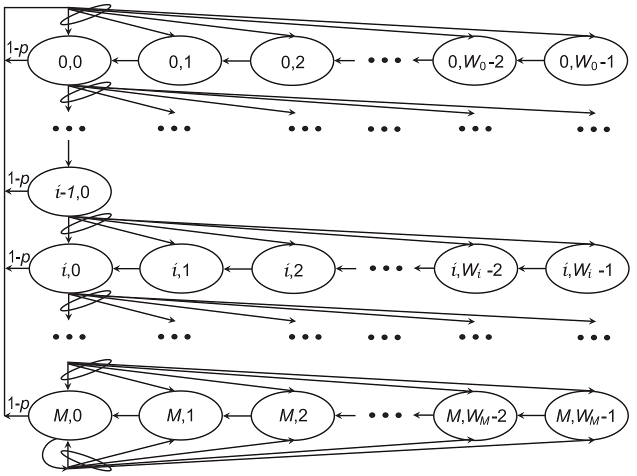

Fig. 3. The two-dimensional Markov chain model for the backoff process of the DCF scheme.

backoff stage will still remain at the stage M. The relationship between each state is derived as follows:

$$\begin{cases} P(b_{i,k}|b_{i,k+1}) = 1, & 0 \le k \le W_i - 2, 0 \le i \le M,\\ P(b_{0,k}|b_{i,0}) = (1-p)/W_0, & 0 \le k \le W_0 - 1, 0 \le i \le M,\\ P(b_{i,k}|b_{i-1,0}) = p/W_i, & 0 \le k \le W_i - 1, 1 \le i \le M,\\ P(b_{M,k}|b_{M,0}) = p/W_M, & 0 \le k \le W_M - 1. \end{cases} \quad (2)$$

It is noticed that each steady-state probability $b_{i,k}$ can be expressed as a function of $b_{0,0}$ after transformation based on the equations in (2). Since the sum of all the states will be equal to 1, namely $\sum_{i=0}^{M} \sum_{k=0}^{W_i - 1} b_{i,k} = 1$, $b_{0,0}$ can be obtained as

$$b_{0,0} = \frac{2(1-p)(1-2p)}{(1-2p)(W+1) + pW[1-(2p)^M]}. \quad (3)$$

Let τ be defined as the probability that a WS transmits a RTS packet in a randomly selected time slot. Based on the model in Fig. 3, a WS can transmits its RTS packets only if the backoff counter k reaches zero. Therefore, the parameter τ can be acquired as

$$\tau = \sum_{i=0}^{M} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)}{(1-2p)(W+1) + pW[1-(2p)^M]}. \quad (4)$$

In order to solve τ and p in (4), another relationship between these two parameters should be obtained. Let P_f be denoted as the packet error rate due to the existence of channel noises and P_c be the probability that the packet issued by one WS collides with those from other WSs. Noted that the packet error rate P_f can be computed from the bit error rate which is derived from signal-to-noise ratio (SNR) of the channel states. Assuming that there are N WSs in the wireless network, P_c can be interpreted as the event that at least one WS transmits packets among the remaining $N-1$ WSs, i.e., $P_c = 1 - (1-\tau)^{N-1}$. Therefore, the probability of failed transmission p can be obtained as

$$p = P_c + P_f - P_c P_f = 1 - (1-\tau)^{N-1} + P_f (1-\tau)^{N-1}. \quad (5)$$

By iteratively solving the nonlinear functions (4) and (5), the two parameters τ and p can therefore be obtained. In the next section, the behavior that whether a WS will become an entry in the reservation table will be depicted.

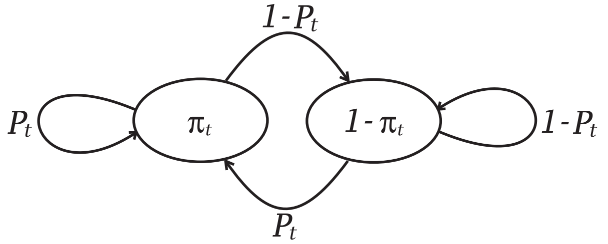

Fig. 4. The Markov model of reservation probability P_t for the proposed ARCR protocol.

5.2 Derivation of Reservation Probability P_t

In this section, the major task is to derive the parameter P_t which represents the transition probability that a WS either is in or will join the reservation table, named as *reservation probability*. As described in Section 4.3, 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 1) the WSs that adopt the DCF scheme for channel contention and 2) 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

$$n_{e,r} = \begin{cases} N, & r = 0,\\ N - r + 1, & 1 \le r \le N. \end{cases} \quad (6)$$

According to (6), 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. Fig. 4 shows the transitions between the steady states according to whether a WS will be recorded in the reservation table $\mathbf{T}$. The parameter π_t is defined as the steady-state probability that a WS will reside in the reservation table $\mathbf{T}$, which can be obtained as

$$\pi_t = \pi_t P_t + (1 - \pi_t) P_t = P_t. \tag{7}$$

Note that transition probabilities from both states toward π_t are assumed equal to simplify calculation complexity. 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 packet in a random slot time. Based on the iterative computation between (4) and (5), the set of parameters $P_{c,r}$ and τ_r can be solved from $r = 0$ to $r = N$. Moreover, the probability for a WS to be in the reservation table can be contributed to either one of the following two factors: 1) a WS is added into the reservation table $\mathbf{T}$ after successfully transmitting packets via channel contention or 2) a WS that exists in table $\mathbf{T}$ 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

$$\begin{aligned} P_t = &\sum_{r=0}^{N} C_r^N \pi_t^r (1 - \pi_t)^{N-r} \\ &\cdot \left[\frac{n_{e,r}}{N}(1 - P_f)(1 - P_{c,r}) + \frac{N - n_{e,r}}{N}(1 - P_f) \right]. \end{aligned} \tag{8}$$

It is noted that $\frac{n_{e,r}}{N}$ in (8) 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 (7) into (8), the parameters π_t and P_t can consequently be obtained by solving the corresponding nonlinear function.

5.3 Throughput Performance of the Proposed ARCR Protocol

Compared to conventional analytical models for the DCF scheme, the analysis for throughput performance of the 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 $\mathbf{T}$, i.e.,

$$P_{tr,r} = 1 - (1 - \tau_r)^{n_{e,r}}. \tag{9}$$

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

$$P_{s,r} = \frac{n_{e,r}\tau_r(1 - \tau_r)^{n_{e,r}-1}}{P_{tr,r}}. \tag{10}$$

To obtain the system throughput with r WSs recorded in $\mathbf{T}$, 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 $\mathbf{T}$, which can be obtained as

$$E[P_r] = \frac{n_{e,r} - 1}{n_{e,r}} E[P] + \frac{1}{n_{e,r}}(N - n_{e,r} + 1)E[P] = \frac{N}{n_{e,r}} E[P], \tag{11}$$

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 $\mathbf{T}$, 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 $\mathbf{T}$. The total payload issued at this case by the entire r WSs in $\mathbf{T}$ 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 (11).

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. With the consideration of the three events mentioned before, the average required time $T_{av,r}$ can be derived as

$$\begin{aligned} T_{av,r} = &(1 - P_{tr,r})\sigma + P_{tr,r}(1 - P_{s,r})T_c \\ &+ P_{tr,r}P_{s,r}(1 - P_f)T_{s,r} + P_{tr,r}P_{s,r}P_f T_{f,r}, \end{aligned} \tag{12}$$

where σ represents the slot time. The probabilities $P_{tr,r}$ and $P_{s,r}$ can be obtained from (9) and (10), respectively. The parameter T_c denotes the time for a WS to sense the occurrence of packet collisions which can be expressed as

$$T_c = T_{RTS-R} + \delta + T_{CTS} + \delta + T_{SIFS} + T_{DIFS}, \tag{13}$$

where δ is the propagation delay, and the remaining parameters in (13) 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 the other hand, the required time for successful transmissions can be acquired as

$$\begin{aligned} T_{s,r} = &\frac{n_{e,r} - 1}{n_{e,r}} [T_{RTS-R} + T_{CTS} + T_{PHY} + T_{MAC} + T_{E[P]} \\ &+ T_{ACK+NTO} + 3T_{SIFS} + 4\delta + T_{DIFS}] \\ &+ \frac{1}{n_{e,r}} [T_{RTS} + T_{CTS} + T_{SIFS} + 2\delta + T_{DIFS} \\ &+ (N - n_{e,r} + 1)(T_{PHY} + T_{MAC} + T_{E[P]} \\ &+ T_{ACK} + 2T_{SIFS} + 2\delta)], \end{aligned} \tag{14}$$

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 (11), the first term in (14) that associated with probability $\frac{n_{e,r}-1}{n_{e,r}}$ denotes the successful transmission conducted by a WS

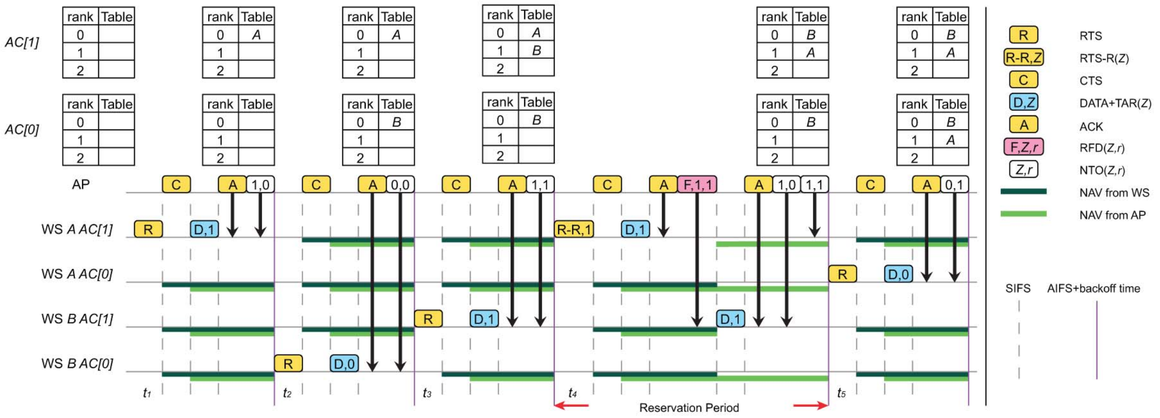

Fig. 5. The timing diagram for the proposed E-ARCR protocol.

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 (11) and (12), the average system throughput S can consequently be derived as

$$S = \frac{\sum_{r=0}^{N} C_r^N \pi_t^r (1-\pi_t)^{N-r} P_{tr,r} P_{s,r} (1-P_f) E[P_r]}{\sum_{r=0}^{N} C_r^N \pi_t^r (1-\pi_t)^{N-r} T_{av,r}}, \qquad (15)$$

where π_t can be obtained by solving (7) and (8). It is noted that the term $P_{tr,r} P_{s,r} (1-P_f) E[P_r]$ in (15) denotes the expected payload to be transmitted with r WSs in the reservation table. The validation of throughput performance S in (15) for the proposed ARCR protocol will be conducted in Section 8.1.1.

6 PROPOSED E-ARCR PROTOCOL

As is not considered in the DCF mechanism, the IEEE 802.11e EDCA scheme [4] supports different traffic types and fulfills their corresponding QoS requirements. In order to achieve the advancement from the DCF method to the EDCA scheme, the E-ARCR protocol is proposed as the enhanced version of the ARCR scheme in order to fulfill the QoS requirements as specified in the EDCA scheme. The E-ARCR protocol will support four ACs in a WS in order to serve various traffic types which possess different priorities for the competition of channel access. As specified in the standard, the access categories are denoted as AC[Z] with $Z = 3, 2, 1$, and 0, where AC[3] represents the highest priority and AC[0] has the lowest priority. The special control functions described in Section 6.1 are designed to facilitate the implementation of the E-ARCR protocol. The operations of the proposed E-ARCR scheme is explained with an arbitrary network scenario in Section 6.2.

6.1 Functional Description

In order to provide prioritized ACs for different traffic, four queues in the same WS are utilized as four virtual stations to contend for channel access. Therefore, instead of adopting a single reservation table as in the ARCR scheme, the proposed E-ARCR protocol exploits four reservation tables in order to record different types of traffic from all the WSs in the network. Each of the four reservation tables will be labeled as $\mathbf{T}_{AC[Z]}$ which matches with the AC[Z] traffic, where $Z = 3, 2, 1$, and 0. The control fields similar to Definitions 1 to 4 are utilized in the E-ARCR protocol associated with different AC[Z]s, including $\mathrm{TAR}(Z)$, $\mathrm{NTO}(Z, r)$, $\mathrm{RTS\text{-}R}(Z)$, and $\mathrm{RFD}(Z, r)$. For example, $\mathrm{TAR}(Z)$ is defined as a control field to inform the AP that AC[Z] of a WS is intending to join the reservation table $\mathbf{T}_{AC[Z]}$.

Considering different priorities among the AC[Z]s, the initial window size $W_{AC[Z]}$ as well as the maximum backoff stage $M_{AC[Z]}$ will be different between the four AC[Z]s. Based on the information acquired from the control field $\mathrm{NTO}(Z, r)$, the random backoff number $k_{earcr,AC[Z]}$ for the specific AC[Z] within a WS will be selected as

$$k_{earcr,AC[Z]} = \begin{cases} U[0, 2^0 W_{AC[Z]} - 1], & r = 0, \\ U[2^{r-1} W_{AC[Z]}, 2^r W_{AC[Z]} - 1], & 1 \le r \le M_{AC[Z]}, \\ U[\ell \cdot 2^{M_{AC[Z]}-1} W_{AC[Z]}, \\ \quad u \cdot 2^{M_{AC[Z]}-1} W_{AC[Z]} - 1], & r > M_{AC[Z]}, \end{cases} \qquad (16)$$

where $\ell = r - M_{AC[Z]} + 1$ and $u = r - M_{AC[Z]} + 2$. Moreover, the AIFS value in the EDCA scheme for each AC[Z] is denoted as $AIFS_{AC[Z]}$ in order to govern different waiting time intervals to start the backoff process. Therefore, the parameters $W_{AC[Z]}$, $M_{AC[Z]}$, and $AIFS_{AC[Z]}$ for each of the four AC[Z] can be manipulated to affect different priorities among the ACs.

6.2 Network Scenarios

The operations of the proposed E-ARCR protocol without packet collisions and channel noise are depicted in Fig. 5. To clearly visualize the network behaviors of the proposed E-ARCR scheme, each of the two WSs is associated with two ACs including AC[1] for high priority and AC[0] for low-priority transmission. Therefore, there will be two reservation tables $\mathbf{T}_{AC[1]}$ and $\mathbf{T}_{AC[0]}$ exploited within the AP. At the beginning, all the four ACs contend for channel by adopting the EDCA scheme and there is no entry recorded in AP's reservation tables, i.e., $\mathbf{T}_{AC[1]} = \mathbf{T}_{AC[0]} = \{\}$. As AC[1] of node A successfully acquires the channel at time t_1, WS A will be added into the reservation table $\mathbf{T}_{AC[1]}$ as the first entry, i.e., $\mathbf{T}_{AC[1]} = \{T_0(A)\}$. After data packets have been successfully delivered from AC[1] of WS A to the AP, the AP will transmit the $\mathrm{ACK{+}NTO}(1,0)$ packet to WS A which indicates that AC[1] of WS A has the transmission order of 0. At the time instant t_2, all the four ACs will continue to contend for the channel access. As WS A has received the NTO(1,0) packet from the AP, WS A will adopt the E-ARCR scheme with random backoff mechanism as defined in (16); while the other three ACs will employ the conventional backoff scheme from the EDCA algorithm. Considering that AC[0] of WS B wins the channel contention and hence it will be recorded as a new entry in the reservation table as $\mathbf{T}_{AC[0]} = \{T_0(B)\}$. Similarly, in the case that AC[1] of WS B acquires the channel access at time t_3, it will join in the reservation table $\mathbf{T}_{AC[1]}$ as the second entry, i.e., $\mathbf{T}_{AC[1]} = \{T_0(A), T_1(B)\}$, and finally receives the $\mathrm{ACK{+}NTO}(1,1)$ packet from the AP after packet transmission.

Assuming that AC[1] of WS A obtains the channel access at time t_4, the RTS-R(1) packet will be delivered by WS A to initiate the reservation period for AC[1] in both WSs A and B. After receiving the $\mathrm{DATA{+}TAR}(1)$ packet from WS A, the AP will respond with the ACK+RFD(1,1) packet where the ACK packet is targeting for AC[1] of WS A and the RFD(1,1) packet is for AC[1] of WS B. According to the received RFD(1,1) message from the AP, AC[1] of WS B can deliver $\mathrm{DATA{+}TAR}(1)$ packet without the requirement for channel contention. At the end of the reservation period, the AP will change the entry order within the reservation table $\mathbf{T}_{AC[1]}$ in a round-robin manner, i.e., $\mathbf{T}_{AC[1]} = \{T_0(B), T_1(A)\}$. It is noted that similar reservation period will be implemented for AC[0] of both WSs A and B. Moreover, the proposed E-ARCR scheme can also be implemented in a more realistic network scenarios with the existence of packet collisions and channel noises, which can be extended from the descriptions as addressed in Section 4.3 for the ARCR protocol.

It is noticed that packet collision will not happen in the original ARCR scheme if all the WSs reside within the reservation table under error-free network environments. In the E-ARCR scheme, however, collisions may still exist even though all ACs in WSs are recorded within their corresponding reservation tables in the AP. The reason is contributed to the usage of more than one reservation table in the network. The first entries in those reservation tables will still contend with each other which results in the occurrence of packet collisions. This is considered the trade-offs by adopting the E-ARCR protocol as the QoS requirement is specified to be fulfilled. The performance of the proposed E-ARCR scheme will be evaluated and compared in Section 8.

7 THROUGHPUT ANALYSIS OF THE PROPOSED E-ARCR PROTOCOL

The throughput analysis of the proposed E-ARCR protocol can be regarded as an extension of that for the ARCR scheme addressed in Section 5. It is noted that certain portion of the WSs will still adopt the conventional EDCA scheme for channel contention; while others utilize the E-ARCR protocol. Therefore, the backoff process of the EDCA scheme will first be described in Section 7.1. The reservation probability for the E-ARCR scheme and the corresponding network throughput will be derived in Sections 7.2 and 7.3, respectively.

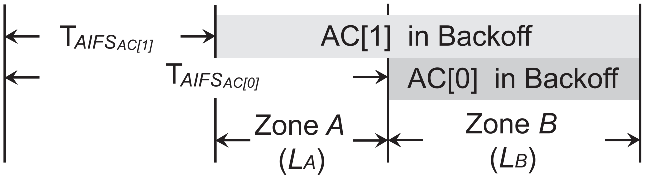

Fig. 6. The EDCA backoff process after the occurrence of busy medium.

7.1 Backoff Process of the EDCA Scheme

Existing research work [26], [27], [28], [29], [30], [31] has been conducted to analyze the backoff process of the EDCA protocol. An analytical approach for throughput and delay performance of the IEEE 802.11e EDCA scheme has been proposed in [26], [27] in order to observe the effect of different CWs and retry limits for each AC. Three-dimensional Markov Chain has been utilized in [28], [29] to model the EDCA mechanism. On the other hand, two-dimensional Markov Chain is adopted in [30], [31] by dividing the backoff interval into different time zones, which will be employed as the baseline model for analyzing the performance of the proposed E-ARCR scheme with additional consideration of error-prone channel effects. As was specified in previous work, without loss of generality, each of the N WSs is considered to possess two ACs in the analysis, including AC[1] and AC[0].

Apart from considering the WS as a whole in the DCF and ARCR schemes, each AC in a WS is viewed individually in the backoff process by adopting both the EDCA and E-ARCR protocols. The Markov chain model as shown in Fig. 3 can still be applied to the EDCA scheme except that individual AC is considered instated of the entire WS. Let $\tau_{AC[Z]}$ denote the probability that AC[Z] transmits the RTS packet in a randomly selected time slot, and $\overline{p}_{AC[Z]}$ is defined as the average probability that AC[Z] fails in transmission due to packet collision or frame errors. Similar to (4), the relationship between $\tau_{AC[Z]}$ and $\overline{p}_{AC[Z]}$ can be acquired as

$$\begin{aligned}\tau_{AC[Z]} = {} & 2(1-2\overline{p}_{AC[Z]}) \cdot [(1-2\overline{p}_{AC[Z]})(W_{AC[Z]}+1) \\ & + \overline{p}_{AC[Z]} W_{AC[Z]} (1-(2\overline{p}_{AC[Z]})^{M_{AC[Z]}})]^{-1}.\end{aligned} \tag{17}$$

It is noted that the averaged value $\overline{p}_{AC[Z]}$ is considered in (17) since the fail transmission probabilities are calculated in two different time zones for each AC[Z], which will be explained as follows: In order to distinguish different QoS requirements among distinct ACs, the ACs which belong to higher priorities will start their backoff processes after a shorter AIFS duration. A smaller number will be obtained by the ACs with higher priorities for backoff countdown, and therefore suffer from fewer channel contentions comparing with the ACs of lower priorities. As illustrated in Fig. 6, resulting from the various values of AIFSs, the backoff period can be divided into two different time regions including

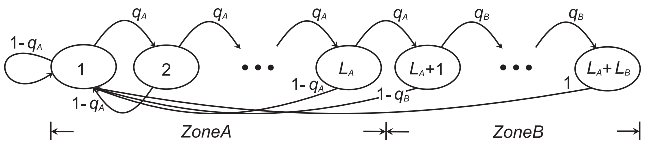

Fig. 7. The Morkov chain model for state transition between backoff slots in two different zones.

Zones A and B. Let L_A and L_B be referred as the numbers of time slots in Zones A and B, respectively. The entire time duration $L_A + L_B$ can be obtained as the maximal backoff window size $M_{AC[1]}$ of the highest priority AC[1], i.e., $L_A + L_B = \min\{2^{M_{AC[Z]}} \cdot W_{AC[Z]} | Z = 1, 0\} = 2^{M_{AC[1]}} W_{AC[1]}$. Within the duration of Zone A, only the high-priority AC[1]s can decrement their backoff numbers and have the chance to transmit their RTS packets. On other other hand, all ACs including both AC[1]s and AC[0]s will contend for channel access in Zone B if there does not exist AC[1] that intends to transmit in Zone A. As can be expected, the states of channel contention for Zones A and B, respectively, will be different.

To evaluate the stationary probability of each zone, it is assumed that every AC is independent to each other and the Morkov chain model for state transition between backoff slots is shown in Fig. 7. Suppose that there are $n_{AC[1]}$ AC[1]s and $n_{AC[0]}$ AC[0]s in the network, and let q_X denote the probability that there does not exist any AC transmitting in Zone X. Therefore, q_A and q_B can be calculated as

$$\begin{cases} q_A = (1 - \tau_{AC[1]})^{n_{AC[1]}}, \\ q_B = (1 - \tau_{AC[1]})^{n_{AC[1]}} (1 - \tau_{AC[0]})^{n_{AC[0]}}. \end{cases} \tag{18}$$

Let z_k be referred as the stationary probability that time slot k locates in the contention zones, which can consequently be acquired as

$$\begin{cases} z_k = z_1 \left(\prod_{i=2}^{k} q_A \right), & 1 < k \leq L_A + 1, \\ z_k = z_1 \left(\prod_{i=2}^{L_A+1} q_A \right) \left(\prod_{i=L_A+2}^{k} q_B \right), & L_A + 1 < k \leq L_A + L_B. \end{cases} \tag{19}$$

By associating (19) with the relationship $\sum_{k=1}^{L_A+L_B} z_k = 1$, the probability z_1 can be derived as

$$z_1 = \left[\frac{1 - {q_A}^{L_A+1}}{1 - q_A} + {q_A}^{L_A} q_B \frac{1 - {q_B}^{L_B-1}}{1 - q_B} \right]^{-1}. \tag{20}$$

Furthermore, let π_A and π_B be the stationary probabilities for a random time slot lies in Zones A and B, respectively. Both parameters can be calculated by incorporating the results from (19) and (20) as

$$\begin{cases} \pi_A = \sum_{k=1}^{L_A} z_k, \\ \pi_B = \sum_{k=1}^{L_B} z_{L_A+k}. \end{cases} \tag{21}$$

Since two different zones are considered in the analytical model of the EDCA scheme, additional derivations are required in order to depict the situations of packet collision. Let $P_{c,AC[Z],X}$ be defined as the collision probability of AC[Z] given that packet collisions occur within Zone X. The collision probabilities for the two types of ACs in contention zones A and B are, respectively, obtained as

$$\begin{cases} P_{c,AC[1],A} = 1 - (1 - \tau_{AC[1]})^{n_{AC[1]}-1}, \\ P_{c,AC[1],B} = 1 - (1 - \tau_{AC[1]})^{n_{AC[1]}-1} (1 - \tau_{AC[0]})^{n_{AC[0]}-1}, \\ P_{c,AC[0],A} = 0, \\ P_{c,AC[0],B} = 1 - (1 - \tau_{AC[1]})^{n_{AC[1]}} (1 - \tau_{AC[0]})^{n_{AC[0]}-1}. \end{cases} \tag{22}$$

Noted that the reason for $P_{c,AC[0],A} = 0$ in (22) is that AC[0] will only conduct packet transmission within Zone B. Moreover, let $\overline{P}_{c,AC[Z]}$ with $Z = 1$ and 0 be defined as the average collision probability of AC[Z] in these two contention zones. Since $\pi_A + \pi_B = 1$, the average collision probability $\overline{P}_{c,AC[1]}$ and $\overline{P}_{c,AC[0]}$ can be obtained by averaging (22) as

$$\begin{cases} \overline{P}_{c,AC[1]} & = \frac{P_{c,AC[1],A} \cdot \pi_A + P_{c,AC[1],B} \cdot \pi_B}{\pi_A + \pi_B} \\ & = P_{c,AC[1],A} \cdot \pi_A + P_{c,AC[1],B} \cdot \pi_B, \\ \overline{P}_{c,AC[0]} & = P_{c,AC[0],B}. \end{cases} \tag{23}$$

The average probability $\overline{p}_{AC[Z]}$ that AC[Z] fails in transmission due to packet collisions or channel noises can be acquired from (23) as

$$\overline{p}_{AC[Z]} = \overline{P}_{c,AC[Z]} + P_f - (\overline{P}_{c,AC[Z]} \cdot P_f) \tag{24}$$

for $Z = 1, 0$, and P_f denotes the packet error rate. From (18) to (24), it is observed that both $\overline{p}_{AC[1]}$ and $\overline{p}_{AC[0]}$ are functions of $\tau_{AC[1]}$ and $\tau_{AC[0]}$; while (17) provides another relationship between $\overline{p}_{AC[Z]}$ and $\tau_{AC[Z]}$ for $Z = 1$ and 0. Consequently, the unknown parameters $\overline{p}_{AC[1]}$, $\overline{p}_{AC[0]}$, $\tau_{AC[1]}$, and $\tau_{AC[0]}$ can be iteratively solved.

7.2 Derivation of Reservation Probability $P_{t,AC[Z]}$

The reservation probability $P_{t,AC[Z]}$ will be derived in this section. It is noted that $P_{t,AC[Z]}$ represents the transition probability that an AC[Z] of a WS either is in or will join in the reservation table $\mathbf{T}_{AC[Z]}$ for $Z = 1, 0$. As shown in Fig. 4, the derivation of reservation probability for the ARCR scheme can be extended to the E-ARCR protocol by considering the Markov model for each reservation table $\mathbf{T}_{AC[Z]}$ with $Z = 1, 0$. Let $\pi_{t,AC[Z]}$ be defined as the stationary probability that an AC[Z] of a WS stays in the reservation table $\mathbf{T}_{AC[Z]}$. Similar to (7), the relationship between $P_{t,AC[Z]}$ and $\pi_{t,AC[Z]}$ can be obtained as

$$\pi_{t,AC[Z]} = P_{t,AC[Z]}, \tag{25}$$

for $Z = 1, 0$. Another relationship between $P_{t,AC[Z]}$ and $\pi_{t,AC[Z]}$ is required for solving the reservation probability $P_{t,AC[Z]}$. Given that there are i AC[1]s and j AC[0]s in the reservation tables $\mathbf{T}_{AC[1]}$ and $\mathbf{T}_{AC[0]}$, respectively, the effective numbers of AC[1]s and AC[0]s that actually contend for channel access become $n_{e,i}$ and $n_{e,j}$ which can be obtained from (6) by replacing r with i and j. The parameters $P_{c,AC[Z],X,i,j}$ and $\tau_{AC[Z],i,j}$ are, respectively, denoted as the collision probabilities and the events that an AC[Z] transmits its RTS packet in a random slot time. Noted that the subscript X in $P_{c,AC[Z],X,i,j}$ indicates that the probability is computed for either Zone A or B with $X = A$ or B. By iteratively computing the relationship from (17) to (24), the set of parameters $P_{c,AC[Z],X,i,j}$ and $\tau_{AC[Z],i,j}$ can be obtained for $i, j = 0$ to N. It is noticed that the parameters $n_{AC[1]}$ and $n_{AC[0]}$ in (17)-(24) are, respectively, replaced by $n_{e,i}$ and $n_{e,j}$ with the consideration of reservation tables. Moreover, the reservation probability $P_{t,AC[Z]}$ can also be regarded as the probability of successful transmission under the situations that an AC[Z] is either inside or outside of its corresponding reservation table $\mathbf{T}_{AC[Z]}$, i.e.,

$$\begin{aligned} P_{t,AC[Z]} = &\sum_{i=0}^{N}\sum_{j=0}^{N} C_i^N \pi_{t,AC[1]}^i (1-\pi_{t,AC[1]})^{N-i} \\ &\cdot C_j^N \pi_{t,AC[0]}^j (1-\pi_{t,AC[0]})^{N-j} P_{t,AC[Z],i,j} \end{aligned} \tag{26}$$

for $Z = 1, 0$. It is noted that $P_{t,AC[Z],i,j}$ in (26) represents the probability that an AC[Z] of a WS joins in the reservation table $\mathbf{T}_{AC[Z]}$ (for $Z = 1, 0$) given that there are i AC[1]s and j AC[0]s in the reservation tables $\mathbf{T}_{AC[1]}$ and $\mathbf{T}_{AC[0]}$, respectively. Both parameters can be derived as

$$\begin{aligned} P_{t,AC[1],i,j} = &\pi_{A,i,j}(1-P_f)\left[\frac{n_{e,i}}{N}(1-P_{c,AC[1],A,i,j}) + \frac{N-n_{e,i}}{N}\right] \\ &+ \pi_{B,i,j}(1-P_f)\left[\frac{n_{e,i}}{N}(1-P_{c,AC[1],B,i,j}) + \frac{N-n_{e,i}}{N}\right], \end{aligned} \tag{27}$$

$$P_{t,AC[0],i,j} = (1-P_f)\left[\frac{n_{e,j}}{N}(1-P_{c,AC[0],B,i,j}) + \frac{N-n_{e,j}}{N}\right], \tag{28}$$

where $\pi_{A,i,j}$ and $\pi_{B,i,j}$ are extended from (21) by considering i AC[1]s and j AC[0]s in their corresponding reservation tables. As a result, the reservation probability $P_{t,AC[Z]}$ in (26) and $\pi_{t,AC[Z]}$ in (25) for $Z = 1, 0$ can be acquired by solving the corresponding nonlinear function, which will be utilized in the computation of throughput performance for the E-ARCR protocol.

7.3 Throughput Performance of the Proposed E-ARCR Protocol

The analytical model for throughput performance of the proposed E-ARCR protocol can be regarded as an extension of that derived for the ARCR scheme in Section 5.3 with additional consideration of different prioritized traffic. As there are i AC[1]s and j AC[0]s in the reservation tables $\mathbf{T}_{AC[1]}$ and $\mathbf{T}_{AC[0]}$, respectively, the parameter $P_{tr,AC[Z],i,j}$ is defined as the probability that there exists at least one AC[Z] to be transmitted in a slot time; while $P_{s,AC[Z],X,i,j}$ is referred as the probability that one AC[Z] successfully transmits its packet in Zone X for $X = A, B$ and $Z = 1, 0$. Therefore, the corresponding probabilities can be obtained as follows:

$$\begin{cases} P_{tr,AC[1],i,j} = 1 - [1-\tau_{AC[1],i,j}]^{n_{e,i}}, \\ P_{tr,AC[0],i,j} = 1 - [1-\tau_{AC[0],i,j}]^{n_{e,j}}, \end{cases} \tag{29}$$

and

$$\begin{cases} P_{s,AC[1],A,i,j} = \frac{n_{e,i}\cdot\tau_{AC[1],i,j}[1-\tau_{AC[1],i,j}]^{n_{e,i}-1}}{P_{tr,AC[1],i,j}}, \\ P_{s,AC[1],B,i,j} \\ \quad = \frac{n_{e,i}\cdot\tau_{AC[1],i,j}[1-\tau_{AC[1],i,j}]^{n_{e,i}-1}[1-\tau_{AC[0],i,j}]^{n_{e,j}-1}}{P_{tr,AC[1],i,j}}, \\ P_{s,AC[0],B,i,j} \\ \quad = \frac{n_{e,j}\cdot\tau_{AC[0],i,j}[1-\tau_{AC[1],i,j}]^{n_{e,i}}[1-\tau_{AC[0],i,j}]^{n_{e,j}-1}}{P_{tr,AC[0],i,j}}, \end{cases} \tag{30}$$

where $\tau_{AC[Z],i,j}$ for $Z = 1, 0$ can be computed from previous section given that there exists $n_{e,i}$ AC[1]s and $n_{e,j}$ AC[0]s contending for the channel access. Furthermore, it is required to calculate the average payload size in each transmission for the E-ARCR protocol. Let $E[P_{AC[Z],i,j}]$ be the average payload size of AC[Z]s in a transmission while there are i AC[1]s and j AC[0]s in the reservation tables $\mathbf{T}_{AC[1]}$ and $\mathbf{T}_{AC[0]}$, respectively. The parameter $E[P_{AC[Z],i,j}]$ can be obtained as

$$\begin{cases} E[P_{AC[1],i,j}] = \Big[\pi_{A,i,j} P_{tr,AC[1],i,j} P_{s,AC[1],A,i,j} \\ \qquad + \pi_{B,i,j} P_{tr,AC[1],i,j} P_{s,AC[1],B,i,j}\Big](1-P_f)\frac{N}{n_{e,i}}E[P], \\ E[P_{AC[0],i,j}] = \pi_{B,i,j} P_{tr,AC[0],i,j} P_{s,AC[0],B,i,j}(1-P_f)\frac{N}{n_{e,j}}E[P], \end{cases} \tag{31}$$

for $Z = 1, 0$, and $E[P]$ denotes the average payload size for both AC[1] and AC[0]. Therefore, the average slot time $\mathcal{T}_{av,i,j}$ for a transmission can be written as

$$\mathcal{T}_{av,i,j} = \pi_{A,i,j}\cdot\rho_{A,i,j} + \pi_{B,i,j}\cdot\rho_{B,i,j}, \tag{32}$$

where $\rho_{X,i,j}$ is referred as the average slot time utilized for a transmission in Zone X as

$$\begin{aligned} \rho_{A,i,j} &= P_{I,A,i,j}\cdot\sigma + P_{tr,AC[1],i,j}P_{s,AC[1],A,i,j}\cdot\mathcal{T}_{s,i} \\ &\quad + [1 - P_{I,A,i,j} - P_{tr,AC[1],i,j}P_{s,AC[1],A,i,j}]\cdot\mathcal{T}_c, \\ \rho_{B,i,j} &= P_{I,B,i,j}\cdot\sigma + P_{tr,AC[1],i,j}P_{s,AC[1],B,i,j}\cdot\mathcal{T}_{s,i} \\ &\quad + P_{tr,AC[0],i,j}P_{s,AC[0],B,i,j}\cdot\mathcal{T}_{s,j} \\ &\quad + [1 - P_{I,B,i,j} - P_{tr,AC[1],i,j}P_{s,AC[1],B,i,j} \\ &\quad - P_{tr,AC[0],i,j}P_{s,AC[0],B,i,j}]\cdot\mathcal{T}_c. \end{aligned} \tag{33}$$

It is noted that $P_{I,X,i,j}$ in (33) denotes the probability that the channel is idle in Zone X, which can be acquired as

$$\begin{cases} P_{I,A,i,j} = [1-\tau_{AC[1],i,j}]^{n_{e,i}}, \\ P_{I,B,i,j} = [1-\tau_{AC[1],i,j}]^{n_{e,i}}[1-\tau_{AC[0],i,j}]^{n_{e,j}}. \end{cases} \tag{34}$$

The time $\mathcal{T}_c$ for an AC of a WS to sense the collisions can be obtained similar to T_c in (13) with additional consideration of QoS requirement, i.e.,

$$\mathcal{T}_c = T_{RTS-R} + \delta + T_{CTS} + \delta + T_{SIFS} + T_{AIFS_{AC[1]}}. \tag{35}$$

On the other hand, similar to (14), both the required time $\mathcal{T}_{s,k}$ (for $k = i$ or j) for a successful transmission and the time duration of failed transmission $\mathcal{T}_{f,k}$ are considered equal with the same reason as described in Section 5.3. Since $\mathcal{T}_{f,k} = \mathcal{T}_{s,k}$, both values are combined and utilized in (33) as

$$\begin{aligned} \mathcal{T}_{s,k} = &\frac{n_{e,k}-1}{n_{e,k}}[T_{RTS-R} + T_{CTS} + T_{PHY} + T_{MAC} + T_{E[P]} \\ &+ T_{ACK+NTO} + 3T_{SIFS} + 4\delta + T_{AIFS_{AC[1]}}] \\ &+ \frac{1}{n_{e,k}}[T_{RTS-R} + T_{CTS} + T_{SIFS} + 2\delta + T_{AIFS_{AC[1]}} \\ &+ (N - n_{e,k} + 1)(T_{PHY} + T_{MAC} + T_{E[P]} \\ &+ T_{ACK+NTO} + 2T_{SIFS} + 2\delta)]. \end{aligned} \tag{36}$$

By incorporating $\pi_{t,AC[Z]}$ in (25), $E[P_{AC[Z],i,j}]$ in (31), and $\mathcal{T}_{av,i,j}$ in (32), the average system throughput $S_{AC[Z]}$ conditioned on i AC[1]s and j AC[0]s within the reservation tables $\mathbf{T}_{AC[1]}$ and $\mathbf{T}_{AC[0]}$ can be derived as (37) for $Z = 1, 0$. The throughput performance $S_{AC[Z]}$ in (37) for the proposed E-ARCR scheme will be validated and evaluated in Section 8.2.1.

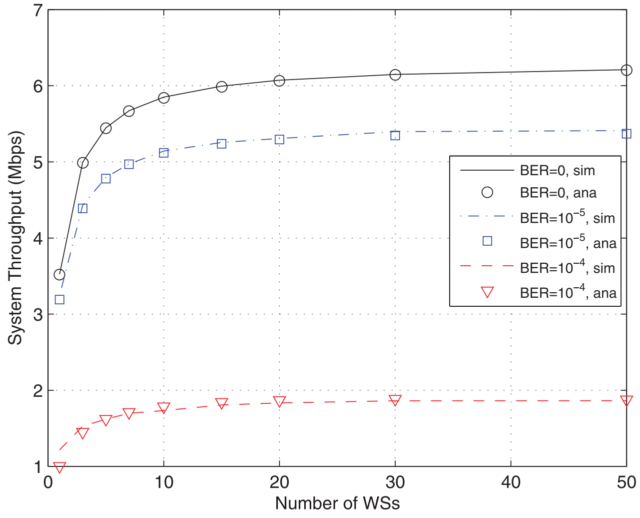

Fig. 8. Performance validation for the ARCR protocol: system throughput versus number of WSs.

$$S_{AC[Z]} = \left(\sum_{i=0}^{N} \sum_{j=0}^{N} C_i^N \pi^i_{t,AC[1]} \left(1-\pi_{t,AC[1]}\right)^{N-i} C_j^N \pi^j_{t,AC[0]} \left(1-\pi_{t,AC[0]}\right)^{N-j} \cdot E[P_{AC[Z],i,j}] \right) \Bigg/ \left(\sum_{i=0}^{N} \sum_{j=0}^{N} C_i^N \pi^i_{t,AC[1]} \left(1-\pi_{t,AC[1]}\right)^{N-i} C_j^N \pi^j_{t,AC[0]} \left(1-\pi_{t,AC[0]}\right)^{N-j} \cdot T_{av,i,j} \right). \quad (37)$$

8 PERFORMANCE EVALUATION

In this section, the performance of the proposed ARCR and E-ARCR protocols will be validated and compared with existing schemes via the well-developed network simulator (NS-2) [32]. All the simulation runs will be conducted for 100 seconds. Performance validation and comparison for the ARCR scheme are conducted in Sections 8.1.1 and 8.1.2; while that for the E-ARCR protocol are shown in Sections 8.2.1 and 8.2.2.

8.1 Performance Validation and Comparison for the ARCR Protocol

8.1.1 Performance Validation

In order to validate the analytical model for the proposed ARCR scheme, the system throughput S as derived in (15) is compared with simulation results as shown in Figs. 8 and 9. 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. Fig. 8 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. 9 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.

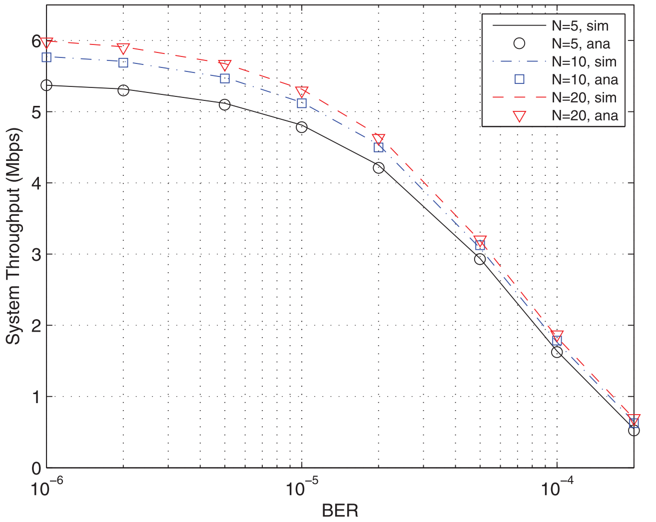

Fig. 9. Performance validation for the ARCR protocol: system throughput versus BER.

8.1.2 Performance Comparison

As shown in Figs. 10, 11, 12, and 13, the proposed ARCR protocol is compared with the DCF and GDCF schemes [5], [6] 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 set equal to 2. Fig. 10 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 two protocols under different numbers of WSs, e.g., around 50 percent gain at $N = 10$ under error-free channel condition. Noted that the GDCF method is slightly superior to the DCF scheme with more 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

TABLE 1
System Parameters

Parameter	Value	
	ARCR	E-ARCR
Minimum window size (W)	32	Not applicable
Maximum backoff stage (M)	5	Not applicable
Data rate	11 Mbps	
Basic rate	1 Mbps	
Slot time (σ)	20 μs	
T_{SIFS}	10 μs	
T_{DIFS}	50 μs	Not applicable
PHY header	192 bits	
Propagation delay (δ)	1 μs	
Payload size ($E[P]$)	8184 bits	
MAC header + TAR	224 bits	240 bits
RTS/RTS-R	160 bits	176 bits
CTS	112 bits	
ACK + RFD/NTO	$112 + 16$ bits	$128 + 16$ bits

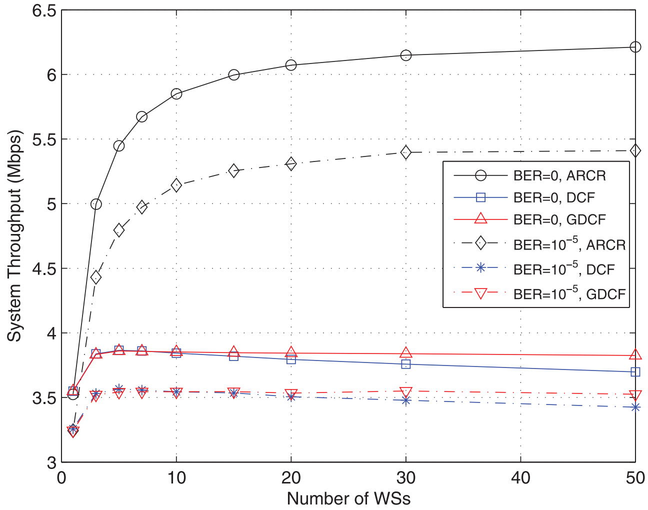

Fig. 10. Performance comparison for the ARCR protocol: system throughput versus number of WSs.

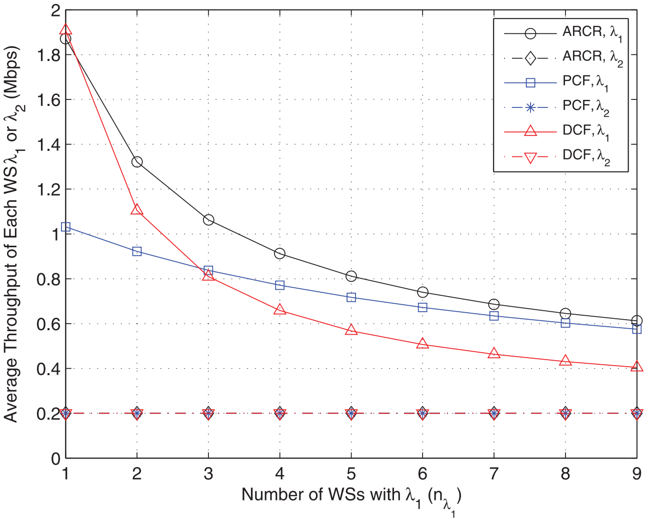

Fig. 12. Performance comparison for the ARCR protocol: average throughput of each WS versus number of WSs with λ_1 (n_{λ_1}) ($n_{\lambda_2} = 10 - n_{\lambda_1}$, $\lambda_1 = 2$ Mbps, and $\lambda_2 = 0.2$ Mbps).

incurred by adopting the GDCF scheme especially under larger number of WSs, which results in comparably larger system throughput. Fig. 11 illustrates the comparison of throughput performance versus different BER values under $N = 5$ and 50. The proposed ARCR protocol still outperforms the other two schemes under various BER values, e.g., around 33 percent gain at BER = 10^{-5} under $N = 5$ scenario. It can also be observed that the system throughput of three 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.

Moreover, the proposed ARCR protocol is compared with the distributed DCF scheme and the centralized PCF protocol given that the arrival rate is constant bit rate (CBR) and the queue size is equal to 50 in each WS. 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 or bps) and with low packet arrival rate (λ_2 bps). Note that the unit of bps is applied to represent packet arrival rate. 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. 12. Noted that the packet arrival rates $\lambda_1 = 2$ Mbps and $\lambda_2 =$ 200 Kbps, and the number of WSs with packets arrival rate

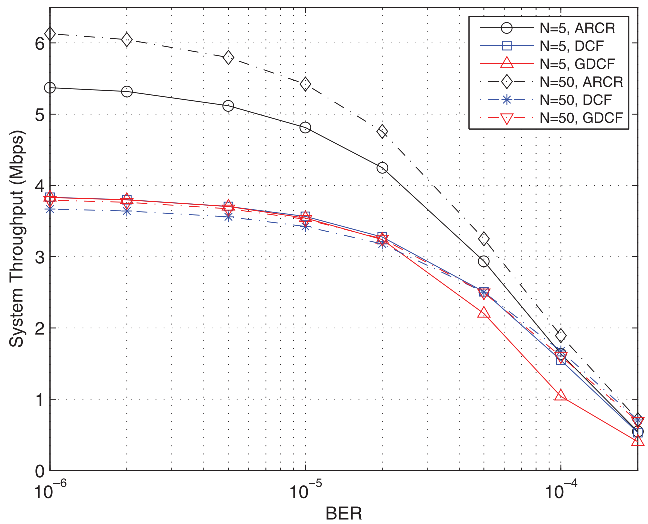

Fig. 11. Performance comparison for the ARCR protocol: system throughput versus BER.

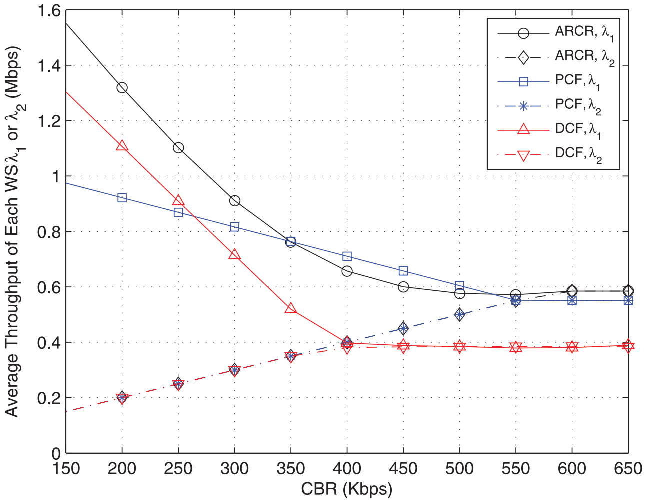

Fig. 13. Performance comparison for the ARCR protocol: average throughput of each WS versus packet arrival rate λ_2 ($n_{\lambda_1} = 2$, $n_{\lambda_2} = 8$, and $\lambda_1 = 2$ Mbps).

TABLE 2
Backoff Parameters for Different ACs

Access Category (AC[Z])	$W_{AC[Z]}$	$M_{AC[Z]}$	$AIFSN_{AC[Z]}$
VO	8	1	2
VI	16	1	2
BE	32	5	3
BK	32	5	7

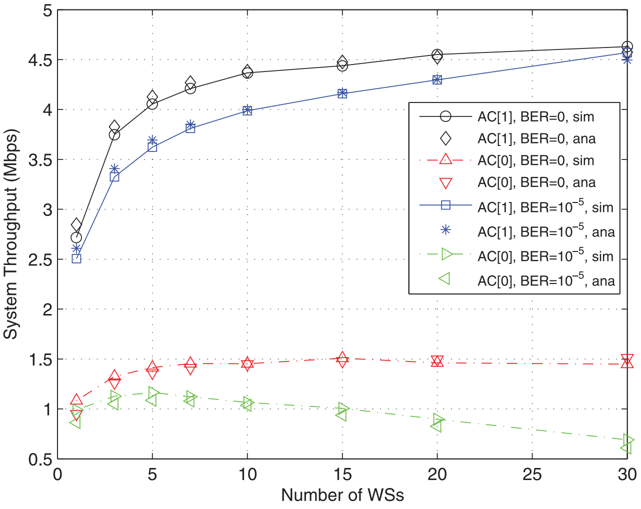

Fig. 14. Performance validation for the E-ARCR protocol: system throughput versus number of WSs for the VI (AC[1]s) and BE (AC[0]s) traffic.

λ_2 becomes $n_{\lambda_2} = 10 - n_{\lambda_1}$. It can be observed from Fig. 12 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 the 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.

Fig. 13 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 overheads resulting from the centralized-based PCF scheme. Therefore, the merits of adopting the proposed ARCR scheme can be perceived.

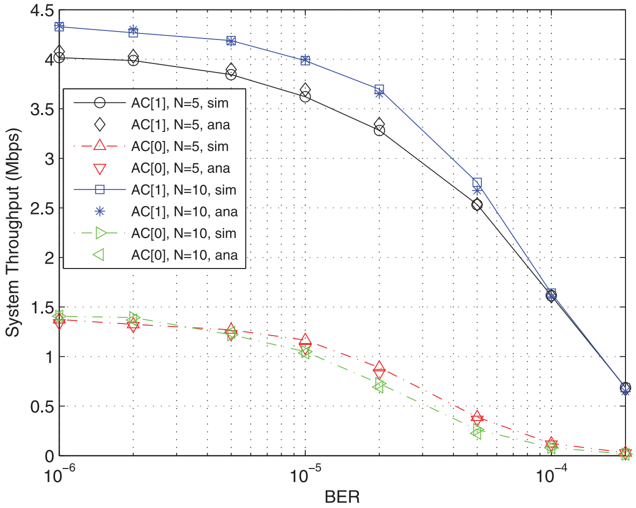

Fig. 15. Performance validation for the E-ARCR protocol: system throughput versus BER for the VI (AC[1]s) and BE (AC[0]s) traffic.

8.2 Performance Validation and Comparison for the E-ARCR Protocol

8.2.1 *Performance Validation*

In this section, the proposed E-ARCR protocol with different QoS considerations is validated and evaluated via simulations. The system parameters listed in Table 1 are also utilized; while the backoff parameters for different ACs in the proposed E-ARCR protocol are referred from the EDCA scheme and are listed in Table 2. It is noted that the four ACs defined in the EDCA protocol has the priority from high to low as follows: voice (VO), video (VI), best effort (BE), and background (BK). Saturation traffic is assumed for the queue of each AC. The corresponding $T_{AIFS_{AC[Z]}}$ value for each AC[Z] traffic can be obtained as $T_{AIFS_{AC[Z]}} = \sigma \cdot AIFSN_{AC[Z]} + T_{SIFS}$.

The analytical model for throughput performance $S_{AC[Z]}$ in (37) of the proposed E-ARCR scheme is validated via simulations with prioritized ACs in terms of different numbers of WSs (N) and BER values. Figs. 14 and 15 show the performance validation for both the VI (i.e., AC[1]s) and BE (i.e., AC[0]s) traffic. It is assumed that each WS has both AC[1] and AC[0] to be transmitted, and the relationship between the system throughput and the number of WSs is represented in Fig. 14 under BER $= 0$ and 10^{-5}. It can be seen that the analytical model can match with the simulated results under different numbers of WSs. By observing the case of AC[0] with BER $= 10^{-5}$, the system throughput first

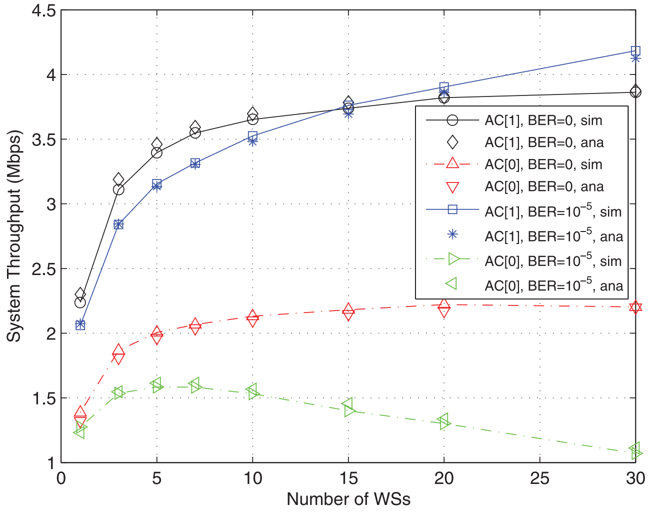

Fig. 16. Performance validation for the E-ARCR protocol: system throughput versus number of WSs for the BE (AC[1]s) and BK (AC[0]s) traffic.

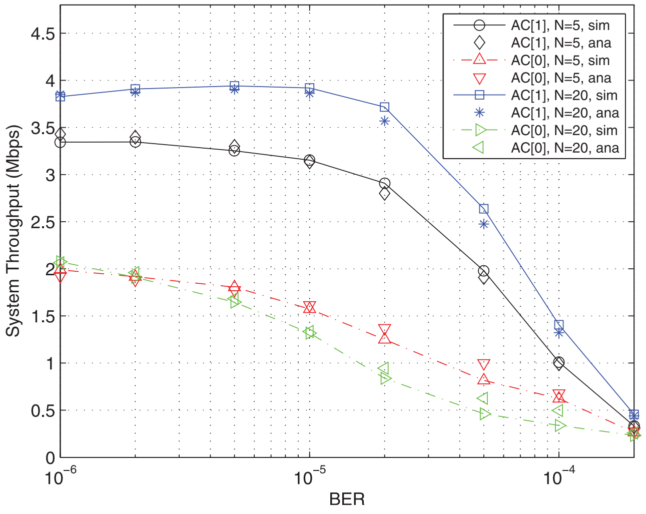

Fig. 17. Performance validation for the E-ARCR protocol: system throughput versus BER for the BE (AC[1]s) and BK (AC[0]s) traffic.

increases and decreases afterwards as the number of WSs is augmented. This is mainly caused by its lower priority and higher BER conditions that make most of the AC[0]s depart from the reservation table $\mathbf{T}_{AC[0]}$ to compete for the channel access with the increased number of WSs. Severe packet collision will consequently be incurred which leads to the degradation of system throughput. Fig. 15 shows the system throughput versus the BER values with $N = 5$ and 10, in which both the analytical and simulation results are coincide with each other. It is also observed that the two cases of AC[0]s (i.e., with $N = 5$ and 10) intersect with each other around BER $= 3.5 \times 10^{-6}$. With lower BER values, most of the AC[0]s are located in the reservation table $\mathbf{T}_{AC[0]}$ such that the throughput will be higher with larger number of WSs, i.e., $N = 10$. However, with increased BER values, it is difficult for the AC[0]s to be recorded in $\mathbf{T}_{AC[0]}$ which results in severe packet collisions and degraded system throughput as the number of WSs is larger.

In order to verify the analytical throughput with different AC pairs, the ACs with BE and BK types are chosen as AC[1]s and AC[0]s, respectively, in the following validations. As depicted in Table 2, the time slot difference between the BE and BK traffic is four, i.e., $AIFSN_{AC[0]} - AIFSN_{AC[1]} = 4$; while that for the previous case between the VI and BE traffic is one. Therefore, a larger size of Zone A will be acquired in this case as shown in Fig. 6 since larger difference between $T_{AIFS_{AC[0]}}$ and $T_{AIFS_{AC[1]}}$ is obtained. With larger size of Zone A, AC[1]s will have better chance to win the channel access, which consequently results in declined throughput performance for AC[0]s as the BER values are increased. This intuitive concepts can be validated by observing the difference between the two cases with AC[1] and AC[0] in both Figs. 14 and 16 as follows: By adopting the E-ARCR scheme under the case with BER $= 0$, almost all AC[1]s and AC[0]s should be recorded in their corresponding reservation tables, which results in the situations that only the first two entries in $\mathbf{T}_{AC[1]}$ and $\mathbf{T}_{AC[0]}$ are contending for the channel access. However, as the BER value becomes 10^{-5}, some of the ACs will be removed from their corresponding reservation tables, which incurs comparably severe channel contention. In the case that larger Zone A is acquired by implementing both BE and BK traffic, AC[1]s will have higher opportunity to obtain the channel access compared to AC[0]s.

As shown in Fig. 16, AC[1]s with BER $= 10^{-5}$ can even exceed that with BER $= 0$ under larger number of WSs since most of the AC[0]s are blocked from contending the channel under BER $= 10^{-5}$. Consequently, as the number of WSs is increased, AC[0] will suffer from the degraded system throughput as illustrated in Fig. 16. It is also noted that the total system throughput from AC[1]s and AC[0]s at BER $=$ 0 is still higher than that at BER $= 10^{-5}$, e.g., around 6 Mbps at BER $= 0$ compared to 5.3 Mbps at BER $= 10^{-5}$ under $N = 30$ in Fig. 16. This prioritized blocking situations is not remarkable in Fig. 14 due to the smaller size of Zone A, which will not significantly promote the system throughput for AC[1]s. Fig. 17 shows the system throughput versus BER for both the BE and BK traffic under $N = 5$ and 20. Similar performance trends can be observed in comparison with Fig. 15 where the system throughput in all cases decrease as the BER values are increased. Owing to the prioritized blocking situation as described in the previous paragraph, the throughput with AC[1]s and $N = 20$ will be slightly augmented as the BER values are increased until the BER value reaches around 5×10^{-6}.

8.2.2 Performance Comparison

To evaluate the throughput performance in the sense of QoS requirements, the proposed E-ARCR protocol is compared with the EDCA scheme under different prioritized ACs. It is also assumed that the queue of each AC is saturated. Noted that the centralized HCCA protocol is not utilized for performance comparison due to its fair scheduling-based polling approach, which will not be suitable to be compared with the prioritized-based classifications within the E-ARCR scheme. In the HCCA protocol, the CFP supports high-priority traffic and low-priority packets are transmitted in the CP. There does not exist a convincing method to determine the ratio of CFP to CP, which makes the comparison between the proposed E-ARCR scheme and HCCA protocol difficult. The simulation parameters can be obtained from Tables 1 and 2.

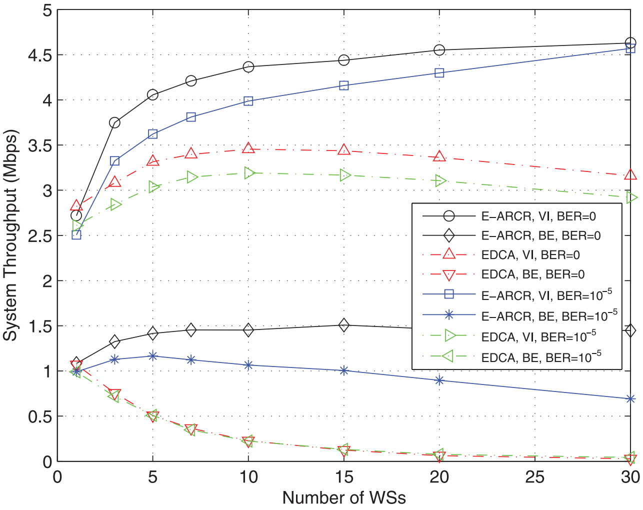

Fig. 18. Performance comparison for the E-ARCR protocol: system throughput versus number of WSs for the VI and BE traffic.

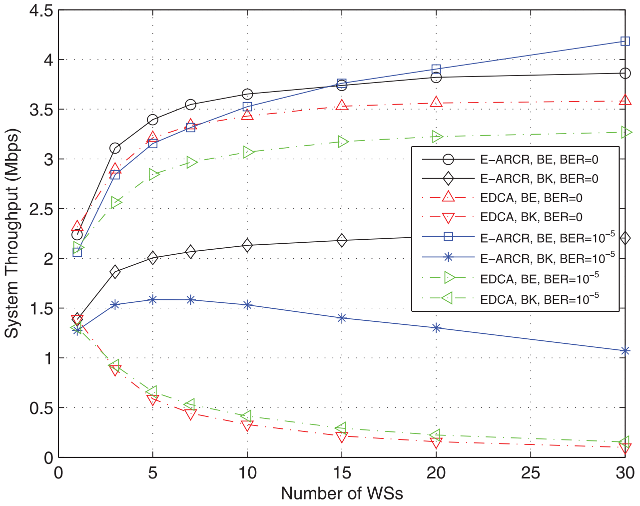

Fig. 20. Performance comparison for the E-ARCR protocol: system throughput versus number of WSs for the BE and BK traffic.

Fig. 18 shows the system throughput of VI and BE traffic versus the number of WSs under BER $= 0$ and 10^{-5}. The E-ARCR protocol can provide higher throughput performance in both the VI and BE traffic compared to that from the EDCA scheme under different numbers of WSs, e.g., around 20 percent gain and 200 percent gain for VI and BE traffic at $N = 5$ under BER $= 0$ condition, respectively. As the number of WSs is augmented, the system throughput from the EDCA method with VI traffic under both BER $= 0$ and 10^{-5} will increase and decrease afterwards owing to severe packet collisions with larger numbers of WSs. Moreover, the EDCA scheme also results in poor system throughput on the BE traffic primarily due to both the severe packet collisions and the BE's comparably lower priority. Fig. 19 illustrates the system throughput of both the VI and BE traffic versus BER under $N = 5$ and 30. It can be observed that the throughput of the E-ARCR scheme with VI cases is higher as $N = 30$ compared to that equals 5 until BER exceeds 10^{-4}. On the other hand, due to severe packet collisions, the throughput performance for the VI traffic with larger number of WSs ($N = 30$) will be less than that with smaller number of WSs ($N = 5$) by adopting the EDCA protocol. Furthermore, similar to the explanation as described in Fig. 15, the two BE traffic by adopting the proposed E-ARCR scheme (i.e., with $N = 5$ and 30) intersect with each other, which denotes higher throughput for the case of $N = 5$ compared to that for $N = 30$ under higher BER values. The reason is attributed to the situation that most of the ACs are removed from the reservation tables by adopting the E-ARCR protocol, which results in higher packet collisions in the network.

Fig. 20 illustrates the system throughput of both BE and BK traffic versus the number of WSs under BER $= 0$ and 10^{-5}, while Fig. 21 depicts the system throughput of both BE and BK traffic versus BER under $N = 5$ and 30. The prioritized blocking situation as described in Fig. 16 is also observed in Fig. 20 by adopting the proposed E-ARCR scheme with BE traffic, where higher throughput is obtained under BER $= 10^{-5}$ compared to that at BER $= 0$ with larger number of WSs. This phenomenon also results in the increased system throughput at BER $= 10^{-5}$ by exploiting the E-ARCR protocol with BE at $N = 30$ as in

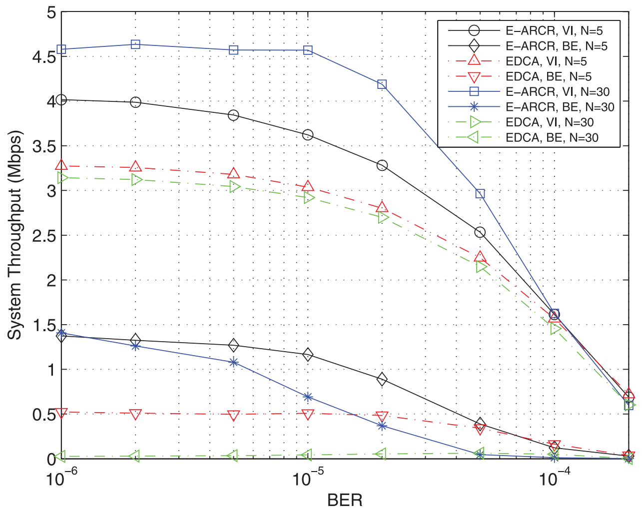

Fig. 19. Performance comparison for the E-ARCR protocol: system throughput versus BER for the VI and BE traffic.

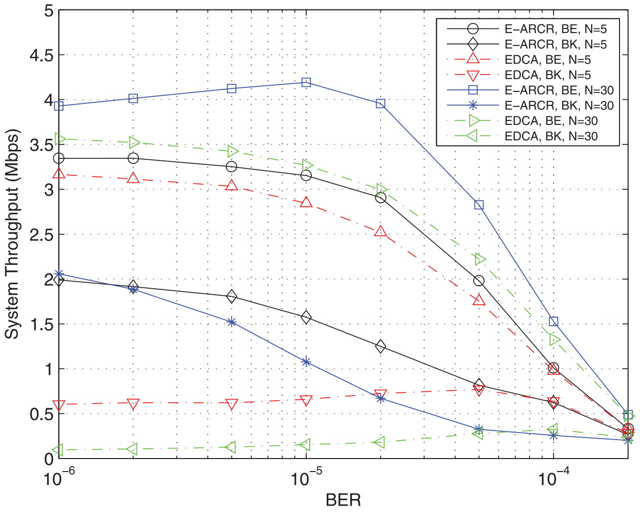

Fig. 21. Performance comparison for the E-ARCR protocol: system throughput versus BER for the BE and BK traffic.

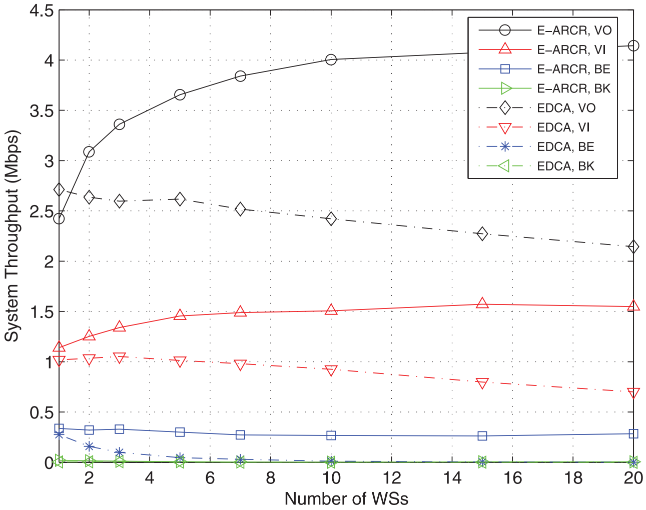

Fig. 22. Performance comparison: system throughput versus the number of WSs for VO, VI, BE, and BK traffic (BER $= 0$).

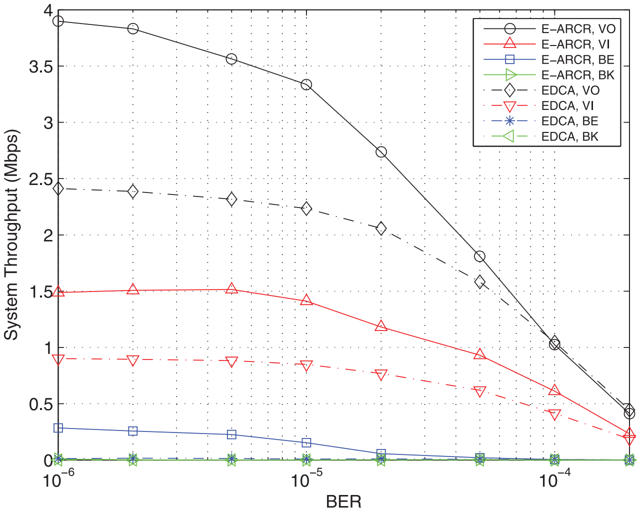

Fig. 23. Performance comparison: system throughput versus BER for VO, VI, BE, and BK traffic ($N = 10$).

Fig. 21. Furthermore, comparing the EDCA BE traffic in Fig. 20 with the EDCA VI traffic in Fig. 18, the throughput performance of the EDCA BE traffic will not decrease as the number of WSs is increased. The reason is that $W_{BE} = 32$ and $M_{BE} = 5$ are large enough for the EDCA BE traffic to handle additional backoff processes and consequently reduce the collision probability. On the other hand, the parameters $W_{VI} = 16$ and $M_{VI} = 1$ of EDCA VI traffic are comparably small that ACs with VI traffic will frequently collide with each other, which results in degraded system throughput as the number of WSs is augmented.

Finally, the proposed E-ARCR protocol is compared with the EDCA scheme by considering all different types of ACs, including VO, VI, BE, and BK traffic. Fig. 22 shows the system throughput of each traffic type versus the number of WSs for BER $= 0$. It can be observed that the throughput of VO, VI, and BE traffic from the proposed E-ARCR scheme increases with the number of WSs; while that for the EDCA protocol is decreased as the number of WSs is augmented. Noted that the throughput of BK traffic in both the E-ARCR and EDCA methods is nearly equal to zero due to its lowest channel access priority. The reason for the degraded throughput performance of the EDCA scheme can be attributed to the small sizes of contention windows and insufficient backoff stages that are designed to secure high-priority traffic, e.g., $M_{VO} = 1$ and $W_{VO} = 8$. This can result in severe packet collision in the case that there exists excessive number of WSs in the network. On the other hand, there are almost only four ACs (i.e., the first entry from each of the four reservation tables) competing for the channel access by adopting the proposed E-ARCR scheme under $\text{BER} = 0$. Consequently, the collisions scarcely happen and the QoS requirement of the E-ARCR VI traffic can be achieved without sacrificing system throughput. Fig. 23 depicts the system throughput for each of the four traffic types versus BER given that $N = 10$. It can be observed that the proposed E-ARCR can outperform the conventional EDCA scheme under most of the BER values, e.g., with additional 1.1 Mbps of system throughput can be acquired by the E-ARCR VO traffic under $\text{BER} = 10^{-5}$. The merits of the proposed E-ARCR protocol can consequently be observed which can fulfill the QoS requirements with enhanced network throughput.

9 CONCLUSION

In this paper, an adaptive reservation-assisted collision resolution 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 piggyback mechanisms. Based on the design of reservation table at the access point, excessive packet collision can be effectively alleviated and the random access backoff delays can be reduced in the networks. Moreover, in order to support QoS requirements, an enhanced ARCR protocol is proposed by applying multiple reservation tables at the AP for each prioritized traffic. It will not only increase the throughput of ACs with higher priority but also prevent the ACs with lower priority from starvation of channel access. The analytical models of system throughput for both the proposed ARCR and E-ARCR protocols are derived and validated via simulations. Numerical results show that the proposed ARCR and E-ARCR protocols outperform the other existing schemes with enhanced network throughput and better channel utilization.

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