User-Centric Management of Wireless LANs

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***Abstract*—With the ever increasing deployment density of Wireless Local Area Networks (WLANs), more and more access points (APs) are deployed within users' vicinity. The effective management of these APs to optimize the users' throughput becomes an important challenge in high-density deployment environments. In this paper, we propose a user-centric network management framework to optimize users' throughput taking into consideration both the network conditions sensed by users and their access priorities. The proposed framework is built around an information pipeline that facilitates the sharing of the information needed for optimal management of communication resources. Theoretical analysis and extensive simulations are presented on two major management activities: AP association and channel selection, and demonstrate that the proposed user-centric network management framework significantly outperforms traditional network management framework in the high-density deployment environment.**

***Index Terms*—Wireless LANs, access points, 802.11, network management, performance modeling.**

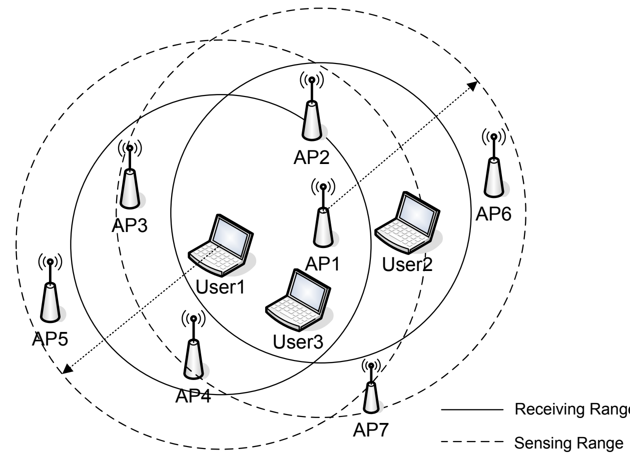

Fig. 1. Illustration of different sensing ranges of users and APs.

I. Introduction

THE past few years have seen a tremendous growth in the deployment of Wireless Local Area Networks (WLANs) conforming to IEEE 802.11 family of standards [2]. As a result, we are witnessing the emergence of wireless hot-spots characterized by the high-density deployment of WLAN users and access points (APs) [4]. An important feature of the high-density deployment is that users can find multiple APs (often from different service providers) in both receiving range and carrier sensing range[1]. Furthermore, due to the limited number of orthogonal channels (only 3 in IEEE 802.11b/g and 12 in IEEE 802.11a), APs may operate over the same channels as well.

Before joining a WLAN, each user must select an AP within its receiving range to associate with. Once the association is completed, the selected AP will serve the user till disassociation. Intuitively, the potential throughput that the user can obtain after the association depends on the load of and channel conditions to the selected AP. Meanwhile, WLAN devices communicate via a Carrier Sensing Multiple Access / Contention Avoidance (CSMA/CA) mechanism, and the devices operating on the same channel and in the sensing range of each other share the bandwidth of the channel. Correspondingly, the throughput of the user is also related to the load of other devices within its sensing range that use the same channel, even if these other devices do not associate with the AP the user has selected. Therefore, it is a challenge to provide effective network management that includes both AP association for balancing the load in each AP and channel selection for balancing the load in each channel to improve user throughput.

Similar to the framework of cellular networks [23], the traditional network management framework of WLANs is AP-centric in nature, where network management activities, e.g., AP association and channel selection, are mainly based on the information collected by the APs with little input from users. It is well known that cellular networks benefit from the carefully designed frequency distribution, which decreases the interference among base stations, and complicated signaling between users and stations. However, WLANs cannot get enough information to do that. For instead, users associate with the AP with the highest signal strength, which is usually the nearest AP, and the operating channel is selected manually or according to the load distribution sensed by the AP [5]. As shown in Fig. 1, AP1, which is associated with User1 due to higher signal strength than others, has a different sensing range from that of User1. As a consequence, the selected channel is often the least congested one from the viewpoint of AP1. However, such a selection will not be the optimal for User1 given that AP5, which is located within the sensing range of User1 but out of AP1's, operates in the same channel and has a high traffic load, because the packets transmitted from AP1 to User1 will be disrupted by the traffic of AP5. From the viewpoint of AP association, a better choice for User1 should be to select an AP operating in a different channel with AP5 and also with light traffic

Manuscript received April 30, 2010; revised November 19, 2010 and February 6, 2011. The associate editor coordinating the review of this paper and approving it for publication was M. Sloman.

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Digital Object Identifier 10.1109/TNSM.2011.072611.100031

[1]Users can communicate with the APs within their receiving range, and can sense the transmissions of APs within their carrier sensing range. To enhance the communication reliability, the receiving range is always smaller than the sensing range.

load for association; from the viewpoint of channel selection, AP1 should select the channel which it thinks has least congestion but also its associated users indicate as having least congestion. Therefore, the schemes [6][7][8] over AP-centric network management framework, which take into account only the signal strength and load distribution sensed by the APs but ignore the network conditions sensed by users, cannot optimize the throughput that users eventually receive in high-density deployment environments.

In addition, the AP-centric framework is not suitable for WLANs such as these defined in IEEE 802.11e [9] to provide differentiated access priorities to support different Quality-of-Service (QoS). The access priority of a user, which is not known by the AP before association and ignored in the AP-centric network management framework, seriously influences the eventual throughput of the user. For example, assume that User1 in Fig.1 has packets with access priority p_r, there are two candidate APs for User 1 with the same traffic load: (a) the users currently associated with AP1 have packets of access priority p_r or higher; and (b) the users currently associated with AP3 have packets of access priority lower than p_r. In the AP-centric framework, AP1 may be selected in terms of the load only, but actually AP3 will bring higher throughput for User1 due to the differentiation of different access priorities.

In this paper, we propose a user-centric network management framework, which provides an information sharing pipeline between users and APs in order to maximize the throughput users eventually receive. Under the proposed framework, the network conditions sensed by a user and its access priority are taken into account in the network management activities. Hereinafter, the network conditions refer to the channel allocation and load of APs in the sensing range of the user. Different from the AP-centric network management framework, the user in the proposed framework actively senses the network conditions and delivers the sensed results with its access priority to the AP candidates in the receiving range. In terms of the information above, the AP candidates can compute the potential throughput after a potential association and return the computational results to the user to aid its AP association decision. Meanwhile, the APs benefit from the information provided by the associated users and obtain the network conditions out of their sensing ranges. As a consequence, an optimal channel selection becomes possible in the proposed framework. Through a theoretical analysis, we show the positive impact of our user-centric management framework and formulate procedures for optimal AP association and channel selection. Also, we demonstrate, through extensive simulations, the effectiveness of the proposed framework when compared with the traditional AP-centric network management framework.

This paper is an extension of [1] where in addition to network management framework, management algorithms, and simulation validation, we have added the implementation scheme for avoiding the performance decline due to frequent management operation.

The rest of the paper is organized as follows. Section II gives a brief overview to network management and related activities in WLANs. In Section III, we present the user-centric network management framework, and then in Section IV provide a theoretical analysis of the performance in two major management activities: AP association and channel selection. A discussion for avoiding frequent management operation in practical implementation is given in Section V. Extensive simulations are given in Section VI to evaluate the performance improvement. Related work is summarized in Section VII. Finally, Section VIII concludes the paper.

II. Overview of Network Management in WLANs

In this section, we highlight the basic management entities and related management activities for WLANs with special emphasis on AP association and channel selection.

A. Basic Management Entities and Activities in WLANs

The IEEE 802.11 family of WLAN standards [2] defines three management entities for WLAN devices: (*a*) Station Management Entity (SME); (*b*) MAC Sublayer Management Entity (MLME), and (*c*) Physical Layer Management Entity (PLME). MLME and PLME are responsible for synchronization, power management, association and reassociation, etc. These lower level operations are usually "burned" in the firmware of network devices to meet the rigorous requirement in processing latency, which means that they are executed by hardware instead of management software. Hence, MLME and PLME are out of the scope of network management, but they provide some information and pipelines for network information exchange by means of the interface between MLME and SME. SME is responsible for gathering layer-dependent status from various layer management entities and setting layer-specific parameters. Hence, it is a core entity for network management.

The main network management activities of APs include

- **Parameter configuration**
  - channel selection: to minimize the number of APs operating on the same channel within the sensing range of each other;
  - power configuration: to achieve a full coverage of the service area;
- **User information management**
  - AP association: to determine the admission control for users' association requests;
  - priority management: to achieve the management of differentiated access priorities based on QoS;
- **Network monitoring**
  - downlink monitoring: to monitor per-link traffic load (from APs to users);
  - uplink monitoring: to monitor per-link traffic load (from users to APs).

Among these activities, the priority management and the network monitoring are passive activities, and the parameter configuration and the AP association lists are positive activities which are meaningful for improving the performance of users. Herein, the "positive" activities refer to those that can be designed to bring benefits and tuned to improve the throughput that users eventually receive. In addition, power configuration is usually done during network deployment, and there is little modification during runtime of the network. Therefore, most

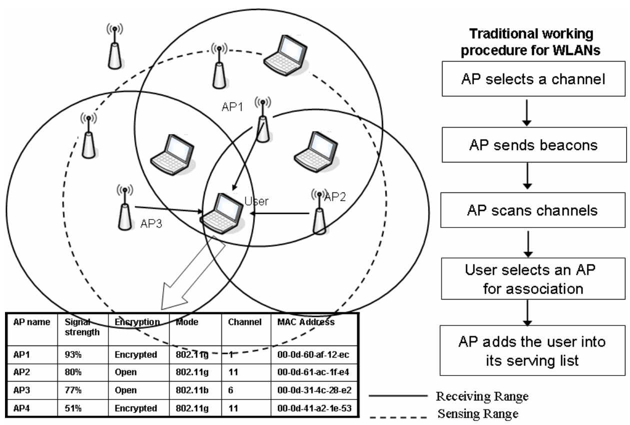

Fig. 2. Network management flow in traditional WLANs.

of network management falls into the scope of AP association and channel selection.

B. AP Association and Channel Selection

To better understand the operation of AP association and channel selection, we start by showing the basic working procedure over the traditional management framework for WLANs in Fig. 2.

In the traditional network management framework, an AP selects its operating channel manually or according to the configuration of neighboring APs in its sensing range; the network conditions experienced by the users play no role. After selecting the channel, the AP periodically delivers the configuration information to neighboring users via *beacon* frames. Although a user is capable of sensing all the transmissions that occur in its sensing range and getting the signal strength and load information of each AP, the user, traditionally, associates with an AP from the set of APs in the receiving range according to the signal strength only. Finally, when receiving the association request from the user, the AP decides whether to admit the user's association based on some security credentials, such as the permissible MAC address, while ignoring the number of users existing in its serving list and their access priorities.

Clearly, the aforementioned AP association and channel selection procedures are AP-centric. They use information that is exclusively AP-related and use none that relates to the users. Although these procedures are simple and workable, they do not improve the throughput. In the next section, we will present a user-centric network management framework, which utilizes the information from user side to optimize the performance of users.

III. User-centric Network Management Framework

The qualifier "user-centric" underscores our design objective that network management activities should aim, among other things, at improving the user throughput. The fundamental principle of the user-centric network management framework is to provide an information sharing pipeline between users and APs that enables enhancing traditional one-sided

TABLE I
INFORMATION HELD BY APS AND USERS

Information	Application	AP	User
Information of users associated with AP	A&C	√	
AP traffic load	A	√	
Traffic load within AP's sensing range	A&C	√	
Traffic load within user's sensing range	A&C		√
Uplink signal strength	A&C	√	
Downlink signal strength	A&C		√
Neighbor APs' channel allocation	C		√
Access priority	A&C		√

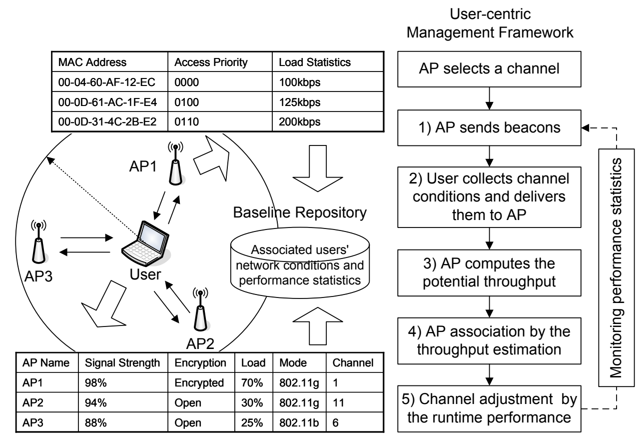

Fig. 3. Network management flow over user-centric framework.

WLAN management to become responsive to user needs. Table I lists the information, as well as who holds it, useful for improving AP association and channel selection. For example, the traffic load within the sensing range of a user determines the available transmission/reception opportunities, and hence it is related to the potential throughput that the user can get. The column titled "Application" indicates what kinds of activities to which the information could apply. Herein, "A" refers to AP association, and "C" refers to channel selection.

The core idea of the user-centric framework is to involve the participation of users into the network management activities. Each user actively senses its peripheral network conditions and claims its access priority rather than passively using the signal strength as the only measurement to judge AP performance. A user can inform candidate APs within its receiving range of the prevailing network conditions with regard to channel allocations and load of neighboring APs within the user's sensing range. Then, the candidate APs can compute the potential throughput that the user can obtain. The user can make its reasonable decision on AP association based on the computational results. Furthermore, each AP can also adjust its operating channel according to the information provided by associated users to optimize the aggregate throughput.

Fig. 3 illustrates the detailed working procedure over user-centric network management framework. At the outset, each AP selects a default channel manually or by some established methods. Then, the management framework enters the following five-step iterative procedure:

1) **AP sends beacons:** each AP periodically sends beacon frames to inform neighboring users about its configuration: channel, data rate, and MAC address etc.
2) **User collects channel conditions and delivers them to**

APs: each user actively scans the channel and collects network conditions including channel allocation and traffic load, by sensing beacon frame transmissions from various APs and data transmissions within its sensing range. This user collected information, shown in the table in the lower-left corner of Fig. 3, is referred to as the user's network snapshot. Then, the user piggybacks the network snapshot and its own access priority with an association request frame to all candidate APs in its receiving range. If there are multiple management domains, they will be sent to the APs in the same domain.

3) **AP computes the potential throughput:** each AP now can estimate the potential throughput for the user according to the information provided by the user, the performance statistics of already associated users and other configurations maintained by itself. Then, it returns the computational result to the user piggyback with the association response frame. The throughput computation formulae are derived in the next section.
4) **User affiliates with corresponding AP in terms of the potential throughput:** the AP, which can bring the maximum potential throughput for the user, will be selected for association and then the user informs the selected AP with a new association request. After that, the selected AP replies with an association response to finalize the association, and stores the user's network snapshot into its baseline repository.
5) **AP optimizes the channel selection according to all users' performance statistics and snapshots:** each AP periodically updates the snapshots and performance statistics of all associated users. When a channel selection is triggered by a lower aggregate throughput or manual command from the service provider, the AP will go through a new round of channel selection according to the latest network snapshots, access priorities and performance statistics of users to maximize the aggregate throughput of associated users.

Compared with the traditional AP-centric framework, the user-centric network management framework provides an information sharing pipeline between users and APs in order to counteract the missing information resulting from their disjoint viewpoints. By means of the pipeline, APs can collect enough information for computing the potential throughput of users, and then users can make an optimal AP association to maximize the eventual throughput. Meanwhile, APs can also dynamically select the operating channels based on the collected information to optimize the aggregate throughput of the associated users. To avoid frequent management operation, the AP association takes place only when a new user joins the network or handoff due to the previous AP cannot guarantee its performance requirement. Similarly, the channel selection is executed only when the overall throughput in the AP under consideration drops to a low level, which results in a bad service provisioning.

We will present a theoretical analysis in the next section to show why this perspective tuning can help the optimization on AP association and channel selection, while the traditional approach cannot.

IV. Theoretical Analysis

For the theoretical analysis, we employ the p-persistent medium access protocol [3] to describe the behavior of the IEEE 802.11 MAC contention access mechanism. The p-persistent access protocol is based on a slotted random access model. Each user with packets waiting to be transmitted chooses to transmit in a slot with probability p. It has been shown that the p-persistent access model closely approximates the performance of IEEE 802.11 MAC contention access mechanism with the same average backoff window size [10]. Furthermore, since the traffic on the downlink (from APs to users) typically dominates the overall network traffic, our analysis will consider the downlink traffic only.

A. System Model

Considering a WLAN with M APs and N users, we index each AP with A_i $(i = 1, 2, ..., M)$ and user with U_j $(j = 1, 2, .., N)$. All APs and users are deployed over the 2-D plane. We assume that all devices employ the same transmit power and use the same sensing and receiving power thresholds. Hence, all devices have the same sensing and receiving ranges.

According to the CSMA mechanism, a user can sense the channel conditions of all APs within its sensing range, and can associate with any AP within its receiving range. Let $\Psi_j^{(k)}$ and $\Phi_j^{(k)}$ denote the set of APs operating on channel k and within the sensing range and receiving range of U_j, respectively. For the throughput computations in this section, we consider packet collisions as the only source of failed transmissions, ignoring the impact of other transmission impediments, e.g., noise, multi-path, etc., to transmission failures. Moreover, the transmission failure of ACK frames are also ignored because ACK frames are transmitted at the basic data rate and have the strongest decoding capability. Therefore, we consider the transmission failure due to contention only. From the CSMA mechanism, one packet transmission of an AP is considered to fail if more than one AP within its sensing range transmits simultaneously.

Let p_i denote the probability that A_i transmits in a time slot, and p_{ij} denote the probability that A_i sends data packets to user U_j at a time slot. Then, the probability that there is a successful transmission from A_i (operating on channel k) to U_j in a time slot is given by

$$p_s = p_{ij} \prod_{\substack{m:\ A_m \in \Psi_j^{(k)} \\ m \neq i}} (1 - p_m). \tag{1}$$

Herein, we drop the index $\{i, j, k\}$ of p_s for notational brevity.

The probability that user U_j senses channel k busy is given by:

$$p_{j,\text{busy}}^{(k)} = 1 - \prod_{m:\ A_m \in \Psi_j^{(k)}} (1 - p_m). \tag{2}$$

Then, if U_j associates with A_i, which operates on channel k, the potential throughput, which is defined as the average payload size transmitted in a unit time, is given by

$$S_{ij}^{(k)} = \frac{p_s \mathrm{E}[L]}{p_{j,\text{busy}}^{(k)} T_{\text{busy}} + (1 - p_{j,\text{busy}}^{(k)}) T_{\text{idle}}}, \tag{3}$$

where E$[L]$ denotes the average payload size of a data packet, and T_{busy} and T_{idle} denote the average length of a busy time slot and an idle time slot, respectively. Note that from [2][11] the time that the channel is captured by a successful or a collided transmission is nearly the same, and thus we use the single parameter T_{busy} to express both of them

Substituting (1) and (2) into (3), we obtain

$$S_{ij}^{(k)} = \frac{p_{ij} E[L] \prod_{\substack{m:\ A_m \in \Psi_j^{(k)} \\ m \neq i}} (1 - p_m)}{T_{\text{busy}} - (T_{\text{busy}} - T_{\text{idle}}) \prod_{m:\ A_m \in \Psi_j^{(k)}} (1 - p_m)}. \quad (4)$$

Note that in (4) all variables except p_{ij} can be directly estimated from the sensing mechanism of user U_j. Furthermore, p_{ij} is related to p_i, the number of users associated with A_i, the traffic load of each user, and also the priority of each user. In the analysis that follows, we derive an expression for this relationship using information that is available by AP A_i and user U_j.

Let Θ_i denote the user set associated with A_i. As described in the 802.11e standard [9], the AP maintains an access queue for downlink transmissions for each priority or each associated user. In this paper, we consider the scenario that the AP allocates every associated user a separate queue, as shown in Fig. 4. Also specified in the standard [9], queues use a virtual contention mechanism like Distributed Coordination Function (DCF) or Enhanced DCF (EDCF) to share the physical radio. With DCF, a user with a packet to transmit selects a backoff window from $[0, CW^{\min}]$, where $CW^{\min}$ is the minimum contention window. The backoff window is decremented at each slot, and the user transmits its packet when the backoff window reaches 0. If the transmission fails due to contention, the user randomly selects a new backoff window from a double extended range $[0, 2CW^{\min}]$ till the contention window reaches to the maximum contention window $CW^{\max}$. Once the user takes a successful transmission, the contention window is moved back to $CW^{\min}$. With EDCF, different priorities correspond to different minimum and maximum contention windows. The higher the priority is, the smaller the minimum and maximum contention windows are. Let ρ_{ij} denote the load of the queue for user U_j in AP A_i, the load is the ratio of the arrival rate over the service rate. The values of ρ_{ij} can be derived from the status of the cache allocated for user U_j in AP A_i. Let CW_{ij} denote the average contention window for the access queue to user U_j, which can be calculated from a Markov model proposed in [12]. Then, the transmit probability of the queue for user U_j is given by

$$p_{ij} = \frac{2\rho_{ij}}{CW_{ij} + 1} \quad (5)$$

and we have

$$p_i = \sum_{U_j \in \Theta_i} p_{ij} = \sum_{U_j \in \Theta_i} \frac{2\rho_{ij}}{CW_{ij} + 1} \quad (6)$$

1) For IEEE 802.11 DCF: For the scenario based on IEEE 802.11 DCF, all users have the same priority, and as a consequence all queues have the same CW_{ij}. As a result, we have

$$p_{ij} = \frac{\rho_{ij}}{\sum_{U_m \in \Theta_i} \rho_{im}} p_i. \quad (7)$$

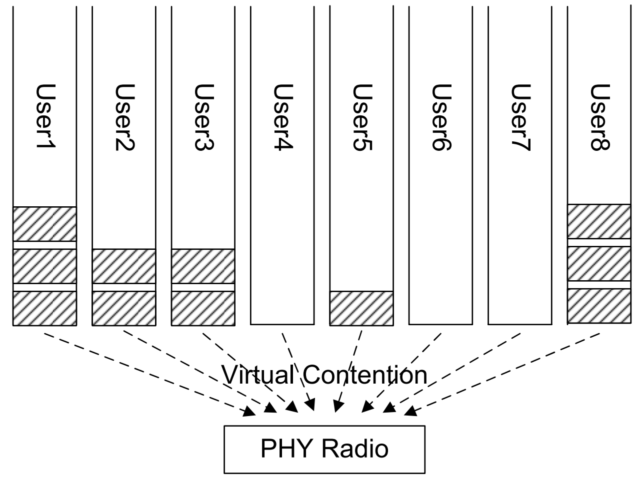

Fig. 4. Virtual contention for multiple queues in IEEE 802.11/11e.

2) For IEEE 802.11e EDCF: For the scenario based on IEEE 802.11e EDCF, queues with different priorities have different minimum and maximum contention windows, which result in different average contention windows. Let $CW_{ij}^{\min}$ and $CW_{ij}^{\max}$ denote the minimum and maximum contention window for the access queue to U_j in AP A_i, and let $p_{i,c}$ denote the probability that there is a collision in the transmission from AP A_i. Then, from our previous work in [13], CW_{ij} is given by

$$CW_{ij} = CW_{ij}^{\min}(1 - p_{i,c}) \left\{ \sum_{k=0}^{m-1} 2^k p_{i,c}^k + \frac{p_{i,c}^m}{1 - p_{i,c}} \right\}, \quad (8)$$

where $m = \log_2 \frac{CW_{ij}^{\max}}{CW_{ij}^{\min}}$. Substituting (8) into (6), we can calculate $p_{i,c}$ with p_i, $CW_{ij}^{\min}$ and $CW_{ij}^{\max}$ given. As a consequence we can get the value of CW_{ij} from (8). Finally, substituting CW_{ij} into (5), we can get the value of p_{ij}. After obtaining p_{ij}, we can use (4) to compute the throughput for user U_j, assuming that user U_j associates with AP A_i. In the remainder of this section, we will show how to utilize the analytical results to design the optimal AP association and the optimal channel selection. Herein, the optimal AP association corresponding to the AP that would provide the maximum throughput to a user, and the optimal channel selection corresponds to the maximum aggregate throughput for all the users associated with the considered AP.

B. Optimal AP Association

AP association is executed when a new user joins the network or handoff due to the previous AP cannot guarantee its performance requirement. According to the optimal AP association definition, user U_j will select AP A_{i^*} that would provide the maximum throughput to it, i.e.,

$$S_{i^*j} = \arg \max_{i: k \in \Omega, A_i \in \Psi_j^{(k)}} S_{ij}^{(k)}, \quad (9)$$

where Ω is the available channel set. By substituting (4) into (9), we have

$$S_{i^*j} = \arg \max_{i:k\in\Omega, A_i\in\Psi_j^{(k)}} \frac{p_{ij}E[L]\prod_{\substack{m:\ A_m\in\Psi_j^{(k)}\\ m\neq i}}(1-p_m)}{T_{\text{busy}}-(T_{\text{busy}}-T_{\text{idle}})\prod_{m:\ A_m\in\Psi_j^{(k)}}(1-p_m)}. \quad (10)$$

From (10), we can find that the throughput depends on the neighbors' network conditions $(p_m, \{A_m \in \Psi_j^{(k)}, k \in \Omega\})$ and the potentially available transmission probability p_{ij} in the associated AP. The former can be obtained directly from the sensing mechanism of user, but the latter depends on the priority of the user's traffic as well as the priorities of all users associated with the particular AP. Therefore, the information pipeline provided by the proposed framework becomes an indispensable requirement to get the optimal AP association.

Traditionally, only the neighbors' network conditions $(p_m, \{A_m \in \Psi_j^{(k)}, k \in \Omega\})$ are possibly available[2]. Therefore, the AP association in a traditional network management framework attains throughput for user U_j given by:

$$\arg \max_{i:k\in\Omega, A_i\in\Psi_j^{(k)}} \frac{\prod_{m:\ A_m\in\Psi_j^{(n)}, m\neq i}(1-p_m)E[L]}{T_{\text{busy}}-\prod_{m:\ A_m\in\Psi_j^{(k)}}(1-p_m)(T_{\text{busy}}-T_{\text{idle}})}, \quad (11)$$

which is a suboptimal throughput level.

C. Optimal Channel Selection

We have mentioned that in the proposed framework the AP can collect the network condition $(p_m, \{A_m \in \Psi_j^{(n)}, n \in \Omega\})$ sensed by the associated users, and thus it is capable of selecting the optimal channel to maximize the aggregate throughput of all users associated with it. Hence, the achievable aggregate throughput for AP A_i in the proposed framework is given by

$$S_i = \arg \max_{k:k\in\Omega} \sum_{j:\ U_j\in\Theta_i} S_{ij}^{(k)}. \quad (12)$$

In contrast, in the traditional network management framework, only the transmit probability of the APs within the sensing range of the considered AP is available for channel selection. Hence, the channel selection is based on the network load of neighboring APs, which is proportion to the transmit probability, i.e.,

$$\arg \min_{k:k\in\Omega} \sum_{m:\ A_m\in\Lambda_i^{(k)}} p_m, \quad (13)$$

where $\Lambda_i^{(k)}$ is the set of APs operating on channel k and located within the sensing range of AP A_i.

The sensing areas of the AP and the associated users are different due to their different locations, i.e., $\{\Lambda_i^{(k)} = \Psi_j^{(k)}$, where $U_j \in \Theta_i\}$, does not always hold. Therefore, the channel selection in the traditional network management framework is not capable of getting the maximum aggregate throughput.

[2]It is available only when the user takes measurement statistics in initial AP scanning when joining the WLAN. Even though several such statistics collecting measurement are possible during the scanning stage, e.g., Intel 2200/2915 wireless card provides the statistics for Receiving Signal Strength Indicator (RSSI), traffic load and packet loss etc., typically, only simple measurements of the RSSI are performed.

V. Implementing the Management Framework

As described in Section III, the AP association is executed when a brand new user arrives in the network or an existing one is handed-off due to receiving low throughput. Channel selection, on the other hand, is triggered by a warning of bad service provisioning. The objective of both of these activities is to improve the throughput users receive individually and in aggregate. Hence, these activities need to coordinate their actions to provide the best possible performance to the users of the network. Specifically, the AP association is executed to maximize the throughput of the considered user under the current channel allocation situation. Therefore, the user throughput may not be optimal after the AP that the user is associated with changes channel. Similarly, the channel selection may not be optimal after the change of associated users. Either change may result in a new round of corresponding management activities. Therefore, before deploying the proposed framework into an actual network, we need to consider the convergence of the iterative management procedures of AP association and channel selection.

Due to the processing and operating costs that result from the channel changes and AP handoffs that are required to keep the optimal AP associations and channel selections, the network may experience oscillatory behavior that can negatively influence its performance. To address this issue, in an operational deployment of the system, we may have to introduce a *hysteresis* in the implementation of the management procedures through a *dual-period* and *dual-threshold* triggering approach to be introduced next.

A. The dual-threshold triggering conditions

AP associations by a user, other than the ones due to newly arriving users, are triggered through the following dual-threshold procedure. A user triggers a new AP association only when:

- its current throughput is smaller than a lower-bound threshold S_{low}^a; and
- its potential throughput due to a new (optimal) AP association improves upon its current throughput by at least a minimum improvement threshold S_{imp}^a.

Specifically, let

$$S_U^*(j) = \max_{k\in\Omega, A_i\in\Psi_j^{(k)}} S_{ij}^{(k)}, \quad (14)$$

be the highest throughput user U_j will receive from any of the APs it can currently associate with. Then, user U_j executes a new AP association procedure, only if:

$$0 < S_{ij,t} < \min\{S_{low}^a, S_U^*(j) - S_{imp}^a\}. \quad (15)$$

Likewise, channel selections by an AP, other the very initial one, are triggered through a dual-threshold procedure as well. Specifically, an AP triggers a new channel selection only when:

- its current aggregate downlink throughput is smaller than a lower-bound threshold S^c_{low}; and
- its potential aggregate throughput due to a new (optimal) channel selection improves upon its current throughput by at least a minimum improvement threshold S^c_{imp}.

Let

$$S^*_A(i) = \max_{n\in\Omega} \sum_{j:\ U_j\in\Theta_i} S^{(n)}_{ij} \tag{16}$$

be the highest aggregate downlink throughput AP A_i can attain if it currently performs a channel selection. Then, AP A_i executes a new channel selection procedure, only if:

$$0 < S_{i,t} < \min\{S^c_{low}, S^*_A(i) - S^c_{imp}\}. \tag{17}$$

B. The dual period operation

It would be too taxing for the network nodes to continuously attempt to optimize their operation. Hence, management decisions for AP association or channel selection are taken periodically, with different periods for each of the management procedures. Specifically, because, AP associations influence the association procedure of only one user, we select a relatively short decision period T_a for initiating this procedure. Then, every T_a time units, users that are already associated reassess their throughput potentials that may be possible to them if they choose to reassociate with another AP.

Because the channel selection operation will result in the reassociation of *all* associated users, which is a much more burdensome for the network that a single AP association, we select a longer decision period T_c for initiating this procedure. Every T_c time units, the AP evaluates its overall performance and decides whether to make a new channel selection.

Finally, to average out random (short-lived) traffic fluctuations during throughput calculations, a smoothing factor is employed:

$$\begin{aligned} S_{ij,t+T_a} &= \beta S_{ij,t} + (1-\beta)\tilde{S}_{ij,t+T_a},\ t = 0, T_a, 2T_a, \ldots,\\ S_{i,t+T_c} &= \alpha S_{i,t} + (1-\alpha)\tilde{S}_{i,t+T_c},\ t = 0, T_c, 2T_c, \ldots, \end{aligned} \tag{18}$$

where $\alpha \in (0,1)$ and $\beta \in (0,1)$ are the smoothing factors, which are widely adopted in network protocols to obtain reliable estimates. The selections of α and β need to consider the compromise between accuracy and promptness, and both of them are set to 0.9 in our work. In addition, $S_{ij,t}$ and $\tilde{S}_{ij,t+T_a}$ are respectively the updated throughput of U_j (currently associated with A_i) at time t and the average throughput in time window $[t, t+T_a)$. Likewise, $S_{i,t}$ and $\tilde{S}_{i,t+T_c}$ are the updated throughput of A_i at the time t and the average throughput estimated in time window $[t, t+T_c)$, respectively.

At each decision time instant indicated in (18), we update the throughput of the APs and users with (18), and then check whether the triggering conditions shown in (15) and (17) are satisfied. If yes, the corresponding management procedures take place, and the optimal schemes mentioned above will be executed.

The choice of the values of the throughput update (and decision) periods T_a and T_c depends on the practical considerations. Short update intervals can bring higher throughput due to the quick adjustments toward the optimal operation. However, this also results in frequent reassociation which influences the user experience due to the hard breakdown[3] in the reassociation process. The typical breakdown time of reassociation is 500 ms to 2 seconds. Therefore, there will need to be an assessment of the impact of hard breakdowns to the provisioned service in selecting the update intervals. This assessment will, inadvertently, depend on the specifics of a WLAN installation and deployment; for the simulated deployment used for the analysis later, we have set T_a = 600s and T_c = 1800s.

Intuitively, the choice of the lower-bounds for the AP reassociation and channel selection is in direct proportion to the average throughput available for each user, which depends on the link transmission speed and the number of users. Therefore, we set the lower-bound to:

$$\begin{aligned} S^a_{low} &= \frac{C_R \cdot R}{N_A \cdot N_U},\\ S^c_{low} &= \frac{C_R \cdot R}{N_A}, \end{aligned} \tag{19}$$

where R is the link transmission speed, $C_R \in (0,1)$ is a mapping factor for available lower-bound throughput and physical transmitting speed; for $R = 54$ Mbps, we set $C_R = 0.5$. N_A is the number of APs within the sensing range of the considered AP, and N_U is the number of user associated with the considered AP.

The choice of the improvement thresholds depends on the breakdown duration of reassociation. As mentioned above, each reassociation causes a short hard breakdown in transmission, which will results in the drop of available throughput. The purpose of the improvement threshold is to guarantee that the throughput improvement of the management operation is larger than the cost for reassociation. In this paper, we have set these thresholds to:

$$\begin{aligned} S^a_{imp} &= C \cdot S^a_{low} \cdot \frac{T_b}{T_a},\\ S^c_{imp} &= C \cdot S^c_{low} \cdot \frac{N_U \cdot T_b}{T_c}, \end{aligned} \tag{20}$$

where T_b is the breakdown duration of reassociation, and $C > 1$ is a constant for leveraging the improvement degree.

VI. Simulations

In this section, we use ns-2 simulations [14] to analyze the throughput performance of our proposed user-centric network management framework. The characteristics of the physical and MAC layers used in the simulations are listed in Table II. We consider a simple random topology: all APs are randomly and uniformly distributed with density 1 AP per unit area; all users are randomly and uniformly distributed, the user density varies with the simulation scenarios. A typical pathloss model [16] is employed as the wireless channel model, the average signal strength P_{ij} at the receiver is expressed as a function of the distance d_{ij} between the transmitter-receiver pair, i.e.,

$$P_{ij} = A \cdot d^{-\gamma}_{ij},$$

[3]The hard breakdown refers to the user losing connectivity with all APs and cannot send out or receive data packets.

TABLE II
Parameters of IEEE 802.11g

Parameter	Value
Physical header(bytes)	24
MAC header (bytes)	34
ACK (bytes)	14
Data rate (Mbps)	54
SIFS time (us)	16
Slot time (us)	9
payload(bytes)	1024

where A is a constant and γ denotes the pathloss coefficient, ranging from 2 (free space) to 4 (indoor). In the simulation, we set $\gamma = 4$ to simulate an indoor environment. The receiving radius is set to 1 unit length, and the sensing radius is set to 2 unit lengths. A user can find (on the average) 3 APs within its receiving range and 12 APs within its sensing range. Three orthogonal channels (1, 6 and 11) are employed. Finally, we consider two levels of access priorities: a low access priority with $\{CW^{\min} = 31, CW^{\max} = 1023\}$ and a high access priority with $\{CW^{\min} = 15, CW^{\max} = 63\}$. For each simulation scenario, the simulation time is 24 hours, and results are obtained by averaging values from 10 different runs with different seeds.

A. Effect of Access Priority

Contrary to the traditional network management framework, the AP association and channel selection over the user-centric network management framework considers the effect of access priority. Therefore, we start with evaluating the effect of priorities on the throughput of users. A simple scenario is considered: one AP serves 8 users. We measure the downlink throughput of one user in different access priorities. The results are shown in Fig. 5. Herein, the x-axis shows the number of users (except the measured user) with high access priority. It is observed that the available throughput for the considered user decreases with the number of users with high priority no matter what access priority it has. The available throughput of the user with high access priority is always greater than that with low access priority. Especially, when all users have traffic of the same access priority, they all receive the same throughput, in which case, the priority level of a user's traffic plays no role. Therefore, the access priority distribution within the AP influences the potential throughput of the considered user significantly, and the AP association scheme should take into account the access priority distribution in the target AP.

B. AP Association over User-centric Network Management Framework

Next we evaluate the throughput attained in three types of management frameworks: one is using AP selection under the traditional management framework where the user associates the AP with the strongest signal strength, another one is using the optimal selection in AP-centric framework described by (11) which is also the method proposed in [20], and the last one is that using our user-centric management framework, described by (9). We consider a case where there are always data packets to transmit on all the queues of all APs. One user is "tagged" as the observing user and we fix the AP association

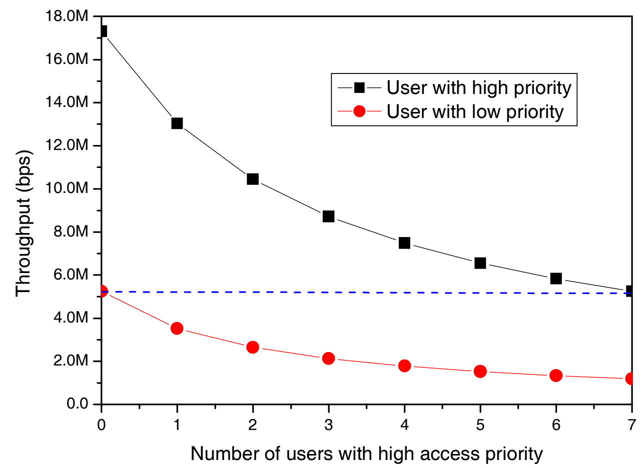

Fig. 5. Impact of the number of high-priority users on the considered high-priority user.

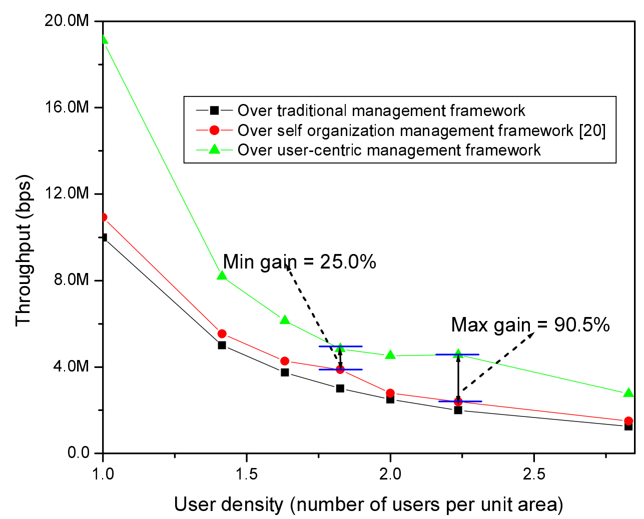

Fig. 6. Throughput comparison for different AP association mechanisms.

of all other users. The number of users with low priority and high priority packets are the same, and the observing user is configured to be a high priority user. To investigate the effect of the user density, which influences the number of users sharing the same AP, different scenarios with varied user density are simulated, and the results are plotted in Fig. 6. It is observed that the AP association based on the user-centric network management framework always outperforms other frameworks, and the throughput gain compared to that of [20] ranges from 25.0% to 90.5% for the simulated scenarios. From the theoretical analysis in Section IV, the throughput gain comes from two aspects: the selection based on the network conditions and the selection based on the access priority situation in APs.

C. Channel Selection over User-centric Network Management Framework

In addition, we investigate the effect of the channel selection on the total throughput of users associated with one AP. We fix the user density to 2 users per unit area, and take one AP as observing AP which associates with two observing users. The

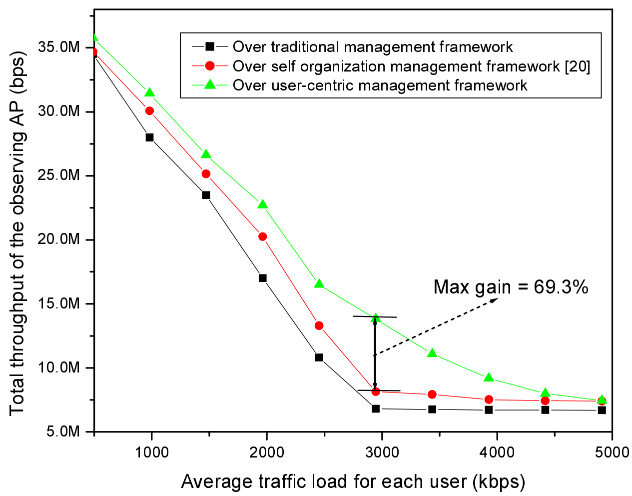

Fig. 7. Throughput comparison for different channel selection mechanisms.

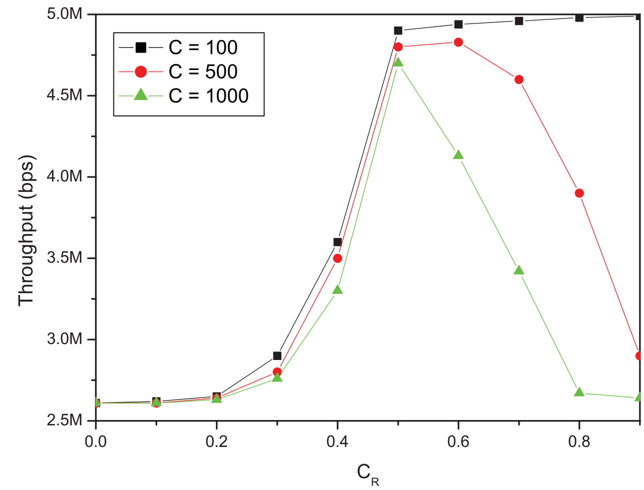

Fig. 8. Impact of dual-threshold on user throughput.

downlink traffic load destined to the other users is assumed to be exponential with varying level of intensity. We firstly randomly select channels for the other APs and fix them during the simulation. The simulation results are plotted in Fig. 7. As a reference, we also show in the figure the throughput performance results using the traditional management framework where channels are selected randomly and the optimal channel selection in AP-centric framework described as (13) which is also the method proposed in [20]. It is observed that the channel selection over user-centric network management framework achieves the highest throughput. The maximum gain compared to that with [20] is up to 69.3% under the simulated scenario and parameters. Note that the channel selection above cannot get significant throughput gain when the average traffic load to the rest of the users is above 4 Mbps. This is because at this traffic level all the APs are saturated and the network conditions for all channels are nearly the same. As a result, the optimal selection cannot get significant gain.

D. Impact of Dual-threshold in Implementation

Finally, we explore the impact of dual-threshold for triggering management operations on user throughput. To avoid frequent management operation, we set the *dual-period* at $T_a = 600s$ and $T_c = 1800s$; additional pairs of T_a and T_c values considered yielded similar results. From (19) and (20), we get that the value of the *dual-threshold* depends on the setting of C_R and C. The lower-bound threshold increases with C_R linearly, and the minimum improvement threshold increases with C linearly. We employ the same simulation scenario as Section VI-B to explore the impact of *dual-threshold* on user throughput. The user density is fixed to 2 users per unit area, and the target user is configured as high-priority user. The simulation result is shown in Fig. 8.

It is observed that both C_R and C influence the user throughput significantly. When $C_R < 0.3$, the throughput remains low, because the lower-bound threshold is too small to trigger the management operation. Similarly, when both C_R and C are large enough, the throughput drops to a low level as well. This is because a large minimum improvement threshold can also prevent the triggering of management operation. Although it is straightforward that a larger lower-bound threshold and a smaller minimum improvement threshold results in a larger throughput, such as $C_R = 0.9$ and $C = 100$, it triggers more management operations for optimization, which influences the user's experience due to the hard breakdown during reassociations. Because the user experience is hard to evaluate, we prefer to leverage the throughput improvement degree and the increment of the management operation frequency, which is defined as the ratio of the number of periods taken by management operation to the total number of periods. In our simulation, the throughput improvement is stable or approaches its maximum value when $C_R = 0.5$, but the management operation frequency changes from 0.132 to 0.368 when C_R ranges from 0.5 to 0.9 with $C = 100$. Therefore, we prefer to set $C_R = 0.5$ and $C = 100$.

VII. Related Work

With respect to frameworks for WLAN performance management, most of the literature focuses on the AP side. The IEEE 802.11 standards [2][9] provide an AP-centric but simple network management framework, where each AP locally manages its associated users. To enable the management flow, IEEE 802.11k [25] defines an information exchange method among users and APs, and IEEE 802.11r [26] further specifies fast Basic Service Set transitions between APs by redefining the security key negotiation protocol, allowing both the negotiation and requests for wireless resources to occur in parallel. In addition, IEEE 802.11s [27] extends the management framework of WLAN to mesh topology. Although these standard management frameworks work well in sparse networks, where there is exactly one AP within each channel, it is difficult to satisfy the management requirement in high-density deployment of WLANs.

Thin-AP [15] and Multi-AP architecture [16] are high-density deployment oriented management frameworks, where all APs are centrally managed by an access controller (AC). In these management frameworks, the joint decoding and frame combination [17][18], which utilize multiple APs (working in the same channel) to obtain reception and transmission diversity, become possible. However, since these frameworks are still AP-centric in nature, the network environment sensed by them is not completely consistent with the user's, and this discrepancy is not taken into account in management activities.

With respect to the issue of AP association, most existing IEEE 802.11 products select an AP based on the signal strength. Unfortunately, this approach has been demonstrated in [6] to result in poor user experience since it does not take the actual load distribution among APs into account. To address this issue, many works pay attention to some alternative metrics for achieving a more reasonable association, such as the packet error rate with the number of associated users [19], the throughput model [20], and the potential bandwidth a user can obtain [21] etc. It is worth noting that the model proposed in [20] tries to optimize the throughput of the user according to the network condition sensed by the AP's only. However, the hidden terminals indicated in [22] are out of the sensing range of the AP's, and as a result the proposed model fails to optimize the throughout of the user due to the interference from hidden terminals. Ref. [7] uses a heuristic linear combination of the transmission rate and throughput to make an accurate decision. The work in [8] further considers the throughput fairness as the spatial distribution of the users becomes more uneven. However, although they strive to estimate the network conditions for deciding AP association, it is actually difficult to make this estimation in the AP-centric approaches. An information pipeline between users and APs, such as the one proposed by our framework, is absolutely necessary to enable the information sharing and hence assist AP association based on the complete information. In addition, we use the access priority to represent a user's subjective requirement in AP association. To the best of our knowledge, this is the first effort that considers AP association based on the combination of the network conditions and the user's access priority.

Another major management activity is channel selection for APs. As mentioned in [22], this should be not separated from the load balancing of users among APs. The purpose of assigning an appropriate channel is to minimize the inter-AP interference since APs operating in the same channel share the bandwidth. Currently, a widely-used method is Least Congested Channel Search (LCCS) [24], which chooses a channel that has the least possibility to conflict with others in terms of its Radio Frequency site survey. As more and more APs are deployed, some papers, such as [11], try to alleviate the inter-AP interference by adjusting the carrier sensing range. Particularly, the work in [5] further takes account of the pseudo-capture effect besides avoiding interference. None of the above works involve users' participation. Ref. [22] indicates that AP-centric methods, in fact, are unable to detect potential interference out of the AP's sensing range. Thus, it proposes a conflict set coloring model to consider the existence of clients among APs during channel selection. Different from our solution, the algorithm in [22] requires collecting the interference relation within the one-hop range of the AP-user link, which is a challenging work in practical environment, especially in the environment that APs are managed by different service providers. Moreover, the algorithm in [22] only optimizes the number of users that share the same channel, but ignore the impact of traffic load and access priority on the throughput. The essence is that we have to change the management perspective into a user-centric one that exploits the user knowledge of the networking environment it plans to operate in.

VIII. Conclusion

In this paper, we have focused on high-density WLAN deploymnets where each user can find multiple APs within its receiving range. Under such environments, we indicate that the traditional network management framework cannot optimize the performance of users because it cannot effectively utilize the network conditions sensed by users and their access priority. To address this issue, we present a user-centric network management framework, which takes maximizing the throughput of users as the fundamental principle and provides an effective information sharing pipeline between users and APs to assist the key network management activities: AP association and channel selection. Our theoretical analysis demonstrates that such a user-centric network management framework can provide complete information for attaining the optimization of AP association and channel selection. The simulation results show that the throughput of users can be significantly improved in the AP association and channel selection over the user-centric network management framework.

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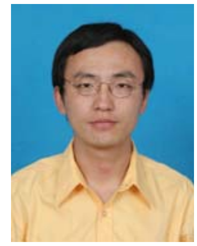

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