Joint Tuning of Physical Carrier Sensing, Power and Rate in High-Density WLAN

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Abstract—Fast proliferation of IEEE 802.11 wireless devices has led to the emergence of High-Density WLAN, where a large number (10s-100s) of Access Points (AP) are deployed to service a larger number (100s-1000s) of users. In such network it is a challenge to improve the throughput because each device has to share channel with all the other devices within its carrier sensing range. So some traditional settings of 802.11 devices need to be self-adaptively tuned. In this paper, we investigate the joint tuning of physical carrier sensing, transmission power and data rate in High-Density WLAN. With introducing an analytical model, we propose two simple yet effective tuning rules to maximize spatial reuse and keep the fairness among users. We also develop a distributed joint tuning algorithm based on these rules. Extensive simulation results show that the proposed joint tuning algorithm achieves significant improvements in both aggregate network throughput and fairness.

I. INTRODUCTION

The past few years have seen a tremendous growth in the deployment of Wireless Local Area Networks (WLAN) conforming to the IEEE 802.11 standard [1]. In [2], the authors showed that large-scale WLANs with high density deployment have emerged widely in various hotspots. Such network comprises of a large number (10s-100s) of Access Points (AP). These APs can be as close as only a few meters away from each other, forming a multi-cell network to service an even larger number of users (100s-1000s) - easily becoming a High-Density WLAN.

With High-Density WLAN, improving the throughput per user is challenging due to the limitation of Carrier Sensing Multiple Access (CSMA) mechanism employed by IEEE 802.11. With CSMA, a user performs Physical Carrier Sensing (PCS), so called Clear Channel Assessment (CCA), to sample the energy in the channel before a data transmission. The transmission will proceed only if the sampled energy is below a threshold known as the PCS threshold. In [3], the authors first investigated the effect of PCS threshold on the throughput per user, and illuminated that tuning the PCS threshold can improve the throughput per user significantly. Later on, a hardware-centric approach [5] was taken to implement a PCS adaptation algorithm using Intel IPW2915 wireless cards. In our previous work [4], we deduced the optimal PCS threshold with an analytical model and proposed a heuristic PCS tuning algorithm to adapt the PCS threshold to the network condition.

In [6] and [7], the authors indicated that the optimal PCS threshold varies with the physical data rate. In [8], the authors investigated the relationship between the transmission power and PCS threshold, and indicated that the tuning of transmission power is capable of changing the requirement of the PCS threshold and alleviating the interference to neighbor transmissions. However, to the best of our knowledge, there is no work on the joint tuning of PCS threshold, transmission power and data rate, which can achieve more significant performance gain in the throughput per user.

In this paper, we focus on High-Density WLAN and propose an analytical model to investigate the relationship among PCS threshold, transmission power and data rate. With the analytical model, we deduce two rules that enable users to tune PCS threshold, transmission power and data rate but not influencing others. Then, based on these rules, we propose a distributed joint tuning scheme, which adapts the PCS threshold, transmission power and data rate to the network condition in a distributed mode. Extensive simulation results based on OPNET are given to validate the performance of the proposed scheme.

The remainder of this paper is organized as follows. In Section II, we introduce an analytical model to study the rules of joint tuning in a distributed environment. Section III presents the details of the joint tuning algorithm. Related simulation results are shown in Section V. Finally, we draw the conclusion in Section VI.

II. ANALYTICAL MODEL

From [9], for each data rate $R$, there is a threshold $\gamma(R)$ indicating the required Signal-to-Interference-and-Noise Ratio (SINR) for decoding. If the user wants to transmit data at the speed of $R$ with high successful probability (e.g., 99%), it should satisfy the inequation

$$\frac{P_g(d)}{N_0 + P_I} \geq \gamma(R)$$

(1)

Herein, $N_0$ is the power of thermal noise, $P_I$ is the transmission power, $g(d)$ is the channel gain which is a function of the distance $d$,

$$g(d) = g_0 d^{-\alpha}$$

(2)

and $P_I$ is the interference power from neighboring transmissions. We conduct the scenario with no hidden terminals, i.e. tuning PCS threshold to make the carrier sensing range cover...
the interfering range completely. Therefore, $P_t$ is smaller than $kP_{CCA}$, where $P_{CCA}$ is the PCS threshold and $k$ represents the number of ongoing transmissions within the PCS range. Thus, we have

$$\frac{P_t g(d)}{N_0 + kP_{CCA}} \geq \gamma(R) \quad (3)$$

If $P_{CCA}$ and $P_t$ are set to satisfy (3), there will be no hidden terminals and $P_t \rightarrow 0$.

It is well known that $\gamma(R)$ is a monotonically increasing function of $R$. From (3), the maximum achievable data rate can be approximated by

$$R_{\text{max}} = \gamma^{-1}\left(\frac{P_{t,\text{max}} g(d)}{N_0}\right) \quad (4)$$

which is obtained under the condition that $P_{CCA} \ll N_0$.

Herein, $P_{t,\text{max}}$ is the maximum power provided by the user. Note that $R_{\text{max}}$ is obtained under the absence of interference, which implies that it cannot be improved by relaxing the restriction to $P_t$. In practical systems, the feasible data rates are limited to discrete values, for example, $\{1, 2, 5.5, 11\text{Mbps}\}$ in IEEE 802.11b and $\{6, 9, 12, 18, 24, 36, 48, 54\text{Mbps}\}$ in IEEE 802.11a/g. Without the loss of generality, we assume there are $M$ data rate indexed as $\{r_1, r_2, ..., r_M\}$ ($r_1 < r_2 < ... < r_M$). From (4), we have

$$R_{\text{max}} = \left\{ \begin{array}{ll}
r_i, & \gamma(r_i) \leq \frac{P_{t,\text{max}} g(d)}{N_0} < \gamma(r_{i+1}), 1 \leq i < M \\
r_M, & \frac{P_{t,\text{max}} g(d)}{N_0} \geq \gamma(r_M) \end{array} \right. \quad (5)$$

Based on (5), $R_{\text{max}}$ can be calculated using the value of SNR from physical layer. When $\gamma(r_{\text{max}}) < \gamma(R_{\text{max}})$, we can decrease the transmission power so as to save power and alleviate the interference to neighbor users. From (3), we have

$$P_t = \frac{(\gamma(R_{\text{max}}) + \sigma)(N_0 + kP_{CCA})}{g(d)} \quad (6)$$

where $\sigma$ is a safety margin for providing enough reliability. Herein, $kP_{CCA}$ is employed to estimate the total interference power. Although $k$ is still an unknown factor, the approximation error can be compensated by choosing a relatively conservative value which is usually 4 or 6.

From (6), the transmitter-receiver pair with short distance will select a high PCS threshold, which brings serious interference to neighbor users. To alleviate this issue, we introduce a rule to balance the transmission power and the PCS threshold: keeping the product of the PCS threshold and the transmission power equal to a fixed constant, i.e.,

$$P_t \cdot P_{CCA} = \beta_1 \quad (7)$$

Herein, $\beta_1$ is set according to the default value of WLAN NIC, i.e., $\beta_1 = P_{t,\text{max}} P_{CCA,d}$ where $P_{CCA,d}$ is the default setting of WLAN NIC (generally -80 dBm) and $P_{t,\text{max}}$ is the maximum value (generally 100mW).

The mathematical validation of (7) is ignored in his paper due to limited space. Similar proof can be found in [8] that (7) can alleviate the collisions due to asymmetric PCS threshold.

With (7), the transmitter-receiver pairs with short distance will use a high $P_{CCA}$ and a small $P_t$, but those with long distance will employ a low $P_{CCA}$ and a large $P_t$, which enforces them to contend channel with more users. Thus, the scheme employing rule (7) is not fair. To address the fairness issue, we continue to propose a fairness related rule to achieve time-sharing fairness among users. The time-sharing fairness means that the time each user occupies the channel is in proportion to $\frac{1}{n_{\text{users}}}$, where $n_{\text{users}}$ is the number of users within the PCS range. Therefore, the time-sharing fairness can be obtained by keeping $n_{\text{users}} \propto R_{\text{max}}^{-1}$.

It is well known that $P_{CCA} \propto R_{\text{max}}^{-\eta}$, $R_e$ is the PCS range. In a uniformly distributed network, the number of users within the PCS range $n_{\text{users}}$ meets $n_{\text{users}} \propto R_e^2$. Thus, we have

$$P_{CCA} \propto R_e^{-\eta} \quad (8)$$

It follows that

$$n_{\text{users}} \propto R_{\text{max}}^{-1} \iff P_{CCA} \propto R_e^{-\eta} \iff P_{CCA} \cdot R_{\text{max}}^{-\eta} = \beta_2 \quad (9)$$

Herein, $\beta_2$ is a constant, and its value is also based on the default value of WLAN NIC, i.e., $\beta_2 = \gamma(R_{\text{max}})$, where $r_1$ is the minimum data rate of WLAN NIC (1Mbps for 802.11b, 6Mbps for 802.11a/g).

In practical tuning, the rules (7) and (9) should be employed as two inequations:

$$\left\{ \begin{array}{l}
\frac{P_t \cdot P_{CCA}}{P_{t,\text{max}} \cdot P_{CCA,d}} \leq \frac{(\gamma(R_{\text{max}}) + \sigma)(N_0 + kP_{CCA})}{g(d)} \\
\frac{P_{CCA} \cdot R_{\text{max}}^{-\eta}}{P_{CCA,d} \cdot r_1^{-\eta}} \leq \beta_2 \end{array} \right. \quad (10)$$

III. POWER EFFICIENT RATE OPTIMIZED PCS TUNING

From the analysis above, users can obtain the maximum data rate by getting the information of the receiver’s SNR, which comes from the per-frame Reception Signal Strength Indicator (RSSI) value (in dBm). Note that the RSSI is the signal strength of received frames. Thus, a precise signal strength measurement requires a closed-loop feedback, such as RTS/CTS interaction. However, such an information exchange will bring additional overhead. In Fig.1, we plot the RSSI distribution for a pair of downlink and uplink, which obtained from practical devices based on Intel 2200/2915 wireless card. It is observed that the uplink and the downlink have nearly the same RSSI distribution. This is mainly because WLAN employs a single channel in both forward link and reverse link, thus we can use the RSSI of the received frames to approximate the channel strength of transmitting link.

With the obtained RSSI, $R_{\text{max}}$ can be determined by (5). Then, we can decrease $P_t$ for power saving and increase $P_{CCA}$ for spatial reuse according to

$$\left\{ \begin{array}{l}
P_t = \frac{(\gamma(R_{\text{max}}) + \sigma)(N_0 + kP_{CCA})}{g(d)} \\
P_{CCA} = \frac{\beta_1}{P_t} \end{array} \right. \quad (11)$$
From (11), the PCS threshold is given by

$$P_{CCA} = \frac{\sqrt{4[\gamma(R_{max}) + \sigma |k|]g(d)} + \gamma(R_{max}) + 2\sigma^2 N_0}{2k} \frac{N_0}{2k}$$

When $P_{CCA} \gg N_0$, (12) is simplified to

$$P_{CCA} = \sqrt{\frac{\beta_1 g(d)}{2[\gamma(R_{max}) + \sigma |k|]} }$$

With the description above, we give a detailed joint tuning solution as follows:

**Joint Tuning Algorithm**
1. Select a user as tuning target.
2. Get target user’s SNR value, estimate the maximum feasible data rate by (5).
3. Measure receiving signal strength to estimate the channel fading $g(d)$ to the target node.
4. Calculate the feasible PCS threshold by (13).
5. If $P_{CCA} \cdot \frac{\tau_1}{R_{max}} > P_{CCA,d} \cdot \frac{\tau_1}{R_{max}}$, change PCS threshold by $P_{CCA} = \frac{P_{CCA,d} \cdot \frac{\tau_1}{R_{max}}}{P_{CCA} \cdot \frac{\tau_1}{R_{max}}}$.
6. Set the transmission power by $P_t = \frac{P_{CCA}}{P_{CCA} \cdot \frac{\tau_1}{R_{max}}}$.
7. If target node’s SNR changes, return to 2.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed scheme in IEEE 802.11g with OPNET simulator V10.5. We enhance the OPNET pipeline models to support the calculation of SINR, and then we measure the SINR thresholds for various IEEE 802.11g rates through single-link simulation. The result is shown in Table I.

| TABLE I |
| 802.11g SINR THRESHOLD FOR EACH RATE |
| Rate | 6Mbps | 9Mbps | 12Mbps | 18Mbps |
| SINR | 5dB | 7dB | 10dB | 10dB |
| Rate | 24Mbps | 36Mbps | 48Mbps | 54Mbps |
| SINR | 15dB | 17dB | 22dB | 23dB |

We deploy several pairs of transmissions, each pair consists of an AP and a station. Constant-bit-rate cuplex UDP traffic (Interval: 0.0001s, Packet Size: 1024 bytes) is generated between each AP and the corresponding station. We implement the joint tuning algorithm in MAC layer.

To better illustrate the reason of performance improvement, we first investigate a simple two-cell scenario, which consists of two links only. After that, we simulate a multi-cell scenario with 8 links to evaluate the performance of the proposed algorithm in a dense deployment.

A. Two-Cell Scenario

We first simulate a simple two-cell scenario, which consists of two links (“AP.1→STA.1” and “AP.2→STA.2”). For the purpose of comparison, 3 cases are considered:

- **Case 1: Default configuration**
  All nodes are configured to the default setting of IEEE 802.11g { $P_{CCA}$: 80dBm, $P_t$: 20dBm, Rate: 54Mbps}.

- **Case 2: Optimal setting of $P_{CCA}$**
  All nodes are configured to the optimal $P_{CCA}$ (-60dBm for this scenario, -63dBm for multi-cell scenario), which is obtained by searching. But $P_t$ and $Rate$ are not tuned.

- **Case 3: Joint tuning of $P_{CCA}$, power, and rate**
  All nodes adapt $P_{CCA}$, $P_t$ and $Rate$ according to the proposed algorithm.
Fig. 3 shows the aggregate throughput comparison. From this figure, it is observed that the joint tuning algorithm outperforms the default configuration and that with the optimal $P_{CCA}$ only. With the default configuration, 4 nodes share the channel with the CSMA/CA mechanism and cannot transmit simultaneously. With the optimal $P_{CCA}$ in Case 2, two pairs can transmit simultaneously because they cannot sense each other. However, due to no power control and rate adaption, the link with long distance is interfered by the other link. As shown in Table II (T1, T2, T3 represent the throughput obtained in Case 1, Case 2, Case 3 respectively), the link of “AP.2—STA.2” is nearly starved, thus the gain of aggregate throughput is limited. With the proposed joint tuning algorithm, both links achieve the best performance and the aggregate throughput almost doubles. Table II shows the detailed results. The joint tuning algorithm makes link 2, whose distance is longer, choose lower rate, lower PCS threshold and higher power. So both links can transmit simultaneously without interfering each other.

<table>
<thead>
<tr>
<th>Link</th>
<th>$R$</th>
<th>$P_1$</th>
<th>$P_{CCA}$</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link 1</td>
<td>54Mbps</td>
<td>7.6dBm</td>
<td>-67.6dBm</td>
<td>13.6M</td>
<td>28.9M</td>
<td>27.6M</td>
</tr>
<tr>
<td>Link 2</td>
<td>36Mbps</td>
<td>13.9dBm</td>
<td>-73.9dBm</td>
<td>13.6M</td>
<td>5.0M</td>
<td>27.6M</td>
</tr>
</tbody>
</table>

### B. Multi-Cell Scenario

![Multi-Cell Scenario](image)

For a high density deployment with 8 links, the results of aggregate throughput and per-link throughput are plotted in Fig. 5 and Fig. 6, respectively. It is observed that tuning $P_{CCA}$ can obtain significant gain compared to the default configuration, and the joint tuning algorithm can get additional gain (up to 20%) by adapting the power and rate. As shown in Fig. 6, the joint tuning algorithm can also improve the fairness among different links significantly. In particular, Link 4 and Link 8 will be no longer starved to zero-throughput as done in that based on the optimal PCS configuration, showing the effectiveness of joint tuning on the fairness issue.

### V. CONCLUSION

In this paper, we introduced and verified two simple yet effective rules for the joint tuning of PCS threshold, power and rate in High-Density WLAN. A distributed joint tuning algorithm was proposed and evaluated. Extensive simulation results showed that the proposed algorithm can improve both aggregate network throughput and fairness.

### REFERENCES


