JACPoT: A Joint Algorithm for Channel and Power Assignment in Enterprise Wireless Networks

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Abstract—The demand for wireless communication in enterprise network has been increasing with the advent of “smart working environment.” In enterprise wireless network, high density of access points (APs) and limited frequency resources raise the significance of radio resource management. In this paper, we propose a centralized algorithm, named JACPoT, for jointly executable transmission power control (TPC) and dynamic channel assignment (DCA). The proposed algorithm first guarantees that the links between AP and client stations are robust to the inter-cell interference via TPC. Next, it minimizes contention between neighboring APs via DCA utilizing a novel metric and annealed Gibbs sampler. Through ns-3 simulations based on measurement in real office environments, we demonstrate that JACPoT reduces uplink frame collisions by 36% and significantly enhances both data and voice traffic delivery.

Index Terms—Enterprise network, IEEE 802.11 WLAN, dynamic channel assignment, transmit power control.

I. INTRODUCTION

The skyrocketing demand for high performance wireless access has raised the density of wireless LAN (WLAN) access points (APs). With the existence of many APs and non-AP stations (STAs), the significance of radio resource management (RRM) is more emphasized. Accordingly, IEEE 802.11ax task group has been recently launched to improve spectral efficiency of WLAN, especially, in dense deployment scenarios [1].

At the same time, the demand for enterprise WLAN supporting various office applications has been increased with the advent of new working environments using diverse smart devices. Since enterprise WLAN requires stable performance in delivering both heavy traffic and real-time applications, APs are deployed very densely in general. The communication in such densely deployed WLAN, however, suffers from severe inter-cell interference (ICI). To be more specific, the ICI louder than clear channel assessment (CCA) threshold, which we call exposed interference in this paper, degrades network performance by intensifying contention. On the other hand, the ICI quieter than CCA threshold, called hidden interference, degrades the performance by deteriorating signal-to-interference-plus-noise-ratio (SINR).

In the above-mentioned enterprise environment, the radio resource can be more advertently managed thanks to the existence of AP controller (APC). As illustrated in Fig. 1, APs are connected to an APC, and send feedback information, e.g., received signal strength (RSS) and traffic load, to the APC. Then the APC conducts RRM operation such as transmit power control (TPC) and dynamic channel assignment (DCA) in a centralized manner. Specifically, TPC schemes assign appropriate transmit powers to each AP to adapt environmental changes in network. DCA schemes, on the other hand, dynamically assign frequency channels to each AP to maximize spatial reuse in an adaptive manner.

The goal of our study is to propose a jointly executable TPC and DCA algorithm specialized in enterprise wireless network. We first propose a simple TPC scheme that guarantees successful packet transmissions by assigning appropriate transmit power to endure hidden interferences and minimize ICI. Secondly, we propose a novel metric for network performance which precisely reflects performance degradation due to the contention among co-channel APs, i.e., the APs operate in the same frequency channel. Combining the proposed TPC scheme and metric, and then adopting a meta-heuristic algorithm, we finally propose JACPoT (Joint Algorithm for Channel and Power assignment).

In contrast to the existing work, JACPoT (i) jointly assigns frequency channels and transmit powers, and (ii) considers the physical asymmetry between AP and STA devices such as different receive sensitivity, antenna gain, etc. Through ns-3 simulation based on the measurement results in real office environments, the performance of JACPoT is comparatively evaluated with existing schemes.

The rest of the paper is organized as follows. In Section II, we review the existing schemes for TPC and DCA. Section III introduces JACPoT in a nutshell. Section IV and Section V describe the proposed TPC and DCA schemes, respectively. Simulation-based performance evaluation is presented in Section VI, and Section VII concludes the paper.
II. RELATED WORK

We first introduce existing TPC and DCA schemes. Since we consider enterprise WLAN where APC manages connected APs, we focus more on centralized schemes.

A. TPC Schemes

There have been remarkable studies on TPC algorithms in the literature. Power control for AP performance enhancement (PCAP) proposed in [2] consists of two steps. The first (second) step aims to maximize (maximize) the mean (variance) of AP utility, defined as the weighted product of its associated STAs’ datarates. These datarates are predicted by calculating the worst case SINR and using SINR-datarate table.

In [3], S. Bae et al. propose an RRM scheme including TPC and DCA. The proposed TPC scheme controls the transmit power so that the RSS of STAs in neighboring cells becomes under the CCA threshold to reduce unnecessary contentions. However, the scheme does not consider the channel variation caused by multi-path fading.

In Cisco’s TPC version 1 [4], AP reduces transmit power if RSS of its third loudest neighbor AP is larger than a TPC threshold. This scheme does not consider different channels of APs, and the performance highly depends on the selection of TPC threshold, which is configured manually.

B. DCA Schemes

In this section, we introduce several DCA schemes in the literature. In [5], the proposed scheme aims at minimizing the signal strength from neighboring APs at a reference AP. With given channels, neighboring APs take turns to select the operating channel which yields the minimum interference to the reference AP. The authors of [6] propose a heuristic algorithm to minimize an objective function, the effective channel utilization of the most stressed bottleneck AP, based on interferer classification. This heuristic algorithm repeatedly assigns the best channel to the most stressed AP until no better channel plan exists.

In [7], the authors propose a novel metric for DCA by a product of RSS, interference factor, and channel occupancy time (COT). A distributed algorithm is then proposed to minimize the metric for each AP by changing channel set. In Cisco’s DCA scheme [4], a cost metric (CM) for an AP is first defined as a function of RSS, noise, interference, utilization, and traffic load. According to the CM, the worst AP in an RF subgroup and its first hop neighbors find new channel plans to minimize the worst AP’s CM.

A DCA scheme in [8] maximizes a metric based on interference graph. The metric models the potential capacity of each AP by taking into account the effects of both co-channel and adjacent channel interference as well as the loads of neighboring APs. In [3], S. Bae et al. propose a DCA scheme which assigns the channel with the minimum number of STAs in the overlapping coverage. Each STA periodically reports a list of RSS values from its neighboring APs.

All these TPC and DCA schemes, however, do not consider the physical asymmetry between AP and STA devices, e.g., receive sensitivity, antenna gain, etc., which can greatly affect the performance of WiFi devices. Whereas we propose a TPC and DCA scheme considering the heterogeneity of WiFi devices with different RF parameter set.

III. JACPoT: OVERVIEW

We now present the proposed RRM framework. We assume that each AP continually collects statistics of RSSs from other APs and STAs, noise level, and traffic load in every channel using a monitoring radio. An APC periodically gathers the statistics from the APs under its control and conducts JACPoT based on the statistics. We call this periodic a run.

We first define a metric, named network cost, for weighing up the network-wide performance for a given channel plan, i.e., the set of channels assigned to APs in the network. Network cost is defined as the sum of APs’ individual metrics, called residual ICI (RI). More specific description of RI and network cost is presented in Section V. JACPoT is then composed of the following three steps at each run.

- **Step 1. Channel plan search:** For the optimal channel plan search, we adopt a metaheuristic algorithm annealed Gibbs sampler (AGS) [9] which we will discuss specifically in Section V. For the fast convergence of AGS, we assign the initial channel plan by a simple greedy search. Specifically, each AP takes turns to choose a channel providing the lowest network cost until no AP can further lower the network cost by changing its channel unilaterally. Next, the APC finds the (near-)optimal channel plan by AGS using the network cost. The key point is that the network cost is computed using the expected transmit power levels of APs after TPC operation. The detailed explanation of the channel plan search is presented in Section V.

- **Step 2. DCA decision:** Secondly, we decide whether to assign only transmit power or both transmit power and channel together. Due to the temporal disconnection and protocol overheads such as channel switch announcement (CSA) frame exchange, frequent changes of the operating channel is undesirable. To avoid frequent channel reassignments,

\[ \text{...} \]

\[ \text{Eq. 1} \]

\[ \text{Eq. 2} \]
of an AP, as small as possible, while maintaining the RSS at the AP from the STA. The philosophy of the proposed TPC is to make the RSS at the AP from its associated STAs from itself. Since there is no standard compliant protocol for RSS feedback from STAs, the RSS at the AP should be kept high enough for all hidden interference from co-channel neighbors. It means that a STA from an AP should be able to hear the associated AP even with the existence of an interference louder than the CCA threshold.

We first define inner condition to guarantee stable links between the AP and its client STAs.

**A. Inner Condition**

We first define inner condition to guarantee stable links within a cell. Inner condition states that all client STAs should be able to hear the associated AP even with the existence of hidden interference from co-channel neighbors. It means that the transmit power of AP should be kept high enough for all client STAs to satisfy the SINR requirement for successful packet decoding. To this end, AP should know RSSs at its associated STAs from itself. Since there is no standard compliant protocol for RSS feedback from STAs, the RSS at a STA from an AP should be estimated using RSS of the reverse link, i.e., the RSS at the AP from the STA. We call this estimated RSS (ERSS). Assuming the channel reciprocity, ERSS is given as

\[ \text{ERSS}_{\text{AP}\rightarrow\text{STA}} = \text{RSS}_{\text{STA}ightarrow\text{AP}} + P_{\text{AP}} - P_{\text{STA}} + \Delta_{\text{comb}} \]

where \( P_{\text{AP}} \) and \( P_{\text{STA}} \) represent transmit power levels of AP and STA. \( \Delta_{\text{comb}} \) is the difference of combining gains of AP and STA due to the different number of antennas. Compared with STAs, APs generally have more antennas which yield higher combining gain. All the above values are on the dB scale.

To guarantee a successful packet reception after a unit power decrease, the inner condition is expressed as

\[ \text{ERSS}_{\text{AP}\rightarrow\text{STA}} + \delta_t > \text{S}_{t,k}^{\text{th}} \quad \forall t \in T \]

where \( \text{S}_{t,k}^{\text{th}} \) is the RSS threshold in dBm, defined as the required RSS for STA \( t \) to receive packets using target MCS \( k \) with the frame error rate (FER) of 10%, and \( T \) is a set of STAs associated to AP \( t \), respectively. Since inner condition guarantees a successful packet reception with a target MCS, AP and STAs choose MCSs equal or higher order MCSs than the target MCS for data transmissions. By using higher MCSs for data transmission on average, fewer collisions are expected thanks to the shortened frame airtime.

A packet using MCS \( k \) can be received by STA \( t \) with FER of 10%, if the RSS, denoted by \( S_t \) (dBm), satisfies

\[ S_t - (I + N)_{\text{dB}} \geq \text{SINR}_k \]

where \( \text{SINR}_k \) is the required SINR value to get FER of 10% using the maximum packet size and MCS \( k \), and \( I \) and \( N \) represent interference and noise power, respectively. Therefore, RSS threshold of STA \( t \) using MCS \( k \) is given by

\[ \text{S}_{t,k}^{\text{th}} \triangleq \text{SINR}_k + (I + N)_{\text{worst}, \text{dB}} + \lambda_{t,p} \]

where \( (I + N)_{\text{worst}, \text{dB}} \) represents the power of interference plus noise in the worst case. \( \lambda_{t,p} \) is a margin for signal fluctuation due to multipath fading, and it is added to cover up to the \( (1 - p) \)th percentile of RSS values.

We expect that the worst interference to a STA happens when its associated AP cannot sense the interference by a narrow margin, because the AP would not transmit with the existence of an interference louder than the CCA threshold. If we only consider interference from co-channel APs, STAs

<table>
<thead>
<tr>
<th>Table I</th>
<th>REQUIRED SINR OF 10% FER FOR 802.11n MCSs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINR</td>
<td>0</td>
</tr>
<tr>
<td>3.56</td>
<td>6.55</td>
</tr>
</tbody>
</table>

\(^2\)The value of \( \delta_t \) depends on AP devices. For example, Cisco Aironet 1140 series AP can adjust transmit power by 3 dB, i.e., \( \delta_t = 3 \) dB [10].

\(^3\)The RF parameters of STA is assumed to be known by the APC, e.g., through one-time device registration with the enterprise WLAN system.

\(^4\)The maximum MSDU size for 802.11n WLAN is 7,935 bytes [11].

\(^5\)APs transmission occupy the air during most of time, because downlink traffic dominates the total traffic in general 802.11 WLANs [13].
generally hear signals from neighbor APs with smaller RSS than its associated AP. Therefore, the worst case interference is given by the CCA threshold of the AP. Consequently, the RSS threshold of STA \( t \) is rewritten as
\[
S_{i,k}^{th} = \text{SINR}_k + (C_{i}^{th} + \text{NF}_i)_{\text{dB}} + \lambda_{i,p}
\]
where \( C_{i}^{th} \) is the AP’s CCA threshold and \( \text{NF}_i \) is STA \( t \)'s noise floor, both on the linear scale.

On the other hand, To determine the value of \( \lambda_{i,p} \), each AP collects RSS statistics and finds the top \( p \) RSS value for each STA. For example, if the average RSS and top 95% from a STA are \(-60\) dBm and \(-70\) dBm, respectively. \( \lambda_{i,95\%} \) is given by \(-60 - (-70) = 10\) dB. \( p \) can be adaptively determined according to traffic type and load.

B. Outer Condition

Secondly, we define outer condition to reduce contention domains of APs as much as possible. Outer condition states that an AP needs to reduce its transmit power, if any of its co-channel neighbor APs hears it as louder than the CCA threshold. Thus, outer condition is given as
\[
\text{RSS}_{i,j} > C_{j}^{th}, \ 3\ j \in A_i
\]
where \( \text{RSS}_{i,j} \) and \( C_{j}^{th} \) represent the average RSS from AP \( i \) at AP \( j \) and AP \( j \)'s CCA threshold, respectively, and \( A_i \) is a set of AP \( i \)'s co-channel APs. We only consider ICI between APs for the same reasons as in footnote 6.

V. PROPOSED DCA SCHEME

In this section, we propose a DCA scheme which is jointly executable with the proposed TPC scheme. Note that the proposed TPC scheme guarantees that links between an AP and its client STAs are robust to hidden interference. The purpose of the proposed DCA scheme is to minimize the performance degradation due to contention among co-channel cells. The bottom line is assuming that the proposed TPC has been done for each channel plan, and finding the optimal channel plan which has the lowest degree of contention.

A. Residual Inter-cell Interference

We borrow the concept of contention factor (CF), a DCA metric proposed in [15], to estimate the degree of contention. CF assumes that performance degradation due to contention is proportional to the gap between the current power level and the desirable power level (DPL). DPL is the maximum allowed transmit power for an AP in order not to cause exposed interference to co-channel APs.

In this work, we modify CF into a new metric which is named RI. The modification is twofold. First, RI expects the degree of contention after the proposed TPC is applied, while CF measures degree of contention with the current power. Second, RI has a form of log function, while CF is a linear function. To be specific, we newly define two terms; desirable power decrease (DPD) and allowed power decrease (APD). DPD\(_{i,j}\) represents how much power AP \( i \) should decrease not to satisfy outer condition by AP \( j \).

\[
\text{DPD}_{i,j} \triangleq \min \{ \text{RSS}_{i,j} - C_j^{th} \}^+ \tag{9}
\]

where \([x]^+ = \max(0, x)\). Next, APD\(_i\) represents how much power AP \( i \) can decrease while satisfying inner condition.

\[
\text{APD}_i \triangleq \min \left( \overline{P}_i - P_{m,i}, \left[ \frac{\min_{t \in A_i} (\text{ERSS}_{i,t} - S_{i,t}^{th})}{\delta_p} \right] \times \delta_p \right) \tag{10}
\]

where \( \overline{P}_i \) and \( P_{m,i} \) are AP \( i \)'s current and minimum transmit powers in dBm, respectively, and \([x]^+\) is the greatest integer less than or equal to \( x \). Then, the performance degradation due to AP \( i \) is analyzed by DPD and APD as follows.

1) If \( \text{APD}_i > \text{DPD}_{i,j}, \ \forall j \neq i \), AP \( i \) can lower its transmit power until no neighbor APs can sense its signal, i.e., no neighboring APs contend with AP \( i \). Thus, AP \( i \) causes negligible performance degradation in the network.

2) If \( \text{APD}_i \leq \text{DPD}_{i,j}, \ \exists j \neq i \), AP \( i \) is sensed by AP \( j \) after lowering transmit power by the proposed TPC, and AP \( j \) contends with AP \( i \). In this case, the degree of contention at cell \( j \) depends on \( \Delta_{i,j} \triangleq \text{DPD}_{i,j} - \text{APD}_i \) for two reasons. Firstly, more STA in cell \( j \) can sense a signal from AP \( i \) and contend with the AP as \( \Delta_{i,j} \) increases. Secondly, the probability that AP and STAs in cell \( j \) sense a signal from AP \( i \) increases as \( \Delta_{i,j} \) increases.\(^7\) The effects of increasing \( \Delta_{i,j} \) on the performance degradation from contention becomes less significant as \( \Delta_{i,j} \) becomes larger, and eventually converges to a certain level.

We capture this relationship between the performance degradation and \( \Delta_{i,j} \) by modeling it with a log function, which is non-decreasing and concave. Thus, RI, is defined as

\[
\text{RI}_i \triangleq \tau_i \sum_{j \in A_i} \log \left( 1 + [\text{DPD}_{i,j} - \text{APD}_i]^+] \right) \tag{11}
\]

where \( \tau_i \) is AP \( i \)'s traffic load.\(^8\) Network cost is then defined by the sum of \( N \) AP’s RI as

\[
\epsilon_{\text{net}} \triangleq \sum_{i=1}^{N} \text{RI}_i \tag{12}
\]

\(^7\) Due to the multi-path fading, a signal from AP \( i \) may not be sensed by AP \( j \) temporarily, although RSS\(_{i,j} \geq C_j^{th}\). If \( \Delta_{i,j} \) is large enough, the devices in cell \( j \) always sense a signal from AP \( i \).

\(^8\) Traffic load can be defined in various ways, e.g., number of associated STAs, traffic source rate, or channel occupancy time. In this work, we define the traffic load as the transmission time of AP \( i \) divided by total time.
Algorithm 1 JACPoT

1: $ch \leftarrow \text{GreedySearch} \triangleright$ Initialize channel plan by greedy search in Section III (ch: Channel plan)
2: $(c^*_\text{net}, p) \leftarrow \text{FINDNETCOST}(ch) \triangleright$ Initialize optimal network cost $(c^*_\text{net})$ $(p$: Transmit power plan)
3: $t \leftarrow 1$
4: while $t \leq t_{\text{max}}$ do $\triangleright$ For each iteration $t < t_{\text{max}}$
5: $T \leftarrow \frac{T_{\text{i}}}{\log(1+t)}$ $\triangleright$ Update temperature according to cooling schedule
6: for $i \leftarrow 1..n$ do $\triangleright$ For all APs ($n$: # of APs)
7: for all $c_h \in 1, 2, \cdots, m$ do $\triangleright$ For all channels ($m$: # of channels)
8: $ch \leftarrow (c_{h1}, \cdots, c_{hn}), ch_N$ ($c_{hN}$: Channel plan)
9: $(c^*_\text{net}(ch_h), p) \leftarrow \text{FINDNETCOST}(ch)$
10: $\mu_i(ch_h) \leftarrow \frac{(e^{-\frac{c^*_\text{net}(ch_h)}{T}})}{\left(\sum_{c_h' \in (1, 2, \cdots, m)} e^{-\frac{c^*_\text{net}(c_h')}{T}}\right)}$ $\triangleright$ Compute $\mu_i$.
11: end for
12: pick $c_h \sim \mu_i(ch_h)$ $\triangleright$ Randomly choose $c_h$ according to $\mu_i(ch_h)$
13: update $(ch, p)$ using $c_h$ $\triangleright$ Update channel plan
14: end for
15: if $c^*_\text{net} < c^*_\text{net}$ then $\triangleright$ Update optimal plans according to $c^*_\text{net}$
16: $(ch^*, p^*, c^*_\text{net}) \leftarrow (ch, p, c^*_\text{net})$ ($ch^*$: Optimal channel plan, $p^*$: Optimal transmit power plan)
17: end if
18: $t \leftarrow t + 1$
19: end while

20: function FINDNETCOST(ch)
21: for $i \leftarrow 1..n$ do $\triangleright$ For all APs in the network
22: $\text{APD}_i \leftarrow$ compute APD using (10)
23: for $j \leftarrow 1..m$ do
24: $\text{DPD}_{ij} \leftarrow$ compute DPD using (9)
25: $\text{RI}_i \leftarrow$ compute RI using (11)
26: end for
27: $\mu_i \leftarrow \min(\text{max}_j \text{DPD}_{ij}, \text{APD}_i)$ $\triangleright$ Compute $\mu_i$
28: end for
29: $c^*_\text{net} \leftarrow \sum \text{RI}_i$ $\triangleright$ Update $c^*_\text{net}$
30: return $(c^*_\text{net}, p)$ $\triangleright p = (p_1, p_2, \cdots, p_n)$
31: end function

B. Annealed Gibbs Sampler (AGS)

Now, we find a channel plan minimizing the above-defined network cost. However, the number of possible channel plans grows exponentially with the number of APs in the network. For example, a network composed of 10 APs with 4 channels has $4^{10} \approx 10^6$ possible channel plans. In other word, if we search exhaustively, the search space size is about $10^6$. To reduce the search space and make this optimization more feasible, we use AGS to find the optimal channel plan.

AGS combines the notion of Gibbs sampler and simulated annealing [16]. To put it briefly, each node updates its state, i.e., $s$, according to jumping probability, which is given as

$$\mu(s) = \frac{e^{-\varepsilon(s)/T}}{\sum_{s' \in S} e^{-\varepsilon(s')/T}},$$

where $S$ is a set of possible states. Energy denoted by $\varepsilon(s)$ is a measure of each state’s optimality, where a state with smaller energy is more desirable. In JACPoT, a state and energy correspond to a channel plan and the network cost of the channel plan, respectively.

Temperature, denoted by $T$, controls the sensitivity of jumping probability to the energy. If temperature is high, the jumping probability of a state less depends on the state’s energy. For convergence to the optimal state, the temperature is updated according to cooling schedule for each iteration $t$.

Compared with random sampling, the result of AGS algorithms, especially the AGS with logarithm base 2 and $T_0 = 1$, rapidly converges to the optimal value from exhaustive search. In addition, average calculation time of AGS algorithms is about 20 seconds, and smaller than that of exhaustive search by several orders of magnitude. Since the calculation time of AGS grows proportionally (not exponentially) to the number of APs, and is readily controllable by limiting the maximum number of iterations, it is possible to find the (near-)optimal network cost within a reasonable time. The detailed operation of JACPoT is described in Algorithm 1.

VI. PERFORMANCE EVALUATION

In this section, the performance of JACPoT is evaluated via ns-3 simulation [18]. For a realistic simulation, we first modified TGn pathloss model (developed to evaluate 802.11n proposals) based on the measurement results in real office environments with many cubicles and glass walls. As a result, we use a higher pathloss exponent and rapidly decreasing signal strength at long distance due to the penetration loss. To capture the physical asymmetry between AP and STA devices, in addition, we adopt a WiFi simulation model proposed in [14]. We consider an enterprise wireless network with two tier hexagonal cell deployment with 19 APs as shown in Fig. 4. Four non-overlapping available channels are assumed, and Minstrel rate adaptation algorithm [19] using 802.11n data rates with a single spatial stream is adopted. Detailed simulation environment is described in Table II.

A. DCA Metric

First, we compare the proposed metric, i.e., RI, with existing metrics to see how correctly it measures the network perfor-
Table II: Simulation models and parameters.

<table>
<thead>
<tr>
<th>Model &amp; parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit power</td>
<td>$-1 \sim 20$ dBm (AP), $12.5$ dBm (STA)</td>
</tr>
<tr>
<td>CCA threshold</td>
<td>$-82$ dBm</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>$3$ dB (AP), $0$ dB (STA)</td>
</tr>
<tr>
<td>Handgrip loss</td>
<td>$-6.2$ dB (STA)</td>
</tr>
<tr>
<td>Noise floor</td>
<td>$3.5$ dB (AP), $9.4$ dB (STA)</td>
</tr>
<tr>
<td>Pathloss model</td>
<td>$28.8$ log$d + 46.7$, $d \leq 28.5$ m</td>
</tr>
<tr>
<td>Fading model</td>
<td>Jakes model (doppler velocity= $0.1$ m/s)</td>
</tr>
</tbody>
</table>

For a given topology with a random channel plan, we measure both sum throughput and sum of each metric, i.e., RSS, COT, Load, and RI. Specifically, RSS is given similar to the metric proposed in [5] as \( m_i^{\text{rss}} = \sum_{j \in \mathcal{A}_i} \text{RSS}_{j,i} \). COT is the metric proposed in [7], and is given by \( m_i^{\text{cot}} = \text{COT}_{i} \). \( \sum_{j \in \mathcal{A}_i} \text{RSS}_{j,i} \), where COT is the channel occupancy time monitored by AP \( i \). Load is the metric proposed in [6], and is given by \( m_i^{\text{load}} = \rho_i + \sum_{j \in \mathcal{C}_i(1)} \rho_j + \sum_{(m,n) \in \mathcal{C}_i(2)} \rho_m \rho_n \), where \( \rho_i \) and \( \mathcal{C}_i(k) \) are the effective channel utilization and class-\( k \) interferers for AP \( i \), respectively. The inter-AP distance \( d_{AP} \) is 10, 15, 20 m, and the number of STAs in a cell is a uniform random variable over \([1, N_{\text{max}}]\).

- **RI shows strong correlation with network throughput**

Fig. 5 shows the correlation between the throughput and the metrics for 100 random channel plans. The throughput and the sum metric values are normalized to the aggregate source rate and the maximum value of sum metric, respectively. The diagrams show that RI achieves higher (negative) correlation with the throughput compared with other metrics. In addition, RI is more discriminative in the sense that the values of sum metric are more widely scattered in \( x \)-axis.

- **The accuracy of RI increases with more number of STAs**

Table III shows the average correlation coefficient of each metric for different \( N_{\text{max}} \). RI yields very strong correlation especially when there are many STAs since the performance degradation modeling in Section V-A fits better with a large number of STAs. Therefore, our scheme is more suitable for dense environments.

**B. Performance of JACPoT**

Next, we randomly distribute 100 STAs in the network with 19 cells. All STAs have TCP traffic of 0.8 Mbps for downlink (DL) and 0.2 Mbps for uplink (UL). 10% of total STAs have VoIP traffic using G.711 codec with inter-packet interval of 20 ms. The sum throughput of DL and UL traffic as well as and R-score, which is given by the minimum of R-scores for DL and UL, are measured for 20 s. For each \( d_{AP} \) of 10, 15, 20 m, we repeat the simulation 10 times with different random seeds. As comparison schemes, we choose random channel plan with fixed transmit power (Rnd./Fixed), and regular channel plan as shown in Fig. 4 with Cisco TPC version 1 (Reg./Cisco). 97% STAs achieve full throughput in both UL and DL.

Table III: Correlation coefficients between each metric and throughput.

<table>
<thead>
<tr>
<th>( N_{\text{max}} )</th>
<th>RSS</th>
<th>COT</th>
<th>Load</th>
<th>RI</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$-0.39$</td>
<td>$-0.46$</td>
<td>$-0.77$</td>
<td>$-0.92$</td>
</tr>
<tr>
<td>20</td>
<td>$-0.36$</td>
<td>$-0.39$</td>
<td>$-0.51$</td>
<td>$-0.95$</td>
</tr>
<tr>
<td>30</td>
<td>$-0.38$</td>
<td>$-0.39$</td>
<td>$-0.35$</td>
<td>$-0.97$</td>
</tr>
</tbody>
</table>

Fig. 5. Correlation between normalized aggregate TCP throughput and sum metrics: \( d_{AP} = 10 $ m, \( N_{\text{max}} = 10 \).

- **DL throughput gain using higher order MCSs**

Error statistics shown in Figs. 6(c) and 6(d) explain the performance gain. For DL transmission, the ratios of frame reception error due to low RSS, i.e., channel errors, and the
error due to interference, i.e., collision errors, are comparable. Even with a slightly higher channel error rate compared with Reg./Cisco, JACPoT yields greater throughput in DL because higher order MCSs are used on average. In addition, JACPoT keeps DL channel error rate under 10% regardless of $d_{AP}$ as the proposed TPC guarantees.

- UL collisions are reduced by 36%

On the other hand, collision errors are dominant in UL, since STAs have more hidden terminals due to handgrip loss and small antenna gain. By reducing ICI, JACPoT reduces UL collision errors by 36% compared with Reg./Cisco. Therefore, VoIP performance which is generally limited by UL frame errors is enhanced by JACPoT.

VII. CONCLUDING REMARKS

In this paper, we have proposed JACPoT, a centralized and jointly executable TPC and DCA scheme for enterprise WLAN. While most existing schemes do not consider the physical asymmetry between AP and STAs devices, JACPoT is designed by focusing on the network environment with the asymmetry. We confirm the feasibility of JACPoT based on AGS, and examine the accuracy of the proposed DCA metric. Finally, the simulation results demonstrate JACPoT enhances both data and voice traffic delivery by reducing collisions and promoting higher data rate usage. As future work, we are planning to extend our scheme considering channel bonding.

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REFERENCES