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Joint Radio Resource Management of Channel-Assignment and User-Association for Load Balancing in Dense WLAN Environment

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ABSTRACT IEEE 802.11-based wireless local area network (WLAN) is currently the most popular communication system and a lot of access points (APs) have been densely deployed over heavily populated areas. In such dense WLAN environment, the WLAN users can suffer from performance degradation due to high co-channel and adjacent-channel interference among APs. To tackling such user performance degradation problem, we propose a two-phase radio resource management (RRM) framework, of which the first phase is channel assignment (CA) and the second phase is user association for channel load balancing (UA-ChLB). In designing the RRM framework, we take account of typical WLAN environment where dual bands are supported and two types of APs coexist: controlled-APs, which are managed by a centralized controller, and stand-alone APs, which independently operate for themselves. The proposed CA method utilizes a channel bonding technique, which provides a high data rate by integrating multiple basic channels while reducing the interference among neighboring APs. The proposed hybrid UA-ChLB scheme, which is composed of distributed/centralized UA-ChLB, efficiently coordinates the channel load among neighboring APs and between two bands of 2.4 and 5 GHz, under consideration of the wireless channel quality, interference, and traffic conditions. We implement a prototype system in practice using the proposed RRM scheme. The experimental results show that the proposed RRM scheme greatly improves both throughput and fairness in dense WLAN environment, as compared with some existing schemes.

INDEX TERMS Radio resource management, wireless local area network (WLAN), channel assignment (CA), user association (UA), load balancing (LB).

I. INTRODUCTION

Nowadays, IEEE 802.11-based wireless local area network (WLAN) technologies have been widely used, since these technologies effectively support various services being attractive to users, such as general multimedia, full HD video streaming, and file download, and so on. Furthermore, the WLAN capacity can be easily enhanced with a relatively low cost, by additionally installing WLAN access points (APs). This leads to wide spread of WLAN APs over heavily populated areas (e.g., public, residential, and enterprise areas). In such regions where the APs are densely deployed, service coverage of neighboring APs can overlap each other and the neighboring APs can commonly use the same channels because of a limited number of available WLAN channels. Then, the network performance may be severely degraded due to capacity reduction by channel sharing and interference among neighboring APs. As an example, according to experimental results at a huge underground shopping mall in Seoul, where 277 WLAN APs are deployed and 917 users are served by these APs, the average user throughput was about 0.2 Mbps [1]. Without a doubt, most of WLAN users at this shopping mall experienced unsatisfied service quality from such low throughput.

It is noted that the communication environment where densely deployed WLAN APs are accessed by lots of users,

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shortly "dense WLAN environment," is currently common to us. Thus, providing desirable service quality to users under such environment can be an important role of network designers and operators. In this paper, we are also interested in enhancing per-user network performance in the dense WLAN environment.

One of technical approaches for effectively tackling the performance degradation under dense WLAN environment is to elaborately manage radio resource. The representative radio resource management (RRM) techniques are channel assignment (CA) for avoiding interference among neighboring APs and user association for balancing network load among APs (UA-LB). It is obvious that, since the recent IEEE 802.11 standard such as 802.11n/ac allows bonding of multiple basic channels for high potential capacity, the researchers should design CA and UA-LB while keeping in mind the characteristics of dense WLAN environment such as not only channel sharing and interference but also channel bonding.

Various CA schemes to minimize the interference among APs (for example, [2]–[8]) are found in literatures. However, there are actually few works which consider channel bonding and interference together under the dense WLAN environment, like [9]. Moreover, according to our previous work in [9], coarsely utilizing channel bonding in CA may rather degrade the performance by incurring limited channel sharing and excessive interference. For this reason, an elaborate CA scheme which effectually avoids interference under channel bonding is necessary.

On the other hand, when designing a UA-LB scheme, we should take band characteristic into account, since radio propagation property and configuration of overlapped channels are different depending on whether the frequency band of channel is 2.4 GHz or 5 GHz. Typically, co-channel interference (CCI) and adjacent channel interference (ACI) among neighboring APs are much more serious in 2.4 GHz than in 5 GHz band. Moreover, channel sharing among neighboring APs occurs more frequently in 2.4 GHz-band channels. Accordingly, the interference handling is much more important in 2.4 GHz-band channels. Since most of commercial APs support dual-band (i.e., both 2.4 GHz and 5 GHz), we should take account of band characteristics and interference together in designing the UA-LB. However, the existing studies on UA-LB in [10]–[17] did not consider the above mentioned band characteristics. Only few works related to band-steering (BSTR) (e.g., [18] and [19]) intend to balance the load between two frequency bands of one AP, through UA.

The BSTR methods in [18] and [19] determine which band is assigned to each user, mainly based on channel quality of user on the corresponding frequency band. However, since load balancing is also influenced by channel capacity and traffic amount, it is obvious that not only channel quality but also interference and traffic volume should be jointly considered for efficient load balancing between two frequency bands. We, in this paper, design a joint CA and UA-LB scheme while keeping in mind all factors above mentioned, i.e., channel sharing, band characteristics, channel bonding, interference, and the amount of traffic.

On the other hand, in the dense WLAN environment of real world, two types of APs are likely to coexist: controlled-APs (C-APs), which are managed by a centralized controller, and stand-alone APs (S-APs), each of which independently operates without any coordinator. Note that S-APs and C-APs undergo severe interference from each other, if their radio resource usage is not carefully coordinated. Thus, this coexistence of C-APs and S-APs can have a great effect on the CA results for C-APs and the UA-LB decision for WLAN stations (STAs). However, unfortunately, the coordination between S-APs and C-APs is a difficult problem because it is not easy to recognize the status information (e.g., load, amount of traffic, interference level) of the other type of APs. To our best knowledge, except for few CA schemes such as [6] and [9], there is no published study of the RRM including both CA and UA-LB, under the dense WLAN environment where C-APs and S-APs coexist.

In this paper, we suggest a design framework for CA and UA-LB, in the dense WLAN environment where two types of APs (i.e., S-APs and C-APs) coexist and each of WLAN devices (i.e., S-APs, C-APs, and STAs) supports dual-band of 2.4 GHz and 5 GHz by using two wireless network interfaces. The suggested RRM framework comprehensively takes account of current overall network conditions (e.g., wireless channel quality, interference, the amount of traffic). Then, we design a joint CA and UA-LB scheme under this RRM framework.

The remainder of this paper is organized as follows. Some existing works related to CA and UA are presented in the next section. We describe the system model under consideration in Section III and suggest a two-phase RRM framework in dense WLAN environment in Section IV. Section V describes the proposed UA-LB scheme. In Section VI, we implement the proposed schemes and some existing schemes, and assess their performances based on the experimental results. Finally, the paper is concluded with Section VII.

II. RELATED WORKS

A. CHANNEL ASSIGNMENT (CA) SCHEMES

The existing CA schemes in [3]–[9] can be categorized into centralized CA ([6]–[9]) and distributed CA ([3]–[5]), depending on whether there is a central coordinator allocating channels to all APs, or not.

In distributed CA, each AP determines its operating channel for itself, without any controller. In the automatic channel selection (ACS) scheme [3], each AP selects a basic channel having the lowest interference after scanning available channels. With the random channel selection (RCS) scheme in [4], an AP selects consecutive basic channels for bonding at random from available channels. In the CA scheme of [5], an AP selects the channel with the lowest potential interference as its operating channel, where the potential interference from neighbor APs can be calculated based on traffic state information within the beacon frame.

On the other hand, in the centralized CA schemes [6]–[8], a centralized controller decides the channel allocation for C-APs, by using various information reported from these C-APs. In [6], the CA problem is formulated as a maximum weight matching problem on bipartite graph and is solved by the Hungarian method, where the weight of each channel is calculated based on the estimated interference level of the channel. In the CA scheme of [7], the controller collects the interference level among C-APs, and allocates the basic channels to C-APs so that the total interference level among APs through the entire network is minimized. A graph coloring-based CA scheme in [8] determines an appropriate primary channel of each AP, when a bonding channel is already given to each AP.

B. USER ASSOCIATION (UA) SCHEMES

The UA schemes in [10]–[17] treat the association of each STA with one of neighboring APs, whereas the schemes in [18] and [19] determine which band is assigned to each STA within an AP supporting dual-band of 2.4 GHz and 5 GHz. We now shortly describe these existing schemes in sequence.

Similarly with the existing CA schemes, the UA schemes in [10]–[17] can also be categorized into distributed UA ([10]–[13]) and centralized UA ([14]–[17]).

In the distributed UA where each STA selects its AP for itself, the metric for AP selection is different in each scheme. Under the FAME scheme [10], a STA selects the best AP for maximizing the MAC efficiency metric, which is derived based on the link rate, traffic amount, and collision rate. In [11], a STA is associated with an AP having the highest SINR (signal to interference plus noise ratio). With the Wi-Fi seeker scheme in [12], each STA chooses an AP having the lowest interference level which can be estimated by measuring the beacon collision rate and RSSI (received signal strength indicator) variation. In [13], a STA calculates the expected throughput from each AP by using the broadcasted channel occupancy information from neighboring APs and STAs, and selects the AP with the highest expected throughput.

The centralized UA schemes have a central coordinator which determines UA for all STAs over the entire network. In [14], the authors take account of the effect due to interference among APs sharing the same channel and formulate a proportional fair UA problem. This UA problem is relaxed into a convex optimization problem and its solution is got by solving the relaxed problem. In [15], the authors define a fittingness factor, which indicates the UA suitability and is calculated by the utility function based on the SINR and quality-of-service (QoS) requirement of each STA. Then, the UA between each STA and AP aims at maximizing the fittingness factor. The UA scheme in [16] distributes the load among APs to maximize the overall network throughput. To solve this UA problem in the dense WLAN environment, authors in [16] transform it into a weighted bipartite graph matching problem and solve it by finding the semi-optimal matching of the graph. The UA scheme in [17] puts some APs with low load into a sleep mode. Then, the STAs associated with these sleeping APs are moved into other APs so that the load among active APs is well balanced.

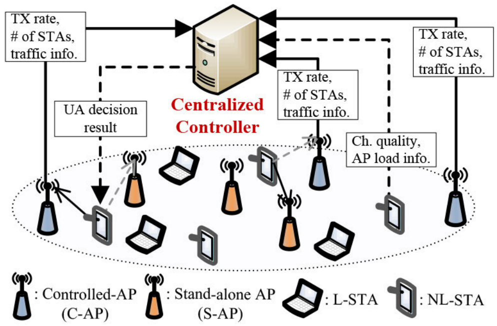

FIGURE 1. System model.

On the other hand, the BSTR-based UA schemes in [18] and [19] intend to balance the load between the 2.4 GHz-band channel and the 5 GHz-band channel within one AP. In [18], the STAs within one AP are distributed into two frequency bands, based on the number of STAs in each band and channel quality. This BSTR scheme tries to maintain a predefined ratio between the number of associated users in 2.4 GHz band and that in 5 GHz band. When recognizing the congestion in 2.4 GHz band, the STA currently associated with 2:4 GHz-band channel can adjust its own UA to a 5 GHz-band channel, if SNR and RSSI in the 5 GHz-band channel are higher than the predefined SNR and RSSI thresholds. In [19], the BSTR between two frequency bands are determined based on RSSI, medium occupancy ratio, and past BSTR results. When the medium occupancy ratio of 2.4 GHz band is relatively high, some STAs in 2.4 GHz band can be moved into 5 GHz band while satisfying the RSSI requirement in 5 GHz.

III. SYSTEM MODEL

In this section, we describe the system model under consideration and input parameters of RRM scheme.

A. SYSTEM MODEL

Fig. 1 depicts the system model under consideration, representing dense WLAN environment. There coexist two types of APs: C-APs and S-APs. The C-APs are connected to a centralized controller through wired link (*e.g.,* Ethernet) and thus the controller can acquire directly from each C-AP various information, such as the number of associated STAs, traffic arrival rates of STAs, and transmission rate. Each S-AP operates independently, so that the controller cannot directly obtain information from S-APs. All of C-APs and S-APs are dual-band APs supporting both 2.4 GHz and 5 GHz bands.

The STAs are classified into legacy STA (L-STA) and non-legacy STA (NL-STA). The L-STA is a typical IEEE 802.11 STA where the association of STA with AP is determined

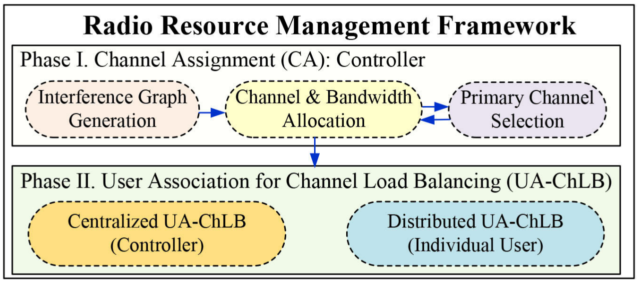

FIGURE 2. Proposed RRM framework.

based on the RSSI, whereas the NL-STA is an IEEE 802.11 STA where the proposed scheme is additionally implemented. The NL-STAs are again subdivided into two types, according to whether the NL-STA is associated with C-AP or S-AP. The NL-STA associated with C-AP is referred to as C-STA, and the NL-STA associated with S-AP is referred to as S-STA.

B. INPUT PARAMETERS OF TWO-PHASE RRM

We will suggest, in the next section, a two-phase RRM framework for enhancing WLAN performance under the above system model, which is composed of the CA in the first phase and the UA-LB in the second phase (see Fig. 2).

Since interference signal causes the performance degradation, it is desirable to allocate different channels if possible, for APs being potential interferer to each other. Thus, the prerequisite task of CA is to identify, for each AP, its interfering APs. On the other hand, since the goal of our UA-LB work is to improve channel efficiency by appropriately balancing the load in the viewpoint of entire network, we need to firstly estimate the load and channel efficiency prior to specifically designing the UA-LB scheme. Now, we examine input parameters for two-phase RRM exemplified above, in more detail.

1) INTERFERING AP

As mentioned above, in allocating channels to APs, it is essential to investigate interference relationship among APs. As the criteria of detecting such interference relationship, we use the minimum clear channel assessment (CCA) threshold of IEEE 802.11. Let $\xi_{\text{CCA-CS}}$ be the minimum threshold for carrier sense-based CCA of a basic channel. Note that $\xi_{\text{CCA-CS}} = -82$ dBm for a single basic channel (20 MHz) in IEEE 802.11. Let us consider the situation that, while AP-l is transmitting on a channel, another AP-k does carrier sensing on the same channel. If the AP-k detects the signal strength stronger than $\xi_{\text{CCA-CS}}$, the AP-k regards the channel as being busy and does not access the channel. Then, the AP-l is referred to as a directly interfering AP of AP-k.

On the other hand, some channels on ISM band are overlapped with each other. Unlike 5 GHz band where most of channels are not overlapped, adjacent channels in 2.4 GHz band are overlapped each other except three channels with number known as ch. 1, ch. 6, and ch. 11. Although two neighboring APs use different channels, if their channels are overlapped, these APs can suffer from severe adjacent-channel-interference (ACI) from each other. We calculate the ACI at AP-k from neighboring AP-l, based on the RSSI at AP-k from AP-l and the ratio of leakage power (i.e., power leakage ratio) from the channel of AP-l to the channel of AP-k. According to [23] and [24], the power leakage ratio of two channels depends on the distance between them, i.e., the lower ratio from a channel being farther away. We define the number difference of two channels as the channel distance between them. Let $d(k, l)$ be the channel distance between the channels of AP-k and AP-l. And, let $\rho_{d(k,l)}$ denote the power leakage ratio for the channel distance of $d(k, l)$. Table 1 shows the power leakage ratio with respect to channel distance in 2.4 GHz band of 802.11 WLAN, referred from [23] and [24]. When $RSSI(k, l)$ is the RSSI value for beacon of AP-l measured by AP-k, the ACI at AP-k from AP-l, denoted by $\mathcal{I}_{ACI}(k, l)$, is calculated as follows.

TABLE 1. Power leakage ratio (2.4 GHz).

Channel distance	1	2	3	4	5
Leakage ratio (%)	79.06	52.67	26.51	0.627	0.121

$$\mathcal{I}_{ACI}(k, l) = \rho_{d(k,l)} \times RSSI(k, l). \tag{1}$$

If the ACL between two adjacent APs using different channels is higher than a predefined threshold, they can be the interfering AP to each other. We define another CCA threshold based on energy detection, $\xi_{\text{CCA-ED}}$. When $\mathcal{I}_{ACI}(k, l) > \xi_{\text{CCA-ED}}$, the AP-$l$ is also referred to as a directly interfering AP of AP-k although these two APs do not use the same channel. Note that $\xi_{\text{CCA-ED}} = -62$ dBm for a single basic channel (20 MHz) in IEEE 802.11.

On the other hand, consider that AP-k is outside the carrier sensing coverage of AP-l but some STAs of AP-k is within the carrier sensing coverage of AP-l. Note that this is a very common situation where the coverage areas of two APs are partly overlapped. Then, since AP-k cannot detect transmission of AP-l, AP-l is not a directly interfering AP of AP-k. However, the STAs of AP-k within overlapped area can detect transmission of AP-l and their transmission can be disturbed by AP-l. We define that the AP-l and AP-k have a hidden interference relationship between them and are a hidden interferer of each other. The interference relationship among APs is used as input of the CA process.

2) BROADCAST INFORMATION OF AP

Each AP, irrespective of its type (i.e., C-AP or S-AP), broadcasts the following status information for each of two bands, through beacon frames: the number of associated STAs, the channel load, and average spectral efficiency. This information is used to realize the proposed scheme and is calculated as follows.

Let $\mathcal{S}(k, B)$ denote the set of STAs associated with the band-B channel of AP-k, where B is 2.4 GHz or 5 GHz. When $|s|$ denotes the cardinality of a set s, $|\mathcal{S}(k, B)|$ is the number of associated STAs for the band-B channel of AP-k. Let us define the channel load as the channel occupancy time portion for transmitting the traffic of all associated STAs. For the STA-i associated with AP-k in band-B, when α_i is the traffic arrival rate of STA-i and $C_{k,i}$ is the link rate between AP-k and STA-i, the channel time portion for transmitting the traffic of STA-i is calculated as $\frac{\alpha_i}{C_{k,i}}$. Then, we calculate the channel load of AP-k in band-B, denoted by $L(k, B)$, like in [17].

$$L(k, B) = \sum_{i \in \mathcal{S}(k,B)} \frac{\alpha_i}{C_{k,i}}, \tag{2}$$

Next, we calculate the average spectral efficiency (SE) for the band-B channel of AP-k, denoted by $\Gamma(k, B)$. Let $SNR_{k,i}$ be the signal-to-noise ratio (SNR) between AP-k and STA-i. According to [20], for given $SNR_{k,i}$, the average SE between AP-k and STA-i is

$$f\left(SNR_{k,i}\right) = \min\left(2.7,\ \log_2\left(1 + 0.25 \cdot SNR_{k,i}\right)\right). \tag{3}$$

Then, according to [21] and [22], $\Gamma(k, B)$ is calculated as the harmonic mean of the SEs of associated STAs.

$$\Gamma(k, B) = \frac{|\mathcal{S}(k, B)|}{\sum_{i \in \mathcal{S}(k,B)} \frac{1}{f(SNR_{k,i})}}. \tag{4}$$

The AP-k broadcasts $|\mathcal{S}(k, B)|$, $L(k, B)$, and $\Gamma(k, B)$ for each band-B channel, through beacon frame. These are used for UA-LB work.

IV. TWO-PHASE RRM FRAMEWORK IN DENSE WLAN ENVIRONMENT

In this section, we suggest a two-phase RRM framework for enhancing network performance in a typical dense WLAN environment of Fig. 1. The suggested two-phase RRM framework is depicted in Fig. 2. The first phase is the CA for minimizing the interference among WLAN basic service sets (BSSs) while fully exploiting channel sharing and channel bonding. The second phase is the UA-LB for associating each STA with a pair of AP and band-channel (i.e., which band channel of which AP) for given CA result of the first phase, so that the network load is well balanced among assigned channels of APs. Since the load balancing in this UA work means the load balancing among assigned channels (not among APs), hereafter, this second phase is denominated as UA-ChLB rather than UA-LB. Now, we give a short overview of each RRM phase.

A. CHANNEL ASSIGNMENT

As depicted in Fig. 2, the CA task is composed of three subtasks: generating the interference graph among APs, allocating the operation channel and its bandwidth to each AP, and selecting the primary channel among the allocated basic channels of each AP. Now, we explain each subtask, using our previous work in [9]. Since the CA scheme in [9] was designed under the same system model as that in Section III, this scheme is well matched to the CA part of Fig. 2. Accordingly, we summarize the CA scheme in [9] without newly designing another CA scheme, in this subsection.

1) INTERFERENCE GRAPH GENERATION

The graph generation process in [9] is as follows, separately for each band. The controller requests C-APs to search the neighboring S-APs (i.e., stand-alone APs) by scanning all channels. Then, each C-AP can detect its directly interfering S-APs and get the operating channel information of neighboring S-APs. Next, the controller makes a beacon broadcasting schedule of each C-AP in time-division manner. A C-AP broadcasts beacon frame at its scheduled time, on a predefined channel. Then, other C-APs can observe its direct interference relationship with the C-AP by listening to the broadcasted beacon. After that, according to reporting schedule, each C-AP reports its interfering C-APs and S-APs to the controller (of course, also the channel number of each neighboring S-AP). From this reported information, the controller can acquire direct interference relationship among all APs, including C-APs and S-APs.

On the other hand, similarly to C-APs, each NL-STA also detects its directly interfering S-APs and C-APs and reports the list to the controller. It is noted that, based on this reported information, the controller can get the hidden interference relationship among APs. For example, if there is no direct relationship between AP-k and AP-l but there is an NL-STA having direct interference relationship with both AP-l and AP-k, respectively, then the AP-k and AP-l are hidden interferer to each other.

By using the reported information from C-APs and NL-STAs, the controller generates the weighted interference graph where APs (both C-APs and S-APs) become the vertexes and the interfering APs are connected with edges. The weight of an edge depends on whether the interference relationship of the edge is direct or hidden: the weight of a direct interference edge is set to 1, and the weight of hidden interference edge from AP-k to AP-l is set to $\frac{N_{k,l}}{N_k}$, where N_k is the number of STAs which can hear AP-k and $N_{k,l}$ is the number of STAs which can hear both of AP-k and AP-l. Then, the weight represents the probability of channel sharing between AP-k and AP-l when assigning the same channel to them.

2) CHANNEL AND BANDWIDTH ALLOCATION

After generating interference graphs, the controller performs channel and bandwidth allocation for each C-AP.

Let $\mathcal{W}_B$ denote the set of all feasible channels for allocation, in band $B \in \{2.4, 5\}$ GHz. Since the channel bonding is allowed for each band, all channels in $\mathcal{W}_B$ do not have the same bandwidth. For example, when bonding two basic channels of 2.4 GHz band, the bonded channel becomes another 2.4 GHz-band channel with 40 MHz bandwidth. Thus, the bandwidth of a channel can be naturally identified by the channel itself. As a result, channel allocation includes bandwidth allocation.

The goal of CA in [9] is to allocate the channels so as to maximize the total throughput of entire network, while allowing channel sharing. Note that, since each AP supports dual-band, one channel in each of two bands can be assigned to an AP. Thus, the controller performs the following channel and bandwidth allocation work, separately for each band. We will omit the band index B for convenience in description.

When c_k denotes a channel allocated to AP-k, channel allocation is represented as $(c_1, c_2, \cdots, c_K)$ where K is the number of C-APs. Since the same channel or overlapped channels can be allocated to two APs having interference relationship, the maximum throughput of each AP is affected by such channel sharing. For given $(c_1, c_2, \cdots, c_K)$ and the channels of S-APs, the channel sharing factor of each C-AP is calculated based on the weighted interference graph, which is to add all weights of interference edges of the C-AP for the corresponding channel allocation. Then, the maximum throughput of a C-AP under channel sharing is got by dividing its maximum throughput under no sharing by its channel sharing factor. The CA work is formulated as the optimization problem for maximizing the throughput sum of all C-APs.

3) PRIMARY CHANNEL SELECTION

As the final subtask, the controller determines the primary basic channel of each bonded channel for given CA result. Note that IEEE 802.11ac standard supports two strategies of using the bonded channel: the static strategy is to always use the whole allocated basic channels for every transmission, whereas the dynamic strategy allows AP and STAs to use just free contiguous basic channels including primary channel. According to [8], for static bonding strategy, two types of channel invading can also occur among two adjacent APs using the same channel: total invading where one AP always wins in channel access, and a partial invading where one AP has the lower channel access opportunity than the other AP. Under invading situation, note that the primary channel section may have a great effect on the performance.

In [9], the controller selects the primary channel for bonded channel of each C-AP, while taking bonding strategy and invading type into account. More specifically, if AP-k and AP-l have total invading relation, their primary channels should be set on the same basic channel. Otherwise, i.e., for partial invading or dynamic channel bonding case, their primary channels should be set to different basic channels which are farthest away from each other.

The readers can refer to [9] for the detail of the CA scheme, summarized above.

B. USER ASSOCIATION FOR BALANCING LOAD ON CHANNELS

The controller periodically performs the UA-ChLB work, based on various status information reported from all NL-STAs and C-APs. Since the state of STAs (traffic, location, etc) may be changed dynamically, it can be better to carry out the UA-ChLB more often, in the viewpoint of performance. But, this may incur a considerable reporting overhead. That is, there is a trade-off between performance and communication overhead. To properly handle this trade-off, we propose the hybrid scheme, composed of distributed UA-ChLB and centralized UA-ChLB. The centralized UA-ChLB is carried out by the controller with longer period and the distributed UA-ChLB is performed independently by each STA, at any time.

On the other hand, the CA work can be performed with much longer period than the centralized UA-ChLB since interference relationship among APs (mainly influenced by positions of APs) is expected to be not greatly changed over time.

As already stated before, since the CA scheme [9] (summarized in Section IV-A) can be used for the CA part of Fig. 2, we will concentrate on designing the centralized UA-ChLB and the distributed UA-ChLB, under situation that the operating channels of each C-AP have been determined already by the CA scheme [9].

V. HYBRID UA-ChLB

In the proposed UA-ChLB, the controller performs the UA task (i.e., determines serving AP and operating channel within the serving AP) for NL-STAs with period of T_{UA}. This work is referred to as the centralized UA-ChLB by the controller. It is noted that an NL-STA can be associated with S-AP if the NL-STA is expected to get better transmission opportunity from the S-AP than C-APs, for example, when the NL-STA is very close to the S-AP or the load of S-AP is low. On the other hand, the network status can be greatly changed during the interval of centralized UA-ChLB work. To efficiently cope with such fluctuation of network status with low overhead, we take a strategy to adjunctively use the distributed UA-ChLB during the interval of centralized UA-ChLB. In the distributed UA-ChLB, each NL-STA can change its serving AP and/or the serving channel, at any time if the predefined condition for such handover is held.

A. DISTRIBUTED UA-ChLB

Consider an NL-STA-i associated with the band-B channel of AP-k, where the AP-k can be C-AP or S-AP. Remind that AP-k, irrespective of C-AP or S-AP, broadcasts $[L(k, B), |\mathcal{S}(k, B)|, \Gamma(k, B)]$ for each band-B, through its beacon frames, where $L(k, B)$, $|\mathcal{S}(k, B)|$, and $\Gamma(k, B)$ are the total load, the number of associated STAs, and the SE for band-B channel in AP-k, respectively.

When getting $[L(k, B), |\mathcal{S}(k, B)|, \Gamma(k, B)]$, the NL-STA-$i$ checks whether $L(k, B)$ is higher than a predefined threshold value L_{th}. If $L(k, B) > L_{\mathrm{th}}$, the STA-$i$ conducts a persistent test with the probability of $\frac{1}{|\mathcal{S}(k,B)|}$. When the persistent test is passed, the NL-STA-i performs the following task which determines the target AP and band for handover.

Firstly, the NL-STA-i gets the information of neighboring APs by hearing beacon frames through the full channel scanning process. Next, for each channel of all neighboring APs, the NL-STA-i assesses the average SE of channel when it is associated with the corresponding channel, as follows. Let $\Gamma_i(j, B)$ be the average SE for the band-B channel of AP-j assessed by NL-STA-i (refer to the equations (3), (4)).

Since the NL-STA-i is newly added,

$$\Gamma_i(j,B) = \frac{1+|\mathcal{S}(j,B)|}{\frac{1}{f(SNR_{j,i})}+\frac{|\mathcal{S}(j,B)|}{\Gamma(j,B)}}, \tag{5}$$

where $SNR_{j,i}$ is the SNR of AP-j at NL-STA-i measured by hearing the beacon of AP-j. On the other hand, it is obvious that the resource efficiency (RE) of this new assigned NL-STA-i on the band-B channel of AP-j is affected by not only the existing load of AP-j but also the loads of neighboring APs of NL-STA-i on the corresponding channel. It is obvious that the higher load leads to the lower RE. Thus, when the NL-STA-i is newly associated with the band-B channel of AP-j, the expected RE of NL-STA-i, $RE_i(j,B)$, is likely to be inversely proportional to the total load of the channel. Let $\mathcal{A}_i(j,B)$ be the set of neighboring APs of NL-STA-i using the band-B channel of AP-j and let $\mathfrak{L}_i(j,B)$ denote the total load for band-B channel of AP-j being estimated by NL-STA-i. Because the load of NL-STA-i should be added,

$$\mathfrak{L}_i(j,B) = \frac{\alpha_i}{C_{j,i}} + \sum_{m\in\mathcal{A}_i(j,B)} L(m,B). \tag{6}$$

Then, the decreasing factor of RE is defined as $\beta_i(j,B) := \frac{1}{1+\mathfrak{L}_i(j,B)}$, where we add 1 to $\mathfrak{L}(j,B)$ in the denominator so that $\beta_i(k,B)$ has a real positive value such that $0 < \beta_i(k,B) \leq 1$. And, the NL-STA-i estimates the RE for the band-B channel of AP-j, as follows.

$$RE_i(j,B) := \beta_i(j,B)\cdot\Gamma_i(j,B). \tag{7}$$

The NL-STA-i determines the target AP-j^* and band-B^* as

$$(j^*,B^*) = \underset{j\in\mathcal{A}_i(j,B),B\in\{2.4\text{ GHz},5\text{ GHz}\}}{\operatorname{argmax}} RE_i(j,B). \tag{8}$$

B. CENTRALIZED UA-ChLB

Remind that an AP being governed by the controller is called C-AP and the STA where the proposed UA-ChLB is implemented is called NL-STA. Since the controller only manages the C-APs, it receives the information from both C-APs and the NL-STAs connected to C-APs (i.e., C-STAs).

The controller performs the UA for all C-STAs with the period of T_{UA}. Since a C-STA can be associated with not only C-AP but also S-AP, the UA should estimate the link rate between the C-STA and its each neighboring AP. Since the link rate is calculated based on the link quality (i.e., SNR value), the controller requests all C-STAs to search their neighboring S-APs by scanning channels.[1] In addition, since the controller knows channels assigned to C-APs, it provides the channel information of neighboring C-APs to C-STAs, through their current serving C-APs. Each C-STA, by hearing the beacons of its neighboring S-APs and C-APs for each band, measures the SNR of beacon and gets the information within beacon. Then, it reports the list of neighboring APs and the information within beacon and SNR of beacon for each neighboring AP. Remind that any AP, irrespective of C-AP or S-AP, broadcasts a beacon containing the number of associated STAs, the channel load, and the average SE, for each band channel. The controller also directly gets the information for UA from each C-AP, i.e., the list of associated STAs, the traffic arrival rate of each C-STA, the channel load, and the SE for each band channel.

The controller determines the serving AP and serving channel of each C-STA for maximizing the total RE of entire network, based on the above information reported from C-APs and C-STAs. We firstly formulate the centralized UA-ChLB work as a mixed-integer quadratic fractional programming (MIQFP) problem, which can be transformed into a mixed-integer quadratic programming (MIQP). Then, we get the UA result by solving the transformed MIQP problem.

1) PROBLEM FORMULATION

We define notation for the information that the controller gathers at the start of the centralized UA-ChLB process, as follows. Let $\hat{S}_{\text{CSTA}}$ denote the set of NL-STAs connected to all C-APs. For the band-B channel of AP-k, let $\hat{S}(k,B)$ be the set of all associated STAs and let $\hat{S}_{\text{CSTA}}(k,B)$ be the set of associated C-STAs. When $y_{\text{C-AP}}(k)$ is a binary variable indicating whether the AP-k is C-AP or not, if the AP-k is C-AP, $y_{\text{C-AP}}(k)=1$; otherwise, $y_{\text{C-AP}}(k)=0$. Obviously, if $y_{\text{C-AP}}(k)=0$, $\hat{S}_{\text{CSTA}}(k,B)=\emptyset$.

We represent a feasible UA result as a matrix $\mathbf{X} := [x_i(k,B)]$, where $x_i(k,B)$ is a binary variable indicating whether C-STA-i is associated with the band-B channel of AP-k or not. This is, if the C-STA-i is associated with the band-B channel of AP-k, $x_i(k,B) = 1$; otherwise, $x_i(k,B)=0$.

As mentioned before, the controller tries to maximize the total RE of entire network, which is the sum of the REs of all APs. Similarly in the distributed UA-ChLB of the previous

[1] Although full channel scanning is performed in the CA process, since the period of CA is much longer than T_{UA}, the information on neighboring S-APs may be changed.

$$L(k,B) = \hat{L}(k,B) + \sum_{i\in\hat{S}_{\text{CSTA}}} x_i(k,B)\frac{\alpha_i}{C_{k,i}} - y_{\text{C-AP}}(k)\sum_{n\in\hat{S}_{\text{CSTA}}(k,B)}\frac{\alpha_n}{C_{k,n}}. \tag{9}$$

$$\Gamma(k,B) = \frac{\left|\hat{S}(k,B)\right| + \sum_{i\in\hat{S}_{\text{CSTA}}} x_i(k,B) - y_{\text{C-AP}}(k)\left|\hat{S}_{\text{CSTA}}(k,B)\right|}{\frac{\left|\hat{S}(k,B)\right|}{\hat{\Gamma}(k,B)} + \sum_{i\in\hat{S}_{\text{CSTA}}}\frac{x_i(k,B)}{f(SNR_{k,i})} - y_{\text{C-AP}}(k)\sum_{n\in\hat{S}_{\text{CSTA}}(k,B)}\frac{1}{f(SNR_{k,n})}}. \tag{10}$$

subsection, we define the RE for the band-B channel of AP-k as the channel SE multiplied by the decreasing factor which is inversely proportional to the load.

Firstly, let us estimate the load for the band-B channel of any AP-k, denoted by $L(k, B)$. When $\hat{L}(k, B)$ denotes the load on the band-B channel of AP-k got from the beacon of AP-k at the start of the current centralized UA-ChLB process, $L(k, B)$ is estimated as (9), shown at the bottom of the previous page. Since the controller re-associates only the NL-STAs within C-APs, if AP-k is S-AP (i.e., $y_{\text{C-AP}}(k) = 0$), the estimated load for the band-B channel of AP-k is the sum of its existing load and the loads of newly associated NL-STAs among the STAs in $\hat{S}_{\text{CSTA}}$. And, if AP-k is C-AP, the load of its past associated NL-STAs should be additionally subtracted. Since the channel sharing is allowed, the load on the band-B channel of AP-k should be assessed by counting the loads of neighboring APs using the same channel together. Accordingly, the total load on the band-B channel of AP-k is estimated as

$$\mathfrak{L}(k, B) := \sum_{j \in \{k\} \cup \mathcal{A}(k,B)} L(j, B), \tag{11}$$

where $\mathcal{A}(k, B)$ be the set of neighboring APs of AP-k, sharing the band-B channel of AP-k. Then, since the higher $\mathfrak{L}(k, B)$ means that the AP-k may occupy the smaller portion of channel time, the RE for the band-B channel of AP-k is expected to be lower for higher $\mathfrak{L}(k, B)$. Thus, we set the decreasing factor $\beta(k, B)$ as a real positive value being proportional to the reciprocal of $\mathfrak{L}(k, B)$.

$$\beta(k, B) = \frac{1}{1 + \mathfrak{L}(k, B)}. \tag{12}$$

Note that $0 < \beta(k, B) \leq 1$, by adding 1 to the denominator.

On the other hand, the estimated average SE for band-B channel of AP-k, denoted by $\Gamma(k, B)$, is defined as a harmonic mean of the SEs of associated STAs. In (10), as shown at the bottom of the previous page, $f(SNR_{k,i})$ is the SE between STA-i and AP-k (refer to (3)) and $\hat{\Gamma}(k, B)$ is the average SE for the band-B cannel of AP-k got by hearing the beacon of AP-k at the start of the current centralized UA-ChLB process. Note that the numerator of (10) is the total number of STAs and its denominator is the sum of the reciprocals of SE for all STAs.

The controller calculates the RE of AP-k on its band-B channel, denoted by $RE(k, B)$, as follows.

$$RE(k, B) := \beta(k, B) \cdot \Gamma(k, B). \tag{13}$$

Then, the optimization problem for centralized UA-ChLB, which maximizes the RE of entire network, can be formulated as (14) and the solution is the new AP/channel association for each STA in $\hat{S}_{\text{CSTA}}$.

$$\max_{\mathbf{X}} \sum_{(k,B)\in\mathcal{C}} RE(k, B) \tag{14}$$

$$\text{s.t.} \sum_{(k,B)\in\mathcal{C}} x_i(k, B) = 1, \quad \forall i \in \hat{S}_{\text{CSTA}},\ \forall (k, B) \in \mathcal{C} \tag{15}$$

$$x_i(k, B) \in \{0, 1\}, \quad \forall i \in \hat{S}_{\text{CSTA}},\ \forall (k, B) \in \mathcal{C} \tag{16}$$

$$\mathfrak{L}(k, B) \leq L_{\text{th}}, \quad \forall (k, B) \in \mathcal{C} \tag{17}$$

where $\mathcal{C}$ is the set of which each component is a pair of each AP and its assigned channel, and is given as the input of this UA-ChLB process. It is noted that the controller knows the assigned channels of C-APs because it performs the CA work and it also knows the channel information of each S-AP because C-STAs report the channel information for their neighboring S-APs.

The constraint (15) is to ensure that each C-STA is associated with just an AP and one channel of the AP, and the constraint (16) is self-evident. The constraint (17) is the maximum load condition that $\mathfrak{L}(k, B)$ should be less than a predefined threshold L_{th}.

2) EQUIVALENT MIQP PROBLEM

Since the objective function (14) has a fractional form, this problem is an MIQFP problem, which is the NP-hard being difficult to solve directly. Therefore, we transform this original problem into an equivalent solvable MIQP problem.

According to a parametric technique in [25], by introducing additional variables (i.e., parameters), an MIQFP problem of fractional form can be transformed into its equivalent MIQP problem of quadratic form. We introduce the parameter $\lambda(k, B)$ for each $(k, B) \in \mathcal{C}$. For simple description, let us denote the numerator and the denominator of average SE in (10) by $\Gamma_{\text{nu}}(k, B)$ and $\Gamma_{\text{de}}(k, B)$, respectively. Then, the problem in (14) – (17) is transformed into the following MIQP problem.

$$\max_{\mathbf{X}} \sum_{(k,B)\in\mathcal{C}} \Big(\beta(k, B)\Gamma_{\text{nu}}(k, B) - \lambda(k, B)\Gamma_{\text{de}}(k, B)\Big) \tag{18}$$

$$\text{s.t.} \sum_{(k,B)\in\mathcal{C}} x_i(k, B) = 1, \quad \forall i \in \hat{S}_{\text{CSTA}},\ \forall (k, B) \in \mathcal{C} \tag{19}$$

$$x_i(k, B) \in \{0, 1\}, \quad \forall i \in \hat{S}_{\text{CSTA}},\ \forall (k, B) \in \mathcal{C} \tag{20}$$

$$\mathfrak{L}(k, B) \leq L_{\text{th}}, \quad \forall (k, B) \in \mathcal{C} \tag{21}$$

For given $\lambda(k, B)$'s, the MIQP problem in (18) – (21) can be solved by applying the branch and bound (BB) technique. By using the CPLEX MIQP solver[2] [26], we obtain the solution for given $\lambda(k, B)$'s.

3) SOLUTION ALGORITHM

The solution of original problem, $\mathbf{X}^*$, is obtained by solving the transformed problem in (18) – (21) with the optimal values of $\lambda(k, B)$'s for maximizing the objective function (18). It is well known that these optimal parameter values, $\lambda(k, B)^*$'s, can be got by applying the Dinkelbach's method [27]. According to the Dinkelbach's method, each $\lambda(k, B)$ is initially set to 0, and its value is repeatedly updated and finally converges to $\lambda^*(k, B)$.

Algorithm 1 is the solution algorithm of centralized UA-ChLB problem, based on the Dinkelbach's method. The

[2] There are actually plenty of solvers which use the BB technique to solve MIQP problems, including CPLEX.

algorithm is terminated when all parameters converge to their respective optimal values, i.e., when the gap between the old and new values is not larger than a predefined threshold ϵ.

Algorithm 1 Solution Algorithm of Centralized UA-ChLB

$\lambda(k, B) \leftarrow 0$, $\lambda^{old}(k, B) \leftarrow 1$ for all $(k, B) \in \mathcal{C}$.
$\epsilon \leftarrow 10^{-5}$, stop $\leftarrow$ *false*.
while stop = *false* **do**
  Solve the problem (18) – (21), for given $\lambda(k, B)$'s
  stop $\leftarrow$ *true*
  for all $(k, B) \in \mathcal{C}$ **do**
    if $|\lambda(k, B) - \lambda^{old}(k, B)| > \epsilon$ **then**
      $\lambda^{old}(k, B) \leftarrow \lambda(k, B)$
      Calculate$RE(k, B)$ by using Eq. (13)
      $\lambda(k, B) \leftarrow RE(k, B)$
      stop $\leftarrow$ *false*
    end if
  end for
end while
return $\mathbf{X}^*$

Remark: The NL-STAs which were associated with C-APs are newly associated with C-AP or S-AP, based on the centralized UA-ChLB result. During the interval of the centralized UA-ChLB, since each NL-STA can change its serving AP and serving channel whenever the condition for handover is satisfied, the proposed scheme has the desirable properties, which are the efficiency of centralized allocation and the fast adaptation of distributed control.

VI. PERFORMANCE EVALUATION

In this section, we assess the performances of the proposed RRM scheme and some existing schemes, based on the experimental results.

A. IMPLEMENTATION

We have implemented a prototype system for the proposed RRM scheme using three different entities: a centralized controller, NL-STAs, and APs (S-AP and C-AP).

1) CENTRALIZED CONTROLLER

The centralized controller includes a module for CA and a module for centralized UA-ChLB, which were developed by using the Java programming language (JDK version 7). For the UA-ChLB scheme, the Java version of CPLEX MIQP solver in [26] was integrated into the controller. A desktop PC using Intel i7 with 16GB RAM was used to run the controller.

2) NL-STAs

We used laptop computers (Samsung NT200B5C and NT500R5P) operated by Linux (Ubuntu 14.04), for NL-STAs. A wireless network interface card using Realtek 8812AU chipset is equipped to support 802.11n/ac in each laptop computer. Using the Java and iw tool (Linux), we implemented three software modules: a module for reporting wireless channel conditions and load of neighboring APs, a module for applying its UA result notified by the controller, and a module for distributed UA-ChLB.

3) APs

We used TP-Link APs (TL-WDR4300, Archer C7 AC1750) operated by OpenWRT. To include the information (the number of STAs, load of AP, and average SE) in the broadcasted beacon, we modified the hostapd in the user layer without modification of Wi-Fi driver. To calculate the load of AP, the traffic amount of each STA needs to be obtained. To do this, the existing traffic monitoring tool such as *Darkstat* in each AP was exploited. Note that, through this traffic monitoring tool, the statistical information of incoming/outcoming traffic per STA can be collected. Then, the collected information is stored as a log file in the memory of each AP, and the controller can obtain the information by periodically accessing the log file.

B. EXPERIMENTAL ENVIRONMENT

We set up the experiment environment as shown in Fig. 3, where a total of 14 APs are deployed in rooms and corridor on the same floor of building. A total of nine APs from AP-1 to AP-9 are C-APs using 802.11n/ac (TP-Link Archer C7 AC1750) connected to the controller, whereas a total of five APs from AP-10 to AP-14 are S-APs using 802.11n (TP-Link TL-WDR4300), which independently operates. The transmission power of each AP is set to 10 dBm. To construct the dense WLAN environment where the frequency resource is insufficient, we merely use four basic channels having bandwidth of 20 MHz in each band: in the 2.4 GHz band, the channels with number ch. 1, ch. 2, ch. 4, and ch. 6; in the 5GHz band, ch. 36, ch. 40, ch. 44, and ch. 48. Other channels having bandwidth wider than a basic channel can be constructed by bonding multiple non-overlapped basic channels. Then, there are a total of five channels in the 2.4 GHz band: four basic channels and one bonding channel of 40 MHz. In addition, there are a total of seven channels in the 5 GHz band: four basic channels, two 40 MHz bonding channels, and one 80 MHz bonding channel. Each S-AP only uses a single basic channel, whereas a C-AP can use not only a basic channel but also a bonding channel. As seen in Fig. 3, the channels assigned to each S-AP is expressed as a pair of channel numbers in each band with blue numbers around corresponding S-AP, such as (2.4 GHz-band channel, 5 GHz-band channel). The total number of STAs in the network is denoted by N and the maximum value of N in our experiment is 36. When the STAs are deployed at maximum, the position of each STA (from STA-1 to STA-36) is like in Fig. 3.

C. EXPERIMENTAL SETTINGS

We conduct the experiments, gradually increasing N by 6, i.e., N is changed to $6, 12, \cdots, 30, 36$. When increasing N by one level, we select six STAs with index difference of 6, in sequence, so that the selected STAs can be more evenly distributed in the network. As an example, suppose that the

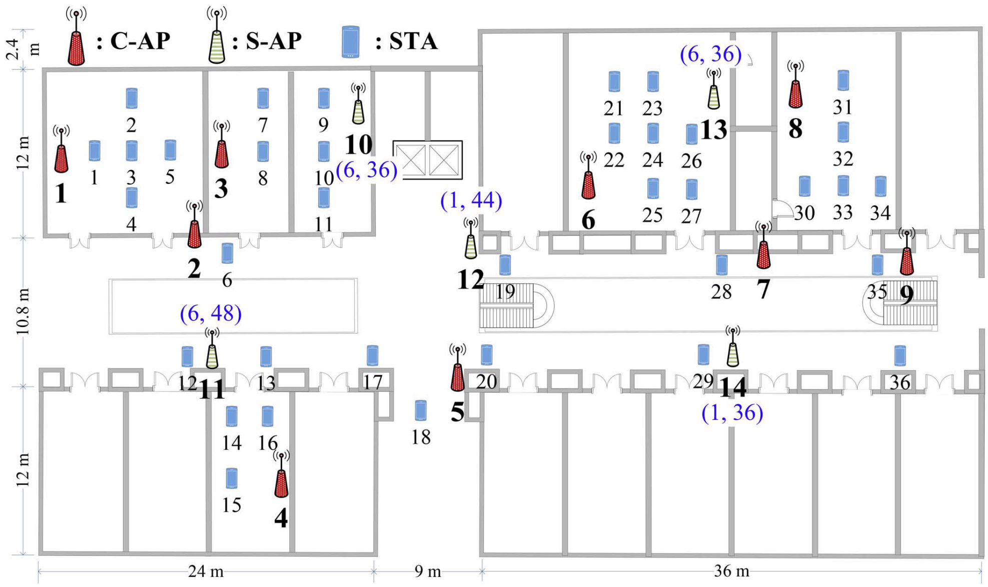

FIGURE 3. Experimental indoor environment.

index set of existing six STAs is {2, 8, 14, 20, 26, 32}. Then, the index set of 12 STAs including newly added 6 STAs may be {2, 4, 8, 10, 14, 16, 20, 22, 26, 28, 32, 34}.

In order to measure the throughput per STA, the UDP traffic is generated at the rate of α by using *iperf* and is transmitted to each STA associated with S-AP or C-AP. To avoid the interference from other external APs in the building, experiments are conducted for the time with little external traffic (e.g., late night or early in the morning). In the CA scheme, the RSSI thresholds for generating the interference graph are $\xi_{\text{CCA-CS}} = -82$ dBm, $\xi_{\text{CCA-ED}} = -62$ dBm. The parameter values for the proposed UA scheme are $T_{\text{UA}} = 5$ min and $L_{\text{th}} = 0.9$.

The performance metrics are as follows: average throughput per STA, total throughput of STAs in the network, and fairness. The Jain's fairness index is adopted as fairness metric: $\psi = \left(\sum_{i=1}^{N} \Phi_i\right)^2 / \left(N \cdot \sum_{i=1}^{N} {\Phi_i}^2\right)$, where Φ_i is the throughput of STA-i. Note that $\frac{1}{N} \leq \psi \leq 1$. When ψ is close to 1, all STAs are expected to get almost the same throughput.

D. COMPARISON SCHEMES

For performance comparison with the proposed RRM, we implemented some RRM schemes, which combine existing CA and UA schemes. As the existing CA schemes for comparison, we took the random channel selection (RCS) scheme and the centralized version of CA scheme in [3] (namely, LIC). In the RCS, a basic channel or a bonding channel is randomly allocated to each C-AP. In the LIC, the controller assigns a basic channel with the least number of interference sources to each AP, based on the interference graph.

As the existing UA schemes for comparison, we choose RSSI-based UA, band-steering in [18] (namely, BSTR), and FAME in [10]. The RSSI-based UA selects the AP/band with the highest RSSI among neighboring APs. The BSTR scheme in [18] coordinates the ratio between the number of STAs in 2.4 GHz band and that in 5 GHz band, where each STA firstly selects the C-AP with the highest RSSI as its serving AP and then each C-AP performs the ratio coordination. The FAME scheme in [10] makes a connection between AP/band and each STA for maximizing the MAC efficiency metric, which is derived based on the link rate, traffic amount, and collision rate.

TABLE 2. Channel assignment results (2.4 GHz ch., 5 GHz ch.).

	RCS	LIC	Proposed
AP-1	(4, 48)	(1, 40)	(1, 36-40)
AP-2	(2, 36)	(6, 36)	(6, 48)
AP-3	(1, 44-48)	(4, 44)	(6, 44)
AP-4	(6, 44)	(2, 48)	(1, 36-40)
AP-5	(1, 40)	(2, 48)	(1, 48)
AP-6	(4, 36-40)	(6, 44)	(6, 40)
AP-7	(6, 48)	(4, 40)	(2, 40)
AP-8	(2, 40)	(1, 48)	(6, 44-48)
AP-9	(2, 36)	(2, 36)	(2, 36)

E. EXPERIMENTAL RESULTS

Table 2 shows the CA results for C-APs in each comparison scheme. Since the RCS scheme randomly allocates channels to C-APs, neighboring APs can use the same or overlapped channels. For example, the AP-1, AP-2, and AP-3 being adjacent to each other use overlapped channels in the 2.4 GHz band and, the AP-1 and AP-3 use the same channel in the 5 GHz band. We can predict severe interference among these APs in both bands. The LIC scheme allocates a basic channel to each C-AP while reducing the interference among neighboring APs. As compared with the RCS scheme, neighboring APs use different channels to minimize the CCI in the 5 GHz band, but there still exists the ACI in the 2.4 GHz band

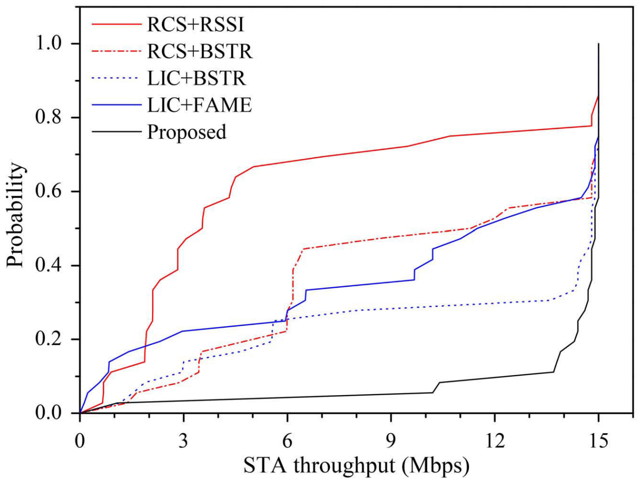

FIGURE 4. CDF of STA throughput ($N = 36$, $\alpha = 15$ Mbps).

due to the deficiency of non-overlapped channels. In our proposed CA scheme, channels are allocated to C-APs under consideration of mutual interference among APs (S-APs and C-APs). In particular, bonding channels can be allocated to some APs (AP-1, AP-4, and AP-8) in the 5 GHz band while minimizing the mutual interference. For this reason, the network performance of the proposed CA scheme would be better than that of LIC.

Fig. 4 shows the cumulative distribution function (CDF) of STA throughput, when the number of STAs within the network, N, is 36 and the traffic generation rate of a STA, α, is 15 Mbps. Also, Table 3 presents the average STA throughput and fairness in the same settings.

Firstly, we compare the performance of CA schemes from Fig. 4 and Table 3. Under the RCS scheme assigning the channels randomly, there exists severe interference (CCI and/or ACI) among APs because neighboring APs may use the same or adjacent channels. Whereas, in the LIC scheme, neighboring APs use different channels to minimize the CCI in the 5 GHz band. This results in the performance gap between RCS and LIC, which can be observed by comparing two cases of using BSTR scheme in Fig. 4 and Table 3. In our proposed CA scheme [9], an available channel (basic channel or bonding channel) is allocated to each C-AP under consideration of direct/hidden interference. Since STAs associated with those C-APs suffer from the relatively less interference, the throughput performance of the STAs is enhanced.

Next, let us discuss the performance of UA schemes from Fig. 4 and Table 3. Note that the STAs associated with the channels of 2.4 GHz band are more severely influenced by the interference among APs, compared with the STAs in 5 GHz band.[3] Thus, with the same CA scheme randomly selecting

TABLE 3. Performance comparison ($N = 36$, $\alpha = 15$ Mbps).

	RCS+ RSSI	RCS+ BSTR	LIC+ FAME	LIC+ BSTR	Proposed
Average STA throughput (Mbps)	6.21	9.99	7.14	11.79	14.14
Fairness	0.56	0.80	0.77	0.85	0.97

the channels (i.e., RCS), the RSSI-based UA provides much lower performance than the BSTR-based UA, where some STAs in the 2.4 GHz band can be moved to the 5 GHz band for load balancing after initial UA based on RSSI. On the other hand, the performance of the FAME UA scheme in [10] is much lower than that of BSTR scheme. This is because the FAME scheme does not consider the interference factor, even if a considerable number of STAs are associated with APs in the 2.4 GHz band having the severe interference. Furthermore, some STAs can be associated with APs of which RSSI is relatively low because the UA between AP/band and each STA is determined based on only the MAC efficiency defined in [10]. Then, the throughput performance of these STAs, particularly in the 2.4 GHz, can be very low. As a result, about 30% of total STAs have the throughput less than 6.5 Mbps, and the average STA throughput is merely 7.14 Mbps. Owing to the performance gap between STAs in the two frequency bands, the fairness becomes relatively low as 0.77 (see Fig. 4 and Table 3). However, note that although BSTR is used, there are still a considerable number of STAs in the 2.4 GHz band and these STAs suffer from performance degradation due to the interference among APs.

In contrast, by using the proposed UA scheme, STAs can be associated with non-overlapped channels of each band in a balanced way. In addition, since only STAs which can be accommodated to each channel of S-APs and C-APs under consideration of both channel interference and traffic amount are associated with the APs, the utilization ratio of the total frequency resource is significantly enhanced. For this reason, as seen in Fig. 4, the overall throughput performance of STAs in the proposed scheme is much higher than in the comparison schemes. Also, since there exists the very small performance gap among STAs, the fairness value is close to 1, as shown in Table 3.

Fig. 5 depicts the CDF of STA throughput when $N = 36$ and $\alpha = 25$ Mbps, and Table 4 shows the average STA throughput and fairness in the same settings. Although α increases to 25 Mbps, the performance trend is very similar with the results when $\alpha = 15$ Mbps in Fig. 5 and Table 4. Owing to larger performance gap between STAs in each band, the fairness value is less with $\alpha = 25$ Mbps than $\alpha = 15$ Mbps, in all schemes. However, the decrease of fairness in the proposed scheme is much smaller than that in the other schemes.

Table 5 shows the performance comparison between the two frequency bands, where $N = 36$ and $\alpha = 25$ Mbps. Under the proposed scheme in comparison with the other schemes, even if there are much more STAs associated to 5 GHz band, the average STA throughput in 5 GHz band is

[3] Generally, frequency characteristic (*e.g.*, diffraction, penetration) of 2.4 GHz band is even better than that of 5 GHz band. However, such characteristic in the dense WLAN environment unfortunately has harmful effects on interference. Furthermore, in the 2.4 GHz band, there are overlapped channels causing the ACI. For this reason, the interference level is much higher in the 2.4 GHz band than in 5 GHz band.

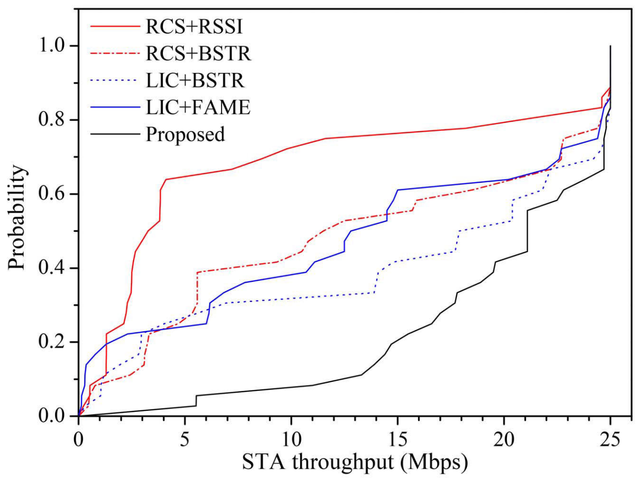

FIGURE 5. CDF of STA throughput ($N = 36$, $\alpha = 25$ Mbps).

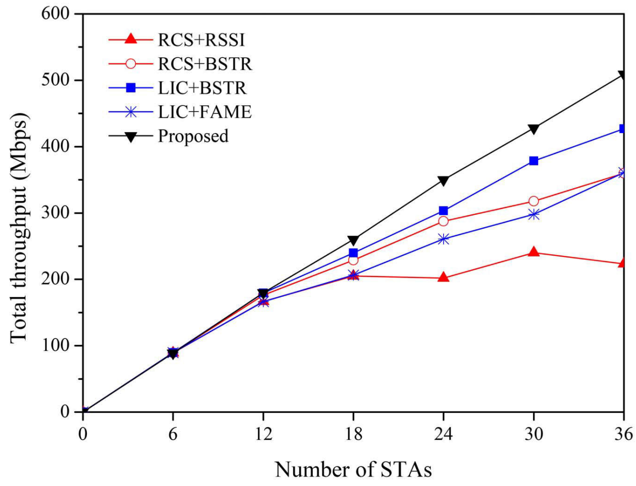

FIGURE 6. Total throughput according to N ($\alpha = 15$ Mbps).

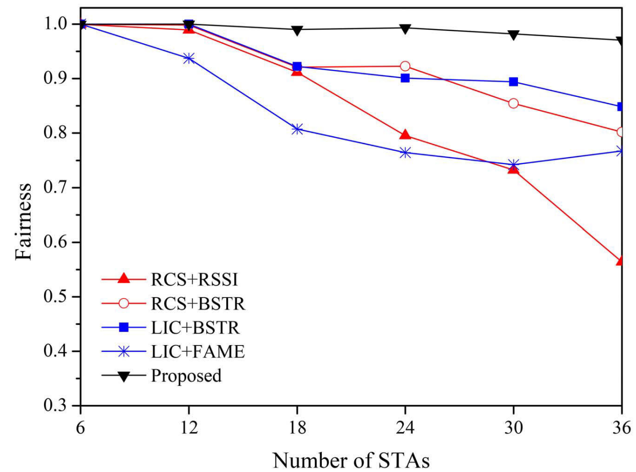

FIGURE 7. Fairness according to N ($\alpha = 15$ Mbps).

TABLE 4. Performance comparison ($N = 36$, $\alpha = 25$ Mbps).

	RCS+ RSSI	RCS+ BSTR	LIC+ FAME	LIC+ BSTR	Proposed
Average STA throughput (Mbps)	8.44	13.57	9.29	15.73	19.97
Fairness	0.46	0.68	0.68	0.74	0.93

TABLE 5. Comparison between two frequency bands ($N = 36$, $\alpha = 25$ Mbps).

	Band (GHz)	Number of STAs	Avg. STA Throughput (Mbps)	Total Throughput (Mbps)
RCS+RSSI	2.4	31	5.88	182.49
	5	5	24.28	121.4
RCS+BSTR	2.4	19	14.06	267.10
	5	17	13.02	221.36
LIC+FAME	2.4	18	8.25	148.49
	5	18	19.12	344.19
LIC+BSTR	2.4	20	11.16	223.14
	5	16	21.46	343.3
Proposed	2.4	10	18.44	184.4
	5	26	20.56	534.57

maintained to a relatively high value above 20 Mbps. Moreover, the performance gap between the two frequency bands in the average STA throughput is very small. For this reason, as depicted in Table 4, the average STA throughput and fairness are much higher than those of comparison schemes.

Fig. 6 and Fig. 7 show the total throughput and fairness according to N, respectively, when $\alpha = 15$ Mbps. In the RSSI-based UA combined with RCS CA, even if N is larger than 18, the total throughput is maintained without greatly increasing. This is because there are a relatively large number of associated STAs in the 2.4 GHz band having low capacity. As shown in Fig. 6, the enhancement ratio of the total throughput according to increasing N is higher in the proposed scheme than in comparison schemes. Accordingly, the performance gaps in total throughput between the proposed and other schemes get larger as N increases. On the other hand, we can see in Fig. 7 that, under the comparison UA schemes (i.e., RSSI-based, BSTR, and FAME), the fairness greatly decreases with the increases of N. This is because the number of STAs associated with 2.4 GHz band (as a result, the number of STAs having low throughput) increases. On the contrary, in the proposed RRM, the total throughput linearly increases with increasing N (see Fig. 6). Furthermore, as shown in Fig. 7, the fairness value is close to 1, since most of STAs in the network maintain the high throughput and the performance gap among the STAs is very small.

Fig. 8 and Fig. 9 depict the total throughput and fairness according to α, respectively. As seen in Fig. 8, when α increases, the total throughput increases but its enhancement ratio gradually decreases. Especially, in the RCS CA and RSSI-based UA scheme, when $\alpha \geq 10$ Mbps, the total throughput becomes saturated. With increasing α, the performance gaps in total throughput and fairness between the proposed RRM and other schemes get larger. In the comparison schemes, the fairness value is significantly decreased with increasing α. On the contrary, in the proposed RRM, when α increases, the fairness value is maintained close to 1 (see Fig. 9). This means that the proposed CA method effectively allocates channels so that the interference among APs is minimized. Furthermore, by the proposed UA-ChLB scheme, the frequency resource of S-APs and C-APs is efficiently

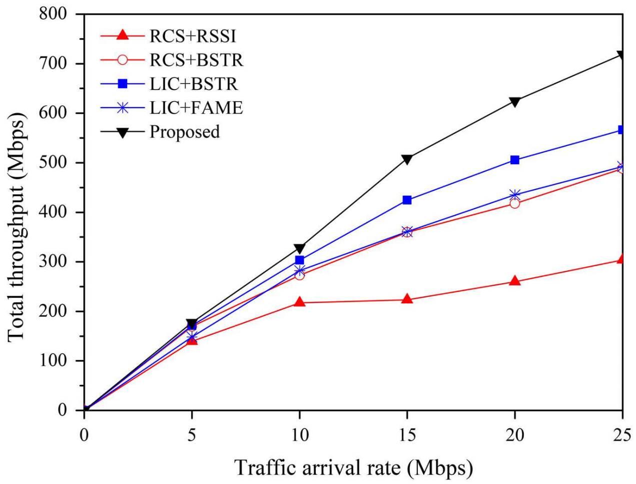

FIGURE 8. **Total throughput according to α ($N = 36$).**

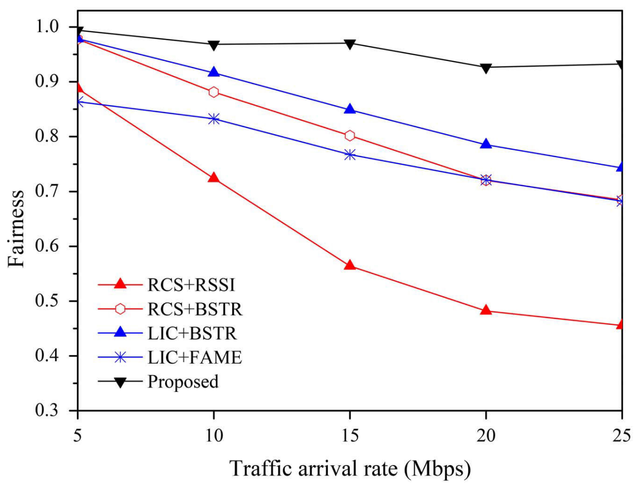

FIGURE 9. **Fairness according to α ($N = 36$).**

utilized under consideration of several factors such as wireless channel quality, traffic amount, and channel interference level.

VII. CONCLUSION

In this paper, we have proposed a two-phase RRM framework for enhancing overall network performance in dense WLAN environment, of which core entities are interference-controlled CA in the first phase and user association for channel load balancing (UA-ChLB) in the second phase. The proposed CA scheme allows a channel bonding and supports dual band of 2.4 and 5 GHz, and efficiently controls the CCI and ACI among APs based on the direct/hidden interference graph. The proposed hybrid UA-ChLB scheme is composed of distributed UA-ChLB and centralized UA-ChLB. Under consideration of wireless channel quality, traffic volume, and channel interference, the distributed UA-ChLB scheme is independently performed by each STA, whereas the controller optimally determines the user association for balancing the load of overall network using the centralized UA-ChLB scheme. The centralized UA-ChLB scheme has been formulated as a MIQFP problem which is NP-hard. To solve this optimization problem, we have used the transformation technique to convert the MIQFP problem into the solvable MIQP problem which can be optimally solved using branch and bound technique. We have implemented the proposed scheme and some existing schemes using real devices (*e.g.,* laptop computers, commercial APs), and have conducted experiments for evaluating their performances in dense WLAN indoor environment. The experimental results have demonstrated that the proposed RRM scheme greatly improves throughput and fairness in the dense WLAN environment where S-APs and C-APs coexist. Consequently, our work would provide a guideline for designing or managing the dense WLAN environment.

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