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A Novel Successive-Interference-Cancellation-Aware Design for Wireless Networks Using Software-Defined Networking

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ABSTRACT In traditional CSMA/CA-based MAC designs supporting successive interference cancellation (SIC), channel utilization is inefficient, because the inherited CSMA/CA-style contention approach often forces the whole channel to remain idle and the early released channel is not utilized. In this paper, we propose Multi-CQ, which is the first software-defined networking (SDN)-based MAC design for wireless LANs that supports SIC and significantly improves the channel utilization. Multi-CQ, adopting SDN's functional separation idea and OFDMA, makes contention and data transmission be executed over two subchannels independently and concurrently, where the superposition coding are used for decoding combined signals, and multiple CQs (contention queues) are introduced to coordinate the concurrency. This concurrent execution greatly reduces the waste in channel contention. Next, adopting SDN's central control idea, Multi-CQ controller selects nodes who can finish their frame transmissions in almost equal time, thereby improving the channel utilization. Finally, we develop a theoretical model to optimize bandwidth allocation for channel contention and data transmission. Extensive simulations verify the effectiveness of our design and the accuracy of our theoretical model. This study is also helpful to better design wireless MAC protocols supporting other advanced functionalities such as MU-MIMO.

INDEX TERMS SDN, SIC, WiFi.

I. INTRODUCTION

A. BACKGROUND

With the ongoing development of communications technologies, many physical layer designs have been implemented. As a 5G development potential technology, non-orthogonal multiple access (NOMA) [1]–[4] has attracted great attention in recent years. The core technology of NOMA is successive interference cancellation (SIC). In this technology, multiple nodes can transmit their frames to a receiver simultaneously, and the receiver iteratively decodes the overlapping frames using SIC. SIC enables simultaneous transmission and therefore it can effectively increase the channel capacity of a physical layer and significantly improve channel utilization.

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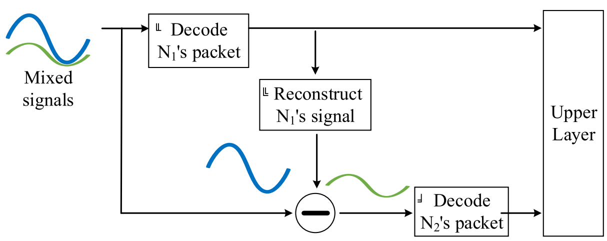

FIGURE 1. Successive interference cancellation (SIC) technology.

Figure 1 explains the SIC decoding process. If N_1 and N_2 simultaneously transmit frames to an access point (AP), the AP first decodes the frame with the stronger signal (say, N_1's frame) and then decodes the frame with the weaker signal (say, N_2's frame) after removing the strong signal from the mixed signal.

B. MOTIVATION

SIC has great potential to increase channel capacity and improve channel utilization. Therefore, existing studies [5]–[7] considered integrating SIC technology into 802.11 CSMA/CA protocols (which are called CSMA/CA-SIC protocols hereafter). The CSMA/CA-SIC protocols first let nodes perform multiple rounds of contention to generate multiple sequential winners and then let the winners transmit their frames concurrently. Figure 2. (a) shows an example of the CSMA/CA-SIC protocol. In the contention process, N_1 and N_2 contend for the channel and become sequential winners. In the transmission process, N_1 and N_2 transmit their frames to the AP at the same time.

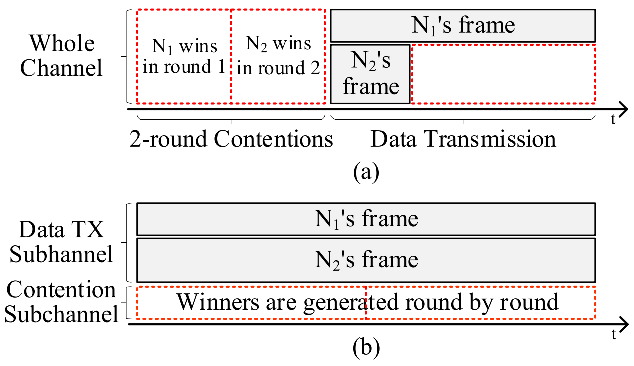

FIGURE 2. The channel-contention and data-transmission processes in (a) conventional CSMA/CA-SIC protocols and (b) the proposed Multi-CQ.

CSMA/CA-SIC designs often lead to low channel utilization because of two drawbacks:

- On one hand, these protocols retain the serial execution characteristics of channel contention and data transmission (i.e., each node first wins the channel and then transmits data). In this serial execution, the channel is allocated in a coarse-grained manner (i.e., the entire channel is allocated as a single resource), leading to low channel utilization. For example, when all nodes keep counting down in contention, the whole channel remains idle.
- On the other hand, in data transmission, if the transmission time of one frame (say, N_1's frame) is significantly longer than that of another frame (say, N_2's frame), little is gained from SIC, because the whole channel is not fully exploited after one node (say, N_2) finishes its transmission early.

This motivates the design of a novel wireless MAC protocol that overcomes these two drawbacks.

C. OUR CONTRIBUTIONS

In this paper, SDN's concepts are borrowed to resolve the drawbacks in traditional CSMA/CA-SIC protocols. To address the first drawback, SDN's functionality-separation idea of separating the channel-contention and data-transmission processes into two subchannels for concurrent execution is applied to fully utilize a channel and allow more nodes to become winners for consequent data transmission. Figure 2 (b) instantiates the two processes of the proposed Multi-CQ, where each node vies for the channel over a contention subchannel while transmitting data over the data Tx (transmission) subchannel. To overcome the second drawback, SDN's central control idea is applied to let the AP select appropriate nodes (from more winners) for simultaneously finishing frame transmissions. *In addition, we introduce multiple CQs (contention queues) to coordinate the two processes (i.e., store the contention results for the data transmission) and enable centralized control. Conceptually, contention queues are used to coordinate the data and control planes for SDN-based wireless contention, which plays a role like that of the OpenFlow table that coordinates the data and control planes for SDN-based wired networks.* In summary, the contributions of this paper are as follows.

- Propose Multi-CQ. Multi-CQ is the first SDN-based design for wireless contention that supports SIC and significantly improves channel utilization.
- Develop a queueing model that optimizes bandwidth allocations for channel contention and data transmission. Our model factors in various design parameters and hence characterizes their impacts on system throughput.
- Verify via extensive simulations the effectiveness of the proposed Multi-CQ and the accuracy of the developed model.

The rest of the paper is organized as follows: Section II presents related works. Section III presents the SDN architecture of Multi-CQ. Section IV outlines the Multi-CQ protocol. Section V models the system performance. Section VI reports on simulations that verify the accuracy of our theoretical model. Finally, Section VII concludes the paper.

II. RELATED WORKS

Multi-CQ aims at a SIC-aware wireless MAC design that uses SDN methods. Existing related designs can be classified into two types: SIC-aware designs (which have the drawbacks mentioned in Section I) and SDN-aware designs (which do not support SIC). We outline these related designs in the following sections.

A. SIC-AWARE DESIGNS

Existing SIC-aware protocols are mainly considered in past studies as the basis for new SIC-aware MAC protocols or for modifying existing protocols to exploit SIC [5]–[8]. However, none of these studies can solve the two drawbacks we mentioned in Section I.B. k-SIC [5] divides users into 2 k groups. Senders contend for the channel with CSMA/CA in each round of the contention process. Based on the result of contention, the receiver determines which user-group can perform SIC transmission. CSMA-SIC [6] requires that each round of the contention process contain multiple competitions. Winners from each round send an RTS frame to the AP which selects the winners. The selected nodes can then transmit data with the SIC technique. AutoMAC [7] takes advantage of rateless coding to realize SIC for uplink transmissions, aiming to maximize the PHY capacity. User selection is not adopted in the design because the nodes do not have priority. A 3D-Pipeline [8] has a contention scheme where the contention process is divided into several parallel stages and executed in a 3D time, frequency, and space domain. The fairness of competition is ensured in a contention process that lacks a user-selection mechanism.

B. SDN-AWARE DESIGNS

Existing studies of SDN-aware protocols mainly consider exploiting SDN for wireless MAC access [9]–[13]. However, none of these studies supports SIC transmission. CSMA/CQ [9] aims to enable concurrent control and data channels. The whole channel is separated into two individual channels based on the OFDMA technique. Therefore, the contention process and data transmission process can be performed over the two individual channels, respectively. SDN-based architecture [10] is a virtual AP (VAP) based on SDN. It uses the SDN controller to control network features, such as client mobility, association, and QoS parameters, to meet different VAP performance requirements. E2E QoS [11] is a novel slice orchestration framework in SDN-WiFi. It monitors traffic to clarify the needs of different applications. In response to different programs' needs, the SDN controller performs slice control and configures different QoS parameters for it to improve network performance. Based on the SDN framework, OpenTDMF [12] introduces TDMA to wireless local area networks. In OpenTDMF, the controller adopts a central coordination method to synchronize a wireless network's channel selection and time synchronization. Wi-Balance [13] uses an SDN controller to monitor network traffic data for calculating optimized contention parameters in EDCA, complying with different QoS requirements for different services.

III. MULTI-CQ ARCHITECTURE

In this section, we design an SDN-based Multi-CQ architecture, which mainly consists of data and control planes, to overcome the two drawbacks of traditional CSMA/CA-SIC protocols mentioned in Section I.B. In the data plane, we define two sub-planes to separate the channel-contention and data-transmission processes into conventional CSMA/CA protocols and introduce a third sub-plane (i.e., the CQ plane) to coordinate the two processes (i.e., store many contention results in CQ for subsequent data transmissions). These three sub-planes jointly overcome the barrier to serial execution in traditional CSMA/CA-SIC designs. In the control plane, the controller centrally manipulates CQ to schedule appropriate nodes (from the contention results) for simultaneous frame transmission; this circumvents the significantly different transmission times in traditional CSMA/CA-SIC designs.

A whole channel can be divided into contention and data-transmission subchannels as shown in Figure 3.

- The data plane consists of the following sub-planes for parallel transmissions.

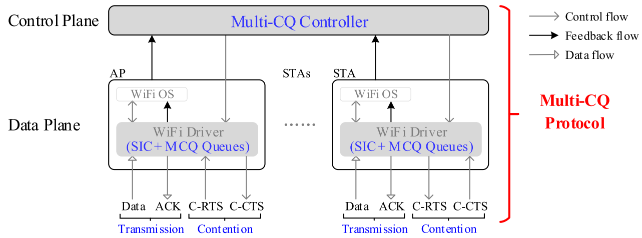

FIGURE 3. SDN-based Multi-CQ architecture.

- **Contention sub-plane**: This sub-plane handles the contention process over the contention subchannel. In the contention subchannel, each node adopts the conventional 802.11 RTS/CTS method to contend for a data-transmission subchannel reservation. Two frames are defined: C-RTS (contention-RTS), and C-CTS (contention-CTS). The frames are sent on the contention subchannel instead of the whole channel as in 802.11. They behave exactly like conventional RTS and CTS frames.
- **CQ sub-plane**: This sub-plane coordinates the contention and transmission processes. In our design, each node and the AP own multiple contention queues. Upon winning a contention, a node or the AP adds its information (e.g., the node ID, the frame size, and data rate) to its corresponding queue and simultaneously broadcasts this information. All other nodes that receive the information add it to their corresponding queue.
- **Transmission sub-plane**: This sub-plane handles the transmission process over the data-transmission subchannel. In our design, the nodes, whose IDs are in the heads of MCQ queues, send a SIC-based data transmission to their receiver which sends back an ACK upon successful reception. Upon receiving the ACK, all nodes and the AP will delete these nodes' IDs from their queues.

- The control plane mainly has two functions. The first one is dispatch of the configuration parameters (e.g., the number of subcarriers for contention and data-transmission subchannels) to all nodes and the AP. The second one is selection of appropriate nodes for data transmission and updates to all CQs. To enable simultaneous completion of frame transmissions, the controller real-time monitors the CQs, selects appropriate nodes according to their frame length and data rate, and determines whether to update their sequences in CQs. If update is necessary, the controller broadcasts the updated items. Upon receiving the update messages, all nodes and the AP perform the corresponding operations.

The software implementation of Multi-CQ can be based on conventional WiFi components (including WiFi OS and WiFi driver) and SDN components. For example, CAPWAP [14] can be installed in a WiFi OS to create a tunnel for feedbacks from the controller to the WiFi driver, and patches in the WiFi driver can be added to create CQs and implement the

PHY and MAC protocols. Hardware support of Multi-CQ is addressed in the PHY design in Section IV.A.

IV. MULTI-CQ PROTOCOL

In this section, focusing on an infrastructure-based wireless LAN (consisting of one AP and many nodes, as shown in Figure 4), we present the PHY and MAC protocols of Multi-CQ.

A. PHY

1) PHYSICAL LAYER DESIGN

In Multi-CQ, OFDMA technology is adopted in the physical layer. The whole channel consists of M subcarriers, and the channel is divided into two subchannels: contention subchannel and transmission subchannel. As shown in Figure 4 (b), the contention subchannel contains M_c subcarriers while data transmission subchannel contains M_d subcarriers. Each node has two antennas: a contention antenna and a transmission antenna (i.e., data-transmission antenna), as shown in Figure 4 (b). The contention antenna works on the contention subchannel, and the transmission antenna works on the transmission subchannel. We assume that these two antennas can work concurrently as in [9].

Multi-CQ executes the contention process and the transmission process in parallel. To achieve this, Multi-CQ needs to contain four independent processing modules: the contention transmitter and contention receiver in the contention process and the SIC-supported data transmitter and the SIC-supported data receiver in the transmission process.

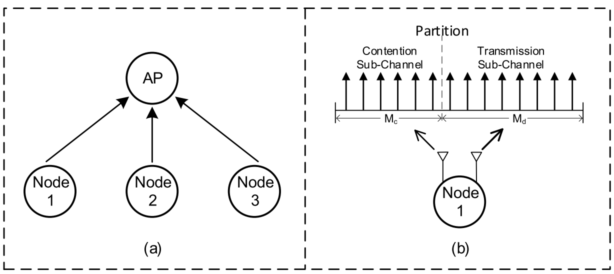

FIGURE 4. An infrastructure-based WLAN.

- **Contention Transmitter**: the contention transmitter has the same modules as a traditional WiFi node (e.g., serial to parallel, channel encoding, scrambling, interleaving, modulation, IFFT, CP insert, RF, and contention antenna).
  - The IFFT module should be modified as follows. 1) After the contention data are generated and modulated, the module maps the competition data to the corresponding contention subcarriers (say, the M_c subcarriers), and resets all the remaining subcarriers to zero; 2) after the OFDM symbol is generated through IFFT, it is passed to the RF-front for transmission. In our design, the contention transmitter does not support SIC technology. In Figure 5, both N_1 and N_2 are equipped with our contention transmitter. When all sub-carriers pass our modified IFFT module, the module sets the non-contention sub-carriers (say, M-M_c) to zero (indicated by padding in Figure 5) and outputs an OFDM symbol containing only contention information.
- **Contention receiver**: the contention receiver also has the same modules as traditional WiFi (e.g., receiving antennas, RF, CP remove, FFT, demodulation, deinterleaving, descrambling, channel decoding, and parallel to serial).
  - This FFT module should be modified as follows: 1) The module performs an FFT transformation on the entire OFDM symbol to obtain all the I/Q sampling data of all the subcarriers; 2) sample data of the contention subcarriers are passed to the demodulation module. In Figure 5, when an OFDM Symbol passes through the modified FFT module, the module filters out non-contention subcarriers (say, M-M_c, indicated by padding in Figure 5), extracts only the sampled data of the contention subcarriers and passes them to the constellation demodulation module.
- **SIC-supported data transmitter**: The SIC-supported data transmitter has the same modules as a traditional

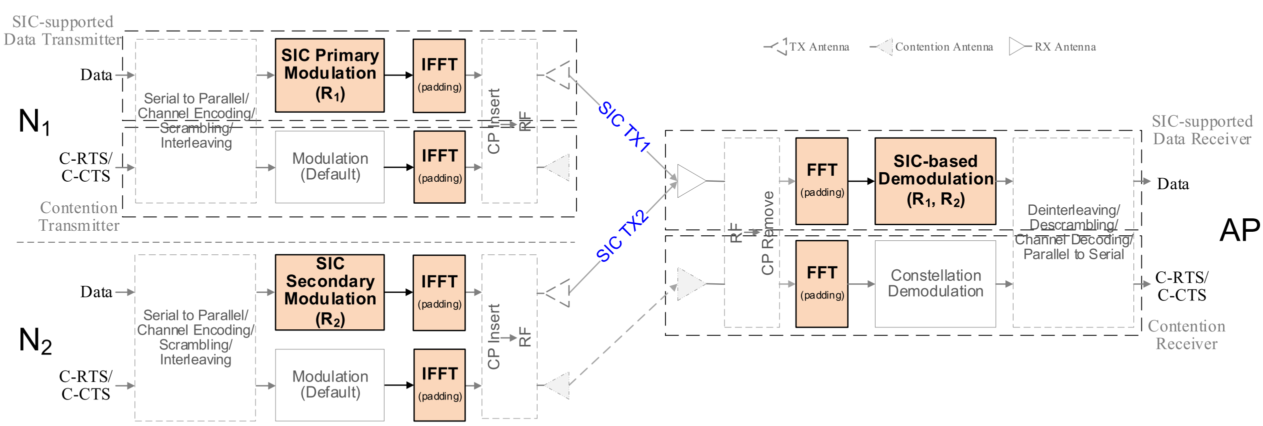

FIGURE 5. Overview of the PHY-layer architecture of uplink transmission.

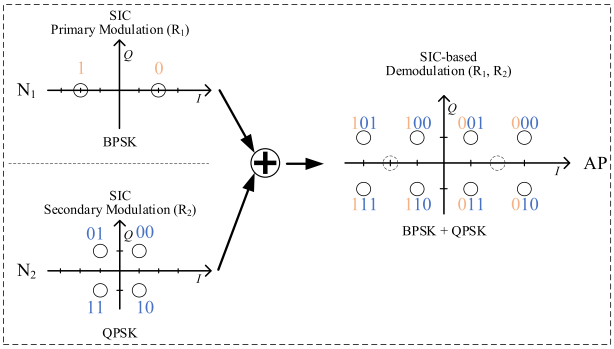

FIGURE 6. Overview of SIC superposition coding and decoding process.

WiFi node except the modulation and IFFT modules that support SIC transmission.

- Modulation module: Unlike the traditional fixed constellation mapping method, this module uses different constellation diagrams to map nodes in different SIC roles, such as the primary transmitter or secondary transmitter. When the role of the node is determined, its constellation diagram is determined. Different constellations are superimposed in the channel. Since the contention queues share the global transmission information, both nodes and AP can construct this superimposed constellation. This superimposed constellation is used in the demodulation process. In Figure 6, nodes N_1 and N_2 perform SIC transmission; N_1 is the primary transmitter, and N_2 is the secondary transmitter. The transmitter's constellations are shown in Figure 6, where N_1 is a constellation diagram using Binary phase-shift keying (BPSK), and N_2 is a constellation diagram using Quadrature Phase Shift Keying (QPSK) for modulation.
- IFFT module: This module operates like the IFFT module in the contention transmitter. When transmission data are modulated, this module maps the data to its corresponding transmission subcarriers (say, the M_d subcarriers), and the remaining subcarriers are set to zero. After that, the IFFT module performs an IFFT transform to generate the OFDM symbol and pass it to the RF-front.

■ **SIC-supported data receiver**: the contention receiver also has the same modules as traditional WiFi nodes except for FFT and SIC-based demodulation modules that support SIC transmission. In Multi-CQ, the SIC-based demodulation module is located after the FFT module. The SIC demodulation used in Multi-CQ is based on the constellation instead of the time-domain demodulation method shown in Figure 1 (say, the iterative signal method in time-domain). The decoupling of the contention and the transmission processes is done with OFDMA technology in the frequency domain (say, after the FFT module). However, traditional SIC demodulation can only work in the time domain and should be completed before moving to the FFT module. It will cause coupling between the competition process and the transmission process.

- FFT module: This module operates like the FFT module in the contention receiver. The entire OFDM symbol performs the FFT transformation, and only the I/Q sampling data of transmission subcarriers is passed to the demodulation module.
- SIC-based demodulation module: When the FFT module's signal is input, this module extracts the I/Q values of the receiving sample point and selects the corresponding constellation point closest to this sample point. Then, based on the mapping relationship between the superposition constellation and its information, the corresponding constellation point information is decoded. As mentioned for the SIC modulation module, all APs and nodes know this mapping relationship (based on the globally shared contention queue information). The mapping relationship also contains the position and corresponding information of the original constellation. For example, each point contains three-bit information as shown in Figure 6. The first digit corresponds to the primary transmitter of BPSK, and the last two digits correspond to the secondary transmitter of QPSK. Then, the constellation points are located according to the received sampling points' coordinates, the corresponding three-bit information is obtained; the first bit of the three-bit code is the primary transmitter's information and the last two bits are the secondary transmitter's information.

2) COMPLEXITY ANALYSIS

In Multi-CQ, a superposition-coding-based approach to implementing SIC is adopted. Figure 6 explains the complexity of this approach.

Two nodes (say, N_1 and N_2) simultaneously transmit their data to the AP; there, N_1 and N_2 use the k_1-symbol and k_2-symbol constellation diagrams, respectively.

In this approach, the nodes and the AP negotiate their adopted constellation configurations before transmission. In N_1 and N_2, the modulation operation maps bits into just one constellation point, and therefore the time complexity is O(1). For the AP, demodulation is the reverse process and hence has a time complexity of O(1) as well. Their main difference is in their space complexity. N_1 needs to store k_1 points and N_2 needs to store k_2 points, while the AP needs to store $k_1 \times k_2$ points.

B. MAC

1) OVERVIEW

The MAC layer contains three processes: contention, queuing, and transmission. The queuing process coordinates the other two processes. For discussion purposes, there are two users for simultaneous SIC transmission and therefore two contention queues.

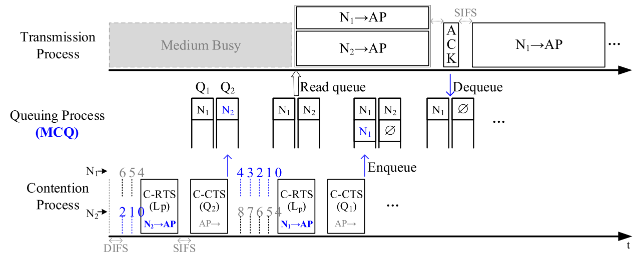

FIGURE 7. An example of channel contention and data transmission in our design.

- **Contention Process**: Nodes contend for the channel through the DCF scheme in RTS/CTS mode [15], [16] in this process. First, all nodes perform backoff during this process. Second, if there is a winner after the backoff, the winner sends a C-RTS frame to the AP. The C-RTS includes this winner's node ID and the size of the frame it will send. Third, when the AP receives the C-RTS frame, it launches a user-selection operation. Then, the AP feeds back the result of user-selection by broadcasting a C-CTS frame to all nodes. Fourth, when the nodes receive the C-CTS frame, they decode and extract the frame's necessary information. Note that the winner cannot transmit its frame right after receiving the C-CTS feedback from the AP. It must extract information such as the node ID and frame size from the C-CTS frame. In Figure 7, in the contention process, all nodes run the backoff algorithm over the contention subchannel. If N_2 is the winner, it sends a C-RTS frame that includes its node_ID and frame size to the AP. After the AP receives the C-RTS, it enqueues the winner's node ID 'N_2' to Q_2 (as shown in the blue Enqueue of Figure 7) since this winner's frame size is less than a user-selection threshold. The result (i.e., 'N_2' to Q_2 and frame size) is broadcast to all nodes with a C-CTS frame. When nodes receive the C-CTS frame, they also enqueue 'N_2' to their local Q_2 according to its decoded information.
- **Queuing Process:** The queuing process coordinates the contention process and transmission process. Each node independently manipulates its own contention queue according to the AP's feedback. With the designed AP, the enqueue and dequeue strategies are controlled by the Multi-CQ control plane, and thus a centralized user selection is performed. The user selection operation determines which contention queue the contention winner's ID is enqueued in according to the size of the winner's frame size and the preset user-selection threshold $L_{threshold}$. This threshold is pre-configurated by the controller in the control plane. The operation result is fed back to all nodes. Two contention queues are used in this scenario. Q_1 is used to store the Node_ID whose corresponding node sends the bigger frame in Figure 7. Q_2 is used to store the Node_ID whose corresponding node sends the smaller frame in Figure 7. For example, when the AP receives the N_2 C-RTS frame, it compares the frame size information $L_{payload}$ decoded from the C-RTS with the preset user-selection threshold. Since $L_{payload}$ is bigger than $L_{threshold}$, N_2 is enqueued to Q_2 (shown as the first blue Enqueue in Figure 7).
- **Transmission Process**: In this process, nodes transmit their frames sequentially in the order of their ID enqueued in contention queues after control plane user selection. The transmission process is like that of TDMA. When the transmission subchannel is idle, nodes whose node IDs wait in the front of the contention queue can transmit their frames. If both CQs are not empty, then a SIC transmission can be executed. If one contention queue is empty and the other is not empty, then a non-SIC protocol transmits a frame. If both CQs are empty, no nodes transmit. After transmission, the AP feeds back an ACK and dequeues the involved node IDs from the contention queue. Figure 7 shows that Q_1.front lays N_1 and Q_2.front lays N_2 when the transmission subchannel is idle. Therefore, in this case, N_1 and N_2 transmit their frames concurrently using SIC. After their transmission, dequeuing is performed.

The concurrency of the above three processes are enabled with the Multi-CQ design. The chance of concurrent transmission is ensured as much as possible with the Multi-CQ architecture, which leads to full use of channel resources and improvement in the system's overall throughput. Next, the details of the Multi-CQ MAC layer are discussed.

2) CONTENTION QUEUES

The contention queue (as illustrated in Figure 8) in Multi-CQ is used to store node IDs (i.e., Node_ID) and a frame length (i.e., $L_{payload}$). For simplicity, two contention queues (i.e., Q_1 and Q_2) are used in this paper. Q_1 stores the node_IDs whose corresponding nodes are the primary transmitter at rate R_p, while Q_2 is used to store the node_IDs whose corresponding nodes are the secondary transmitter at rate R_s. The different rates correspond to the different constellation modulations, as shown in Figure 6. Node_ID is assigned by the AP during the association process. $L_{payload}$ is the length of a frame's payload (in bytes).

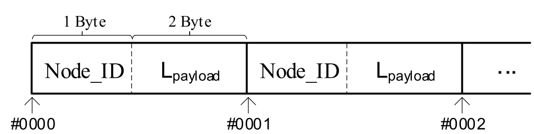

FIGURE 8. Contention queue architecture.

3) CONTROL FRAMES

As shown in Figure 9, three kinds of control frames are used in the Multi-CQ design: C-RTS, C-CTS, and ACK.

- C-RTS (Contention - Request To Send)/C-CTS (Contention - Clear To Send): The contention channel winner sends C-RTS to reserve the channel, and the receiver will return a C-CTS to acknowledge. C-RTS and C-CTS are based on a typical 802.11 frame (including the PHY header and MAC header) and include three more fields: Node_ID, $L_{payload}$, and Q_{id}.

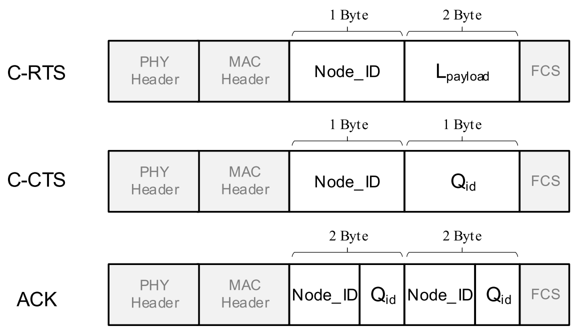

FIGURE 9. Control frames architecture (including C-RTS, C-CTS, and ACK).

- ACK (Acknowledgement): A designed ACK is used in the transmission subchannel to acknowledge a data frame. The ACK is different from the traditional ACK, which contains several acknowledgement fields (including the Node_ID and Q_{id}). This paper assumes each ACK contains two acknowledgement fields. For example, the <Node_1, Q_1> of the first field confirms that node one is the primary transmitter located in Q_1, and <Node_2, Q_2> of secondary field is the secondary transmitter located in Q_2.

4) ALGORITHMS DETAILS

This section presents the contention process algorithm details (Algorithm 1 and Algorithm 2) and the transmission process algorithm details (Algorithm 3 and Algorithm 4).

Algorithm 1 Contention Process (Node)

01: Perform backoff
02: // *Case 1: Node counts down to zero*
03: Send a C-RTS (Node_ID, $L_{payload}$)
04: Delay (SIFS)
05: // *If Node itself wins*
06: **if** Receive a C-CTS feedback **then**
07: Enqueue (Q_{id}, C-CTS.Node_ID)
08: **else** // *RTS collides.*
09: Increase CW and re-contention
10: // *Case 2: Node is in back-off*
11: **if** Receive a C-CTS, **then**
12: Enqueue (Q_{id}, C-CTS.Node_ID)

Algorithm 1 specifies the contention process of a node. Each node transmits an RTS frame over the contention subchannel to win a transmission chance over the transmission subchannel in the contention process. The algorithm works as follows. First, each node performs the backoff mechanism by counting down a backoff counter. Second, when a node's backoff counter decreases to zero, it indicates that the node is about to be the winner of the contention and will send a C-RTS to the AP. Third, the winning node waits for a SIFS time to receive an AP's C-CTS feedback frame. Fourth, a node in the contention process can be either a winner or still in the backoff state when a C-CTS is received (line 6 and line 11). In these two cases, each node will enqueue the Node_ID extracted from the C-CTS frame (denoted by C-CTS->Node_ID) to a specific queue according to the Q_{id}. Otherwise, there is a collision. In this case, collided nodes will repeat the contention process by backing off and doubling their contention windows (line 8).

Algorithm 2 Contention Process (AP)

01: Receive a C-RTS
02: Delay (SIFS)
03: // *Execute user-selection*
04: **if** C-RTS. $L_{payload} > L_{threshold}$ **then**
05: $Q_{id} = Q_1$
06: **else**
07: $Q_{id} = Q_2$
08: Feedback a C-CTS(C-CTS.Node_ID, Q_{id})
09: Enqueue (Q_{id}, C-CTS.Node_ID)

Similarly, Algorithm 2 specifies the contention process of an AP. In this contention process, the AP is responsible for responding to C-RTS sent by nodes over the contention subchannel. The algorithm works as follows. First, when the AP receives a C-RTS frame, it waits for a SIFS time (lines 1-2). Second, the AP extracts $L_{payload}$ from the received C-RTS (denoted by C-RTS-> $L_{payload}$). Then it executes a user-selection algorithm according to $L_{payload}$. If C-RTS-> $L_{payload}$ exceeds a predefined threshold (denoted by $L_{payload}$), Q_{id} is set to Q_1. Otherwise, Q_{id} is set to Q_2 (lines 4-7). Third, the AP feeds back a C-CTS frame containing the winning Node_ID and the chosen Q_{id} that the winner belongs to (line 8). Finally, it will enqueue the Q_{id} and C-CTS-> Node_ID to its local contention queue according to Q_{id}.

Algorithm 3 Transmission Process (Node)

01: **While** (Sending)
02: // *Case 1: Data transmission with SIC*
03: **if** Q_1.front ~= Null **&&** Q_2.front ~= Null **then**
04: **if** Q_1.front ~= Q_2.front **then**
05: **if** Node_ID == Q_1.front **then**
06: Send data with Rate R_p
07: **else if** Node_ID == Q_2.front **then**
08: Send data with Rate R_s
09: **if** Q_1.front == Q_2.front **then**
10: **if** Node_ID == Q_1.front **then**
11: Send data with Rate R_b
12: // *Case 2: Data transmission without SIC*
13: **if** Q_1.front ~= Null **&&** Q_2.front == Null **then**
14: **if** Node_ID == Q_1.front **then**
15: Send data with Rate R_b
16: **if** Q_1.front == Null **&&** Q_2.front ~= Null **then**
17: **if** Node_ID == Q_2.front **then**
18: Send data with Rate R_b
19: // *Receiving ACK*
20: **While** (Receiving ACK)
21: Dequeue (ACK.Q_{id},ACK.Node_ID)

Algorithm 3 illustrates the transmission process of a node. The node determines whether it uses SIC transmission or single transmission without SIC based on the contention queue information in the transmission process. The algorithm works as follows.

- Case 1: Both Q_1.front and Q_2.front are not empty (line 3).
  - If the front elements of Q_1 and Q_2 are different (line 4-8), the nodes whose Node_ID is Q_1.front and Q_2.front perform SIC transmission. The node of Q_1.front uses the rate R_p, and the node of Q_2.front uses the rate R_s.
  - If the front elements of Q1 and Q2 are the same (line 9-11) this node will transmit the frame in Q1.front at the default rate R_b, since a single node cannot perform SIC transmission.
- Case 2: If only one of Q_1.front and Q_2.front is not empty (line 13 and line 16), the default rate R_b is used to send the data frame of this node (i.e., Q_1.front or Q_2.front).
- Case 3: If both Q_1.front and Q_2.front are empty, then no data transmission is performed.

When the transmission is finished, the node will wait for an ACK frame. After receiving ACK feedback, the Node_ID will be removed from the corresponding contention queue (line 20-21).

Algorithm 4 Transmission Process (AP)

01: **While** (Receive Signal S)
02: *// Case 1: Data transmission with SIC*
03: **if** Q_1.front ~= Null **&&** Q_2.front ~= Null **then**
04:     **if** Q_1.front ~= Q_2.front **then**
05:         $(Data_1, Data_2)$ = SIC_Decode(S)
06:     **if** Q_1.front == Q_2.front **then**
07:         $Data_1$ = Non_SIC_Decode(S)
08: *// Case 2: Data transmission without SIC*
09: **if** Q_1.front ~= Null **&&** Q_2.front == Null **then**
10:     $Data_1$ = Non_SIC_Decode(S)
11: **if** Q_1.front == Null **&&** Q_2.front ~= Null **then**
12:     $Data_2$ = Non_SIC_Decode(S)
13: *// Feedback ACK*
14: Feedback a ACK(ACK.Q_{id},ACK.Node_ID)

Algorithm 4 illustrates the transmission process of an AP. The node determines whether the node uses a superposition constellation or a basic constellation for SIC demodulation. The algorithm works as follows.

- Case 1: Both Q_1.front and Q_2.front are not empty (line 3).
  - If the front elements of Q_1 and Q_2 are different (line 4-5), the AP performs SIC decoding based on the superposition constellation.
  - If the front element of Q_1 and Q_2 are the same (line 6-7), the AP uses the basic constellation for decoding at rate R_b.
- Case 2: If only one of Q_1.front or Q_2.front is not empty (line 9 and line 11), the AP uses the basic constellation for decoding at rate R_b.
- Case 3: If both Q_1.front and Q_2.front are empty, the AP does not receive.

After the AP successfully demodulates a data frame, it will feed back an ACK to the transmitting node (line 14).

V. SYSTEM MODEL

In this section, the model of the Multi-CQ system is detailed. The model's concept was derived from [17]–[20]. The Multi-CQ system is modeled for two special cases: one case is for an unsaturated contention queue and the other case is for a saturated contention queue. To facilitate the theoretical analysis, the Multi-CQ system's contention process is assumed to be in a saturation regime (which means each node always has frames to transmit), and the contention queue storage is assumed to be infinitely large.

A. MODELING IDEAS

The Multi-CQ protocol can be abstracted as a FIFO model. As shown in Figure 10, the system model consists of two parts: the contention process and the transmission process. Each node in Multi-CQ does contention backoff, and the winner writes its ID to the contention queue to reserve the transmission subchannel. Then a node transmits its data according to the contention queue order when the transmission subchannel is idle.

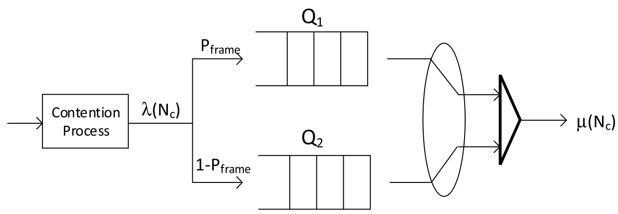

FIGURE 10. Arrival rate and dequeue rate.

Throughput is defined as the number of bits processed per unit of time (i.e., bps). The throughput is denoted as in (1).

$$\Gamma\left(M_c\right)=\min\left[\lambda\left(M_c\right),\mu\left(M_c\right)\right]L_p \tag{1}$$

where λ is the arrival rate of the transmission channel, μ is the dequeue rate of the transmission channel, and L_p is the average frame length. To simplify the analysis, it is assumed that there are two kinds of frames entering the queues, long frames (say, the frame in Q_1) and short frames (say, the frame in Q_2), each with a probability of P_{frame}. The details are as follows.

B. CASE 1: CONTENTION QUEUES ARE UNSATURATED

When λ is small, the system throughput is limited by the arrival rate λ. At that point, as soon as a frame arrives, it can be immediately sent. That is, the throughput can be identified as in (2).

$$\Gamma\left(M_c\right)=\lambda\left(M_c\right)L_p \tag{2}$$

It is assumed that there are only two types of frames in the network, long frames (i.e., the frames in Q_1) and short frames (i.e., the frames in Q_2), so we can obtain (3).

$$L_p = P_{frame} * L_{payload\_long} + \left(1 - P_{frame}\right) * L_{payload\_short} \tag{3}$$

where $\lambda(M_c)$ is given in (4) of [9].

C. CASE 2: CONTENTION QUEUES ARE SATURATED

When the λ is greater than μ, the Multi-CQ contention queue is saturated, and the dequeue rate μ limits the system throughput. Then the throughput can be formulated as in (4).

$$\Gamma\left(M_c\right) = \mu\left(M_c\right) L_p \tag{4}$$

At this point, the transmission channel can continuously transmit data like a TDMA system. If the transmission of two units at a time is considered, there are three cases of μ, which are denoted as μ_{long} (representing long frames), μ_{short} (representing short frames), and μ_{SIC} (representing concurrent transmission at SIC rate).

$$\mu_{long}\left(M_c\right) = \frac{1}{T_{cifs} + T_{sifs} + \frac{L_h + L_{payload\_long} + L_{ack}}{R_{carrier}(M - M_c)}} \tag{5}$$

$$\mu_{short}\left(M_c\right) = \frac{1}{T_{cifs} + T_{sifs} + \frac{L_h + L_{payload\_short} + L_{ack}}{R_{carrier}(M - M_c)}} \tag{6}$$

$$\mu_{SIC}\left(M_c\right) = \frac{1}{T_{cifs} + T_{sifs} + \frac{L_h + (L_{payload\_long} + L_{payload\_short}) + L_{ack}}{Gain_{SIC} * R_{carrier}(M - M_c)}} \tag{7}$$

where T_{cifs} is the time of CIFS (instead of DIFS used in Multi-CQ) in transmission subchannel, T_{sifs} is the time of SIFS, L_h is the length of headers (including the PHY header and MAC header), L_{ack} is the length of ACK, and $Gain_{SIC}$ is the capacity gains with SIC transmission.

Since the probabilities of occurrence of the two kinds of frames are equal, there are only four combinations of them: (Long, Short), (Long, Short), (Short, Long), and (Short, Short). In the design, a long frame and a short frame can be sent concurrently using SIC, so the combinations for SIC transmission are (Long, Short) and (Short, Long), which have a probability of 2/4. Therefore, we can obtain the dequeue rate as in (8).

$$\mu\left(M_c\right) = \frac{1}{4} * \mu_{long}\left(M_c\right) + \frac{1}{4} * \mu_{short}\left(M_c\right) + \frac{2}{4} * \mu_{SIC}\left(M_c\right) \tag{8}$$

However, even though frames are transmitted in two different CQs, SIC technology cannot be used since they are frames from the same node, as shown in Algorithm 3 (line 9-11). Since they are from the same node and SIC can only be used for multiple different nodes, in this case, the node can only do the normal transmission without SIC. It is assumed that the contention process has short-term equity. That is, among N nodes, the probability of getting the same node from Q_1 and Q_2 is equivalent to the probability of getting two different nodes from Q_1 and Q_2 (i.e., equal to $1/[N \times (N-1)]$). The upper dequeue rate becomes (4).

$$\mu\left(M_c\right) = \frac{1}{4} * \mu_{long}\left(M_c\right) + \left(\frac{1}{4} + \frac{1}{N(N-1)}\right) * \mu_{short}\left(M_c\right) + \left(\frac{2}{4} - \frac{1}{N(N-1)}\right) * \mu_{SIC}\left(M_c\right) \tag{9}$$

VI. PERFORMANCE EVALUATION

This section verifies the theoretical model and compares Multi-CQ performance with different protocols and with different parameters as tested with a C++ simulator. This simulator was also adopted in [9], [21]–[23].

TABLE 1. Parameter settings in simulation.

M_c	10	L_{ACK}	14 Bytes
M_d	38	$L_{threshold}$	500 Bytes
σ(slot)	20 μs	$L_{short\_pay\,load}$	327 Bytes
T_{CIFS}	12 μs	$L_{long\_pay\,load}$	1000 Bytes
T_{SIFS}	10 μs	SIC_{gain}	1.327
T_{DIFS}	50 μs	$R_{carrier}$	1.125 Mbps
$L_{headers}$	54 Bytes	R_p	14 Mbps
$L_{C\text{-}RTS}$	20 Bytes	R_s	42.75 Mbps
$L_{C\text{-}CTS}$	14 Bytes	R_b	42.75 Mbps

Table 1 lists the parameter settings of our simulation. Each simulation value is an average of the results from five simulation runs, where each run lasts for 100 seconds.

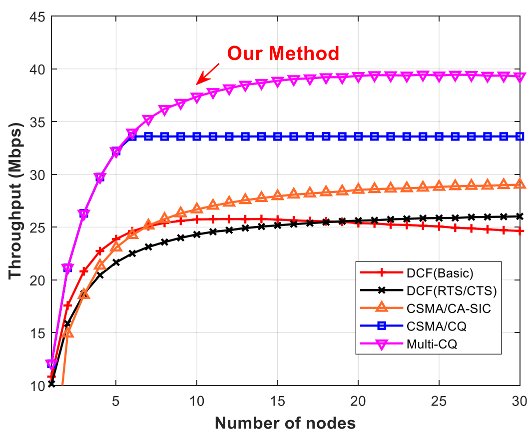

FIGURE 11. Comparison of the throughput among Multi-CQ, CSMA/CA-SIC, CSMA/CQ, DCF RTS/CTS mode, and DCF Basic mode.

Figure 11 shows a comparison of throughputs among Multi-CQ, DCF basic mode [16], DCF RTS/CTS mode [16], CSMA/CA-SIC [6], and CSMA/CQ [9] with parameters M_c:M_d = 6:42 when the number of nodes N varies from 1 to 30. It can be observed from this figure that the throughput of Multi-CQ and CSMA/CQ increases faster than that of the other protocols as N increases. Then, Multi-CQ continues to increase slowly to a bigger value with N, while CSMA/CQ just stays at a fixed value when N reaches 6. The throughput in Multi-CQ is always better than those in DCF basic mode, DCF RTS/CTS mode, CSMA/CQ, and CSMA/CA-SIC.

The throughput increment in Multi-CQ is approximately 15%. As shown in Figure 11, the throughput of Multi-CQ increases from 33 Mbps to 39 Mbps as N increases from 5 to 30, while the throughput of CSMA/CQ reaches and stays at 34 Mbps, and the remaining protocols reach 25 Mbps at most. The reason for the higher throughput in Multi-CQ is that there is a higher probability of concurrent transmission. It can also be seen that the throughput in DCF basic mode first increases and then decreases with increasing N. The main reason for this phenomenon is that more collisions occur with increasing numbers of contending nodes. In contrast to DCF in RTS/CTS mode, these collisions frequently corrupt data frames more than smaller RTS frames, which leads to more wasted time for data transmission.

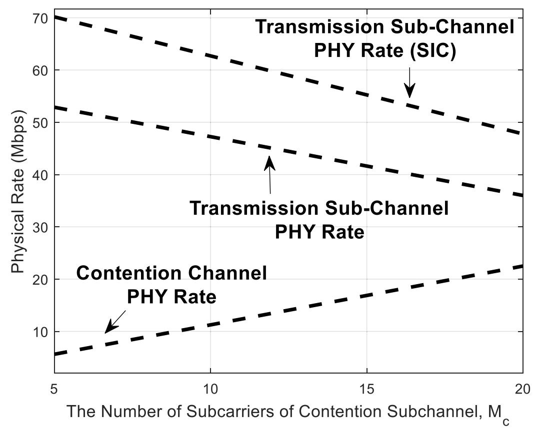

FIGURE 12. Physical Rate of Contention Subchannel and Transmission Subchannel.

Figure 12 plots the physical rates of contention in the subchannel and the transmission subchannel (in Mbps), as the number of subcarriers of the contention channel M_c varies from 5 to 20. In this figure, as the number of subcarriers of contention subchannel increases, the channel's corresponding transmission rate becomes higher. At the same time, since the total number of subcarriers remains unchanged, the number of data subcarriers also decreases, so the transmission rate of the transmission channel also decreases. The figure also shows that the transmission rate with SIC is higher than it is without SIC.

Figure 13 plots the theoretical and simulated throughputs (in Mbps) of Multi-CQ with M_c set to 5, 10, 15, and 20 as the number of nodes N varies from 1 to 30. The highest throughput can reach 39 Mbps when M_c is set to 10. However, the throughput decreases when M_c is larger or smaller than 10 (i.e., M_c is equal to 6, 16, or 20). Therefore, an optimal throughput exists as M_c increases for Multi-CQ. The reason for this could be as follows. Since the sum of M_c and M_d is a constant value M, an increase in M_c will lead to a decrease in M_d. This means that more bandwidth resources are allocated for contention and less for transmission. Hence, with a larger M_c, too much resource is occupied by the contention process, which is unnecessary for the contention process and therefore reduces data transmission time. With a smaller M_c, too little

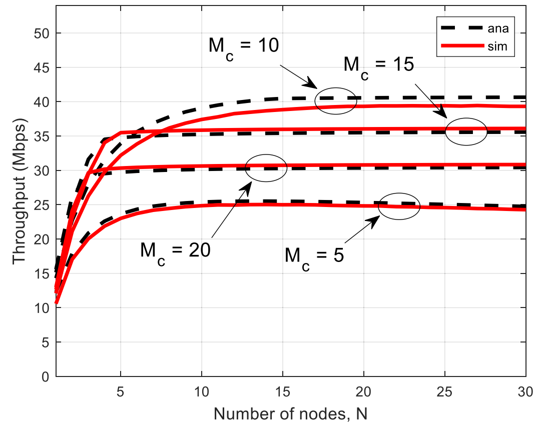

FIGURE 13. Throughput vs. Number of nodes (N) for $M_c = 5, 10, 15,$ and 20.

resource is allocated to the contention process which results in not enough time for the contention process to produce a winner for data transmission. Therefore, more rounds of contention are needed, leading to low utilization of channel resources.

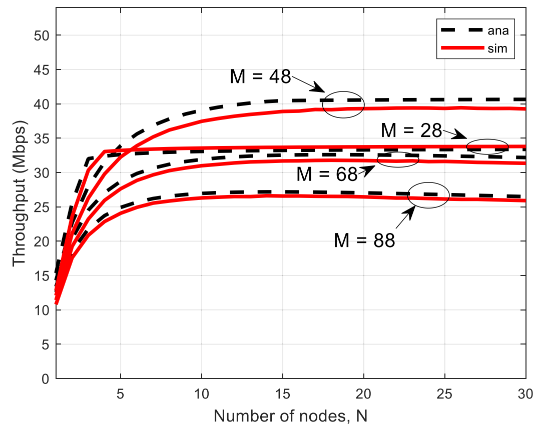

FIGURE 14. Throughput vs. Number of nodes (N), when M = 28, 48, 68, and 88.

Figure 14 plots the throughputs (in Mbps) when total subcarriers M is set to 28, 48, 68 and 88 as the number of nodes N varies from 1 to 30. M_c is set to 10 in this experiment. As shown in the figure, the highest system throughput can reach 39 Mbps when M is set to 48, but larger or smaller values of M (i.e., $M = 28, 68, 88$) lead to lower throughput. This is because a larger M means more bandwidth will be used for the transmission process. Therefore, the contention queue is unsaturated in this case (since the M_c is a constant). Similarly, a smaller M indicates that the bandwidth of the transmission process is limited. Thus, the contention queue is saturated, leading to a decrease in system throughput.

Figure 15 shows the throughputs (in Mbps) of Multi-CQ with M_c set to 5, 10 and 15 as the number of total subcarriers M varies from 20 to 90. In this experiment, the total number of nodes is set to 10. It can be observed that the throughput with different M_c settings increases and then stays unchanged as M grows larger. The reason for no change in throughput

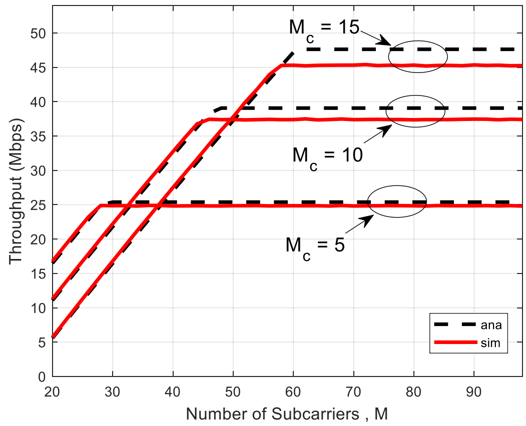

FIGURE 15. Throughput vs. Number of Subcarriers (M), when $M_c = 5, 10, 15$, and 20.

is that the saturated throughput of the system is reached. Besides, with a larger M_c, there is a higher system saturation throughput.

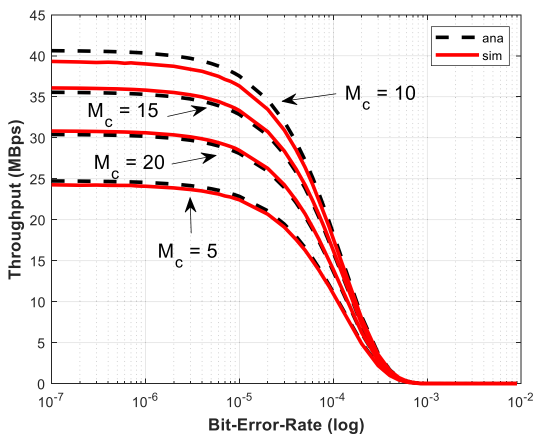

FIGURE 16. Throughput vs. Bit-error-Rate, when $M_c = 5, 10, 15$, and 20.

Figure 16 plots the throughputs (in Mbps) with M_c set to 5, 10, 15, and 20, as the Bit-Error-Rate (BER) varies from 10^{-7} to 10^{-2}. In this figure, the simulation results match the theoretical values. The results show that as the BER increases, the throughput decreases (that is, when BER is greater than 10^{-5}) and gradually approaches 0 (when BER is greater than 10^{-3}). This is because the BER causes the contents of data frames to be transmitted incorrectly. After the receiver receives an errored data frame, the correct data cannot be obtained. As a result, the receiver cannot acquire accurate data, resulting in a decrease in throughput. In addition, when the BER is low (that is, when the BER is less than 10^{-3}), the allocation of different subcarriers results in different throughputs when M_c is set to 10 in this experiment.

VII. CONCLUSION

Existing SIC-based MAC designs have two drawbacks. 1) The serial execution of contention and transmission leads to low channel utilization and 2) transmissions without user selection leads to wasted SIC transmission capacity. To overcome these drawbacks, we propose a novel design called Multi-CQ. To the best of our knowledge, Multi-CQ is the first protocol to apply SDN to wireless MAC protocols that support SIC. In our design, which incorporates SDN's functional separation concept, the concurrent execution of channel contention and data transmission is allowed over two subchannels (based on OFDMA technology). A contention queue is introduced to coordinate the concurrency, thereby overcoming the serial execution drawback. In applying SDN's central control concept, we adopt a centralized control mechanism based on the contention queue to reduce the time disparities of concurrent frame transmission, thereby overcoming the second drawback. We also develop a theoretical model of bandwidth allocation for channel contention and data transmission. Extensive simulations verify the effectiveness of our design and the accuracy of our theoretical model. As a result, Multi-CQ achieves higher throughput than existing designs.

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