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Joint Transmit Power Control and Rate Adaptation for Wireless LANs

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Abstract Wireless local area networks (WLANs) are widely deployed recently. But many basic service sets (BSSs) nearby have to share a common channel due to the limitation in the spectrum resource. To get higher throughput with newly deployed access points (APs), it is necessary to improve spatial reuse of the channels by transmit power control (TPC). The achievable throughput, however, heavily depends on other factors such as rate adaptation (RA). Moreover, TPC without careful design may lead to asymmetric links and degrade fairness. In this paper, we jointly design TPC and RA to further improve total throughput of WLANs, and suggest (i) choosing power for each BSS by maximizing throughput which takes tradeoff between transmit rate and spatial reuse of channels, and, (ii) avoiding potential asymmetric links by explicit coordination among APs: each BSS uses almost the same power as its co-channel neighbors while BSSs far from each other may use different power levels as required. Extensive simulation evaluations confirm that the proposed scheme can greatly improve total throughput of dense WLANs, meanwhile fairness is retained.

Keywords Wireless LAN · Transmit power control · Rate adaptation · Asymmetric link

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1 Introduction

With the fast growth of smartphone market, the volume of data traffic explodes on cellular networks. WiFi offloading is suggested to solve this problem in [1,2], where cellular networks ensure coverage and QoS (quality of service) of voice traffic while most data traffic is offloaded to wireless local area networks (WLANs). The 2.4 GHz ISM (industrial, scientific and medical) band for 802.11 b/g has only three orthogonal channels. The eight channels at 5.2 and 5.3 GHz bands for 802.11a/n are limited to the indoor use. To accommodate the exponentially increasing data traffic, the 5.6 GHz band, with 11 orthogonal channels of 20 MHz, was allocated to WLANs in Japan recently. This band is available for outdoor use and is being applied to smartphones. Besides the spectrum allocation, a new trend in WLANs is to improve performance by centralized management.[1]

Transmit power control (TPC) is both necessary and feasible for WLANs. The necessity comes from the pressure of improving per-node throughput and total throughput. The number of orthogonal channels is limited. Many access points (APs) have to contend for the same channel when APs are densely deployed. Without careful design, the increase in the AP density only adds to co-channel interference. Although channel assignment [3] or AP selection can partially alleviate this problem, their performance is limited by the channel bandwidth. Cells in cellular networks evolved from macro cells to micro cells, pico cells and currently femto cells [4]. As an analogy, the ultimate solution to improve the throughput of WLANs is to decrease the size of each basic service set (BSS) by TPC. TPC also becomes feasible with the increase in the number of deployed APs. In such scenarios, most nodes can find an AP nearby and the full transmit power becomes more than necessary. Instead, transmissions can be done with just enough power to enable more parallel transmissions.

A tradeoff between TPC and rate adaptation (RA) usually is necessary [5,6]. With carrier-sense multiple access (CSMA) [7] in WLANs, transmissions cannot be done simultaneously on links nearby sharing the same channel. This exposed terminal problem limits spatial reuse of spectrum. More exposed terminals are generated under a larger power. On the other hand, transmit power should be high enough to guarantee a certain level of transmit rate (QoS) over a link. This conflict calls for a nice tradeoff. In addition, simply adjusting power per link may generate asymmetric links (some links may be starved) [8] due to the carrier sense (CS) mechanism of CSMA. Previous works on TPC are either too simple to exploit the full capability of TPC, or too complex to be practical. *A good TPC protocol should be designed to maximize throughput, avoid potential asymmetric links and be made very simple to facilitate its deployment*.

In this paper, we aim to maximize total throughput of WLANs through jointly designing TPC and RA. TPC is performed via the management part in a centralized way. Channel access, using the computed power, remains distributed for the simplicity and flexibility. We investigate two aspects: (i) How to choose power levels to balance the tradeoff between transmit rate and spectrum reuse. Receive signal strength indicator (RSSI)-based RA is adopted and a suitable interference margin is set to resist potential interferences. The power for each BSS is found by maximizing its BSS throughput, taking into account the channel contention among co-channel BSSs. (ii) How to avoid asymmetric links (to ensure fairness). The basic policy is that each BSS uses almost the same power as its co-channel nearby BSSs and that two BSSs far away may use different power levels. Extensive simulation evaluations

[1] Public WLANs run by cellular-network operators are managed in a centralized way. As for private WLANs, more and more users mutually share their APs and form the largest Wi-Fi (Wireless Fidelity) community—FON (http://www.fon.com/), where centralized management is also a trend.

confirm that the proposed scheme can effectively improve total throughput of dense WLANs, meanwhile fairness is retained.

The rest of the paper is organized as follows: Problem definition and related work are discussed in Sect. 2. System model and TPC algorithm are presented in Sect. 3. Protocol designs of RA and TPC are described in detail in Sect. 4. Simulation results are analyzed in Sect. 5. Finally we conclude the paper with Sect. 6.

2 Related Work and Problem Definition

WLANs adopt CSMA [7] as the main channel access mechanism. A node regards the channel as being idle if the detected RSSI is less than a pre-determined CS threshold, CS_{th}. All nodes within the CS range of a sender defer from channel access, which causes serious exposed terminal problem [9, Chapter 4.2.3]. On the other hand, weak signals neglected by CS remain as interferences. Potential collisions inside a same CS range may greatly degrade system performance. In consequence, the achievable throughput depends on both per-link rate and spatial, exclusive channel share among links.

2.1 Rate Adaptation

RA schemes are used to find a proper rate for each outgoing packet. Conventional RA schemes [10,11] only consider channel fading. They rely on statistics of packet loss to trigger a rate drop and build on the auto-rate fall back (ARF) mechanism [12]. Their differences usually lie in how to tune the thresholds [10] and in what criterion to use [11].

Collision-aware RA schemes are also studied recently. In congested CSMA networks, there are two kinds of packet loss, caused by either collision or fading. These packet losses should be handled differently, backoff for collision and RA for fading. The initial effort made to distinguish the packet loss was addressed in [13]. Later, different schemes were successively suggested to statistically tell collision from fading at the sender [14–16], where the rate is dropped only when packet loss is caused by fading. Some cross-layer designs are suggested to diagnose the reason of packet loss and find a proper rate based on confidence information of decoded bits [17,18]. But it is still necessary to feed the rate information from the receiver to the sender. Instead, the RSSI of ACK frames is often used to estimate the signal to noise ratio (SNR) [19]. However, the SNR at the sender is different from that at the receiver in the presence of interference and this may degrade the RA performance.

2.2 Spatial Reuse of Channels

Maximizing spatial reuse of channels can be done via reducing transmit power or increasing CS threshold [5,6], or using both. Initial efforts in TPC remove the redundancy in transmit power, dropping the transmit power in such a way that the maximal rate is still available [20]. Concurrent transmissions are enabled via TPC in [21], using the instant feedback of interference information from the receiver to the sender. The two-step TPC scheme, suggested in [22], adjusts the power so that the transmit rate of a link under TPC is no worse than the one achieved without TPC. These schemes all heavily depend on RA. TPC usually applies to dense and congested networks. As described above, in such scenarios, RA schemes such as ARF usually do not work well [15]. SNR-based RA [19] cannot effectively take into account potential interference at the receiver. And the feedback of interference information [21] takes much overhead. The effect of TPC also depends on power granularity. This is investigated in [23]. It is shown that typically 2–4 power levels are sufficient for off-the-shelf WLAN cards. But more power levels will be needed when power can be adjusted in a larger range. Recently, a hardware-independent TPC interface is also studied in [24].

Simply adjusting power per link in WLANs may generate asymmetric links [8], which further lead to starvation or hidden terminal problems. The simplest solution is to use a common power within the whole network, as suggested in [8], where several extensions were also studied. However, in this way, even a single link with poor quality may lead to the use of a large power in the network. A refinement is to divide links requiring different powers into separate groups. At the same moment transmissions take place only inside a single group, where the same power is used [25]. The potential hidden terminal problem is mitigated in [26] by investigating the interfering relationship between nearby nodes. But the two schemes [25,26] require tight scheduling, which makes the protocol very complex. Recently, joint optimization of transmit power and CS threshold is suggested to solve this problem in a distributed way [27]. In another scheme [28], each node randomly selects a transmit power from all available power levels to access the medium. The access probabilities of each power setting is determined according to the arrival rate of traffic and the service rate. The two schemes [27,28], however, take a relatively long time to converge.

Channel reuse can also be realized in different ways. In most CSMA networks, only one transmission is performed in a CS range. By a centralized scheduling, two senders can transmit simultaneously to two far-separated receivers [29,30]. An even aggressive policy is to make full-duplex transmission by complex antenna design [31]. On this basis, interference notification [32] also becomes possible. But each collision unavoidably leads to the waste of channel resource. Therefore, TPC is still necessary in order to reduce the collision domain and control the collision probability.

2.3 Our Work: Joint Design of TPC and RA

We aim to improve total throughput of WLANs by joint design of TPC and RA, and consider the following problems in the same framework: how to enlarge channel reuse, how to avoid asymmetric links [8], and how to deal with potential interference. The first problem is explained by the left part of Fig. 1. All APs and nodes run on the same channel in the IEEE 802.11a mode. To support the maximal rate [20] (54 Mbps) over the down link from AP_1 to M_1, a high power level is used by AP_1. This hinders simultaneous transmissions over down link AP_2–M_2, and up links M_3–AP_3 and M_4–AP_4. The second problem is explained in Fig. 2. Two adjacent BSSs sharing the same channel use quite different power levels. Radio signal from AP_1 arrives at AP_2 with RSSI greater than CS_{th} but not vice versa. Then, asymmetric links are formed. Accordingly, AP_2 will sense the channel as being busy more often than AP_1. In addition, when M_2 transmits to AP_2, the reception at AP_2 may be ruined

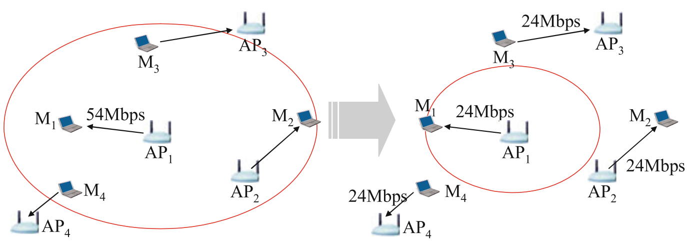

Fig. 1 Tradeoff between transmit rate and channel reuse

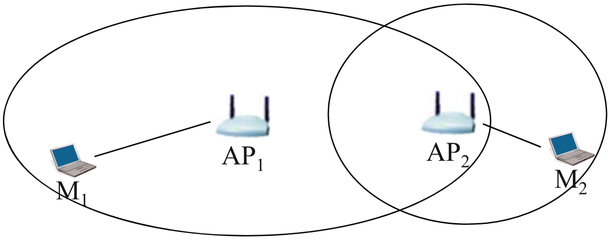

Fig. 2 Potential asymmetric links under uncoordinated TPC

by a concurrent transmission from AP_1. In consequence, the link AP_2–M_2 might be starved. The third problem is related to the CS mechanism. A channel declared to be clear only means that RSSI at the sensing node is less than CS_{th}. The neglected weak signals remain there as interferences and will affect the reception.

The proposed scheme solves the above problems as follows. (i) *Stressing channel reuse*. Instead of insisting use of a big power to ensure the maximal rate [20], power levels are lowered to reduce the number of exposed nodes. This increases spatial reuse of channels, as shown in the right side of Fig. 1. With the drop of power level, the rate over link AP_1–M_1 is reduced to 24 Mbps. But packets can be transmitted in parallel on the other three links and the aggregate rate increases to 96 Mbps. (ii) *Avoiding asymmetric links meanwhile meeting different power requirements*. To avoid asymmetric links, power difference between adjacent BSSs is controlled. But power difference between BSSs far away is allowed by smoothly changing power levels in the network. (iii) *Strengthening RA to endure potential interference*. Dropping power reduces the redundancy in RSSI. The RA scheme, considering the interference neglected by the CS mechanism, ensures that transmissions at the chosen rate will not be corrupted. RA also affects the selection of power levels, which requires joint design of TPC and RA.

3 Transmit Power Control Algorithm

In this section we present the TPC algorithm. We first describe the system model in Sect. 3.1. Then, the relationship between throughput and power levels is formulated in Sect. 3.2. To facilitate protocol design, an approximate solution is suggested in Sect. 3.3.

3.1 System Model

We consider a large and dense network with many APs and nodes sharing a limited number of channels. Because off-the-shelf WLAN cards do not support the dynamic adjustment of CS_{th}, we exploit joint TPC and RA under a fixed CS_{th}. To ensure coverage, management frames, such as beacons, are always transmitted at the full power (P_{mgr}). When there is redundancy in the RSSI, the power (P_{data}) for data frames is reduced. Within each BSS, both the AP and its associated nodes use the same power to transmit data frames and their ACK frames.

All APs are connected to a centralized TPC manager (TPCmgr). APs periodically report self information (AP ID, channel ID), information of associated nodes (node ID, RSSI) and information of neighboring APs (AP ID, RSSI) to TPCmgr. Based on this information, TPCmgr computes data power for each BSS. In the computation, link quality (transmit rate), neighboring relationship among APs (sharing channel by CSMA), and coordination among

APs (avoiding asymmetric links) are considered. TPCmgr sends the computed data power to APs, which further notify the associated nodes via periodical beacons.

We use following notations in subsequent analysis.

1. Altogether there are n APs in a management domain, forming a set $\{AP_j\}$. AP_j has an associated node set, $\boldsymbol{S}_j$, which contains the pairs of <node ID, RSSI>.
2. In the jth BSS, AP_j and its associated nodes in $\boldsymbol{S}_j$ use the same data power P_j. $\boldsymbol{P} = [P_1, P_2, \ldots, P_n]$ is the power vector of all BSSs.
3. AP_j has a neighboring AP set $\boldsymbol{L}_j$ from which beacon frames are received. $\boldsymbol{L}_j$ contains the pairs of $\langle$AP ID, RSSI$\rangle$. AP_j has a smaller neighboring AP set $\boldsymbol{N}_j \subset \boldsymbol{L}_j$. $\boldsymbol{N}_j$ contains APs whose data packets arrive at AP_j with RSSI greater than CS_{th}.
4. $r_{ij}(\boldsymbol{P})$ is the rate determined by RA for the link between AP_j and node M_i.
5. To provide a certain level of QoS, the data rate of each link is no less than a threshold r_{th} (i.e., RSSI is no less than a predetermined threshold $RSSI_{th}$).
6. The available power levels belong to the range $[P_{min}, P_{max}]$, spaced by P_{delta}, all in the unit of dBm.
7. Power difference between AP_j and its neighbors in $\boldsymbol{L}_j$ should be no more than δ_P so as to avoid asymmetric links, as follows:

$$|P_j - P_k| \leq \delta_P, \quad \text{if } AP_k \in \boldsymbol{L}_j. \tag{1}$$

3.2 Optimal Power

Let us consider transferring a unicast packet with a MAC protocol data unit (MPDU) length of l_{ij} over the link M_i–AP_j at rate $r_{ij}(\boldsymbol{P})$. This MPDU is transmitted at the cost of extra protocol overhead (t_o) which includes preamble, SIFS (short inter-frame space) and ACK. The effective bit rate for the MPDU is

$$r'_{ij}(\boldsymbol{P}) = \frac{1}{1 + t_o/\left(l_{ij}/r_{ij}(\boldsymbol{P})\right)} \cdot r_{ij}(\boldsymbol{P}), \tag{2}$$

which is less than $r_{ij}(\boldsymbol{P})$ due to the overhead ratio $t_o/\left(l_{ij}/r_{ij}(\boldsymbol{P})\right)$.

Transmissions take place almost fairly over each link of a BSS, in a long term under the CSMA mechanism. On average, transmitting one bit in the BSS of AP_j takes the time $t_j(\boldsymbol{P})$, as shown in Eq. (3).

$$t_j(\boldsymbol{P}) = \left[\sum_{i \in \boldsymbol{S}_j} 1/r'_{ij}(\boldsymbol{P})\right] / |\boldsymbol{S}_j|. \tag{3}$$

The throughput ($\gamma_j(\boldsymbol{P})$) that can be achieved by AP_j depends on two factors: (i) $t_j(\boldsymbol{P})$ which reflects the average link quality inside the BSS of AP_j and (ii) the number of neighboring APs sharing the same channel and the qualities of links inside those BSSs. AP_j competes with its neighbors in $\boldsymbol{N}_j$ and each AP has the same access chance under CSMA. Then, $\gamma_j(\boldsymbol{P})$ can be calculated by Eq. (4).

$$\gamma_j(\boldsymbol{P}) = 1 \Bigg/ \left[\sum_{k \in \{j\} \cup \boldsymbol{N}_j(\boldsymbol{P})} t_k(\boldsymbol{P})\right]. \tag{4}$$

Obviously the target of TPC is to find the power vector $\boldsymbol{P}$ that maximize the total throughput in Eq. (5), under the constraint of power difference specified in Eq. (1).

$$\boldsymbol{P} = \mathop{\arg\max}_{\boldsymbol{P}, |P_j - P_k| \le \delta_P \text{ for } AP_k \in \boldsymbol{L}_j} \sum_j \gamma_j(\boldsymbol{P}). \tag{5}$$

3.3 Approximate Solution

Directly solving Eq. (5) to find the optimal power is computationally impractical since the search space grows exponentially with the number of APs. We will take some approximation to facilitate the design of a practical protocol.

When δ_P in Eq. (1) is small enough, adjacent APs almost use the same power level. Exploiting this property, $\boldsymbol{P}$ in Eqs. (2–5) can be replaced by P_j, and these equations are simplified as follows:

$$t_j(P_j) = \left[\sum_{i \in \boldsymbol{S}_j} 1/r'_{ij}(P_j)\right] / |\boldsymbol{S}_j|. \tag{6}$$

$$\gamma_j(P_j) = 1 \Bigg/ \left[\sum_{k \in \{j\} \cup \boldsymbol{N}_j(P_j)} t_k(P_j)\right]. \tag{7}$$

$$P_j = \mathop{\arg\max}_{P_j} \gamma_j(P_j). \tag{8}$$

Then, power levels solved by Eq. (8) are post-adjusted so that Eq. (1) is satisfied.

The achievable throughput depends on both transmit rates and the overhead ratio. For a IPv4 packet with 1,500 bytes, when ACK is transmitted at the same rate as the data, the overhead ratio is 26.3 % at 54 Mbps, and 12.5 % at 24 Mbps, relatively small. Therefore, rates play the major roles in the computation of power, and a further approximation can be made to use $r_{ij}(P_j)$ instead of $r'_{ij}(P_j)$ in Eq. (6).

4 Protocol Design of RA and TPC

Based on the analysis in Sect. 3.3, in this section, we present the protocol design, RA in Sect. 4.1 and TPC in Sect. 4.2.

4.1 RSSI-Based Rate Adaptation

Rates in Eq. (6) play an important role in the TPC scheme, especially when trading off per-user transmit rate with channel reuse. TPC removes the RSSI redundancy, dropping the power to increase channel reuse. But it makes the transmission more susceptible to interferences as well. It is important that while reducing power and choosing rate, there should still be enough margin in RSSI to resist potential interferences, which are neglected by the CS mechanism. But too large a margin harms channel reuse.

A node initiates a new transmission if the channel is sensed as being idle. The neglected interference plus noise power is less than CS_{th}. But in a dense network, this value often approaches CS_{th} and it can be conservatively approximated as CS_{th}. The dB difference between CS_{th} and noise power is treated as the interference margin. This interference margin has another effect in this paper. There may be a small difference between powers of adjacent BSSs (no more than δ_P). Setting a little larger interference margin endures the small power difference as well.

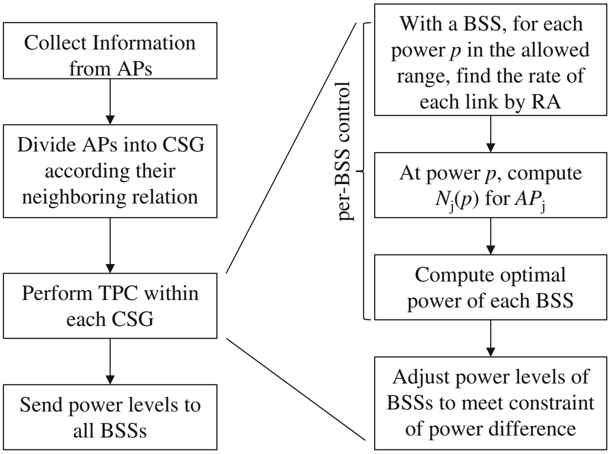

Fig. 3 Flowchart of transmit power control

4.2 Transmit Power Control Protocol

The TPC function is performed periodically by TPCmgr, following the flowchart in Fig. 3. At first, TPCmgr collects information of all APs. On this basis, APs are divided into independent management domains—connected sub-graphs (CSGs). Within each CSG, power is computed for each BSS, and then adjusted so as to meet the power difference requirement. Finally, the power values are sent to all BSSs for data transmissions.

As the effect of TPC depends on association control, it is expected that in the whole system, TPC should run with a longer period than association control. Then, with the result of association control (RSSI of each link), proper power levels are computed for APs. In the case where APs are densely deployed, as a node moves away from one AP towards another, handover is preferred instead of increasing the power levels because the latter will degrade spatial reuse of channels.

4.2.1 Building CSGs

CSGs are built based on the neighboring relationship among APs, for each channel separately. Initially an empty CSG, CSG_1, is created. APs sharing the same channel, CH_i, are sorted into a list, $List_i$, in the increasing order of their IDs. The first AP of $List_i$, AP_1, is removed from $List_i$ and added to CSG_1. Then, neighbors of AP_1 are removed from $List_i$ and added to CSG_1 as well. This is recursively conducted so that all neighbors of APs in the CSG are also added to the same CSG. If APs not belonging to any CSG remain, a new CSG is created and the above procedure is repeated. Fig. 4 shows an example where 12 APs are running on the same channel. Starting with AP_1, a new CSG, CSG_1, is created and AP_1 is added into CSG_1. Next AP_2, the neighbor of AP_1, is added into CSG_1. Recursively, AP_3 (the neighbor of AP_2), AP_4, AP_5 and AP_6 (the neighbors of AP_3), AP_7 and AP_8 (the neighbors of AP_6) are added into CSG_1. As the neighbors of AP_1–AP_8 are also in CSG_1, the construction of CSG_1 is finished. In a similar way, another CSG is constructed with the other four APs.

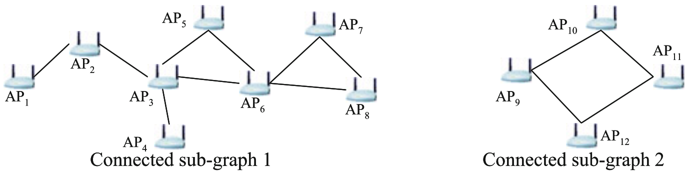

Fig. 4 An example for CSG construction

4.2.2 Computing Data Power for a Single BSS

Computation of power for a single BSS follows three main steps. (i) For a BSS of AP_j, the minimal power $P_{min,j}$, required to meet the QoS requirement over all links inside the BSS, is calculated. Then, for each power p within $(P_{min,j}, P_{max})$, the corresponding quality of the link M_i−AP_j, $RSSI_{ij}(p)$, is calculated, and the resulting rate is computed according to the procedure in Sect. 4.1. Then, $t_j(p)$, the average bit transmission time within the BSS of AP_j at power p, is calculated by Eq. (6). (ii) From the neighbors set $\boldsymbol{L}_j$ of AP_j, the APs, whose data packets transmitted at power p arrive at AP_j with RSSI greater than CS_{th}, are added to $\boldsymbol{N}_j(p)$. (iii) For each candidate power p, the throughput that can be achieved by AP_j, $\gamma_j(p)$, is calculated according to Eq. (7). And the power, P_j^C, which maximizes the BSS throughput, is chosen according to Eq. (8).

4.2.3 Adjusting Data Power Within a CSG

Power levels of APs in the same CSG should be adjusted to meet the power difference requirement. However, the power adjustment should be as minimal as possible so as to enlarge spatial reuse of channels. This is expressed by the following equation.

$$\begin{aligned}\{P_j^N\} &= \arg\min_{P_j^N} \left[\sum_j |P_j^N - P_j^C|\right], \\ \text{s.t. } &(1)\, P_j^C \le P_j^N \le P_{max}, \\ &(2)\, P_j^N \text{ satisfies the constraint in Eq. (1).}\end{aligned} \tag{9}$$

Adjustment of power levels in a CSG is done as follows: At first, the AP (AP_j) with maximal power is found. For each of its neighbors (AP_k) whole power difference $(P_j - P_k)$ is greater than δ_P, the power P_k is raised to meet the difference requirement as $P_k = P_j - \delta_P$. Then, AP_j is marked as being done, and among the remaining APs not marked, the one with maximal power is selected and the above procedure is repeated.

To satisfy Eq. (1), the powers of BSSs near the BSS with local maximal power are raised so that these BSSs will not lose their share of the channel. An example where APs are placed in a line is shown in Fig. 5. Starting from APs (AP_7 and AP_{12}) with local maximal power, lines with the slope rates of $\pm\delta_P$ are drawn, which determine the power (P^N) of adjacent BSSs. These data powers are aligned with the local max power. But the procedure in Sect. 4.2.2 ensures that the local max power will not be too large, after taking the tradeoff between transmit rate and channel reuse.

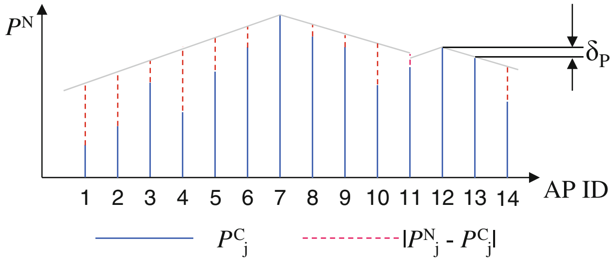

Fig. 5 Adjusting BSS powers

Table 1 SINR threshold for rate adaptation

SINR (dB)		≥ 8.6	≥ 9.2	≥12	≥13.6	≥18.2	≥22	≥24
Rate (Mbps)	6	9	12	18	24	36	48	54

5 Simulation Evaluation and Analysis

In this section we show the evaluation results and analyze how much gain can be achieved by TPC and what is the resulting fairness. The scheme for calculating BSS power in Sect. 4.2.2 is named as PMT (Power for Max Throughput). The scheme for adjusting power in Sect. 4.2.3 is named as smooth power (SP). In comparison, the scheme in [20] is called PMR (Power for Max Rate). The common power (CP) scheme in [8] is used together with PMR or PMT for a comparison. We will evaluate four schemes: NoTPC (no power control, where P_{max} is always used), PMR + CP (a combination of two state-of-the-art schemes suggested in [20,8] to both perform TPC and avoid asymmetric links), PMT + CP and PMT + SP. PMT + SP realizes the full function of the proposed scheme.

We implemented the proposed scheme on top of a commercial network simulator, Scenargie [33], which has a complete implementation of IEEE 802.11 protocol stack. In the evaluation, IEEE 802.11a [7] is used, with default setting unless otherwise specified. As for power related parameters, $P_{min} = -20$ dBm, $P_{max} = 15$ dBm, and $P_{delta} = 1$ dBm, $CS_{th} = -85$ dBm. Max rate in PMR is 54 Mbps. r_{th} = min supportable rate (6 Mbps) is used in PMT and the optimal value of δ_P (3 dBm) for SP is found by simulation. Two ray path loss model is used. With a given power, RSSI of each link is computed, and the resulting rate is found according to Table 1. RSSI is measured when a packet is received, and moving-average of RSSI is used in power computation. Therefore, the proposed TPC scheme still works even if the shadowing effect occurs. But it does not react to fast RSSI fluctuations. Instead, RA is responsible for adjusting rates according to instantaneous time-varying RSSI. Currently the effect of fast fading is not evaluated since most nodes in WLANs are stationary. We tried different TPC periods from 10 to 60 s and did not find significant performance differences. But too small a TPC period will affect the computation of average RSSI and the accuracy of power levels. In the simulation the TPC period is set to 30 s.

Three scenarios are used to evaluate the above schemes. Figure 6 shows the common setting for scenarios I and II. APs are evenly deployed on the grid points in an area of 500 m × 500 m and the AP density is determined by the grid distance (GridDist). In each AP's coverage square determined by the parameter DeployDist, a single node is uniformly distributed. (i) In Scenario I, GridDist is varied and DeployDist equals GridDist/2. (ii) Scenario II is a variant of Scenario I. The GridDist is fixed at 50m and the DeployDist is varied. This scenario can be

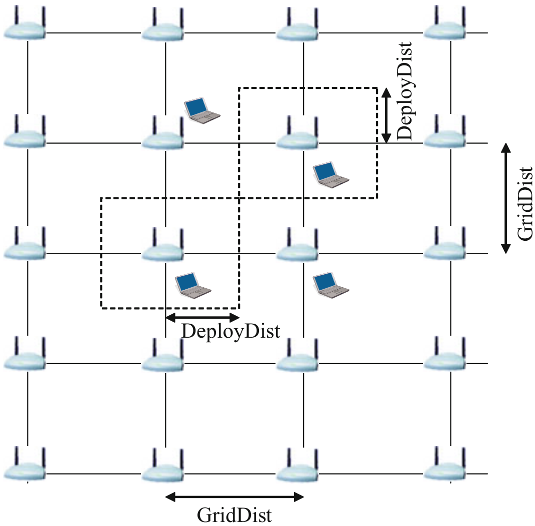

Fig. 6 Scenario I and II, uniform deployment of APs

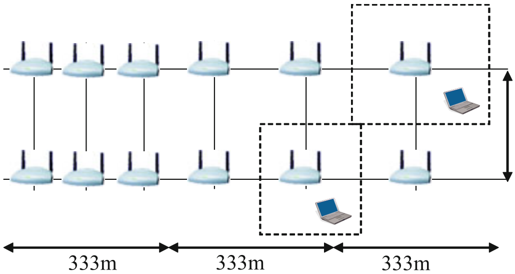

Fig. 7 Scenario III: non-uniform deployment of APs

used to confirm the effect of TPC when nodes are close to their associated APs. (iii) Scenario III is shown in Fig. 7, where there are two rows of APs deployed in a threadlike 1,000 m × 10 m area. Each row has 30 APs. These APs are divided into three groups. The middle group has a fixed number of 10 APs per row, while the difference between the left and right groups is controlled by a parameter. One node with a random position is assigned to each AP.

All nodes and APs have a single antenna and share the same channel. Each node associates with the nearest AP by using RSSI as the AP selection metric. On each link, a CBR (Constant bit rate) flow is started. Traffic rate is set to 5 Mbps in all scenarios. This rate ensures that all flows always have enough data to send. The directions of these flows are randomly chosen in scenario II, and fixed to up-link in other scenarios. In the evaluation, we mainly focus on two metrics: total throughput of the whole network and fairness among different links. Fairness of throughput is calculated according to Jain's fairness index. The results are averaged over 20 runs with different seeds, where the layout of nodes is changed at each seed.

5.1 Choosing δ_P

In this section we investigate power differences between adjacent APs, using the scenario in Fig. 6 with GridDist = 50 m and DeployDist = GridDist/2 (both the number of APs and the

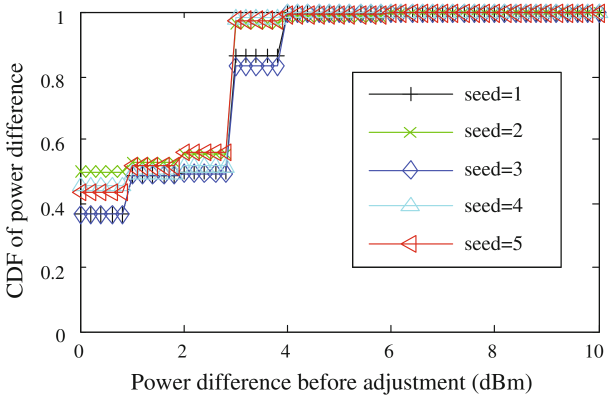

Fig. 8 CDF of power differences between adjacent BSSs (PMT)

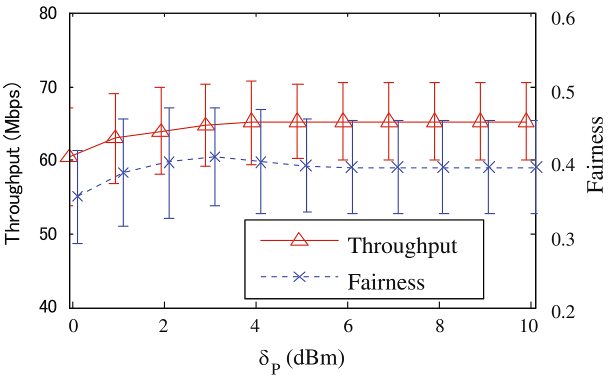

Fig. 9 Throughput and fairness of PMT + SP under different δ_P (95 % confidence interval)

number of nodes are 100). P^C, the data power before adjustment, is examined. Figure 8 shows the cumulative distribution function (CDF) of power differences in the PMT scheme under different node deployments (different simulation seeds). It is clear that in a dense network, the power differences usually are no more than 3dBm, which justifies the approximation in Sect. 3.3. In addition, power differences do exist and a common power for the whole network does not work well. Without changing the CS threshold, it is necessary to smoothly change the power.

An investigation of throughput and fairness achieved by PMT + SP under different values of δ_P is shown in Fig. 9. Both throughput and fairness increase when δ_P increases from 0 to 3 dBm. A further increase in δ_P leads to little increase in throughput but obvious decrease in fairness. Therefore, $\delta_P = 3$ dBm is regarded as the optimal value, and is used in other evaluations.

5.2 Throughput and Fairness Under Scenario I

Next we evaluate the performance of all schemes under different GridDist using Scenario I in Fig. 6. A smaller GridDist means more APs are deployed in the 500 m × 500 m area. Total throughput and fairness of all BSSs are shown in Figs. 10 and 11, respectively. A quick view indicates that PMT outperforms PMR, and SP outperforms CP.

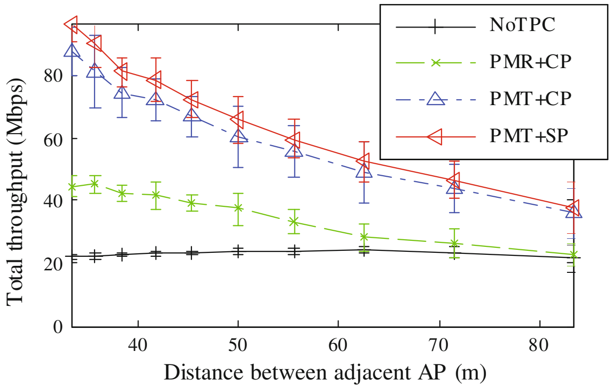

Fig. 10 Total throughput under different grid distances (95 % confidence interval)

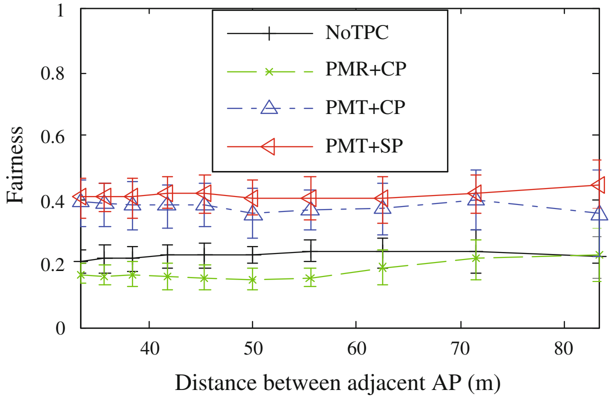

Fig. 11 Fairness under different grid distances (95 % confidence interval)

In Fig. 10, as GridDist decreases, total throughput of the whole network gradually increases when TPC is used. When GridDist is large, APs are not densely deployed. PMR + CP only has marginal gain compared with NoTPC because insisting use of maximal rate harms spectrum reuse. As a comparison, PMT + CP and PMT + SP always outperform PMR + CP, exhibit a higher increasing rate in throughput, and have good performance even at a moderate AP density (a relatively large GridDist). When GridDist = 50m, PMT + SP improves total throughput by 77.1 % compared with PMR + CP, and by 269.1 % compared with NoTPC.

PMT also greatly improves fairness, as shown in Fig. 11. With a relatively large power in PMR or NoTPC, the CS range is large. APs and nodes in the middle of the grids perceive the channel to be busy due to transmissions in any side and defer from accessing the channel with a higher probability than APs and nodes outside. As a result, the inner APs and nodes can hardly grab the channel and fairness is low. Fairness of PMR may even get lower than that of NoTPC because interference margin is not applied in PMR. With the PMT scheme, the power is further reduced and so is the CS range. Although the transmit rate may be lower, the share of the channel for each link increases. And transmissions are successful with a high probability thanks to the interference margin. Therefore, fairness is greatly improved.

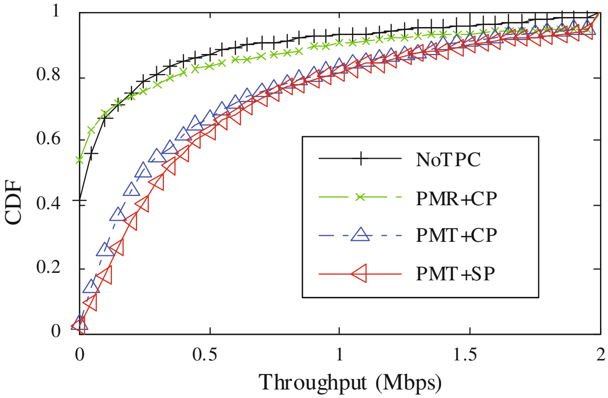

Fig. 12 CDF of per-link throughput (GridDist = 50 m)

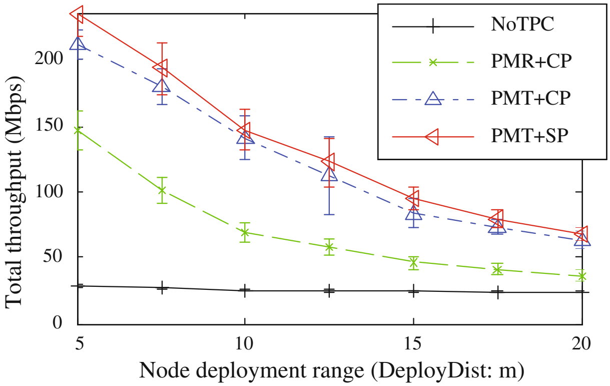

Fig. 13 Total throughput under different AP-node distances (95 % confidence interval)

Figure 12 shows the CDF of the per-link throughput at GridDist = 50 m. At the low throughput end, the effect of PMT is very clear. By reducing power and enabling more parallel transmissions, the percentage of low throughput links is greatly reduced.

5.3 Throughput Under Scenario II and III

In this section we investigate the performance of all schemes under other scenarios.

With scenario II, we evaluate the effect of AP-node distance. Traffic is from nodes to APs on about half of these links and from APs to nodes on the other links. The GridDist between adjacent APs is fixed at 50 m and the DeployDist is decreased from 20 to 5 m. Total throughput is shown in Fig. 13. As DeployDist decreases, statistically the AP-node distance gets shorter. Then the effect of TPC becomes clear. When the DeployDist equals 10 m, PMR + CP improves throughput by 160.5 % compared with NoTPC. PMT + SP further improves throughput by 119.9 % compared with PMR + CP. In scenario I and II, APs are evenly distributed. Therefore, the superiority of SP over CP is not very obvious.

With scenario III in Fig. 7, we investigate the effect of the bias in AP density, where the AP density is defined as the number of APs per row for each group. Figure 14 shows total throughput, where the horizontal axis is the difference in AP density between adjacent groups. At all AP densities, PMT + SP has higher throughput than PMT + CP. This con-

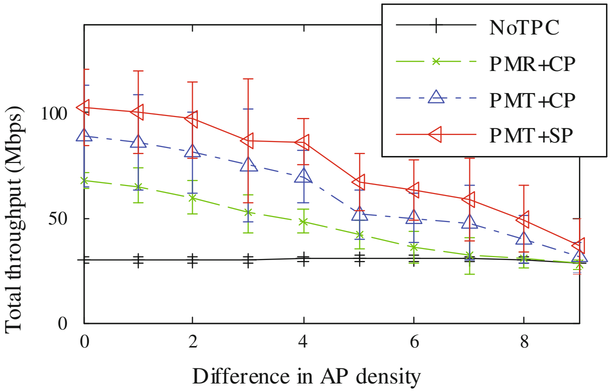

Fig. 14 Total throughput under different AP densities (95 % confidence interval)

firms the necessity of smoothly changing the power in the network so as to make power adapt to the disparity in AP deployment. But when the difference in AP density is too large, total throughput is still degraded due to the following factor: a large power is used in the sparse area to ensure coverage; the dense area nearby will also use a relatively large power so as to avoid asymmetric links. Accordingly, the proposed SP scheme can handle moderate bias in AP densities. To handle a large bias in AP density will require joint design with other functions such as channel assignment. This is left as a future work.

In short, the proposed PMT + SP scheme has higher throughput than other schemes in most scenarios and also retains fairness. The throughput gain is achieved by a better tradeoff between transmit rates and spatial reuse of channels. To this end, a TPCmgr is required and it should periodically collect RSSI of all links from APs, which can be implemented by exploiting IEEE 802.11k. The centralized management enables optimization and simplifies protocol design. The overhead is relatively low when a suitable TPC period is chosen. Such a cost is acceptable if we consider the large throughput gain it brings. In addition, communication overhead between APs and TPCmgr is generated in the wired networks connecting them, and has little effect on the performance of the wireless part.

6 Conclusion and Future Work

In this paper we studied how to apply joint TPC and RA to improve throughput of dense WLANs. The power difference between co-channel nearby BSSs is allowed and controlled. In this way, different powers may be used to adapt to the disparity in AP density while the asymmetric link problem can be mitigated. This also enables the approximation and simplifies the protocol design. Power levels are chosen to achieve the optimal tradeoff between transmit rates and spatial reuse of channels, taking into account the contention among nearby co-channel BSSs. Extensive simulation evaluations confirm that the proposed scheme works well in different scenarios and the throughput gain is especially obvious when APs are densely deployed, when nodes are near their associated APs or when there is disparity in AP density. Meanwhile, fairness is also retained. In the future, we will further study joint design of channel assignment, association control and TPC.

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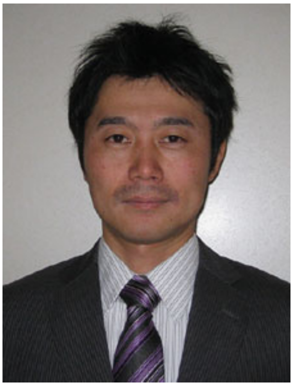

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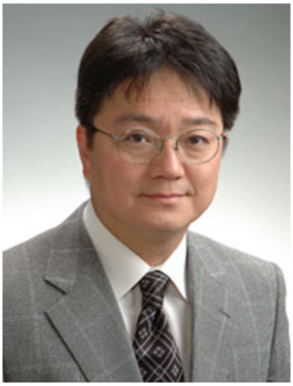

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