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Resource Unit Allocation in Coordinated OFDMA Multi-User Wi-Fi Systems

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***Abstract*—The scheduling of resource units (RUs) in a multi-AP coordination network is considered vital for high spectrum efficiency and effective interference mitigation in future Wi-Fi Networks. In this paper, we propose a RU allocation scheme to maximize the long-term average network throughput of STAs in a multi-AP coordinated Wi-Fi network within a joint coordinated orthogonal frequency-division multiple access (C-OFDMA) and coordinated special reuse (CSR) framework. The proposed scheme ensures that the average rates satisfy the STAs' quality of service (QoS) requirements and the interference in the overlapping basic service sets (OBSSs) is efficiently managed. The original RU allocation problem is formulated as binary integer programming, which is an NP hard. To address this, a heuristic graph coloring model is introduced for RU allocation in OBSSs, where the Sharing-AP allocates RUs with weighted max-min (WMM)-based graph coloring to overlapping STAs while simultaneously assigning RUs to its own STAs within the same frequency band using the WMM algorithm. Simulation results demonstrate that the proposed RU scheduling algorithm enhances overall mean network throughput by 30%. The simplicity and low computational complexity of the proposed algorithm confirm its effectiveness and practicality for implementation.**

***Index Terms*—Coordinated OFDMA, Graph Coloring, Multi-AP Coordination, Resource Allocation, Weighted Max-Min.**

I. Introduction

FOLLOWING the introduction of the IEEE 802.11be, IEEE 802.11bn, has been proposed with the main objective of ultra-high reliability. According to the IEEE 802.11bn task group, multi-access point coordination (MAPC) is a feature to be included in IEEE 802.11bn to enable access points (APs) coordination across different basic service sets (BSSs). Compared to previous standards, this innovation significantly enhances the interference mitigation and leads to better spectral efficiency and higher reliability [1]–[5].

MAPC network design is divided into two principal categories, 1) centralized MAPC (C-MAPC) incorporates a centralized primary controller that possesses comprehensive network information and requires high-performance processors with wired backhaul connections. 2) Distributed MAPC (D-MAPC), operates on a sharing/shared coordination principle without a central controller, allowing any of the APs to assume the sharing role. This architecture enhances network scalability and cost-effectiveness. Signal transmissions in MAPC can be facilitated over the air if the APs are within range of each other or through the wired backhaul. This paper primarily explores the D-MAPC owing to its scalability, cost efficiency, ease of implementation, and the simplicity of integrating it with existing Wi-Fi amendments [5]. Regardless of the specific MAPC architecture, the literature identifies four advanced techniques pivotal to MAPC: coordinated spatial reuse (CSR), coordinated beamforming (CBF) [1], coordinated OFDMA (C-OFDMA), and joint transmission (JTX) [1], [6], [7]. These techniques play crucial roles in enhancing the performance of networks [7], [8].

C-OFDMA can provide simultaneous channel access at different APs with coordination based on frequency separation thus the interference will be managed efficiently compared to the conventional non-MAPC models [1]. For this feature, two types of resource allocation among different APs are available, one idea is that the agreed coordinated AP sets have the same primary channel while the resource units (RUs) are divided between the agreed coordinated AP sets' requirement. However, failing to allocate the entire bandwidth to the coordinated set of APs leads to inefficiencies in resource allocation. [5]. The other one uses different primary channels for the neighborhoods' APs which causes the inter-channel interference (ICI) [5]. This approach allocates entire frequency bands to all stations (STAs) and their respective APs, regardless of whether overlap or interference is present, potentially leading to suboptimal spectrum utilization. As a result, this approach may exhibit inefficiencies, particularly in real-time and industrial applications where optimal spectrum utilization is crucial for performance and reliability. [5].

On the other hand, CSR provides parallel transmission with interference management [6] in the same frequency and time with coordination between APs and transmission power management of APs/STAs. Using C-OFDMA with CSR can highly increase the spectrum efficiency. By coordinating RU allocation, multiple APs can transmit concurrently on the same frequency channels without causing significant interference, leading to more efficient use of the available spectrum [5]. Interference management through RU assignment tackles a fundamental spatial reuse issue. It enables concurrent transmissions in overlapping regions by employing efficient spectrum partitioning and interference mitigation strategies. Therefore, to the best of our knowledge, this paper is the first to propose a RU allocation scheduling and interference management

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scheme within a joint C-OFDMA and CSR framework.

Given the dynamic nature of wireless channels and the limited spectrum availability, RU allocation plays a crucial role, particularly in multi-AP scenarios. Without an efficient RU allocation strategy, interference can significantly degrade network performance. [5]. In the literature, RU allocation is primarily based on real-time channel quality. For instance, the authors in [9], [10] propose a multi-cell OFDMA downlink channel assignment, considering the MAX k-CUT problem in graph theory. While authors [11] proposed RU allocation based on max-min fairness aims to optimize the smallest ratio of achievable throughput to the minimum requested throughput.

The main contribution of this work is the development of a low-complex and practically implementable RU scheduling algorithm for a WiFi network under realistic practical assumptions. The details are as follows. First we propose an RU allocation in a joint C-OFDMA and CSR D-MAPC system model. The main objective of the proposed scheduling algorithm is to maximize the total long-term average network throughput with the average rate quality of service (QoS) satisfaction of each STA. The problem is formulated as a binary integer programming problem which is an NP-hard problem. To solve the problem first a simple yet practical heuristic graph coloring model is proposed for RU allocation in the overlapping basic service set (OBSS) where no precise STAs' locations and no SINR information are needed. Subsequently, a weighted max-min (WMM) algorithm is introduced to allocate RUs for each non-overlapping STA, ensuring the proposed problem formulation is effectively addressed. The simulation results highlight the enhancement in total network throughput achieved by the proposed algorithm, showcasing its effectiveness despite being simple and practical.

The remainder of this paper is structured as follows. Section II presents the proposed system model and problem formulation. Section III proposes the graph-based WMM fair RU allocation algorithm. Section IV provides simulation results to validate performance of the proposed RU allocation technique. Finally, Section V concludes the paper. Through out the paper the terms data rate and throughput are used interchangeably.

II. System Model and Problem Formulation

The system model consists of a number of APs and their STAs operating under a D-MAPC based WiFi network. It uses a joint C-OFDMA and CSR model, where one AP in the MAPC group acts as the Sharing-AP, allocating resources for overlapping STAs to enable simultaneous frequency reuse in different locations. We assume an over-the-air connection between the Sharing-AP and Shared-APs, meaning they are within each other's coverage area, as shown in Fig. 1. The Sharing-AP secures the TXOP based on the lowest backoff time. The uplink transmissions of STAs are considered.

The sets representing the STAs served by the m-th AP, the APs themselves, and the available RUs are denoted as follows: $k \in \mathcal{K} = \{1, 2, \dots, K\}$, $m \in \mathcal{M} = \{1, 2, \dots, M\}$ and $n \in \mathcal{N} = \{1, 2, \dots, N\}$, respectively. Additionally, the set of intersecting regions between OBSSs is represented as:

$$\mathcal{I} = \bigcup_{m,m' \in \mathcal{M}} \{C \mid C \in \mathcal{C}_m \cap \mathcal{C}_{m'},\, m \neq m'\}\,.$$

where $\mathcal{C}_m$ and $\mathcal{C}_{m'}$ represent OBSS areas served by m-th and m'-th APs, respectively. $\mathcal{C}$ is the overlapping area for these two APs and $\mathcal{I}$ aggregates all common regions for any two OBSSs in the system model. Moreover the STAs located in $\mathcal{I}$ are $k' \in \mathcal{K}' = \{1, 2, \dots, K'\}$.

Each STA is limited to one RU per TXOP. All APs are assumed to use the same 20 MHz primary channel [12]. Therefore the co-channel interference needs to be mitigated. In this context, $h^m_{k,n}$ is the channel gain between the k-th STA and the m-th AP on RU n. This gain is assumed to be independent and identically distributed (IID) across each time step, emphasizing the stochastic nature of the channel conditions in this coordinated network model.

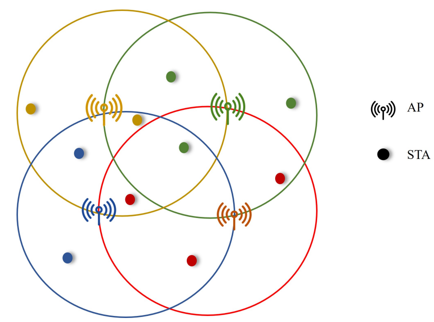

Fig. 1: System Model.

Additionally, all the STAs transmit with a constant power value and $\rho^m_{k,n}(t)$ is defined as a binary variable. When $\rho^m_{k,n}(t) = 1$, it indicates that the k-th STA is using the n-th RU; if it is zero, no resources are allocated for transmission of the k-th STA in the n-th RU. The data rate is defined as follows:

$$r^m_{k,n}(t) = r\left(h^m_{k,n}(t)\right) \frac{T_{\text{TXOP}}}{T_{\text{OFDM}}}, \tag{1}$$

where $h^m_{k,n} = \text{PL}^m_k(d) * g^m_{k,n}$, in which $g^m_{k,n}$ is small scale fading of k-th STA and the m-th AP on RU n and $\text{PL}^m_k(d)$ is denoted as formula in 5. T_{TXOP} is the duration of uplink OFDMA for each TXOP transmission and it is fixed during the simulation. T_{OFDM} denotes the duration of OFDM symbol, and $r(.)$ models the rate selection scheme for the k-th STA of the m-th AP on the n-th RU. As mentioned earlier, in this paper, the main objective is to maximize the long-term average throughput of all OBSSs. Therefore the total throughput of the k-th STA of the m-th AP is defined as follows:

We assume that each STA gets only one RU, therefore the formula can be rewritten as follows:

$$r^m_k(t) := \sum_{n=1}^{N} \rho^m_{k,n}(t) r^m_{k,n}(t). \tag{2}$$

The main goal here is to maximize the average data rate of STAs, therefore the long-term average data rate can be defined as,

$$\bar{r}^m_k := \lim_{T_{\text{total}} \to \infty} \sup \frac{1}{T_{\text{total}}} \sum_{t=0}^{T_{\text{total}}-1} \mathbb{E}\left[r^m_k(t)\right]. \tag{3}$$

The average long-term data rate is a concave, continuous, and entrywise non-decreasing function with respect to the data rates of the STAs. Under the condition that the average data rate for each STA meets the specified minimum data rate threshold. The RU allocation problem in the considered system can be formulated as follows:

$$\underset{\rho^m_{n,k}}{\text{maximize}} \quad \sum_{m=1}^{M}\sum_{k=1}^{K}\bar{r}^m_k \tag{4a}$$

$$\text{subject to} \quad r^{\mathrm{Tr}}_k \leq \bar{r}^m_k, \quad \forall k \in \mathcal{K}, \tag{4b}$$

$$\sum_{k=1}^{K}\rho^m_{k,n}(t) \leq 1, \forall n \in \mathcal{N}, \tag{4c}$$

$$\sum_{n=1}^{N}\rho^m_{k,n}(t) \leq 1, \forall k \in \mathcal{K}, \tag{4d}$$

$$\sum_{k'=1}^{K'}\rho^m_{k',n}(t) \leq 1, \forall n \in \mathcal{N}. \tag{4e}$$

The objective function (4a) is the long-term average of network data rate. Constraint (4b) ensures that the STA's average data rate is greater than r^{Tr}_k, which is the average data rate QoS threshold. The constraints in (4c) and (4d) respectively confirm that for each BSS, RUs can only be allocated to at most one STA, and each STA can have a maximum of one RU. Constraint (4e) ensures that any two overlapping STAs in the set $\mathcal{I}$ cannot get the same RU.

In this model, it is assumed that STAs closer to the AP are able to utilize higher modulation coding schemes (MCSs) for data transmission and reception, while those positioned further away use lower MCSs. APs select the appropriate MCS for each STA based on the received SNR of the STA Further details can be found in Section IV. Additionally, it is assumed that the Sharing-AP gathers information on the channel amplitude response of overlapping STAs, and the BSSs in which these overlapping STAs are located. The pathloss of k-th STA in m-th AP based on the Residential cases of the TGax model [12] is as follows:

$$\mathrm{PL}^m_k(d) = 40.05 + 20 \times \log_{10}(f_c/2.4) + 20 \times \log_{10}(\min(d,5)) + (d > 5) \times 35 \times \log(d/5), \tag{5}$$

where, f_c denotes 5 GHz, and d is the distance between the transmitter and the receiver in meters.

III. Proposed Algorithm

The RU allocation problem defined in (4a)- (4e) is NP-hard, not feasible and the solution cannot be obtained with polynomial time complexity. To determine a feasible solution, we propose a heuristic algorithm based on the drift-plus-penalty method inspired from [11] and a graph coloring based on WMM algorithm. In this algorithm, the Sharing-AP initially gathers information on the channel amplitude response of overlapping STAs, and the BSSs in which these overlapping STAs are located. Then, the Sharing-AP is able to create the undirected graph $G = (\mathcal{N}, \mathcal{E})$ consisting of the set $\mathcal{N}$ of STAs' nodes and the set $\mathcal{E}$ of edges. The edges are between any two STAs' nodes located in at least two same BSSs whereas the nodes are not from the same parent AP. The Sharing-AP's role is to allocate RUs in a way that no two nodes with a common edge get the same color [13], while it chooses the best color (RU) for the nodes concerning their channel gain ($h^m_{k,n}$) that can give the highest data rate for the STAs which is based on WMM algorithm [11] and the Welsh-Powell algorithm [14]. After Sharing-AP colors the graph nodes, then, all APs attempt to assign the unallocated RUs to the rest of the STAs based on the WMM algorithm.

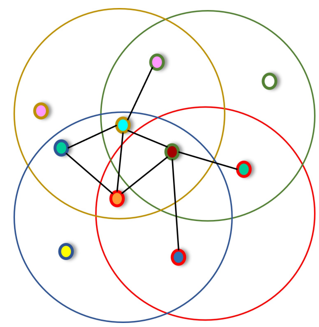

Fig. 2: Undirected Graph between overlapping STAs with colored nodes.

In Fig. 2 the proposed graph coloring model in the 4 OBSSs is depicted, while none of the STAs with the connected edges have the same color. Therefore, the assumptions that need to be considered for the graph coloring based on the WMM algorithm, are as follows:

- All the APs have a fixed 20 MHz bandwidth, with 9-26-tones RUs.
- Each STA can get a maximum of one RU.
- In graph connection the edges are only between the STAs with different parent APs that are in at least two same BSSs.

Algorithm 1 summarizes the proposed algorithm.

Algorithm 1: The proposed RU Allocation Technique

```
for t = 1, 2, ..., T_total do
    Overlapping STAs RU allocation;
    Sharing-AP selection based on lowest backoff time;
    Sharing-AP and Shared-APs signalling to receive information
      about overlapping STAs' channel amplitude response and the
      BSSs in which these overlapping STAs are located;
    Sharing-AP creates a graph in which the graph nodes are
      overlapping STAs and the edges are between any two
      overlapping STAs located in more than one same BSSs from
      different assigned APs;
    Sharing-AP colors the nodes based on the Welch Powell and
      WMM algorithms in [11];
    Non-overlapping STAs RU allocation;
    for m = 1, 2, ..., M do
        m-th AP for the rest of its STAs allocates RUs based on
          WMM algorithm in [11];
        for k = 1, 2, ..., K do
            After RU allocation to all the STAs, m-th AP
              calculates r^m_{k,n} for k-th STA and returns it;
        Update WMM algorithm;
    Repeat this algorithm until T_total;
To evaluate the performance, compute r^m_{k,n} considering SINR.
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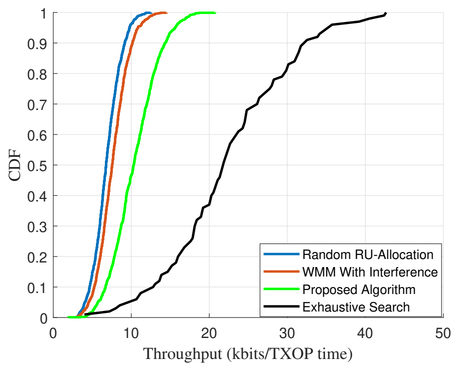
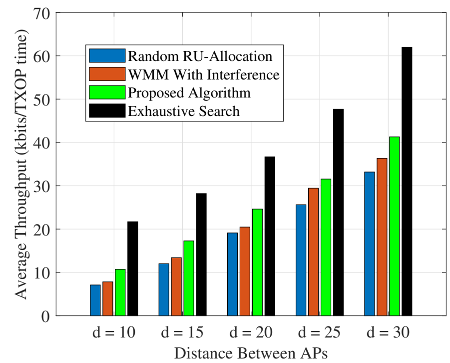
IV. Simulation Results

To evaluate the performance of the proposed algorithm, we consider a D-MAPC based WiFi network with a joint



(a) Empirical CDF of mean aggregate throughput of total number of STAs



(b) Mean aggregate throughput of total number of STAs per APs' distance in meters

Fig. 3: Mean aggregate throughput of the total number of STAs for the scenario where $M = 4$, $K = 5$, $N = 3$.

C-OFDMA and CSR model, under residential settings. A residential Wi-Fi coverage area represented with a radius of d_{max} is considered. All APs are positioned at the center of BSSs. STAs are uniformly distributed within the BSS, following a uniform distribution of $\mathcal{U}(0,1)$. We consider the 26-tone RU allocation while all STAs transmit in every TXOP. The performance of the proposed algorithm is compared with that of a random RU allocation as a serving lower bound and an exhaustive search representing the upper bound. The simulations are performed on a compute node with 50 CPU cores and 80 GB of RAM. Additionally, another benchmark scheme is introduced, derived from [11], where APs do not coordinate with each other for RU allocation to their respective STAs. This means there is no interference management in OBSSs. In the simulation results, this scheme is referred to as WMM With Interference. Table I provides the simulation parameters used in this paper. To determine the data rate, first, the RSSI for each STA is calculated. Using MCS in the look-up Table II, the data rate is calculated with the 26-tone configuration. It is assumed that each AP has only its STAs' RSSI, in other words, each AP does not have any information about the interference that each STA from other APs can bring to it. The RSSI of k-th STAs in m-th AP with n-th allocated RUs is as follows:

$$\text{RSSI}_{k,n}^{m} = 10\log_{10} p - \text{PL}_k^m(d) + 10\log_{10}\left(g_{k,n}^{m}\right) \text{(dBm)}. \quad (6)$$

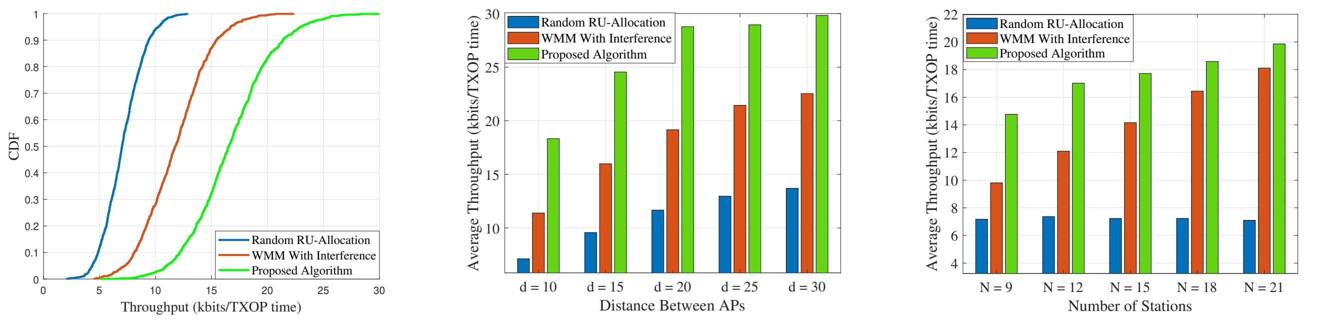
Then based on table II STA's MCS level and its R_c is chosen and for each RU the data rate is calculated as follows:

$$r_k^m = N_R * R_c * \alpha * \frac{T_{\text{TXOP}}}{T_{\text{OFDM}}} \quad \text{(bits/ TXOP time)}. \quad (7)$$

Following the data rate calculation based on the proposed algorithm, the optimal RU combination is assigned to each AP. Finally, after RU allocation, the network performance is evaluated by analyzing the impact of shared RU interference between different APs (co-channel interference). The SINR is then computed, and the data rate, considering the SINR, is determined using (7).

Fig. 3 presents the mean aggregate network throughput per total number of STAs where the scenario is with 4 APs, 5 STAs per each AP and 3-26-tones RUs for each AP. Due to the high computational complexity of the exhaustive search algorithm each Monte Carlo iteration for the exhaustive search curve, involving 4 APs, 5 STAs per AP, and 3 RUs per AP, takes around 8 hours to complete with a compute node with 50 CPU cores and 80 GB of RAM, which shows its high complexity. Fig. (3a) illustrates the empirical CDF of the mean aggregate throughput of the total STAs where the proposed algorithm achieves a higher mean aggregate network throughput near 25% compared to the WMM algorithm with no co-channel interference management and 30% compared to the random RU allocation algorithm. While the exhaustive search algorithm with the unrealistic assumptions of the perfect channel state information of all the STAs with SINR calculation chooses the maximum throughput of the RU combination set for the proposed system model. However due to its high complexity and the unrealistic assumptions, it cannot be implemented in practice. Fig. (3b) demonstrates as the distance between APs increases and the overlapping area decreases, the network's overlapping STAs generate less interference, which also demonstrates the interference level, as closest the APs are the interference level will be higher. As shown, the proposed algorithm achieves a better network throughput with approximately 30% improvement compared to the WMM algorithm due to its effective interference management. In this figure, exhaustive search depicts the upper bound.

Fig. 4 shows the mean aggregate network throughput of all STAs where 4 APs, 12 or more STAs per each AP, and 9-26-tones RUs for each AP is considered. Fig. (4a) demonstrates the proposed algorithm mean aggregated throughput and shows about 30% increment compared to the WMM algorithm with no co-channe interference management and about 60% with random RU allocation as the lower bound. Additionally, Fig. (4b) demonstrates that the aggregate throughput increases as the APs are positioned farther apart. Meanwhile, Fig. (4c) reveals that the proposed algorithm continues to enhance the total network throughput even as the available STAs per AP increases. In contrast, the random RU allocation algorithm maintains a constant total network throughput of 7.10 Kbits/TXOP time, regardless of the number of STAs. For example, when $N = 15$, the proposed algorithm achieves



(a) Empirical CDF of Mean aggregate throughput of all STAs. (b) Mean aggregate throughput of all STAs per APs' distance in meter. (c) Mean aggregate throughput of all STAs per number of STAs in each BSS.

Fig. 4: Mean aggregate throughput of the total number of STAs for the scenario where $M = 4$, $K = 12$, $N = 9$.

a mean aggregate throughput that is 20% higher than that of the WMM algorithm without interference management.

The computational complexity of the considered problem formulation, assuming that STAs exceeds the number of RUs, is $\mathcal{O}(K!^{(M)})$. However, the proposed algorithm reduces this complexity to $\mathcal{O}\left((M \times K) - K'\right)^{(3)} + K' + \mathcal{E})$. Here, the computational complexity of the WMM algorithm combined with Hungarian RU assignment for each AP is $\mathcal{O}\left((M \times K) - K'\right)^{(3)}$ [15], while the approximate computational complexity of graph coloring is $\mathcal{O}(K' + \mathcal{E})$ [14], where $\mathcal{E}$ represents the number of edges between any two overlapping STAs. In this context, K, M, and K' denote the number of STAs in each BSS, the number of APs, and the number of STAs in the OBSSs, respectively.

TABLE I: Simulation parameters

Parameter	Notation Description	Value
$d_{\max}$	Radius of each BSS	20 m
P	Power of each STA	20 dBm
T_{OFDM}	Duration of OFDM Symbol	16 µs
T_{TXOP}	Duration of uplink OFDMA transmission	3.2 ms
T_{total}	Total number of TXOP for simulation in each Monte Carlo	400
V	drift-plus-penalty control parameter	100
d_m	Distance between two APs	20 m
N_R	Number of RU-tones	26

TABLE II: MCS for the 20MHz channel and RUs of 26 subcarriers

Index	Modulation	Bit per symbol α	Coding rate (R_c)	Min. SNR	Min. RSSI (dBm)
1	BPSK	1	1/2	2	−82
2	QPSK	2	1/2	5	−79
3	QPSK	2	3/4	9	−77
4	16-QAM	4	1/2	11	−74
5	16-QAM	4	3/4	15	−70
6	64-QAM	6	2/3	18	−66
7	64-QAM	6	3/4	20	−65
8	64-QAM	6	5/6	25	−64
9	256-QAM	8	3/4	29	−59
10	256-QAM	8	5/6	31	−57

V. Conclusion

In this paper, we proposed a fixed RU scheduling algorithm for the multi-AP coordination system in order to maximize the total network throughput while satisfying the average QoS of each STA using a WMM-based graph coloring approach. The Sharing-AP received its requested information about the overlapping STAs channel amplitude response and the BSSs in which these overlapping STAs are located from the Shared-APs. Simulation results highlighted two main points first the importance of RU allocation in the MAPC system model for interference management. Second, the total mean network throughput increased by 30% with the proposed algorithm due to the interference management in the OBSSs with low complexity. Our future work will consider reinforcement learning techniques to optimize RU allocation under dynamic network conditions.

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