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# Gibbs Sampling Aided Throughput Improvement for Next-Generation Wi-Fi

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**Abstract**—Wireless communications, and in particular wireless local area network (WLAN) technology, has undergone a tremendous evolution in the past decades. After the release of the WLAN standard IEEE 802.11a/b in 1999, Wi-Fi technology soon became pervasive, thanks mainly to its deployment on the unlicensed ISM band. However, high traffic, especially in hotspots and areas with dense deployment of Wi-Fi access points (APs) (e.g., stations, airports, etc.) has caused major issues and a severe degradation of communications quality. The latest WLAN standards (e.g., 802.11ac, 802.11ax) have largely succeeded in improving the link quality and data rate by adopting state-of-the-art PHY layer technologies, e.g., OFDMA, MU-MIMO. However, improvement of the MAC layer in these standards is not noticeable due to restrictions such as hardware limitation and backward compatibility issues for legacy APs. As an effort to improve the MAC layer for the next-generation WLAN standard, in this paper we propose a simple algorithm with low computational complexity for channel selection in Wi-Fi networks. The main idea is to take advantage of the potential of the IEEE 802.11ax MAC to avoid major standard modifications. For this purpose, we employ the channel utilization ratio (CUR), which is measured periodically by each AP based on its channel sensing. Time-averaged CUR values are weighted based on a Gibbs sampling approach and a probability associated to each channel is updated. Finally, a channel is selected based on the aforementioned probabilities in predefined time slots. Simulation results show that the proposed approach can improve the system throughput by up to 5% and transmission delay by up to 20%.

**Index Terms**—Wi-Fi, WLAN, channel allocation, IEEE 802.11, wireless networks, distributed design, throughput.

## I. INTRODUCTION

With the emergence of novel scenarios such as internet of things (IoT) [1] and the development of a variety of internet-based services, network traffic has increased significantly in this decade. This increase has been more apparent on wireless infrastructure due to an increase in number of smartphones and connected devices. 5G research and standardization works are in progress to design a wireless infrastructure capable

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of accommodating such a large demand in system capacity growth [2]. Alongside the cellular network, the wireless local area network (WLAN) is responsible for accommodating a large portion of wireless traffic. Moreover, WLAN data traffic is anticipated to increase fourfold from 2015 to 2020 [3]. One main reason for this increase is WLAN offloading, where operators try to redirect part of their cellular network traffic to their deployed Wi-Fi network with the aim of increasing the system capacity [4]. Another factor which makes the WLAN channel allocation problem even more challenging is the emergence of new technologies and standards which operate in the unlicensed spectrum. Examples here include the LTE-Unlicensed (LTE-U) standard which is developed for 3GPP Releases 10, 11 and 12, as well as its alternative version, licensed assisted access (LAA), which is standardized in 3GPP Release 13 and mandates compliance with the listen before talk (LBT) protocol [5]–[7]. The aforementioned technologies will increase the traffic on unlicensed bands even further in years to come, and disturb the balance on ISM-band channels. This signifies the need to develop more robust, yet practical, channel allocation methods to be easily adopted for the MAC layer in next-generation Wi-Fi standards. The most recent WLAN standard, i.e., 802.11ax [8], which is anticipated to be widely deployed in 2019, has been mostly successful in increasing the system throughput by improving the PHY layer section of the standard. Next-generation Wi-Fi needs more innovation on the MAC layer and channel allocation.

There are abundant research works available in the literature which address the channel allocation problem, using a variety of heuristic algorithms such as tabu search, genetic algorithms, and simulated annealing [9]–[11]. However, these works mostly take a centralized approach or consider contention-free channel access methods such as frequency division multiple access (FDMA) or space division multiple access (SDMA).

The authors in [12] proposed two different channel allocation techniques for dense small cell networks. The two channel allocation algorithms were then combined with a base station (BS) ON/OFF switching algorithm in order to improve the system energy-efficiency (EE) at the same time as the spectral-efficiency (SE). The channel allocation algorithms used a machine learning approach, implemented locally at each BS. Each BS tries to learn the environment and selects a channel based on mixed-strategy game theory. The authors showed

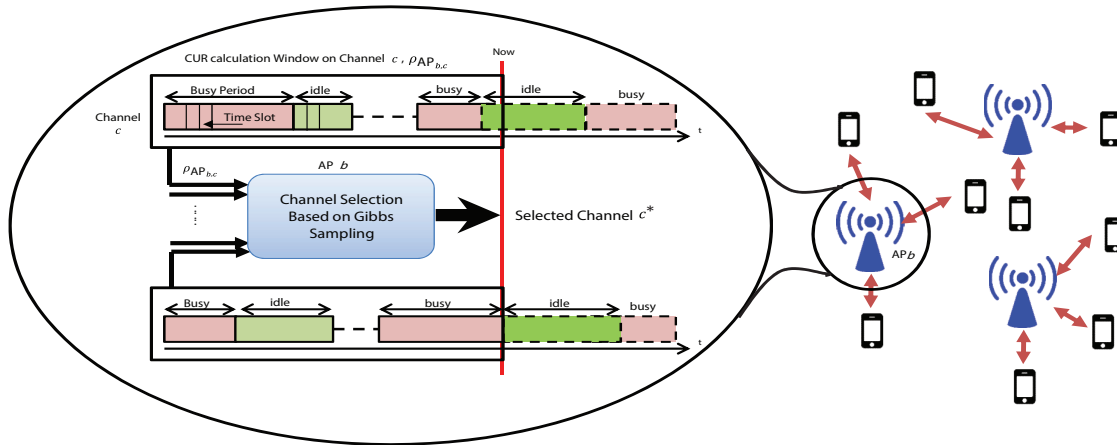


Fig. 1. System model.

that the proposed algorithm can improve both the system EE and SE considerably. However, that paper considers the received interference as the utility function to be maximized and assumes a contention-free MAC, in contrast to the approach adopted in this paper. In [13], a probabilistic neural network (PNN) structure is proposed to predict the future idle period in WLAN channel. Simulation results are performed for various scenarios and prediction length of future idle slots. Simulation results showed that if the PNN is properly tuned, the algorithm can have a successful prediction probability of up to 70%. Despite the simplicity of PNN structure, the computational complexity of artificial neural networks (ANN) may still be high, specifically for implementation on commercial APs. In [14], the authors proposed a detailed channel access procedure in order to balance channel access among WLAN channels by using an alternative primary channel (APCH). The benefit of APCH is that each user can still get transmission opportunity even if the primary channel is busy. In their proposed technique, only one frame is transmitted over the primary channel or an APCH at a time. However, statistically the system throughput improves as there is a second APCH option in the case when the primary channel is busy.

In this paper, we propose a simple algorithm for distributed dynamic channel allocation in Wi-Fi. The algorithm aims at maximizing the system throughput by balancing the load and channel utilization among different channels and ISM bands. The idea is motivated by our recent research in [13]: here we conducted several spectrogram measurement campaigns during evening rush-hour at stations in Japan; it was shown that there exists a considerable number of idle time slots available on both the 2.4 GHz and the 5 GHz ISM bands. With the aid of an efficient algorithm, such idle time slots can be exploited for improving the system throughput and for load balancing. We begin by defining an optimization function whose objective is to maximize the total system throughput while maintaining the channel utilization ratio (CUR) fairness index at an acceptable level. Then, we show that the formulated problem can be modelled by a Markov chain whose states correspond to the vector containing the channel allocations for all APs. We show that this Markov

chain has a stationary distribution and thus can be solved with a Gibbs sampling approach. Finally, a distributed algorithm with low complexity is presented based on Gibbs sampling. The proposed algorithm is implemented locally on each AP as follows: each AP senses the available channels in a periodic order and calculates the CUR metric. The CUR is then averaged in time and the samples are fed into a Gibbs sampler. The output of this Gibbs sampler consequently updates a set of probabilities associated with each channel. Finally, a channel is selected by each AP based on these probabilities, using a Roulette Wheel Selection method. Note that the concept here is different to that of cognitive radio; we neither deal with two set of users (primary and secondary), nor try to limit or avoid the interference towards any groups of users. In fact, each user (AP) seeks to wisely select a channel before starting the contention process for transmission.

The remainder of this paper is structured as follows. In Section II, we introduce our system model along with the notations and then our optimization problem. Section III describes our problem analysis based on a Markov chain model, the solution based on Gibbs sampling, and the proposed channel allocation algorithm. The simulation results are presented in Section IV, and finally conclusions are drawn in Section V.

## II. SYSTEM MODEL

In this section we will present our system model, notations and assumptions, and present the formulation of the optimization problem to be solved.

### A. Notations and network topology

For the network model, we consider a topology in which each AP can accommodate several users (Fig. 1). We employ the following notations. The set of APs is described by  $\mathcal{B}$  and  $B$  is the number of APs in the system. The set of users is represented by  $\mathcal{S}$  (there are  $S$  users) and  $\mathcal{S}_b$  is the set of users associated with AP  $b$  (there are  $S_b$  users associated with AP  $b$ ). The set of all available channels in the system is denoted by  $\mathcal{C}$  (there are  $C$  of these). The set of available communication channels on each frequency band  $i$  is denoted by  $\mathcal{C}_i \subset \mathcal{C}$ ,

for each  $i \in \mathcal{I}$ . Note that the incentive behind utilizing such notation is to emphasize on availability of several channels on each Industrial, Scientific and Medical (ISM) radio band,  $i$ , namely, 920 MHz, 2.4 GHz, 5 GHz, 60 GHz. The basic idea in this research is to improve the Wi-Fi performance by expanding the channel allocation and idle time slot exploitation to all available ISM bands. Currently there are different Wi-Fi standards designed for different ISM bands, e.g., 802.11ac on 5 GHz, 802.11ax on 2.4 and 5 GHz, 802.11ad on 60 GHz and 802.11ah on 920 MHz. However, they are all bound to channels within the band they are designed for. Even for channel bonding they are limited to contiguous channel due to some hardware and standard limitations. AP's chance for channel bonding significantly reduces in crowded scenarios due to high non-availability of adjacent channels for bonding.  $\mathcal{B}_c$  is the set of APs adopting the same channel  $c$  (there are  $B_c$  of these). We assume that each AP can freely choose among permitted channels on each frequency band. In our model we consider a basic service set (BSS) which is an AP and its associated users. As we assume a distrusted *ad hoc* Wi-Fi network model, there is no such topology as extended service set (ESS), as per the 802.11 standard definition, due to independence of different BSSs. However, each BSS can freely choose its channel and handle collision at its MAC layer, based on the CSMA/CA protocol. In this work we consider only downlink communication, but the analysis can be easily extended for uplink scenarios. The long-term throughput depends on three factors: the long-term channel access time achieved by each AP, the number of users associated with each AP, and the average wireless link quality, i.e., the signal-to-noise-plus-interference-ratio (SINR) experienced by users. In this work we focus on improving the first factor, i.e., increasing the system throughput by exploiting the white spaces on less occupied channels and hence balancing the overall CUR.

### B. Optimization problem formulation

In our model we assume FTP traffic with transmission of fixed packet sizes by all users. As a result, the transmission time  $D(s)$  for a data unit of user  $s \in \mathcal{S}$  is defined as a function of its SINR,  $D(s) = 1/\Phi(\text{SINR}(s))$ , where the function  $\Phi$  takes into account how the user's SINR is used to choose an appropriate modulation and coding set (MCS) based on the 802.11 standard. Data units of different users associated to the same AP may experience different transmission times due to their particular instantaneous SINR; however, in the long term they will have similar throughput. Bearing this in mind, the throughput for AP  $b \in \mathcal{B}$  on channel  $c \in \mathcal{C}$  may be expressed as a function of the sum transmission time of all users associated with it, according to:

$$R_{b,c} = \frac{S_b \cdot \zeta_{b,c}(B_c)}{\sum_{s \in \mathcal{S}_{b,c}} D(s)}, \quad \zeta_{b,c} \in (0, 1] \quad (1)$$

where  $S_{b,c}$  is the set of users associated with AP  $b \in \mathcal{B}$  on channel  $c \in \mathcal{C}$ .  $\zeta_{b,c}(B_c)$  is a coefficient denoting the share of AP  $b$  from channel  $c$ . Note that  $\zeta_{b,c}$  is a function of  $B_c$ . If AP  $b$  is the only AP transmitting on channel  $c$ , this value is equal to one; if there are other APs on the same channel this value reduces due to contention.

Before presenting the optimization problem, we define the CUR fairness index based on Raj Jain's equation [15] as

$$\xi = \frac{(\sum_{i \in \mathcal{I}} \sum_{c \in \mathcal{C}_i} \sum_{b \in \mathcal{B}_c} B_c \varrho_{b,c})^2}{\sum_{i \in \mathcal{I}} \sum_{c \in \mathcal{C}_i} \sum_{b \in \mathcal{B}_c} B_c (\sum_{i \in \mathcal{I}} \sum_{c \in \mathcal{C}_i} \sum_{b \in \mathcal{B}_c} B_c \varrho_{b,c}^2)}, \quad (2)$$

where  $\varrho_{b,c}$  is the CUR measured by AP  $b$  on channel  $c$  and is calculated as  $(N_{\text{busy}}/N)$ , where  $N_{\text{busy}}$  is the number of busy time slots sensed during the CUR averaging window of size  $N$ . Note that  $\xi$  approaches one when all APs share each channel equally, i.e., the maximum value of the fairness measure.

It is desired to assign channels for communication so that the aggregate throughput of the Wi-Fi system is maximized; however, it is also desired to balance CUR among available channels, i.e., to penalize solutions for which the approximation  $\xi \approx \alpha$  is not close, where  $\alpha$  is a target CUR value assigned by the system operator. To this end, the optimization function is defined by

$$\max_{\mathbf{c} \in \mathcal{C}^B} \sum_{i \in \mathcal{I}} \sum_{c \in \mathcal{C}_i} \sum_{b \in \mathcal{B}_c} \frac{S_b \cdot \zeta_{b,c}(B_c)}{\sum_{s \in \mathcal{S}_{b,c}} D(s)} - \lambda(\xi - \alpha)^2, \quad (3)$$

where  $\lambda > 0$  is the penalty multiplier and  $\mathbf{c}$  is the channel allocation vector for all APs. The  $i$ -th entry in  $\mathbf{c}$  is equal to the channel allocated to the  $i$ -th AP (the ordering of the APs is arbitrary). The objective in (3) is to maximize the Wi-Fi throughput while balancing CUR among available channels (note that the the penalty function in (3) compares the value of the CUR fairness index with the target value). The solution to the optimization problem (3) is denoted by  $\mathbf{c}^* \in \mathcal{C}^B$ .

## III. SOLUTIONS AND PROPOSED ALGORITHMS

In this section we present a solution to the optimization problem in Section II, along with an algorithm for distributed implementation of channel allocation.

### A. Markov representation of the problem

The problem (3) can be modelled with a Markov chain whose state is the channel allocation vector and the transition probability satisfies [16]

$$\pi(\mathbf{c}) = \frac{1}{Z(T)} e^{\frac{1}{T} (\sum_{i \in \mathcal{I}} \sum_{c \in \mathcal{C}_i} \sum_{b \in \mathcal{B}_c} R_{b,c} - \lambda(\alpha - \xi)^2)}, \quad (4)$$

where  $Z(T)$  is the normalizing constant. The Markov chain is in state  $\mathbf{c}^*$  (the solution to optimization problem (3)) with probability  $1 - \delta$ , where  $\delta \rightarrow 0$  as  $T \rightarrow 0$ .

Gibbs sampling is a practical approach for realizing this Markov Chain for simulation purposes in discrete time instants  $t$ . However for this purpose, the Markov chain should have a stationary distribution. Given the current state  $\mathbf{c} = \mathbf{c}(t)$ , each AP  $b$  uses Gibbs sampling to changes its channel to  $c_b = c_b(t+1)$  according to the following Markov chain update probability (here the discrete-time index  $t$  is omitted for simplicity)

$$\pi(c_b | \mathbf{c}_{-b}) = \frac{\pi(c_b, \mathbf{c}_{-b})}{\sum_{\tilde{c}_b \in \mathcal{C}} \pi(\tilde{c}_b, \mathbf{c}_{-b})} \quad (5)$$

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**Algorithm 1** : Proposed algorithm.

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1: **Input:**  $q_{b,c}(t=0), \bar{q}_{b,c}(t=0), N_c, N$   
2: **Output:**  $\mathbf{c}, \xi$ ,  
3: **Initialization:**  $\mathcal{B} = \{1, \dots, B\}; \mathcal{C} = \{1, \dots, C\};$   
 $t = 0; P_c(t=0) = 1/C$   
4: **while do**  
5:  $t \leftarrow t - 1$ ,  
6: **for**  $\forall b \in \mathcal{B}$  **do**  
7: **for**  $\forall i \in \mathcal{I}$  **do**  
8: **for**  $\forall c \in \mathcal{C}_i$  **do**  
9: (I) Sense Channel,  $c$ ,  
10: (II) Calculate CUR  $q_{b,c}(t)$ ,  
11: (III) Calculate averaged CUR (10) according to  
 $\bar{q}_{b,c}(t) = (1 - \nu)q_{b,c}(t) + \nu\bar{q}_{b,c}(t-1)$ ,  
12: **end for**  
13: **end for**  
14: (IV) Broadcast the value for  $\bar{q}_{b,c}(t)$  to other APs.  
15: (V) Broadcast channel identification for the current  
channel in use,  $c^*(t-1)$ .  
16: (VI) Calculate Gibbs distribution and the probabilities  
in Section (VII) based on (9)  $\forall i \in \mathcal{I}$  and  $\forall c \in \mathcal{C}_i$ :  
$$\Xi(c) = \frac{\exp(\frac{1}{T} \cdot q_{b,c}(t))}{\sum_{c' \in \mathcal{C}} \exp(\frac{1}{T} \cdot q_{b,c'}(t))}$$
  
17: (VII) Update the probability  $P_c$  associated with each  
channel  $c$  via  
 $P_c(t) = P_c(t-1) + (\frac{1}{T})^\eta (\Xi(c) - P_c(t-1))$   
18: **if**  $t \bmod N_c = 0$  **then**  
19: (VIII) Probabilistically select a new channel,  $c^*(t)$ ,  
for AP  $b$ , based on probabilities  $P_c$   
20: **end if**  
21: (IX) Receive values of  $q_{b',c'}(t)$ , and channel identi-  
fiers from other APs  
22: (X) Calculate  $\xi$  in (2) based on values in (IX)  
23: (XI) Tune  $N_c$  and  $N$  based on  $\xi$  accordingly.  
24: **end for**  
25: **end while**

---

where  $\mathbf{c}_{-b} = \mathbf{c}_{-b}(t)$  is the channel allocation vector for all APs other than the target AP  $b$ . In Proposition 1, we argue that this Markov chain has a stationary distribution with balance equations given by

$$\pi(c_b | \mathbf{c}_{-b}) \pi(c'_b, \mathbf{c}_{-b}) = \pi(c'_b | \mathbf{c}_{-b}) \pi(c_b, \mathbf{c}_{-b}). \quad (6)$$

As a result, if we update the channel vector according to this Markov chain, it converges to  $\mathbf{c}^*$  with probability approaching one as  $T \rightarrow 0$ .

*Proposition 1:* The Markov chain with state updates given in (5) has a stationary distribution.

*Proof:* Since the transition from  $c_b(t) = m$  to  $c_b(t+1) = n$  takes place when some BSs update their resource values according to their observations on  $c_b(t)$ , the transition depends only on current channel allocation vector. Moreover, the configuration space  $\mathcal{C}^B$  for the channel allocation vector is finite at each time index  $t$ . Therefore, the mechanism can be modeled as a time-inhomogeneous Markov chain. Since the probability for transition from each state to another is positive,

it implies that the process can start from any configuration  $m$  and ends in any configuration  $n$  with a positive probability. Therefore, the Markov chain has irreducible and positive recurrent properties. Furthermore, because of the presence of self-loops with positive probability, the Markov chain is aperiodic. Since the Markov chain satisfies the three aforementioned properties (i.e., irreducible, positive recurrent and aperiodic), when  $T \rightarrow 0$  the transition probability converges to a stationary distribution.

### B. Gibbs sampling solution

Recalling from Graph theory, assume a undirected graph with  $B$  nodes (APs in this context). Two nodes are neighbors if connected by an edge. Each node is associated with a state variable that belongs to a finite set  $\mathcal{C}$  (set of channels). An energy function  $\mathcal{G}$  associates a real number  $\mathcal{G}(c)$  to each state  $c$  of the graph. The goal is to find states which minimize the energy function. In general this problem will be complex to solve for large networks. However, the problem can be solved using Gibbs sampling, if it can be decomposed based on *cliques* with different sizes. A *clique* of size  $c$  is a set of nodes with cardinality  $c$  which are all neighbours. Let  $\mathcal{B}_c$  denote the set of all cliques of size  $c$  and  $\Upsilon$  a function that assigns a non-negative real number  $\Upsilon(\mathcal{B})$  to all subsets of nodes in  $\mathcal{b}$ . For more details on Gibbs sampling, readers may refer to [16].

The energy function  $\mathcal{G}$  is written based on  $\Upsilon$  according to:

$$\mathcal{G}(c) = \sum_{\mathbf{b} \in \mathcal{B}_c} \Upsilon(\mathbf{b}). \quad (7)$$

Note that the notations above are directly equalized to those in Section II for a less abstract and a more tangible understanding. To highlight the local energy of a specific node (AP),  $b$  on channel  $c$ , the energy function  $\mathcal{G}(c)$  can be rewritten as:

$$\mathcal{G}_b(c) = \sum_{\mathbf{b} \in \mathcal{B}_c: \mathbf{b} \in \mathbf{b}} \Upsilon(\mathbf{b}). \quad (8)$$

Gibbs sampling is the method by which each node,  $b$ , tries to minimize its energy function (8) by transition from one state to another. The transition probability to a target state  $c$  is calculated by sampling a random number according to:

$$\Xi(c) = \frac{\exp(\frac{1}{T} \cdot \mathcal{G}_b(c))}{\sum_{c' \in \mathcal{C}} \exp(\frac{1}{T} \cdot \mathcal{G}_b(c'))}, \quad c \in \mathcal{C} \quad (9)$$

where  $T > 0$  is the temperature parameter. Note that the probability distribution in (9) fulfills the stationary property of Markov chain density function, described in (4) and proof of *Proposition 1*. Specifically, given that the states of each channel for node (AP),  $b$ , only depends on its neighbour. This can also be interpreted as the communication range. Farther APs with larger path loss are considered non-neighbour in this sense and have no effect on target AP's channel dynamics. Status updates of APs can be done in an asynchronous manner.

### C. Proposed algorithm

Here we propose a heuristic, simple, yet efficient approach, adopted by procedure above to solve the channel allocation problem. To simplify the algorithm design procedure, we

TABLE I  
SIMULATION SETUP

Parameter	Value
<b>System</b>	
WLAN Standard Version	IEEE 802.11ac
Room size	25m × 25m × 3m
Number of WLAN AP-User pairs	5~20
AP-User pairs placement	Uniform distribution
<b>App. Layer</b>	
Traffic model	FTP [17] with 1/36 reading time
Traffic simulation time	30s
Packet size (mean)	2 Mbyte
Packet size (maximum)	5 Mbyte
Reading time (mean)	5s
Traffic direction	Downlink
<b>MAC Layer</b>	
Slot time	9 $\mu$ s
SIFS	16 $\mu$ s
DIFS	34 $\mu$ s
CWmin	5
CWmax	1023
Retransmission limit	3 times
Frame aggregation	Not in use
RTS/CTS exchange	In use
Virtual sensing	In use
<b>PHY Layer</b>	
Frequency band	5.2, 5.3 and 5.6 GHz bands
Maximum Tx bandwidth	80MHz
Number of spatial streams	1
Number of frequency segments	4 (#1: ch36~48, #2: ch52~64, #3: ch100~112, #4: ch116~132)
MCS index for data packets	1
MCS index for RTS/CTS/ACK	0
AP's transmit power	20dBm
<b>Channel Model</b>	
Channel model	Path Loss + Shadowing
Pathloss exponent	2
Shadowing standard deviation	0.1dB

assume a single-band single-interface Wi-Fi, which all APs transmit on only one given channel at any time instance  $t$ . As mentioned in Section II, the objective of this work is to maximize the system throughput (3) by maintaining a fair CUR. Intuitively, we can judge that such objective may be reached by balancing the channel utilizations among WLAN APs. Thus, less occupied channels may be used more frequently to reduce the load on highly occupied channels and long term system throughput will improve. We now cast our approach into Gibbs sampling framework by forming the energy function (8) for time  $t$  on channel  $c$  according to:

$$\mathcal{G}(t) = (1 - \nu)\varrho_{b,c}(t) + \nu\bar{\varrho}_{b,c}(t-1) \quad (10)$$

where  $\nu$  is the forgetting factor and  $\bar{\varrho}_{b,c}(t-1)$  is CUR average up to  $t-1$ . After breaking down the overall energy function in (10) into components of individual APs, a distributed algorithm is implemented on each AP (Algorithm 1).

#### IV. SIMULATION RESULTS AND DISCUSSION

In order to evaluate the proposed algorithm, we have developed a simulation testbed based on IEEE WLAN Standard 802.11ac-2013 [18]. Three network layers (Application, MAC and PHY) are implemented. Simulation environment

assumptions and numerical values are summarized in Table I. For simplicity of exposition, we consider only downlink transmission and one user associated with each AP at all time. Pairs of users and APs are placed in a three dimensional space based on a uniform distribution in the initialization phase of the simulation. We assume a channel model based on path loss and shadowing. Data packets are generated based on a file transfer protocol (FTP) model in the application layer according to [17]. However, we have reduced the FTP mean reading time in order to speed up the simulation time and induce a high traffic scenario.

Four different metrics are considered for performance evaluation; (1) MAC layer throughput which only captures the number of successful MAC Protocol Data Unit (MPDU) packets transmitted, and as a result is indirectly related to the maximum number of allowed retransmissions. (2) Transmission delay, which is defined as the average time a user is required to wait before winning the channel for transmission. This metric is in fact a measure of channel traffic and reducing it will significantly help to improve the overall system throughput and quality of service (QoS). (3) Application layer delay, which is defined as the average time required for each FTP packet to leave the application layer's buffer. This metric is a rough estimate of user's quality of experience (QoE). However, it is incapable of reflecting details related to the performance of lower layers, e.g., packet drops in bad channel situations due to reaching the maximum number of retransmissions for request to send (RTS) or data packets. (4) Packet drop ratio which measures the number of dropped packets over total number of transmitted packets by a user during the simulation time. Note that we have performed a Monte Carlo simulation and have averaged all the scenarios for all packets of all users in order to calculate the aforementioned metrics.

Fig. 2 shows the MAC layer throughput for different numbers of AP-user pairs. We can observe that our proposed channel selection technique yields about 5% improvement over the existing WLAN 802.11ac standard. Similar improvements are anticipated over the upcoming 802.11ax standard, as our technique is implemented at MAC layer on top of all existing innovations and enhancements for 802.11ax, e.g., orthogonal frequency division multiple access (OFDMA), 1024-point quadrature amplitude modulation (QAM), etc. Fig. 3 shows the average system transmission delay for different numbers of AP-user pairs. We can observe that our algorithm achieves about 20% improvement over 802.11ac. Fig. 4 shows the application layer delay for different numbers of AP-user pairs. Again, our method outperforms 802.11ac by at least 10%. Finally, Fig. 5 shows the system packet drop ratio for different numbers of AP-user pairs; the proposed method reduces this value significantly (by about 50%) for 20 AP-user pairs.

#### V. CONCLUSION

In this paper, we proposed an intelligent channel selection technique based on Gibbs sampling for multi-channel multi-band WLAN systems. The proposed algorithm has low computational complexity and can therefore be implemented in a distributed manner within each user's MAC layer. Simulation

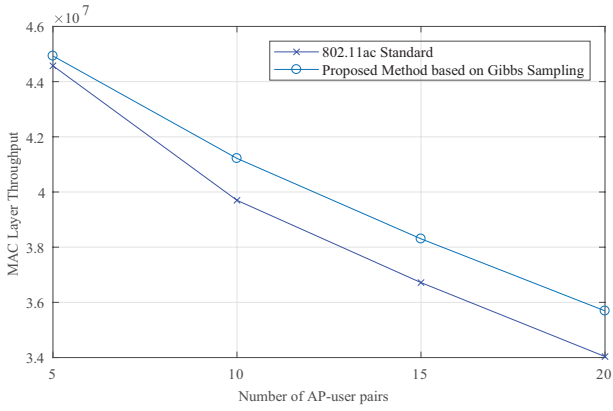


Fig. 2. MAC layer throughput vs the number of AP-user pairs.

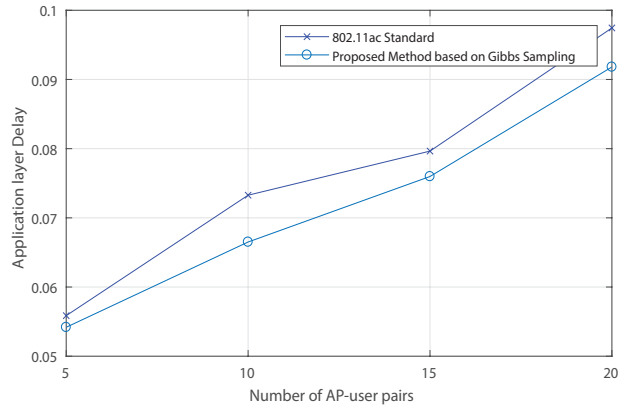


Fig. 4. Application layer delay vs the number of AP-user pairs.

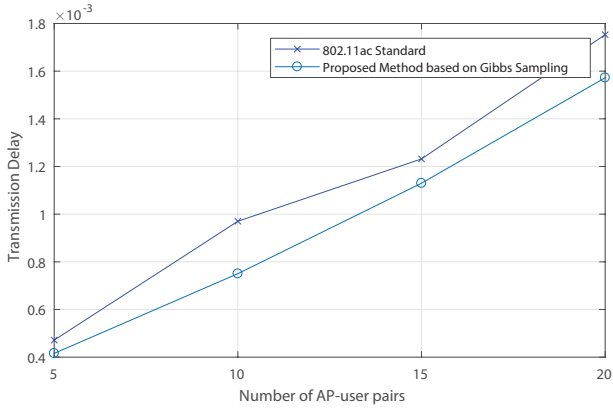


Fig. 3. Transmission delay vs the number of AP-user pairs.

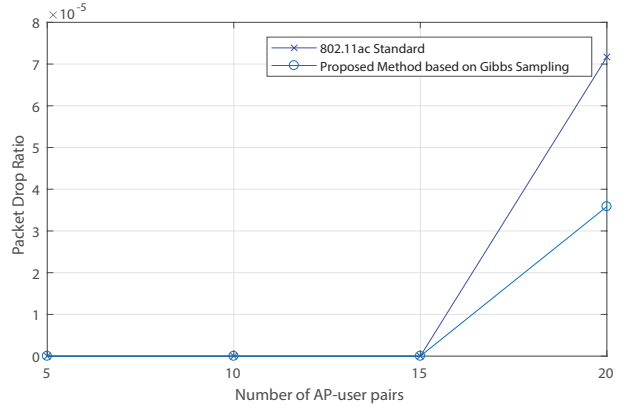


Fig. 5. Packet drop ratio vs the number of AP-user pairs.

results show that the proposed algorithm outperforms the existing Wi-Fi standards, and can effectively reduce the overall packet transmission delay by about 20% and the packet drop ratio by at least 50% in high traffic scenarios. Future work will investigate further improvement of this technique and develop it for joint packet scheduling and WLAN QoS improvement on multiple non-contiguous bands/channels.

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