A Cluster-Based OFDMA MAC Protocol using Carrier-Sensing Scheme for IEEE 802.11ax WLANs

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***Abstract*—Orthogonal Frequency Division Multiple Access (OFDMA) is utilized in wireless local area networks (WLANs) to improve channel utilization and increase network throughput. However, random transmissions by wireless stations can lead to Resource Unit Collision Problem (*RUCP*) and Hidden Node induced *RUCP* (*HN-RUCP*), significantly degrading network throughput. Therefore, this paper proposes a Cluster-based OFDMA MAC protocol using the Carrier-sensing scheme, CC-OFDMA, for dense WLANs. Simulation results conducted using MATLAB show that the CC-OFDMA MAC protocol outperforms related works in terms of transmission latency and collisions.**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is a popular technology for enhancing the performance of dense wireless local area networks (WLANs) by dividing the channel into multiple resource units (RUs). To schedule the uplink (UL) transmission in OFDMA-based WLANs, Uplink-OFDMA Random Access (UORA) has been proposed in IEEE 802.11ax. However, multiple STAs may select the same RU for transmission, resulting in ***Resource Unit Collision Problem (RUCP)***. To mitigate this issue, various solutions have been proposed. In [1], [2], a backoff scheme that depends on the network traffic load is proposed. This approach requires a special control frame and buffer status report. On the other hand, in [3], [4], an arbitration phase is designed, where STAs contend for an RU by transmitting busy-tone signals. If the selected RU is busy, the STA will contend for the RU again later to avoid ***RUCP***. Another approach proposed in [5] is the H-UORA MAC protocol, which combines UORA and the traditional p-persistent CSMA mechanism to alleviate the ***RUCP*** problem. The H-UORA protocol uses UORA for normal data transmission, but when a collision occurs, the p-persistent CSMA mechanism is used to contend for the RU. The p-persistent CSMA mechanism is a well-known contention-based access mechanism that reduces collisions by waiting for a random amount of time before transmitting data. However, STAs that are associated with the same AP may be two-hop neighbors, as shown in Fig. 1. In this scenario, STA_2 is outside the transmission range of STA_1, making them hidden from each other. STA_1 cannot sense the transmission of STA_2 even if they select the same RU to transmit. If STA_1 and STA_2 transmit their data on the same RU, a ***Hidden Node induced Resource Unit Collision Problem (HN-RUCP)*** may occur, particularly in dense IEEE 802.11ax WLANs [3], [5].

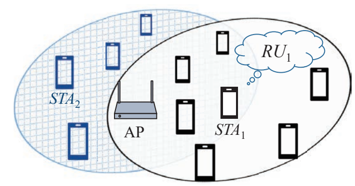


Fig. 1. The scenario of Hidden Node induced Resource Unit Collision Problem (HN-RUCP). The STAs within the grid area are the hidden STAs of STA_1. If STA_1 and hidden STAs, such as STA_2, transmit in the identical RU, HN-RUCP will happen.

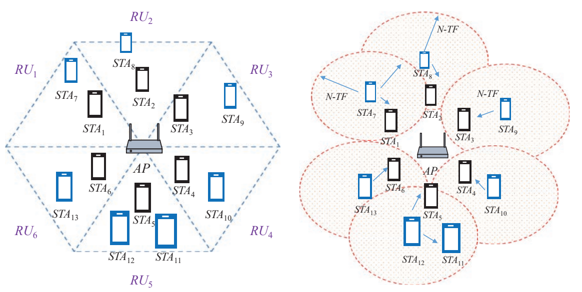
In the paper, we propose a Cluster-based OFDMA MAC protocol using the Carrier-sensing scheme, namely CC-OFDMA, not only to avoid the ***RUCP*** and ***HN-RUCP*** but also to improve the overall network throughput for dense WLANs.

II. The Cluster-based OFDMA MAC protocol using the Carrier-sensing scheme (CC-OFDMA)

The core idea of CC-OFDMA is to use modified carrier-sensing and random backoff mechanisms to avoid ***RUCP***, and a cluster mechanism to prevent ***HN-RUCP*** in dense WLANs. Here we describe the core idea of CC-OFDMA as follows.

A. Clustering mechanism

To avoid ***HN-RUCP***, a simple approach is to ensure that all hidden nodes transmit in different Resource Units (RUs). In CC-OFDMA, neighboring STAs are grouped into clusters, and all the members of a cluster are required to send DATA in the same RU. Ideally, the transmission range of the Access Point (AP) shown in Fig. 2(a) is similar to a hexagonal area that can be divided into six equilateral triangle sub-areas. The associated STAs within each sub-area are grouped into a cluster. Thus, AP can obtain the distance information between itself and the associated STA, either during the association procedure or the previous DATA transmission, based on signal strength. As shown in Fig. 2(b), the AP selects STAs within half of the transmission range as clusterheads, which then broadcast Neighbor-Trigger Frames (N-TFs) to form the cluster. STAs may then join the cluster as members after receiving the N-TF. This is the concept of the clustering scheme in CC-OFDMA, and the detailed procedure is introduced in Section II-C.



(a) (b)

Fig. 2. The concept of Clustering mechanism, where (a) the transmission range of AP could be divided into 6 equilateral triangle sub-areas to avoid ***HN-RUCP***,(b) the clusterhead initiate the clustering procedure.

B. Carrier-sensing and Random backoff mechanisms

To apply the carrier-sensing and random backoff mechanisms in UORA, CC-OFDMA introduces the idea that the AP announces the OFDMA contention window (OCW), the backoff window, and the number of available RUs (N_{RU}) in the Trigger Frame (TF). Similar to UORA, if a STA has data to send, it will generate an OFDMA backoff (OBO) from the OCW and a random backoff value after receiving the TF. Instead of transmitting a busy-tone signal, in CC-OFDMA, the STA subtracts the N_{RU} from the OBO counter and starts sensing the medium for a backoff period when the OBO counter reaches 0. During the sensing period, if the medium remains idle, the STA will select an idle RU for data transmission when the backoff value also reaches 0.

Let us consider an example to illustrate the carrier-sensing and random backoff mechanisms in CC-OFDMA. Suppose that N_{RU}=6, and there are 8 associated STAs (N_{STA}) in the network, denoted as STA_1 to STA_8. The OBO counters and backoff values of the STAs are given in the Table I below.

TABLE I
AN EXAMPLE TO ILLUSTRATE THE BACKOFF MECHANISMS.

STA	OBO counter	Backoff value
STA_1	3	3
STA_2	1	1
STA_3	2	4
STA_4	6	8
STA_5	2	5
STA_6	3	2
STA_7	5	7
STA_8	7	6

Following the CC-OFDMA protocol, the AP announces OFDMA contention window (OCW) and N_{RU} in the TF. Based on the information in the TF, STA_1 to STA_7 can get into the carrier-sensing period since their OBO counters are less than N_{RU}. Assuming that all RUs are idle during the carrier-sensing period, each STA begins its backoff period. In this case, the backoff value of STA_2 is the smallest, i.e., 1. Therefore, STA_2 can directly transmit DATA in a randomly selected RU (RU_1) after sensing one slot time. Next, in slot 2, STA_6's backoff value is counted down to 0. Since all RUs are still idle, STA_6 selects another free RU (RU_2) to transmit its DATA. Now, suppose that STA_4's backoff value has also counted down to 0. However, all RUs are currently occupied by other STAs. Therefore, STA_4 has to wait for the next contention period to transmit its DATA. Finally, after receiving all DATAs successfully, the AP sends an MBA frame to confirm the transmissions. In summary, the carrier-sensing and random backoff mechanisms in CC-OFDMA can effectively reduce collisions and increase network throughput.

C. The detailed procedure of CC-OFDMA

Without loss of generality, it is assumed that time is divided into repetitive UL working periods in CC-OFDMA. Each UL working period comprises one clustering and multiple DATA transmission phases. In WLANs, n RUs are available, with the first and second RUs designated for the transmission of non-clustering and non-associated STAs, respectively. The remaining RUs are reserved for clustering STAs.

At the beginning of a working period, the AP broadcasts a C-TF to initiate the clustering phase, as described in Section II-A. In this phase, n-2 STAs far from the AP are selected as clusterheads, and the AP allocates RUs to the corresponding clusterheads based on the DATA size. After receiving the C-TF, the clusterheads broadcast N-TFs with half of the transmission range in the specified RUs. Associated STAs join the cluster according to the N-TF they receive. If an associated STA receives multiple N-TFs, it follows the clusterhead with the strongest receiving power.

After the clustering phase, AP sends a confirmation TF to validate the clustering and begin the DATA transmission phase. In this phase, each associated STA generates an OBO counter and backoff values randomly, following the design specified in Section II-A. If the OBO counter of an associated STA is smaller than or equal to N_{RU}, the STA directly selects an idle RU to transmit DATA after the backoff value countdown to 0. However, if the OBO counter of an associated STA is less than N_{RU}, the STA first senses its corresponding RU for a backoff period. If the medium is always in the idle state, the associated STA could directly transmit DATA in that RU when the backoff value countdown to 0.

Note that the number of STAs in each cluster may not be identical due to the random topology and the lack of knowledge of the location of each STA. As a result, the proposed clustering scheme may not perform optimally in CC-OFDMA. To address this issue and improve the clustering scheme, as shown in Figure 3, AP will broadcast a C-TF to initiate another clustering phase for clustering reconstruction after several working periods have elapsed.

III. PERFORMANCE EVALUATIONS

To verify the effectiveness of the proposed CC-OFDMA, UORA, H-UORA [5], and Busy-Tone [3] MAC protocols are simulated. The simulations are conducted by the Matlab [6]. AP is deployed at the center of the simulation area. In the

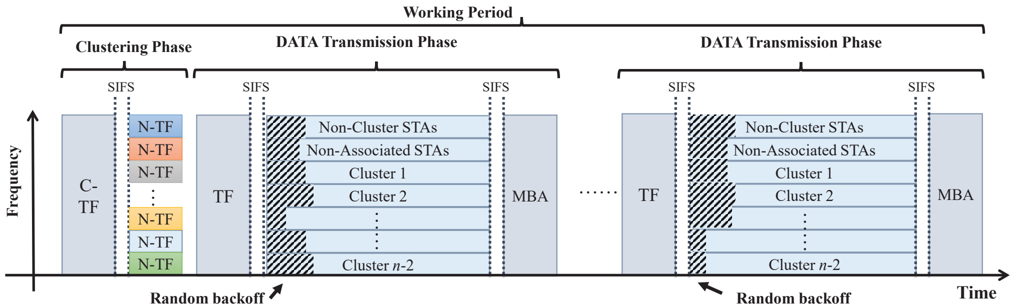
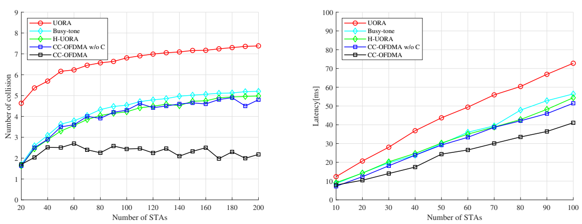


Fig. 3. The procedure of Cluster-based OFDMA MAC protocol using the Carrier-sensing scheme.



(a) (b)

Fig. 4. The comparison of the number of (a) the number of collisions and (b) the transmission latency among UORA, Busy-Tone, CC-OFDMA, and CC-OFDMA without clustering for different N_{STA}.

simulation, we focus on the UL transmission. The general simulation settings are shown in Table II.

TABLE II
SIMULATION SETTINGS.

Parameter	Value
Traffic model	CBR
N_{RU}	9
OCW_{min}	12
OCW_{max}	256
TF Duration	10 μs
Transmission Range	50 m
Simulation Area	150 m * 150 m

The comparison of the number of collisions among these four protocols for different N_{STA} is shown in Fig. 4(a). It is evident the number of collisions in each MAC protocol increases with an increase in N_{STA}. UORA performs the worst due to the severity of both ***HN-RUCP*** and ***RUCP***. CC-OFDMA without clustering performs almost the same as Busytone and H-UORA since they can only alleviate ***RUCP***. It is worth mentioning that CC-OFDMA can avoid ***HN-RUCP*** but not ***RUCP***. Therefore, the number of collisions in CC-OFDMA is not zero.

The comparisons of the transmission latency among these four protocols for different values of N_{STA} are shown in Fig. 4(b). It can be observed that the transmission latency in each MAC protocol increases with an increase in N_{STA}. To alleviate the ***HN-RUCP***, UORA doubles the OCW when a collision occurs, which leads to the worst transmission latency. Although the clustering phase time interval is required for CC-OFDMA, the transmission latency does not increase significantly because CC-OFDMA not only avoids ***HN-RUCP*** but also alleviates ***RUCP***, thus reducing retransmissions. Therefore, CC-OFDMA has the best transmission latency performance among the four protocols.

IV. CONCLUSIONS

Next-generation wireless networks widely support OFDMA wireless transmission. However, uplink transmission in OFDMA-based WLANs can suffer from the ***Resource Unit Collision Problem (RUCP)*** and the ***Hidden Node induced RUCP (HN-RUCP)***. This paper formally investigates both problems and proposes a Cluster-based OFDMA MAC protocol using the Carrier-sensing scheme, CC-OFDMA, to avoid collisions. CC-OFDMA not only alleviates ***RUCP*** and avoids ***HN-RUCP*** but also enhances network performance. Simulation results demonstrate that CC-OFDMA outperforms other protocols in terms of transmission latency and collisions.

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