Throughput Satisfaction-Based Multi-Priority Channel Allocation with Channel-Switching for WiFi

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***Abstract*—With the trend of WiFi pervasively applied in life, WiFi multicast has gained extensive attention in rich multimedia content provision. Unfortunately, the multicast rates remain low in crowded scenarios with severe interference and collisions. Moreover, existing channel allocation algorithms lack in-depth study on per-user throughput requirements. This paper proposes a multi-priority task channel allocation method with task channel-switching to maximize the weighted user's throughput satisfaction rate. In this method, we first design a 0-1 integer nonlinear programming model to describe the channel allocation problem in the scenario of a WiFi multicast task and other tasks with different priorities. Then, to lower the complexity of solving integer nonlinear programming problems, we design a greedy algorithm to obtain high-efficiency channel allocation solutions. The simulation results validate the efficiency of our proposed method in terms of user throughput satisfaction rate.**

***Index Terms*—Channel allocation, channel-switching, multi-priority, throughput satisfaction, WiFi multicast, 0-1 integer nonlinear programming.**

I. Introduction

Recent years have witnessed a rapid growth of WiFi applications in multimedia content distribution. Advertisements in large shopping malls, videos from enterprises, and lectures from universities are streaming over WiFi multicast, which is always the task with the largest throughput requirement and the highest priority [1]–[3]. With the popularity of large screens, the definition of the video transmitted by WiFi multicast is increasing, which demands extensive bandwidth to ensure the quality of service (QoS), especially in the case of using WiFi multicast to provide live services, such as synchronizing the stage footage, where we need to guarantee the bandwidth for the peak throughput of the video stream in order to avoid audio and video out of sync.

Amendments to the 802.11a, 802.11b, 802.11g, 802.11ac, and 802.11ad have raised the maximum achievable rates by providing a large increase in terms of achievable bandwidth. In addition, the 802.11e amendment enables multicast traffic to be differentiated as shown in Table I, and thus the network can be configured to prioritize the multimedia flows [4]–[7].

According to the 802.11ax standard [8], the WiFi band is divided into 2.4GHz band and 5GHz band. The opening of WiFi channels in different countries is slightly different.

TABLE I
User Priority to Access Category(AC) Mappings Defined by 802.11

Priority	802.1D designation	AC	Designation (informative)
lowest	BK	AC_BK	Background
	BE	AC_BE	Best Effort
↓	VI	AC_VI	Video
highest	VO	AC_VO	Voice

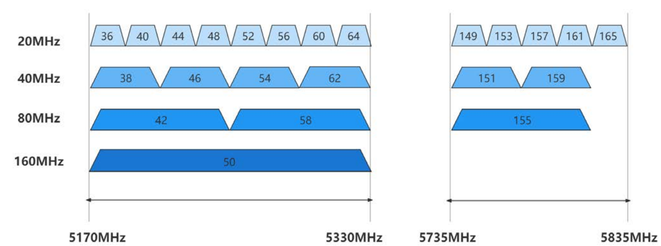

Fig. 1. Channel bonding in the 5 GHz band.

The 5GHz channel has two parts: 36-64 channels and 149-165 channels, whose bandwidths are 20MHz and the distance between adjacent channels is 20MHz. Taking the 5GHz band in Fig. 1 as an example, channels with 40MHz, 80MHz, and 160MHz bandwidth are created by bonding multiple adjacent 20MHz channels. Channel bonding enables users to exploit the increased transmission rates from wider channels.

Wider channels may also increase the competition for the available channel resources. According to the performance evaluation of the distributed coordination function (DCF) scheme employed by IEEE 802.11, the saturation throughput decreases with the increasing collisions, reflecting the necessity of channel allocation via coordinating to prioritize the requirements of high-priority tasks [9].

Many works have studied the IEEE 802.11 channel allocation problem. One common method is graph coloring algorithms, where vertices and edges represent the tasks and the interference relationships [10]–[12]. Different colors represent different channels, and tasks on adjacent edges should not be assigned to the same color to reduce interference. However, graph coloring algorithms can only obtain the allocation scheme from the perspective of reducing interference without taking the widths, noise, and other differences of channels into account. Another approach to optimizing channel allocation is constructing an integer linear programming (ILP) problem. For instance, in [13], the problems of channel allocation and access point (AP) placement are solved simultaneously by ILP, which considers both wireless coverage and load balancing among APs. In [14], via ILP, the AP layout problem is formulated to maximize the total throughput of the whole service area with a prescribed number of APs. In [15], the optimization objective is to maximize the overall system throughput and the fairness of resource sharing among mobile terminals. Unlike the aforementioned studies that maximize the total throughput, [16] formulates a problem to maximize the number of secondary users satisfied in terms of throughput. With the ever-increasing information transmission through WiFi, spectrum resources are scarce. Thus, it is realistic to pursue a higher throughput satisfaction rate.

In this paper, we aim to propose a channel allocation method taking categories, priorities, and throughput requirements of tasks into account. We consider the channel allocation problem after a high-priority task with high throughput requirements, such as WiFi multicast task, is added to the scenario. According to the categories of tasks, we restrict our allocation scheme to maintain VI and VO tasks' original channels. Our objective is to maximize the weighted throughput satisfaction rate according to the task priorities.

II. Problem Formulation

A. Scenario Decription and Pre-experiments

We consider the scenarios where a WiFi multicast task is to join scenarios where multiple unicast tasks are being transmitted. For instance, in a large conference hall, we must use WiFi multicast to synchronize the speaker's speech video. The throughput requirements of the multicast task are high due to the simultaneous transmission to multiple APs and the high definition of the videos. However, before starting the WiFi multicast task, other WiFi unicast services in the scenario are in progress and have their corresponding channels, which should be denoted as the background traffic of our multicast task. D. Dujovne *et al.* [17] demonstrate that in the case of high background traffic, the goodput of multicast based on 802.11b will be reduced by at least 40% compared to the case without background traffic.

In order to investigate the impact of WiFi 6 (802.11ax) background traffic on multicast video streaming, we obtained the average throughput for different channel loads through actual measurements. In our experiments, we first varied the channel load l, defined as the percentage of the channel usage in time (i.e., busy time) in respect to the total channel measurement time. Then we launched the multicast task and obtained its throughput. We selected videos with a resolution of 3840×2160 pixels for screencasting on channel 58 (5250MHz-5330MHz) with 80MHz bandwidth.

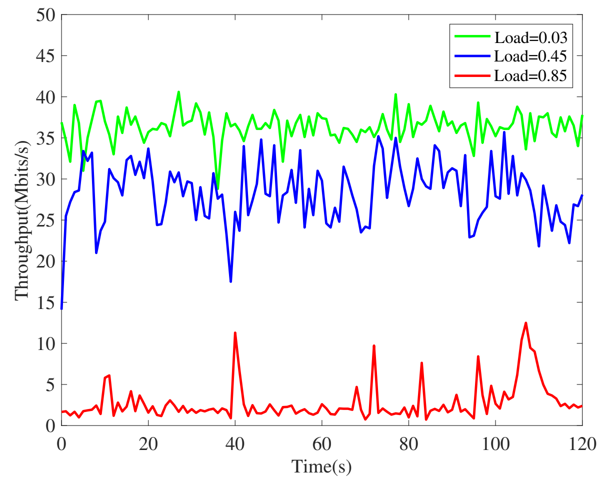

Fig. 2. The throughput of HD wireless screen casting with different loads over time.

Fig. 3. Wireless screen casting images with $l = 0.85$ (in the image above) and $l = 0.03$ (in the image below).

Our experiments prove that at the channel load $l = 0.85$, the average throughput of the video cast is 2.74Mbps which is less than 10% of 36.2Mbps, the one at the channel load $l = 0.03$, as shown in Fig. 2. As the channel load increases, latency and lag are increasingly noticeable. When $l = 0.45$, it has apparent jitters in throughput, with the lowest value at 12Mbps. Fig. 3 shows the video screenshots with different channel loads, which illustrates the significant difference between the two scenarios. The one above is the screen with $l = 0.85$, whose

TABLE II
RECOMMENDED BITRATE OF VIDEOS WITH DIFFERENT DEFINITION

Type	Twitch	YouTube SDR	YouTube HDR
2160p(4K)	-	35-68Mbps	44-85Mbps
1440p(2K)	-	16-24Mbps	20-30Mbps
1080p	6Mbps	8-12Mbps	10-15Mbps
720p	3-4.5Mbps	5-7.5Mbps	6.5-9.5Mbps

definition is much higher than the one below with $l = 0.03$.

We investigate the rate required for video transmission using multicast. I. Shitara *et al.* [18] use scalable video coding (SVC) technology and QoE control suitable for multicast distribution. The multicast transmission rate required to transmit a video with a bitrate of 9Mbps is 6.5-65Mbps. T. Nunome *et al.* [19] employ the constant rate of 12Mbps to transfer the video at a 4Mbps average bitrate. Considering the common use of multicast services – live broadcast and video delivery, we refer to the recommended bitrate offered by Twitch and YouTube, as shown in Table II [20], [21].

Based on the above experiments and references, to ensure the user experience of multimedia streaming services, for scenarios in which the speaker's PowerPoint is synchronized via multicast, an 80MHz bandwidth channel with $l \leq 0.45$ is essential. However, in the case that the video images change rapidly, such as synchronous WiFi multicast of stage performances, audio and video out of sync cannot be allowed, and thus a bandwidth of 80MHz with $l \leq 0.03$ is required. However, it is difficult to find such a channel if we select it directly based on the original allocation. Thus we expect to satisfy the throughput requirement of the WiFi multicast task by allowing some tasks to switch their channels. We are committed to improving the transmission quality of WiFi multicast through channel allocation while minimizing the impact on other tasks with different characteristics.

B. Channel Allocation Problem

Considering the feasibility of channel-switching, our model only allows channel-switching for tasks with categories of BE and BK, which are not particularly sensitive to the delay caused by switching channels. In previous works, the system's performance is usually evaluated by the total throughput. However, different tasks have different throughput requirements. The spectrum should be allocated based on per-user throughput requirements regarding limited channel resources. To take the priorities of tasks in channel allocation into consideration, we introduce an objective function – total score S, which gives different score weights to four categories of tasks and our WiFi multicast task. We aim to maximize the total score to satisfy the objective throughput of tasks, i.e., to maximize the weighted throughput satisfaction rate.

To improve the system performance and simplify the model, we assume that the channels with overlapping frequency bands cannot be selected simultaneously, which results in a waste of spectrum resources. Otherwise, if the spectrum of one signal is included in the spectrum of another signal, then they are unable to perceive the existence of the other party. In this case, both continue to contract, and conflicts occur.

Consider total N tasks, including one WiFi multicast task a_0, and $N-1$ general tasks $a_1, a_2, \cdots, a_{N-1}$. We select the corresponding channel from M channels: $c_0, c_1, \cdots, c_{M-1}$ in WiFi 5GHz band. To describe the result of channel allocation to be designed, we define a 0-1 integer matrix $\boldsymbol{X}$ with the size of $M \times N$, where $X_{m,n}$ denotes the entry in row m, column n, and $X_{m,n} = 1$ means task a_n is transmitted on channel c_m. Each task should be assigned a channel, leading to the following constraint

$$\sum_{m=0}^{M-1} X_{m,n} = 1, \forall n \in \{0, 1, ..., N-1\}. \quad (1)$$

Before adding the WiFi multicast task, the channel allocation of each task is represented by the matrix $\boldsymbol{X}'$, which is defined similarly as $\boldsymbol{X}$.

By detection, we obtain the throughputs $\boldsymbol{t}^{\mathrm{c}} = [t_0^{\mathrm{c}}, t_1^{\mathrm{c}}, \cdots, t_{M-1}^{\mathrm{c}}]^{\mathrm{T}}$ that each channel can provide. The objective throughput of each task $\boldsymbol{t}^{\mathrm{o}} = [t_0^{\mathrm{o}}, t_1^{\mathrm{o}}, \cdots, t_{N-1}^{\mathrm{o}}]^{\mathrm{T}}$ is utilized to calculate the throughput satisfaction rate.

In addition, to effectively use spectrum resources, we restrict that channels with commonly occupied frequency bands cannot be selected simultaneously. In previous works, the problem of selecting non-interfering channels is formulated as the maximum independent set problem in graph theory. Therefore, we employ a graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ to describe our constraints on channel selection, in which the vertex set $\mathcal{V} = \{c_m\}_{m=0}^{M-1}$ represents the channels, and the edge set is $\mathcal{E} = \{E_{m,m'} : c_m, c_{m'}$ have overlapping frequency bands$\}$. Then we have the constraint

$$\Big(\sum_{n=0}^{N-1} X_{m,n}\Big) \times \Big(\sum_{n=0}^{N-1} X_{m',n}\Big) = 0, \quad \forall E_{m,m'} \in \mathcal{E}. \quad (2)$$

When multiple tasks select the same channel, these tasks have to use the channel in turn, according to CSMA/CA. Therefore, if k tasks share a channel, each task will obtain $1/k$ of the channel's throughput. Then the actual throughput of task n, which selects channel m is

$$t_n^{\mathrm{a}} = \frac{t_m^{\mathrm{c}}}{\sum_{n=0}^{N-1} X_{m,n}}. \quad (3)$$

We give different weights to the WiFi multicast task and the four categories of tasks above, which are $\boldsymbol{w} = [w_0, w_1, w_2, w_3, w_4]^{\mathrm{T}}$ with the following relationship

$$w_0 > w_1 > w_2 > w_3 > w_4. \quad (4)$$

The priority weight and mobility of the five categories of tasks are shown in Table III. For each task, we define the weights $\boldsymbol{w}^a = [w_0^a, w_1^a, \cdots, w_{N-1}^a]^{\mathrm{T}}$ with the following constraint

$$w_n^{\mathrm{a}} \in \{w_0, w_1, w_2, w_3, w_4\}, n \in \{0, 1, 2, \cdots, N-1\} \quad (5)$$

according to the categories. In practice, we can also give different weights to different tasks according to different scenarios, which need not be limited to these four categories.

TABLE III
PRIORITY WEIGHT AND MOBILITY

Priority	Type	Weight	Channel Switchable
lowest	BK	w_4	Yes
	BE	w_3	Yes
↓	VI	w_2	No
	VO	w_1	No
highest	multicast	w_0	-

Since the WiFi multicast task is newly added, we do not need to consider whether it is BE, BK, or not. For VI and VO tasks, we need to add a constraint to maintain their original channels

$$X_{m,n} = X'_{m,n}, m \in \{0,1,\cdots,M-1\}, a_n \in \{\text{VI}, \text{VO}\}. \quad (6)$$

Since our criterion is the satisfaction of throughput, we introduce the parameter of throughput satisfaction rate $\boldsymbol{r} = [r_0, r_2, \cdots, r_{N-1}]^{\mathrm{T}}$

$$r_n = \min\left\{\frac{t_n^{\mathrm{a}}}{t_n^{\mathrm{o}}}, 1\right\}, n \in \{0,1,2,\cdots,N-1\}. \quad (7)$$

To sum up, our optimization problem is as follows,

$$\max_{\boldsymbol{X}} \left\{ S = \sum_{n=0}^{N-1} w_n^{\mathrm{a}} \times r_n \right\}, \quad \text{s.t.} \quad (1)-(7). \quad (8)$$

III. CHANNEL ALLOCATION ALGORITHM

This section presents the proposed channel allocation algorithm with high performance. For a general integer nonlinear programming problem, which is proved to be NP-hard, the brute force method is a common scheme that traverses all possible channel allocation combinations and obtains the one that meets the constraints and has the highest score as the final allocation. However, in our problem, due to the large number of channels (taking the WiFi 5GHz band as an example, there are 23 channels after channel bonding), the computations cannot be afforded in general scenarios. For example, the computational complexity for N tasks is $O(23^N)$. Therefore, we propose the Greedy Channel Allocation (GCA) algorithm to provide an approximately optimal solution with low time complexity in Algorithm 1 whose computational complexity is $O(M \times N)$ in the above example.

In order to improve the overall performance, the GCA algorithm guarantees the tasks with higher priority to obtain a better throughput satisfaction rate. Thus, we first find the indexes $\boldsymbol{i} = [i_0, i_1, \cdots, i_{N-1}]^{\mathrm{T}}$ that satisfy $w_{i_0}^{\mathrm{a}} \geq w_{i_1}^{\mathrm{a}} \geq \cdots \geq w_{i_n}^{\mathrm{a}} \geq \cdots \geq w_{i_{N-1}}^{\mathrm{a}}$. We define $\tilde{\boldsymbol{X}} = [\boldsymbol{X}_{:,i_0}, \boldsymbol{X}_{:,i_1}, \cdots, \boldsymbol{X}_{:,i_{N-1}}]$, where $\boldsymbol{X}_{:,i_n} = [X_{0,i_n}, X_{1,i_n}, \cdots, X_{M-1,i_n}]^{\mathrm{T}}$ and $\tilde{\boldsymbol{w}}^{\mathrm{a}} = [w_{i_0}^{\mathrm{a}}, w_{i_1}^{\mathrm{a}}, \cdots, w_{i_{N-1}}^{\mathrm{a}}]^{\mathrm{T}}$, $\tilde{\boldsymbol{t}}^{\mathrm{o}} = [t_{i_0}, t_{i_1}, \cdots, t_{i_{N-1}}]^{\mathrm{T}}$. $\mathcal{M}$ represents the mapping: $\boldsymbol{w}^{\mathrm{a}} \to \tilde{\boldsymbol{w}}^{\mathrm{a}}$, $\boldsymbol{X}' \to \tilde{\boldsymbol{X}}'$, $\boldsymbol{t}^{\mathrm{o}} \to \tilde{\boldsymbol{t}}^{\mathrm{o}}$ (Line 1).

To avoid overlapping frequency bands of channels selected by different tasks, we maintain a selectable channel set $\mathcal{V}^{\mathrm{s}}$. In the initialization phase, all channels are selectable (Line 3).

Algorithm 1 Greedy Channel Allocation Algorithm

Input:
$\{\boldsymbol{X}', \boldsymbol{t}^{\mathrm{c}}, \boldsymbol{t}^{\mathrm{o}}, \mathcal{G}\{\mathcal{V}, \mathcal{E}\}, \boldsymbol{w}^{\mathrm{a}}\}$;
Output:
$\boldsymbol{X}$;

1: Sort $\boldsymbol{w}^{\mathrm{a}}$,$\boldsymbol{t}^{\mathrm{o}}$,$\boldsymbol{X}'$ by priority $\boldsymbol{w}^{\mathrm{a}}$, and get $\mathcal{M}$, $\tilde{\boldsymbol{w}}^{\mathrm{a}}$, $\tilde{\boldsymbol{t}}^{\mathrm{o}}$, $\tilde{\boldsymbol{X}}'$;
2: Initialize the channel allocation matrix $\boldsymbol{X}$ to a zero matrix;
3: Initialize the selectable channel set $\mathcal{V}^s = \mathcal{V}$;
4: **for** $n \in \{n : \tilde{w}_n^{\mathrm{a}} = w_1$ or $\tilde{w}_n^{\mathrm{a}} = w_2\}$ **do**
5: $\quad \tilde{X}_{m,n} = \tilde{X}'_{m,n}$ for $m \in \{0,1,\cdots,M-1\}$;
6: $\quad$ **if** $\tilde{X}_{m,n} = 1$ **then**
7: $\quad\quad$ Remove $c_{m'}$ from $\mathcal{V}^s$, $\quad \forall E_{m,m'} \in \mathcal{E}$;
8: $\quad$ **end if**
9: **end for**
10: **for** $n = 0$ to $N-1$ **do**
11: $\quad$ **if** $\tilde{w}_n^{\mathrm{a}} \neq w_1$ and $\tilde{w}_n^{\mathrm{a}} \neq w_2$ **then**
12: $\quad\quad$ **for** $m \in \{m : c_m \in \mathcal{V}^s\}$ **do**
13: $\quad\quad\quad$ Calculate the overall score of the current $n+1$ tasks if task n choose channel m: S_m^n;
14: $\quad\quad$ **end for**
15: $\quad\quad$ Find $k^* = \max_k \{S_k^n\}$ and assign $\tilde{X}_{k^*,n} = 1$;
16: $\quad\quad$ Remove $c_{m'}$ from $\mathcal{V}^s$, $\quad \forall E_{k^*,m'} \in \mathcal{E}$;
17: $\quad$ **end if**
18: **end for**
19: From $\tilde{\boldsymbol{X}}$ we get the final optimal allocation matrix $\boldsymbol{X}$ according to the inverse of $\mathcal{M}$.

When a new channel is selected, the channels with overlapping frequency bands will be removed from $\mathcal{V}^{\mathrm{s}}$ that satisfies (2) (Lines 7 and 16). Considering that some tasks do not allow channel-switching, we ensure that in the allocation scheme, they maintain their initial channels that satisfy (6) (Line 5). For tasks allowing channel-switching, we assign an appropriate channel for each task in order of priority. For task a_n, the channels of the previous n tasks have been selected. If we select a channel that has been selected, recalculation of the previous n tasks' throughput is required according to (3), due to the reduction of throughput by channel sharing (Line 13). For task a_n, the channel to be selected is the one with the highest total score S^n, which is the total score of the current $n+1$ tasks. After traversing all optional channels N times, we can obtain the channel allocation scheme.

IV. SIMULATION RESULTS

In this section, we validate the performance of the proposed GCA algorithm. We choose the scheme maintaining the original channel allocation, selecting the channels with the maximum throughput satisfaction rate that can be obtained by WiFi multicast task as the baseline. Moreover, we use the optimization modeling software LINGO to get the global optimal solution. We compare the performance of the channel allocation scheme obtained by the baseline, GCA algorithm, and LINGO.

In the simulations, the throughput provided by the channel is positively correlated with the channel's width. Each

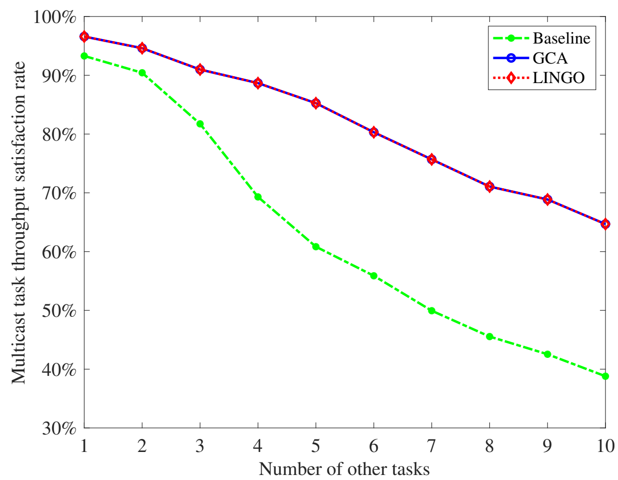

Fig. 4. The multicast task throughput satisfaction rate with respect to the number of other tasks.

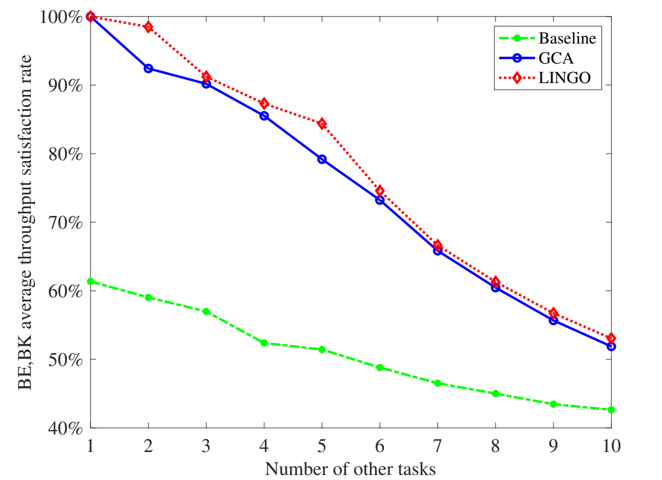

Fig. 6. BE, BK tasks' average throughput satisfaction rate with respect to the number of tasks except for the multicast task.

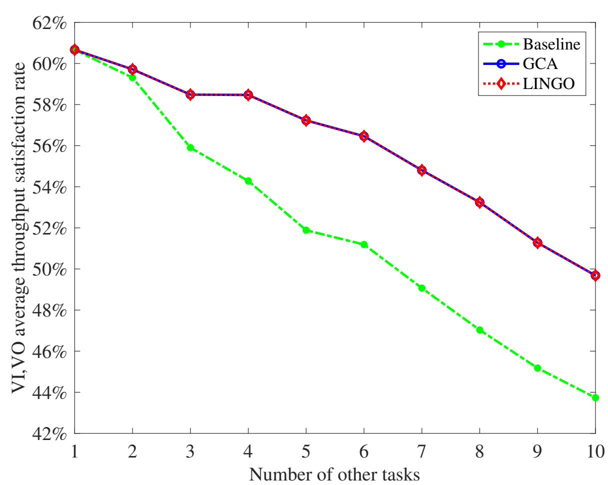

Fig. 5. VI, VO tasks' average throughput satisfaction rate with respect to the number of tasks except for the multicast task.

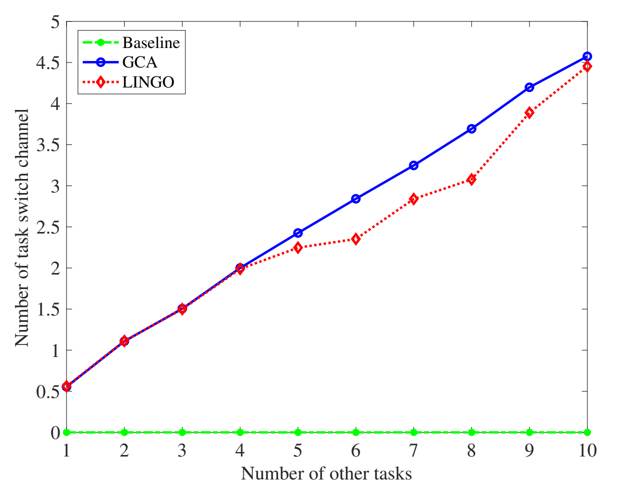

Fig. 7. The number of tasks switching channels after optimization with respect to the number of tasks except for the multicast task.

task's category, objective throughput, and initial channel are randomly generated in each scenario. We randomly generated 200 scenarios for experiments and successively calculated the throughput satisfaction rate and the number of tasks for switching channels when the number of other tasks was 1-10. We compare the performance of the WiFi multicast task, VI, VO tasks, and BE, BK tasks with the increased number of tasks except for the multicast task. The performance is measured by the average throughput satisfaction rate.

Compared to the baseline, our method improves the throughput satisfaction rates of all categories of tasks by switching channels for the tasks with low real-time performance requirements (BE, BK). Moreover, as shown in Fig. 4, with the increase of the number of other tasks, the performance improvement of our method for the multicast task is more significant. GCA algorithm achieves up to 28% throughput satisfaction rate of the WiFi multicast task higher than the baseline. In addition, the GCA algorithm is consistent with the optimal solution in terms of performance for the multicast task. According to Fig. 5, for VI and VO tasks, the average throughput satisfaction rate is limited due to the random selection of the initial channel and their channel non-switchability. Both the GCA algorithm and the optimal solution tend to switch channels for the BE, BK tasks that on VI, VO tasks' channels, and thus the VI, VO tasks' throughput satisfaction are consistent, which provide more performance gains over the baseline as the number of other tasks increasing. As for BE and BK tasks, as shown in Fig. 6, higher throughput satisfaction rates can be obtained by switching channels compared to maintaining the original channel. The GCA algorithm yields a good

TABLE IV
AVERAGE TIME COST OF THE THREE METHODS.

Total number of other tasks	Brute Force	GCA Algorithm	LINGO
1	2.23s	2.04s	2.44s
2	2.69s	2.05s	2.57s
3	430.61s	2.19s	44.79s
4	>24h	2.21s	121.31s
5	-	2.33s	129.91s
6	-	2.34s	134.14s
7	-	2.44s	145.77s
8	-	2.44s	234.20s
9	-	2.50s	506.40s
10	-	2.51s	1618.27s

approximation to the optimal solution, especially when the number of tasks is large. Curves in Fig. 7 show that the GCA algorithm's average number of tasks switching channels is also approximately the same as the optimal solution. By adopting our method, BE and BK tasks' throughput satisfaction rates can be increased by 10% to 39%, especially when fewer tasks exist.

As for the run time performance of the three different methods for solving our mathematical model, we present the comparison of the time cost from Table IV. It is worth noting that, for the brute force method, when the number of other tasks achieves 4, the running time is far more than 24 hours. When we have 5 other tasks, the memory required to run the program exceeds that MATLAB can handle. Since the computational complexity of our GCA algorithm is $O(N \times M)$, which is relatively insensitive to the total number of tasks N. LINGO adopts the Mixed Integer Nonlinear Programming (MINLP) model for solutions. Taking the case $M = 23, N = 11$ as an example, for different scenarios, the number of iterations of the MINLP solver varies from 10^6 to 10^9, whose complexity is much larger than that of the GCA algorithm. Thus our GCA algorithm's time cost is well below that of obtaining the optimal solution by LINGO.

V. CONCLUSION

In this paper, we proposed an efficient method to improve the performance of the multiple WiFi task system based on throughput satisfaction by allowing BE and BK tasks to switch channels. In this method, we formulated the problem into a 0-1 integer nonlinear programming problem and proposed the Greedy Channel Allocation algorithm with low time cost and overall approximately optimal performance. Our method can improve the system performance in multi-priority tasks, especially with a WiFi multicast task through channel allocation, to fully use spectrum resources. Moreover, simulations validated that the GCA algorithm can ensure that the performance of the multicast task is consistent with the optimal solution. The proposed allocation scheme can be performed with low runtime to ensure the quality of tasks in the scenarios once the state of WiFi channels changes.

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