

Distributed Collision-Resolvable Medium Access Control for Wireless LANs with Interference Cancellation Support

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Abstract

Medium access control is critical in wireless networks for efficient spectrum utilization. In this paper, we introduce a novel collision resolution method based on the technique of known interference cancellation, and propose a new MAC protocol named as CR-MAC, in which AP tries to decode all the collided data packets by combining partial retransmissions and known interference cancellation. As the collided transmissions are fully utilized, less retransmission is required, especially in a crowded network. The NS-2 simulation and MATLAB numerical results show that, under various network settings, CR-MAC performs much better than the IEEE 802.11 DCF in terms of the aggregation throughput and the expected packet delay.

Keywords: interference cancellation, MAC protocol, collision resolution

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1. Introduction

Due to the scarce spectrum resource available in wireless LANs (WLANs), the design of effective and efficient medium access control (MAC) protocols that regulate the access of stations to the shared spectrum is critical to wireless network performance. The conventional approaches, e.g., IEEE 802.11 standards including a/b/g/n, share the channelized spectrum resource by slicing it across time, and allocate each slice to at most one station at any time. When multiple stations transmit simultaneously, a collision occurs and no useful data is delivered. Unfortunately, collision is common in WLANs. For example, measurements from a production WLAN show that, more than 10% of the communication links experience severe packet loss due to collisions [1]. The situation is much more severe in the presence of hidden terminals: either the sender stations repeatedly collide with each other and the throughput decline drastically or one sender station captures the channel preventing the others from accessing the channel [2].

To mitigate the impact of collisions in WLANs, IEEE 802.11 standards mainly rely on two mechanisms: carrier sensing with exponential backoff and RTS/CTS handshake. Carrier sensing with exponential backoff allows a sender station to sense the channel, abstain from transmission when the channel is busy, and increase the contention window size exponentially when a collision occurs. Though such mechanism works well in most cases, it fails in the networks with hidden terminals. To eliminate the hidden terminal, IEEE 802.11 adopts a RTS/CTS handshake mechanism, where every sender station must first try to reserve the channel and transmits only if it successfully acquires the reservation. However, experimental results show that, due to the large coordination overhead, RTS/CTS is ineffective in reducing the packet delay and improving network throughput [3, 4]. In fact, the overhead of either of the two mechanisms is high, especially when the data packet is short or the physical data rate is high, and when there are some long-distance communication links in the networks [5].

One of the fundamental reasons is that, the IEEE 802.11 relies on the idea of collision avoidance: on one hand, the collided packets are simply discarded, meaning that no useful information is delivered during the whole collision transmission period; on the other hand, a very high proportion of time is used to retransmit the collided packet even when the major part of the packet already transmitted successfully.

In this paper, rather than collision avoidance, we attempt to embrace the interference and investigate the feasibility of using known interference cancellation (KIC) [6] to enhance the capability of the AP (access point) of resolving collisions. KIC is a novel signal processing technique to utilize the known part of a collided packet. As a result, we do not retransmit all the collided packets but some of them. Even though the idea of known interference cancellation is not new, the novelty of this work lies in the inclusion of this concept in a feasible MAC scheme for a practical WLAN scenario. To the best of our knowledge, the proposed MAC protocol is the first one to take advantage of both KIC and partial retransmissions to improve the efficiency of channel sharing.

The main contributions of this paper compared to existing collision resolution mechanisms are summarized as follows. We turn to a new direction of channel sharing and propose a novel MAC protocol, named as CR-MAC (Collision-Resolvable MAC). In CR-MAC, we cache the latest collision and try to decompose it in combination with the retransmitted partial packets by the KIC technique. CR-MAC operates in a fully distributed manner and does not require any aided control information. In comparison with the conventional mechanism such as IEEE

802.11, CR-MAC can reduce control overhead and greatly enhance the protocol efficiency. The numerical and simulation results show that, CR-MAC outperforms IEEE 802.11 significantly and the throughput gain is up to 25%.

The rest of this paper is organized as follows. The related work is summarized in Section 2 and the background knowledge is briefly reviewed in Section 3. Section 4 describes the proposed CR-MAC protocol. In Section 5, we give a theoretical model to analyze the performance of the protocol. Simulation and numerical results are provided in Section 6. Finally, Section 7 concludes the paper.

2. Related Work

It is a fundamental issue to handle collisions and hidden terminals in wireless LANs. Here we summarize only some of the works closely related to ours.

Backoff Optimization: There are a few of existing works in the literature aiming to improve the efficiency of 802.11 DCF by reducing the average backoff time. Cali et al. proposed to use an optimal contention window size [7]. In [8], a semi-random backoff scheme was introduced to set a dedicated backoff time for each node to avoid collisions. In [9], multiple nodes form a contention group to reduce the number of contention entities in one contention domain. Recently, some works have been proposed to use a novel frequency-domain contention method to replace the exponential backoff in time domain. In [10], Tan et al. employed a physical-layer RTS/CTS signaling frequency-domain backoff for the channel contention. In [11] and [12], the authors also performed backoff in frequency domain, and time-domain counting down is emulated with OFDM subcarrier counting down. However, the above backoff optimization work [7-12] just relieved but do not solved the inefficiency problem, as they still shared the traditional idea of collision avoidance.

Collision Decoding: It is a hot topic recently to handle interference or decode collisions in wireless networks. S.Verdu proposed an advanced signal processing method of successive interference cancellation (SIC) for decoding collisions [13]. In [14], D. Halperin et al. built a SIC prototype and experimentally demonstrated its effectiveness. However, there are some stringent SINR constraints and hard limits for SIC to satisfy, hence the gains from SIC are not easily available in many realistic situations [15]. To overcome this limitation, Gollakota et al. developed a novel interference cancellation approach, named as ZigZag, to decode multiple collisions [16], while it has a well-known weakness of error propagation since decoding future symbols relies on the correct decoding of previous symbols. In addition, Li et al. exploited the flexibility of random linear protocol [5], but the required channel state information (CSI) exchange would be a big burden for wireless networks.

3. Interference Cancellation Technique

3.1 Unknown Interference Cancellation vs. Known Interference Cancellation

Collisions occur when more than one transmission arrive concurrently at a receiver. In a collided signal, the detection of one signal is interfered by the others. However, the signal of interest (SI) still can be decoded when the SI is sufficiently strong and the Signal to Interference and Noise Ratio (SINR) is higher than a given threshold. This is so-called capture effect, which can help a receive node to resolve a collision.

Interference cancellation techniques are proposed to extract packets from a collided signal based on the capture effect [14]. Basically, a packet is detectable when the SINR is larger than

a given threshold even when there are some interfering signals. After a packet is decoded, one can re-generate the corresponding received signal and remove it from the collided signal in order to reduce the interference on the remaining packets. The performance gain depends on the features of collided signals and the receiver's ability to characterize the interference.

There are two major types of interference cancellation. First, unknown interference cancellation, which means that, a receiver has no a prior knowledge of the interference, and for an unknown interference (UI), cancellation is feasible when the signal of UI is decodable, i.e., SINR is sufficiently high. It is inevitable to remove all the UI signals that are too strong to distort the detection of SI. To satisfy the constraints, it requires a careful transmission scheduling and assignment [17, 18]. This is difficult in the distributed networks. In words, unknown interference cancellation, e.g., successive interference cancellation (SIC), does not require any prior knowledge but the gain is limited and even not available in many network scenarios [19].

Second, known interference cancellation (KIC) means that, the interfering transmission is already known by the receiver, and the receiver needs not to detect the signal, but to model and cancel the interfering signals. By removing the known interference, the SINR of SI can be improved, and thereby the feasible bit rate of SI is increased. Compared to unknown interference cancellation, known interference cancellation is not limited to the SINR relation between SI and interfere signals, and offers a broader gain provided that the receiver is aware of the interfering signals.

3.2 The Procedure of Known Interference Cancellation

A KIC-enabled receiver first tries to decode the arriving signal using the normal process. But if the process of Cyclic Redundancy Check (CRC) fails, the receiver checks whether there is a collision by using the method of energy detection, as the overlap of multiple signals will result in a much higher energy level. If there is a collision and partial collided packets can be identified by recognizing their headers, then the collision is considered to be probably resolvable, and the receiver checks whether one of the collided packets is in its cache space, by comparing the header and bits in the clear of both sides. If there is a match, by the operation of known interference cancellation, the signal of the known packet in the collision can be peeled off, and a new packet may be decoded from the remaining signal. If the number of bits in the clear is few and the match is incorrect, the CRC of the decoded packet would fail and the packet is discarded. In most cases, sufficient bits would arrive in the clear and KIC would successfully resolve a collision with a known packet.

The critical step of known interference cancellation is to generate the signal corresponding to the bits of the known collided packet. The preamble and the bits in the clear can aid in modeling the wireless channel. We can adopt the modeling approach as the one in [14], which models all the channel effects by a single function $R(t)$ instead of individually considering fading, frequency offset, and inter-symbol interference. This $R(t)$ is built for every combination of three consecutive symbols. For each combination, we average it over all its occurrences in the clear. Then the signal corresponding to the known bits is generated by applying $R(t)$. This signal is then subtracted from the collision signal and the new resulting signal is passed to a next decoding procedure.

4. CR-MAC Protocol

As illustrated in the above section, KIC technique is a low-complexity but powerful collision resolution method that can be easily implemented at the AP's PHY layer to enhance uplink

communications. However, in a practical network, the KIC scheme must be accompanied by a set of MAC layer functions to collect the necessary prior information about the interfering signals and handle the additional challenges stem from the compatibility with legacies. This section will present a novel MAC protocol named as CR-MAC, which modifies the IEEE 802.11 DCF [20] to account for the demands and restrictions of the KIC technique.

4.1 Framework

We consider an uplink case for one-hop fully connected WLAN, where one AP is located at the center of the network and the other n stations are located around the AP. The principle idea of CR-MAC is that, when a collision occurs, the AP will check whether the collision is resolvable, and if the answer is positive, partial collided packets will be arranged to retransmit subsequently, then all the collided packets would be received successfully with the aid of known interference cancellation. In other words, partial collided packets can be inferred from the collision and the corresponding retransmissions are to be saved, hence CR-MAC is expected to drastically improve the network throughput. For example, considering the case of a resolvable collision consist of two staggered collided packets, we only need to assign one of collided packets to retransmit in the next time slot, then the other collided packet can be obtained by performing the KIC operation between the collision and the subsequent retransmitted packet. Hence, the collided transmission time slot is used effectively, and only one more time slot is required. In conventional collision avoidance approaches, to transmit the two collided packets, at least two more time slots are required.

As shown in Fig. 1, the whole transmission procedure is divided into two periods: random access period, and data transmission period. First, the random access mechanism helps all the stations accessing to the common channel with an equal probability. In addition, it keeps the number of stations concurrently accessing the channel to an appropriate level, as too much concurrent stations will result in a high proportion of insolvable collisions and hence an ineffective data transmission. Second, the data transmission period includes a normal data transmission phase and a few possible retransmission phases, and each data transmission or retransmission phase consists of a data transmission and the corresponding acknowledgement.

In the random access period, the stations perform the similar exponential backoff as the 802.11 DCF, and the only difference is that in the CR-MAC protocol, the stations increase their contention counter only after encountering an insolvable collision; while in the 802.11 DCF, the stations double their contention counter as long as a collision occurs (both an insolvable collision and a resolvable collision are included).

In a data transmission period, there are three possible cases according to the concurrent number of the stations accessing to the channel after the preceding random access period:

- (1) Normal transmission: in this case, there is only one station acquires the medium and transmits data (as depicted in Fig. 1 (a)). Finally, after the data transmission and a SIFS idle time, the AP will send a normal ACK packet to acknowledge the received packet;
- (2) Resolvable collision: in this case, more than one stations (assume the concurrent number is K) acquire the medium and transmit their packets simultaneously, hence a collision consist of K packets occurs. If the preambles and headers of the concurrent packets are staggered (as depicted in Fig. 1 (b)), then the collision is resolvable. Combing with $K - 1$ sequential steps of retransmissions and known interference cancellation operations, all the K collided packets can be decoded successfully by the AP. To be noted here, every retransmission is issued by a RACK packet, and a GACK

packet is sent to acknowledge all the decoded packets in the end of the transmission period;

- (3) Insolvable collision: in this case, if the preambles and headers of some collided packets are fully or partially parallelized (as depicted in Fig. 1 (c)), then the collision is an insolvable collision, on which the KIC operation can't be performed. The AP responds a broadcast NACK packet to infer an insolvable collision, and thereby the collided stations will double their contention window size and content for a next transmission period.

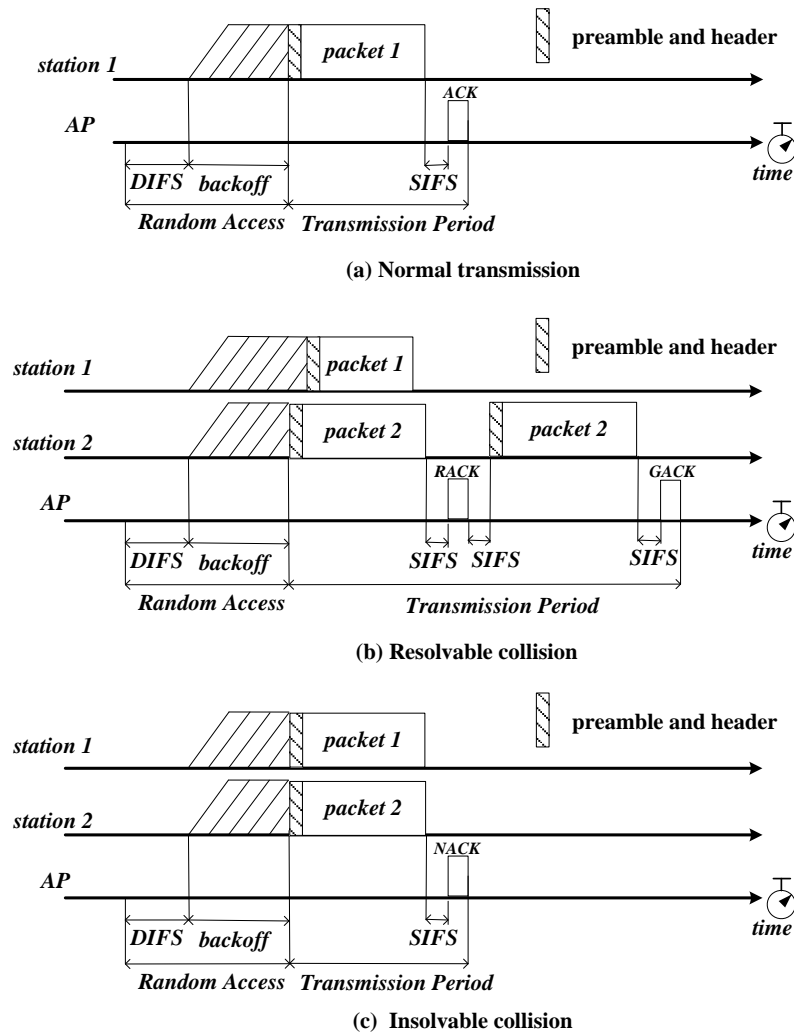


Fig. 1. Protocol operation examples

4.2 Details of the Proposed Protocol

4.2.1 The Preamble and Header

The PPDU (PLCP protocol data unit, and PLCP is the abbreviation for “Physical Layer Convergence Protocol”) preamble of a packet enables the receiver to acquire an incoming signal and synchronize its demodulator. The preamble consists of 12 training symbols, ten of which are short and are used for establishing AGC (automatic gain control), diversity selection, and the

coarse frequency offset estimate of the carrier signal. The receiver uses the other two long training symbols for channel and fine frequency offset estimation. The PPDU header consists of 4 rate bits, 1 reserved bit, 12 Length bits, 1 Parity bit, 6 Tail bits, and 16 Service bits. Besides, we add one additional segments of Src Add (source address) to identify the source station. The header is usually transmitted at the basic data rate using BPSK modulation.

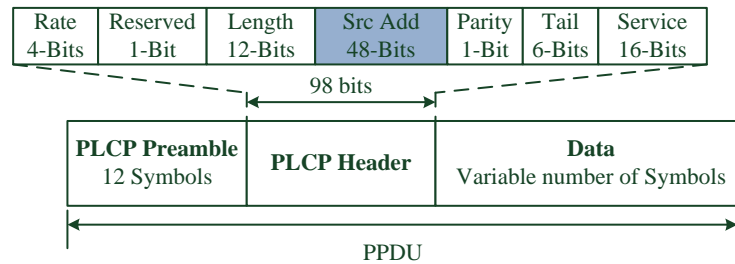


Fig. 2. The format of PPDU

From the process of KIC, it's known that a collision is resolvable if and only if the preambles and headers of the collided packets are staggered. However, in WLANs, as stations are periodically timing synchronized by beacon frames, it's a high probability that the preambles and headers of partial collided packets are fully or partially parallelized (depicted in Fig. 3 (b)). To enhance the resolving likelihood of collisions, we adopt the approach of adding a postamble and trailer at the end of each data packet [21]. The postamble and trailer have the same content as the preamble and header, but in the opposite order. When one end of a collision is synchronized, it is likely that the other end of this collision is staggered since the collided packets are of different packet sizes and transmission rates. If the trailer and postamble (or head and preamble) of a collided packet is in the clear, shown as in Fig. 3 (a) and (c), the AP can decode the head (or trailer) without decoding the whole packet by making use of the training symbols in the preamble (or postamble). Then the AP will know which station is involved in the collision and arrange it to retransmit in the next time slot.

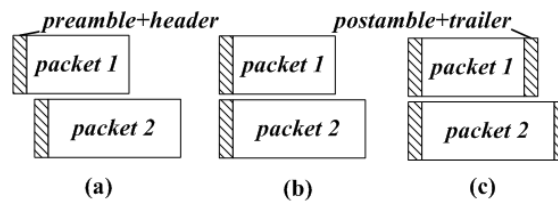


Fig. 3. Three cases of overlapped packets

4.2.2 Modified ACK Frames

The AP delivers quad-mode ACK frames as shown in Fig. 4. The first one is the normal ACK as the same as 802.11, acknowledging to the packet that hasn't been interfered by other packets and received successfully by the AP. The second one is denoted as RACK (retransmission ACK). It requires one of the collided stations to retransmit its latest data packet. A segment named ACK Control, identifying the type of the ACK frame, is added, and the value for RACK is 0000. The third one, denoted as GACK (group ACK), is used to acknowledge K collided packets involved in the collision after $K - 1$ sequential steps of retransmissions and interference cancellation operations, hence the segment of Receiver Address in GACK is extended to K entries. The last one is denoted as NACK (negative ACK), where the value of the additional ACK Control segment is 1111, and NACK announces an insolvable collision.

There is a two-packet collision, in which the length of the involved packets is L_1 and L_2 , respectively. Denote the probability that the two-packet collision is resolvable as $p_r(L_1, L_2)$. We assume that the two collided packets are strictly synchronized at the head side, then $p_r(L_1, L_2)$ can be calculated as follows,

$$\begin{aligned} p_r(L_1, L_2) &= p(L_1 > L_2 + L_{ph} | L_1 > L_2) + p(L_2 > L_1 + L_{ph} | L_2 > L_1) \\ &= 2p(L_1 > L_2 + L_{ph} | L_1 > L_2), \end{aligned} \tag{2}$$

where L_{ph} is denoted as the effective length of the preamble and header, and the estimation $E[p_r(L_1, L_2)]$ is

$$\begin{aligned} p_r &= E[p_r(L_1, L_2)] = 2E[p(L_1 > L_2 + L_{ph}, L_1 > L_2) \cdot p(L_1 > L_2)] \\ &= E[p(L_1 > L_2 + L_{ph}, L_1 > L_2)] = E[1 - D(L_2 + L_{ph}, L_1 < 1500 - L_{ph})], \end{aligned} \tag{3}$$

where $(L) = \int \rho(L)dL$, the distribution function of packet payload L .

Let n be the number of contending stations, W be the minimum contention size, m be the maximum backoff stage, τ be the transmission probability that a station transmits in a randomly chosen slot time (any transmission occurs when the backoff time counter is equal to zero, regardless of the backoff stage). Besides, the condition collision probability (here refers insolvable collisions) of each station, denoted by p , is assumed to constant and independent of the number of retransmissions experienced by this station. This assumption has been validated to be accurate by Bianchi's study [23]. Then we have

$$\begin{aligned} p &= 1 - (1 - \tau)^{n-1} - p_r C_{n-1}^1 \tau (1 - \tau)^{n-2}, \\ \tau &= \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}, \end{aligned} \tag{4}$$

where equation (4) reflects the fact that no collision happens among stations when only one station accesses the channel or there are two stations access the channel simultaneously but the two concurrent packets can be separated from each other. As the derivation of equation (5) is a little bit complicated, interested readers can refer to [23].

Let p_{tr} be the probability that there is at least one transmission in the considered slot time, p_s^1 be the probability that exactly one station transmits on the channel, p_c^2 be the probability that two stations transmits on the channel simultaneously, meaning there is a two-packet collision, and p_c as the probability of having a failure transmission due to an insolvable collision. Then we have expressions as follows:

$$p_{tr} = 1 - (1 - \tau)^n, \tag{6}$$

$$p_s^1 = \frac{C_n^1 \tau (1-\tau)^{n-1}}{p_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{(1-(1-\tau)^n)}, \tag{7}$$

$$p_c^2 = \frac{C_n^2 \tau^2 (1-\tau)^{n-2}}{p_{tr}} = \frac{n(n-1)\tau^2(1-\tau)^{n-2}}{2(1-(1-\tau)^n)}, \tag{8}$$

$$p_c = 1 - p_s^1 - p_r \cdot p_c^2. \tag{9}$$

We know that a successful transmission occurs in cases of normal transmission and resolvable collision, and a failed transmission occurs in the case of insolvable collision. Besides, it's possible that the channel is in idle for the considered time slot. Here, T_s^1 is the average time the channel is sensed busy due to a successful transmission in the case of normal transmission, T_s^2 is the average time the channel is sensed busy due to a successful transmission in the case of resolvable collision, T_c is the average time the channel is sensed busy by each station during an insolvable collision, and σ is the duration of an idle slot time. Then we have

$$T_S^1 = DIFS + \delta + T_H + E \left[\frac{L}{R_{data}} \right] + SIFS + \delta + T_{ACK}, \quad (10)$$

$$T_S^2 = DIFS + \delta + 2T_H + 2E \left[\frac{L_1}{R_{data}} | L_1 > L_2 + L_{ph} \right] + 3SIFS + 3\delta + T_{RACK} + T_{GACK}, \quad (11)$$

$$T_C = DIFS + \delta + T_H + E \left[\frac{\max\{L_1, \dots, L_K\}}{R_{data}} \right] + SIFS + \delta + T_{NACK}, \quad (12)^*$$

where T_{ACK} , T_{RACK} , T_{GACK} , T_{NACK} are the time required for the ACK, RACK, GACK, NACK, respectively, and δ is the propagation delay. Besides, $H = PHY_{hdr} + MAC_{hdr} + L_{ph}$ is the packet overhead, T_H is the packet overhead over the bit rate.

To be noted here, Bianchi's analysis assumed a saturated traffic scenario. Malone et al. [24] extended to the non-saturated scenario. They found that the only difference between the two cases is the expression of transmission probability τ . More specifically, the expression of transmission probability τ for the non-saturated case is given as follows:

$$\tau = b_{(0,0)e} \cdot \frac{q^2}{1-q} \cdot \left(\frac{W}{(1-p)(1-(1-q)^W)} - (1-p) \right), \quad (13)$$

$$\frac{1}{b_{(0,0)e}} = (1-q) + \frac{q^2 \cdot W \cdot (W+1)}{2(1-(1-q)^W)} + \frac{q \cdot (W+1)}{2(1-q)} \cdot \left(\frac{q^2 \cdot W}{2(1-(1-q)^W)} + p \cdot (1-q) - q \cdot (1-p)^2 \right) + \frac{p \cdot q^2}{2(1-p)(1-q)} \cdot \left(\frac{W}{1-(1-q)^W} - (1-p)^2 \right) \cdot \left(2W \cdot \frac{1-p-p(2p)^{m-1}}{1-2p} + 1 \right), \quad (14)$$

where q is the normalized probability of packet generation at a station. By taking $q = 1$, the above equations reduced to those of the saturation case.

*As $E[\max\{L_1, \dots, L_K\}]$ is difficult to calculate, here we simply take its upper limit $L_{max} = 1500$ Bytes.

6. Model Verification and Performance Evaluation

6.1 Analytical Model Verification

We compare MATLAB numerical predictions (num) of the analytical model from Section 5 with simulation results (sim) using the NS-2 simulator [25] for various numbers of stations, and packet arrival rates. The traffic arrivals are Poisson with parameter λ , and the relationship between Poisson parameter λ and normalized packet generation probability q is given in the reference [24]. Results are presented for simulation runs using NS-2 on the IEEE 802.11b channel, and the details can be referred to [26]. Each simulation result is obtained from 20 runs, and each run lasts for 4 minutes.

Consider a single-hop fully connected WLAN with a square area of 100×100 m². In the network, we put one node at the center of the area to act as the AP, and the remaining non-AP nodes, which are randomly deployed around the AP. The transmission range is set to 150m, and then all the nodes are connected. To be in correspondence with the numerical experiments, we perform the simulations with a fixed transmission rate. The packet payloads are randomly generated with the density function given by equation (1). The other important network parameters are tabulated in Tab. 1.

Two performance metrics are considered for the model verification and the following evaluation:

- (1) *Aggregate throughput* S (Mbps) is defined as the number of payload bits successfully transmitted in the network per unit of time under the given offered load.

The Aggregate throughput S can be expressed as follows:

$$S = \frac{E[\text{payloadbitsinatransmissionperiod}]}{E[\text{lengthofatransmissionperiod}]} \quad (15)$$

Specifically, in our analytical model, S is calculated as follows:

$$S = [E[L] \cdot p_s^1 + (E[L_1] + E[L_2]) \cdot p_r \cdot p_c^2] / [(1 - p_{tr}) \cdot \sigma + p_{tr} \cdot p_s^1 \cdot T_s^1 + p_{tr} \cdot p_r \cdot p_c^2 \cdot T_s^2 + p_{tr} \cdot (1 - p_s^1 - p_r \cdot p_c^2) \cdot T_c] \quad (16)**$$

In particularly, *saturation throughput* is the limit aggregate throughput reached by the network as the offered load increases, and represents the maximum load that the network can carry in stable conditions. The saturation throughput is reached when all stations in the network operate in the *saturation condition* [23], i.e., the transmission queue of each station is assumed to be always nonempty.

- (2) *Expected packet delay* $E[D]$ (second) is defined as the time needed for a packet transmission, and is calculated from the time when a packet becomes head of the station's queue to the time when a positive acknowledgement is received. In our analytical model, we adopt the expression proposed by Chatzimisios et al. [27], which expressed $E[D]$ as follows:

$$E[D] = E[X] \cdot E[l] \quad (17)$$

where X is the number of timer decrements, i.e., the initial backoff value, and l is the time interval between two consecutive backoff time counter decrements.

$$E[X] = \sum_{i=0}^{m-1} \left(p^i \cdot \frac{W_i+1}{2} \right) + \frac{p^m \cdot W_{m+1}}{1-p} = \frac{(1-2p) \cdot (W+1) + p \cdot W \cdot (1-(2p)^m)}{2(1-2p) \cdot (1-p)} \quad (18)$$

$$E[l] = (1 - p_{tr}) \cdot \sigma + p_{tr} \cdot p_s^1 \cdot T_s^1 + p_{tr} \cdot p_r \cdot p_c^2 \cdot T_s^2 + p_{tr} \cdot (1 - p_s^1 - p_r \cdot p_c^2) \cdot T_c \quad (19)$$

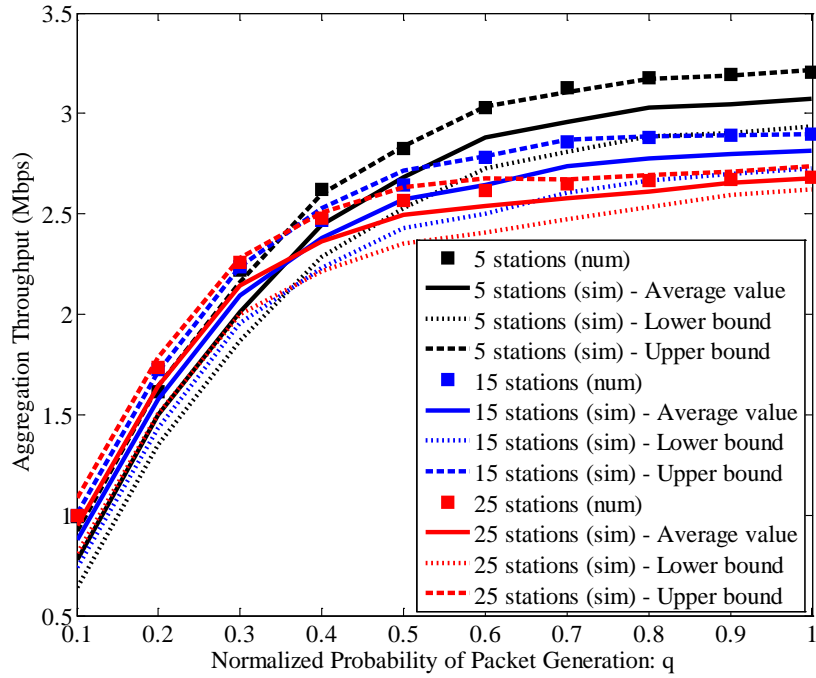
** As L_{ph} is much smaller than the packet payload, here we ignore its impact, and assume that $E[L_1] = E[L_2] = E[L] = \int L \cdot \rho(L) dL = 624 \text{ Bytes}$.

Table 1. 802.11b based Network parameters

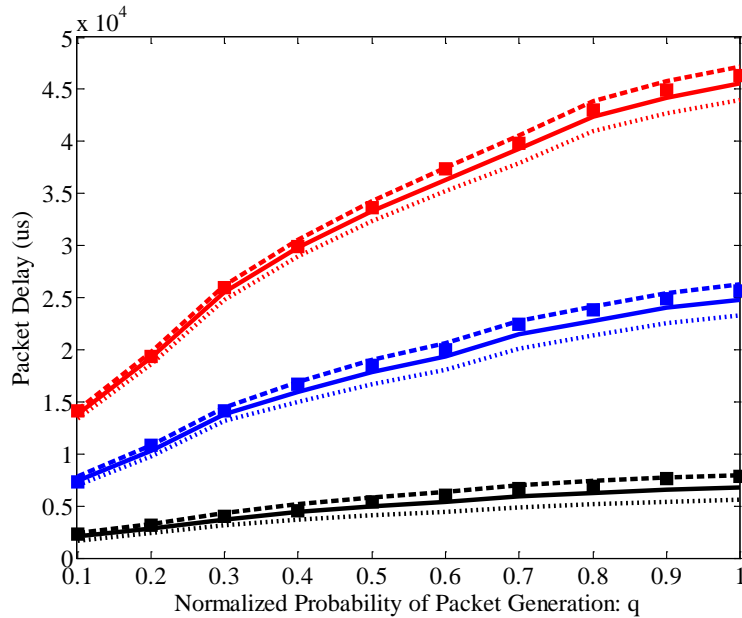
$W = 32, m = 7$ $\sigma = 20 \mu s, \delta = 1 \mu s$ $SIFS = 10 \mu s, DIFS = 50 \mu s$ $PHY_{hdr} = 96 \mu s$ $MAC_{hdr} = 288 \text{ bits}$ $L_{ph} = 48 \mu s$	$R_{basic} = 2 \text{ Mbps}$ $R_{data} = 5.5 \text{ Mbps}$ $L_{ACK} = 112 \text{ bits} + PHY_{hdr}$ $L_{RACK} = 116 \text{ bits} + PHY_{hdr}$ $L_{NACK} = 64 \text{ bits} + PHY_{hdr}$ $L_{GACK}(K = 2) = 160 \text{ bits} + PHY_{hdr}$
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The verification experiment results are shown in Fig. 5 (a) and (b). It is seen that in terms of aggregation throughput and packet delay, the maximum discrepancy between the analytical numerical predictions and the simulation results are 5.87% and 6.75%, respectively, and the simulation and analytical results are more consistent in the cases with larger network sizes. Besides, when the offered arrival rate is far away from saturation (i.e., $q < 0.4$), the aggregation throughput is linearly rising with the offered load, and when the offered arrival rate is close to saturation (i.e., $q > 0.8$), the aggregation throughput is almost fixed. For larger number of stations, the maximum aggregation

throughput is slightly decreased and achieves saturation with a relative lower traffic arrival rate. Moreover, the packet delay is rising fast with both the network size and offered traffic arrival rate.



(a) Aggregation Throughput



(b) Packet Delay (the lines are the same as Fig. 5 (a))

Fig. 5. Performance Comparison between the numerical predications and the simulation results (the interval between the upper bound and lower bound is confidence intervals with 95% confidence level)

6.2 Performance Evaluation

Since the analytical model makes remarkably accurate throughput and delay predictions, in this section, by making use of the above analytical model, we compare the performance of our proposed CR-MAC with that of the reference protocol, IEEE 802.11 DCF [23, 24]. The performance comparison is performed under various network settings, and the impact factors like network size, offered traffic arrival rate, contention window size and data transmission rate are all considered. If not otherwise specified, the network parameters refer to Tab. 1.

6.2.1 Saturation condition

Firstly, we consider the cases with the saturation condition. It should be cautioned that the numerical results are based on case studies. Although the proposed performance analysis method can be applied to general network cases, the absolute value of the saturation throughput depends on the node size, the data transmission rate, and the MAC protocol operations.

Fig. 6 (a) depicts the saturation throughput of the considered network with respect to the node size, represented by the number of stations. We observe that as the increasing of number of station, more and more collisions occur: the collision probability of a data transmission will drastically increase from 9.55% ($n = 5$) to 28.71% ($n = 40$), where $W = 32$. From the Fig.6 (a), we know that we can reduce collisions and improve the throughput by increasing the contention window size W . However, on one hand, the improvement is limited; on the other hand, as this approach produces more idle time slots, it doesn't take effect in all cases. For example, when the contention window size W is increased from 128 to 1024, the network saturation throughput has a large decline in cases of networks with a relative small size. Other than optimizing network parameters to reduce collisions, we adopt another approach of resolving collisions by interference cancellation and partial retransmissions, thus partial collision transmissions can be fully utilized, and the corresponding retransmissions will be saved consequently. Although our interference cancellation operations are limited to the collisions consist of two packets, in the most of cases, the saturation throughput of our proposed CR-MAC protocol distinctly higher than that of 802.11 DCF and the throughput gain is between 10% and 25%. Furthermore, it is represented in the Fig. 6 (a) that the throughput gain increases as the number of stations n increases or the contention window size W decreases. That means the more collisions occur, the larger throughput gain is offered.

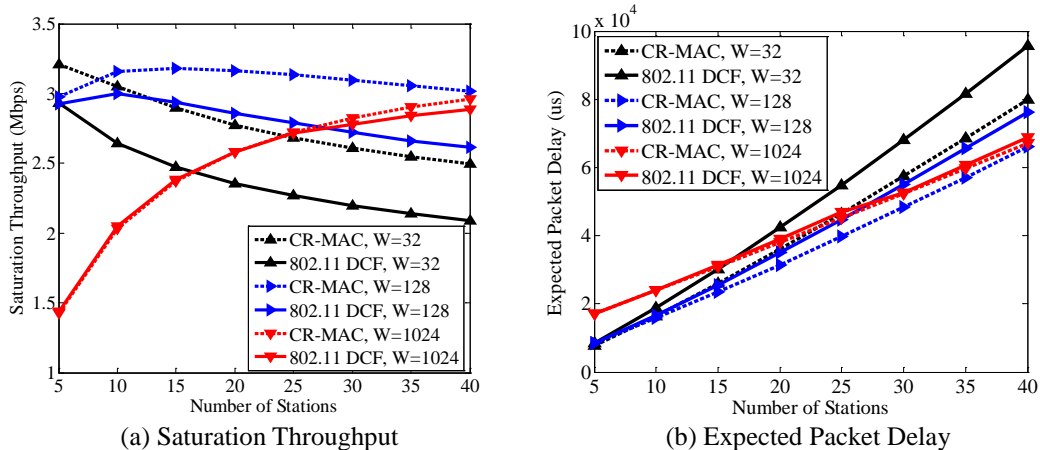


Fig. 6. Performance Comparison under the Saturation Condition

Fig. 6 (b) shows that our proposed CR-MAC protocol improves not only the performance of saturation throughput S but also the performance of expected packet delay $E[D]$. The gains of $E[D]$ are respectively 15.44%, 11.29% and 1.83% in cases of $W = 32$, $W = 128$ and $W = 1024$. Besides, as shown in Fig. 7 (a) and (b), it is seen that regardless of varied data transmission rate, the performance improvements in both saturation throughput and expected packet delay are guaranteed. Since the performance gain of our proposed CR-MAC protocol is independent of various network settings, including the content window size W , the number of stations n and the transmission data rate R_{data} , CR-MAC protocol can be finely compatible with other mechanisms such as backoff optimization and rate adaption.

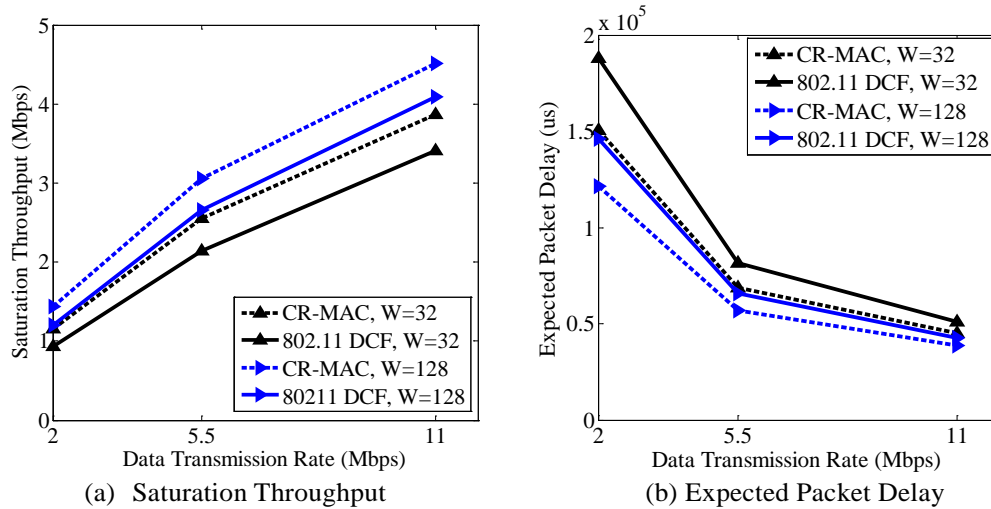


Fig. 7. Performance Comparison under the Saturation Condition with the Number of Stations $n = 35$

6.2.2 Unsaturated condition

In this section, we study the network performance of two protocols under unsaturated conditions. Fig. 8 (a) and (b) compare the aggregation throughput and the expected packet delay for two scenarios: the first scenario is the network with 15 stations, and the second scenario is the network with 25 stations. As shown in Fig. 8, both the aggregation throughput and the expected packet delay increase as the increasing of the offered load. Besides, the network with a smaller size performs better in terms of both the aggregation throughput and the expected packet delay. That is because in the network with a smaller size, there are less stations accessing the channel and hence less collisions occur. The performance difference is much more remarkable when the offer load approaches the saturation condition. Finally, the results show that the CR-MAC protocol performs much better in terms of aggregation throughput and expected packet delay, regardless of the offer load and the network size.

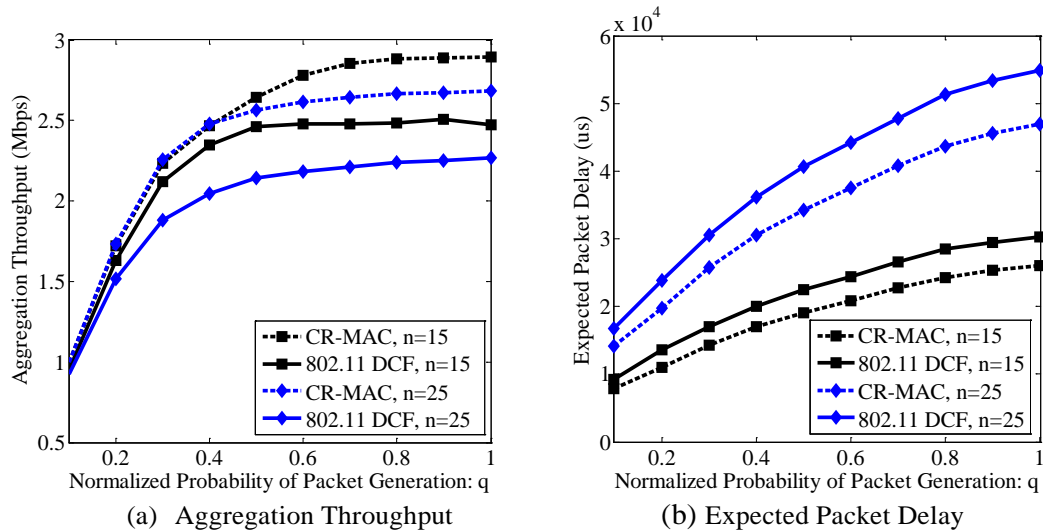


Fig. 8. Performance Comparison under Unsaturated Conditions

7. Conclusion

The performance of modern wireless communication system is interference-limited. To mitigate the effect of collision, we propose to use a novel technique, called known interference cancellation (KIC), to extract packets from the collided signal. A new MAC protocol, named CR-MAC, is designed to exploit the KIC capability in a practical WLAN scenario. When a resolvable collision occurs, partial packets involved in the collision are arranged to retransmit in the subsequent time slots. As the known information in the collided signal is fully utilized, the number of required retransmissions is reduced significantly. The experimental results show that, CR-MAC performs much better than IEEE 802.11 under various network settings.

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