QoE based power control scheme for interference mitigation in high-density WLANs

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Abstract

Mobile data traffic is going through an explosive growth recently as mobile smart devices become more and more ubiquitous, causing huge pressure on cellular network. Taking advantage of its low cost and easy-to-deploy feature, wireless local-area networks (WLAN) becomes increasingly popular to offload data streams from cellular network, followed by higher and higher density of its deployment. However, the high density of WLAN will cause more interference, which results in degradation of its performance. Therefore, in order to enhance the performance of the network, we aim to minimize the interference caused by high density of WLAN. In this paper, we propose a novel power control scheme to achieve the above aim. We use the quality of experience (QoE) evaluation to coordinate the power of each access point (AP) and finally realize the optimization of the entire network. According to the simulation results, our scheme improves the performance of the network significantly in many aspects, including throughput and QoE.

Keywords

power control, high-density WLAN, interference mitigation, QoE

1 Introduction

The density of WLAN has dramatically increased in recent years. On the one hand, WLANs can efficiently offload data streams from cellular network to release its huge pressure. On the other hand, deploying WLAN is really easy and cheap. So the high-density of WLAN is unavoidable.

To improve the performance of high-density WLAN, we must look deep into the IEEE 802.11 protocol [1]. Contrary to cellular networks, in a WLAN network, there is neither granted time nor dedicated frequency for each user. In fact, there are only several non-overlapping channels that can be simultaneously used by the APs. Therefore, many adjacent APs often use the same channel to communicate with its users. This co-channel communication will cause interference among APs. With the higher density of WLAN, this issue will becomes more and more serious. Furthermore, an IEEE 802.11 device uses carrier sense multiple access with collision avoidance (CSMA-CA) and clear channel assessment (CCA). Whenever a node wants to transmit, it need listen to the channel to determine whether another node is transmitting. Due to the high-density of WLAN, there are too many nodes need to transmit at the same time, which causes the channel becoming too busy. As a result, the performance degradation in high-density scene becomes a severe problem. However, CCA threshold adjustment is a very efficiency way to lessen this problem.

CCA threshold adjustment is a scheme that could increase spatial reuse in high-density WLANs through raising the CCA threshold to a suitable value [2]. Then the number of APs which can transmit data simultaneously will increase. Therefore, CCA threshold adjustment can improve the global throughput of the network. But it may cause more interference between neighboring nodes. In order to minimize the severe signal interference, an applicable transmit power control (TPC) scheme is necessary.

In this paper, a new approach to adjust the transmission power is proposed, which could enhance the performance of the current high-density WLAN. First we use a CCA
threshold adaptation to guarantee more concurrent transmission [2]. Secondly, we develop a novel TPC scheme based on QoE evaluation for interference mitigation. In our presented scheme, each AP can obtain the QoE of itself and its neighbors and adjusts its transmission power to optimize the whole WLAN.

The rest of this paper is organized as follows. We summarized the related works and described the motivation of our work briefly in Sect. 2. In Sect. 3, we show the system model and the related formula derivation of our algorithm, and a novel power control algorithm is introduced. In Sect. 4, we describe our simulation setup and analyze the results. Finally, we conclude the paper and reveal our prospects in Sect. 5.

2 Motivation and related work

There are many optimization methods for the current high-density WLAN to enhance its performance. In order to increase the throughput of the global network, CCA adaptation mechanism may be used effectively to optimize the spatial reuse in dense WLAN deployments. In Ref. [2], Jamil et al. propose a method using CCA threshold adjustment to improve the aggregate throughput in WLANs. And in Ref. [3] another CCA threshold selection method is proposed to ensure both real-time and reliability for emergency warning message (EWM) transmission. But CCA threshold adjustment may cause more interference.

Channel allocation has always been a hot research area to mitigate interference. The work in Ref. [4] incorporates the load balancing problem into the channel assignment framework. In the least congested channel search scheme in Ref. [5], each AP autonomously searches for the most lightly loaded channel to minimize the interference between different APs.

In high-density WLANs, the distance between an AP and its client is short enough to maintain their communication link, even though the TPC scheme might reduce the power of some APs. In recent years, several TPC algorithms have been proposed to mitigate interference in WLANs. In fact, TPC was brought from the power control adopted in cellular networks. But many researches have denoted that applying TPC to WLANs is not reliable if it is not applied similarly on all nodes in close proximity to avoid starvation [6–8].

In Ref. [9], Fernandes et al. propose a power control algorithm depended on some complex communication between adjacent APs. However, it brings addition overhead of both communication and computing. And in Ref. [10], Jia et al. propose a power control algorithm called power-controlled estimated rate fallback (PERF) that tunes the transmit power of an AP such that it can support all its clients at the highest transmission rate. But this greedy approach at each node is unlikely to be optimal from the viewpoint of the overall network.

Therefore, we are intended to design an easy and feasible power control scheme to solve the above problem. After doing CCA threshold adjustment and channel allocation, we conduct our power control scheme based on QoE evaluating.

3 Problem formulation

We consider a classic high-density WLAN. For simplicity, the following settings are adopted:

1) To facilitate the analysis, the topology of network is set to be like Fig. 1 which is inerratic. But the analysis results can also be applied to other more complex topology.

2) We focus on downlink video services in high-density WLANs, which are fully saturated.

3) Each AP uses one of the non-overlapping channels specified in IEEE 802.11n standard with 2.4 GHz operational bands, e.g., channel 1, 6, and 11. And each UE is connected with the closest AP.

4) The CCA threshold adjustment ensures all the APs in Fig. 1 (e.g. AP1~AP7) can transmit data simultaneously.

5) Each AP holds a periodically updated table that stores
the information of network status and neighboring APs.

6) In Fig. 1, AP2~AP7 use the same channel as AP1, but due to the CCA threshold adjustment, they can transmit data with their UEs at the same time. The APs in blank spaces are denoted to use different channel from AP1. Hence, we just consider the APs which use the same channel.

3.1 Signal to interference plus noise ratio (SINR)

On a basis of wireless transmission model mentioned in Ref. [11], we apply it to our scenario to get our SINR for a user in AP1 by:

\[ \gamma = \sum_{i \neq j} G_{ij} P_{ij} X_{ij} + N_i \]  \hspace{1cm} (1)

where \( \gamma \) denotes the SINR, \( P_i \) and \( P_j \) are the transmission power of APi and APj, respectively. \( G_{ij} \) is the average channel gain of APi to the users in APj and \( G_{ij} \) is the average channel gain of APj to users in APi. \( X_{ij} \) is the channel allocation indicator indicating whether or not the APi and APj use the same channels. If the APi and APj use the same channel, the value of \( X_{ij} \) is set to 1, otherwise, the value of \( X_{ij} \) is set to 0. \( N_i \) denotes the variance of additional white Gaussian noise (AWGN).

Based on Friis transmission in Ref. [12], the pass loss model in our scenario is given by Eq. (2)

\[ P_l = 32.5 + 20 \log d + 20 \log f \]  \hspace{1cm} (2)

where \( P_l \) presents the path loss (PL), \( d \) presents the distance between the AP and the user, and \( f \) denotes the carrier frequency. Their units come out in ‘km’ and ‘MHz’ separately. Here in our scene, the value of \( f \) is 2.4 GHz. So the pass loss model can be simplified into Eq. (3):

\[ P_l = 100 + 20 \log d \]  \hspace{1cm} (3)

Based on the definition of dBm, the relationship between the channel gain (\( G \)) and PL can be expressed by:

\[ P_l = -10 \log G \]  \hspace{1cm} (4)

Then, the channel gain can be given by:

\[ G = 10^{\frac{P_l}{10} - 20 \log d} \]  \hspace{1cm} (5)

Therefore, we can calculate the SINR through the distance between the AP and the user. Then, the QoE value can be figured out.

3.2 QoE of video application

There are a lot of models to predict video QoE in wireless network. Based on the QoE models presented in Refs. [13–14], we choose a video prediction model considering three most dominant factors i.e., the frame rate (FR), send bit rate (SBR), and packet error rate (PER), and the expression can be obtained as follows:

\[ M = a_1 + a_2 F_r + a_3 \ln V \]

\[ 1 + a_4 E_p + a_5 E_p^2 \]  \hspace{1cm} (6)

where \( a_i (i' = 1, 2, 3, 4, 5) \) are coefficient values, \( M \) denotes the mean opinion score (MOS), \( F_r \) presents the FR, \( V \) presents the SBR and \( E_p \) presents the PER.

According to Ref. [14], content type has significant influence on the visual quality. The authors classify the video content type into three categories (slight movement (SM), gentle walking (GM), rapid movement (RM)). When the different types of video clips are considered, different sets of coefficient values are obtained using the trained method based on subjective quality test. The coefficients for all the three content types are given in Table 1.

| Table 1 Coefficients of metric model for all content types |
|-----------|-----|-----|-----|
| Coefficient | SM  | GW  | RM  |
| \( a_1 \)   | 4.579 | 6   | 3.475 | 7   | 3.094 | 6   |
| \( a_2 \)   | -0.006 | 5   | 0.002 | 2   | -0.006 | 5   |
| \( a_3 \)   | 0.057 | 3   | 0.040 | 7   | 0.146 | 4   |
| \( a_4 \)   | 2.207 | 3   | 2.498 | 4   | 10.043 | 7   |
| \( a_5 \)   | 7.177 | 3   | -3.743 | 3   | 0.686 | 5   |

Denominator of Eq. (6) is measured in terms of PER which reflects the impact of network parameter on the video quality, while the numerator is measured in terms of FR and SBR, which represent the impact of encode parameters on the video quality. Taking into account network parameter, encode parameter and content type, we obtain the appropriate Eq. (6) to describe our QoE model.

The SBR can be calculated by Shannon:

\[ V_s = B \ln (1 + \gamma) \]  \hspace{1cm} (7)

where \( B \) is the bandwidth of wireless network and \( \gamma \) is the SINR obtained.

In real application standards, such as 3GPP, HIPERLAN/2, IEEE802.11a and IEEE 802.16, the bit error rate (BER) expression under a given modulation and coding schemes (MCS) can be approximated by [15]:

\[ E_b(\gamma) = \frac{a_u}{e^{b_u}} \]  \hspace{1cm} (8)

where \( E_b \) presents BER, \( a_u \) and \( b_u \) listed in Table 2 are obtained by fitting Eq. (8) in different MCS modes and \( \gamma \) is the SINR obtained.
is a sensitivity exponent. 

denotes the QoE contrast parameter which shows greater than the increasing trend. Hence, the overall average MOS presents a decreasing trend.

of its adjacent APs decreases. But the decreasing trend is increases its own power, its MOS increases, and the MOS of its adjacent APs decreases. But the increasing trend is greater than the decreasing trend. Hence, the overall average MOS presents an increasing trend.

5) The result of the power change of a single AP will certainly belong to one of the four above conditions. Therefore, when the power of several APs changes simultaneously, the result will be the combination of the four above conditions.

Our goal is to achieve a global optimization of perceptive quality by adjusting the transmission power of APs. When the QoE value of some APs in the network is high while that of the other APs is low, we need to adjust the transmission power of APs to appropriately reduce the SINR of the APs with higher QoE value, and improve the SINR of the ones whose QoE value is lower. As a slight reduction of SINR has smaller influence on the APs with lower QoE value, their QoE values improve a lot because SINR has tremendous influence on them. Consequently, the proposed power control scheme based on QoE can effectively enhance the entire network performance.

Following is the concrete description of the algorithm. 

We propose the novel power control scheme to minimize the interference caused by high density of WLAN. The power increase of an AP will bring about the SINR increase of itself and the SINR descendant of the neighboring APs, and vice versa. As a general rule, improvement of SINR can lead to the increase of QoE. However, when QoE has reached a value that is high enough, further improvement of SINR has little influence on QoE. On the other hand, when video quality is poor, that is, the value of QoE is low, the slight increase of SINR can greatly improve the perceptive quality. Therefore, the influence of the change of power on MOS is divided into the following different conditions:

1) When an AP with higher MOS than its adjacent APs reduces its own power, its MOS decreases, and the MOS of its adjacent APs increases. But the increasing trend is greater than the decreasing trend. Hence, the overall average MOS presents an increasing trend.

2) When an AP with higher MOS than its adjacent APs increases its own power, its MOS increases, and the MOS of its adjacent APs decreases. But the decreasing trend is greater than the increasing trend. Hence, the overall average MOS presents a decreasing trend.

3) When an AP with lower MOS than its adjacent APs reduces its own power, its MOS decreases, and the MOS of its adjacent APs increases. But the decreasing trend is greater than the increasing trend. Hence, the overall average MOS presents a decreasing trend.

4) When an AP with lower MOS than its adjacent APs increases its own power, its MOS increases, and the MOS of its adjacent APs decreases. But the increasing trend is greater than the decreasing trend. Hence, the overall average MOS presents an increasing trend.

Then, the PER can be given by:

\[ E_p = 1 - (1 - E_r)^l \]  (9)

where \( l \) denotes the packet length of the video source.

### 3.3 TPC scheme

We propose the novel power control scheme to effectively enhance the entire network performance.

We set the 0.55 and 0.45 as the thresholds to avoid Ping-Pong effect. Hence, when \( A_i \) is between 0.45 and 0.55, we do not need to adjust the transmission power of AP. When \( A_i \) is less than 0.45, we should reduce the transmission power of AP. When \( A_i \) is greater than 0.55,
we should increase the transmission power of $AP_i$. The pseudo code is presented as follows:

```
1: Transmission power initialization.
2: Set the maximal power $P_{\text{max}}$ and the minimal power $P_{\text{min}}$.
3: while (the algorithm is on)
   4: for $i = 1: M$
      5: calculate $D_i$ according to Eq. (10);
      6: calculate $A_i$ according to Eq. (11);
      7: if ($0.45 < A_i < 0.55$ or $P_i > P_{\text{max}}$ or $P_i < P_{\text{min}}$)
         8: $P_i = P_i$;
      9: elseif ($A_i > 0.55$)
         10: $P_i = P_i + 5$
      11: else
         12: $P_i = P_i - 5$
   13: end if
14: end for
15: end while
```

We can observe that, it is actually the QoE difference between each AP, i.e. $A_i$, which drives the algorithm. When $A_i$ reaches the threshold, a corresponding power adjustment will be conducted. As long as $A_i$ still stays in this interval, the adjustment will continue, until $A_i$ meet the requirements or the power of AP reaches the limit which means a steady state is reached. When the external condition changes, the steady state is broken, then the power control scheme restarts to adjust the power of each AP and achieve a new steady state.

4 Performance evaluation

4.1 Simulation environment

In the previous section, we have analyzed our novel TPC algorithm in high-density WLANs. In this section, the performance of proposed scheme is evaluated using Matlab. The system model is presented in Sect. 3.1. As depicted in Fig. 1, each cell is a hexagon with radius ($R$) of 7 m. The value of the used frequency reuse is three. The hexagon with APs in it represents co-channel cells, while other blank hexagons represent APs that use other channels. After a CCA threshold adjustment, all the co-channel APs can transmit data with users simultaneously. Then we apply power control scheme to optimize the QoE of the entire network. The results of three schemes are presented for comparison: no power control, greedy-based power control and our proposed power control. Users randomly move within the entire network, and there is at least one user in the scope of each AP. The corresponding parameters used in the simulations are given in Table 3.

<table>
<thead>
<tr>
<th>Table 3 Simulation parameters</th>
</tr>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Number of AP</td>
</tr>
<tr>
<td>Maximum transmission power ($P_{\text{max}}$/mV)</td>
</tr>
<tr>
<td>Minimum transmission power ($P_{\text{min}}$/mV)</td>
</tr>
<tr>
<td>Default transmission power/mV</td>
</tr>
<tr>
<td>Sensitivity exponent ($\alpha$)</td>
</tr>
<tr>
<td>Packet length (l)</td>
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<tr>
<td>Modulation type</td>
</tr>
<tr>
<td>Content type</td>
</tr>
<tr>
<td>Bandwidth of wireless network (B)/Mbit</td>
</tr>
</tbody>
</table>

4.2 Simulation results

We evaluate the performance of our approach by comparing it with greedy-based TPC and no TPC system in terms of the average value and variance of the QoE value of all the APs.

In Fig. 2, the type of video content is RM. We plot each AP’s QoE value ($AP_1$, $AP_2$, $AP_3$, $AP_4$, $AP_5$, $AP_6$, and $AP_7$) and the average QoE value of all APs during our novel TPC scheme. We can easily observe that, different APs present different states in the beginning. During the process of our power control scheme, APs with higher QoE lower their transmission power to decrease the interference to other APs. Therefore, their QoE decrease slightly and finally reach a steady state. On the contrary, APs with lower QoE increase their transmission power so that their QoE increase rapidly until reaching the steady state. Ultimately, the average QoE of the entire network improves dramatically.

As shown in Fig. 3, this experiment simulation depicts the comparison of three different schemes: the proposed novel TPC, greedy-based TPC and no TPC in three types of video content. During the first twenty seconds, by
adjusting the power of each AP, the power control scheme improves the QoE of the entire network and reaches a steady state. At the 20th, 60th and 80th second, because of the change of the external condition, the steady state is broken. As a result, the power control scheme restarts to adjust the power of each AP and achieve a new steady state.

Fig. 3 QoE variation in three different systems

However, the external condition does not change much at the 40th second, so the steady state remains the same. Obviously, compare with the network that imposes no power control scheme, the network adopting our scheme presents huge increase in QoE, while greedy-based scheme just slightly improves the QoE of the network, which is very unnoticeable. We can also observe that, under different conditions with three types of video contents, the trends of the curve are all the same, and our proposed scheme all performs the best.

Furthermore, as depicted in Fig. 4, the video content type is RM. During our proposed power control process, the variance of all APs’ QoE decreases rapidly while the variance of all APs’ QoE in greedy-based TPC system is almost the same as a no TPC system. The external condition is the same as Fig. 4. During the first 20 s, by adjusting the power of each AP, the power control scheme improves the QoE of the entire network and reaches a steady state. At the 20th, 60th and 80th second, because of the change of the external condition, the steady state is broken. However, the external condition does not change much at the 40th second, but the variance is not as low as other periods of time. The reason is that the power of APs reaches the limit. Apparently, it proves that our algorithm is reliable as far as fairness is concerned. It is applied similarly on all nodes in close proximity.

Fig. 4 The variance of QoE in three different systems

5 Conclusions and perspectives

This paper proposes an original TPC scheme to mitigate interference in high-density WLANs. The algorithm is discussed and thoroughly analyzed. Novel TPC scheme achieves a good performance compared with the greedy-based TPC system and the no TPC system in QoE and fairness. This approach is tested in the environment of IEEE 802.11n. In the future, we will validate it in IEEE 802.11ac and other protocols up to date.
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