Joint Transmit Power and Physical Carrier Sensing Adaptation based on Loss Differentiation for High Density IEEE 802.11 WLAN

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Abstract

In high density (HD) IEEE 802.11 WLAN, packet loss can occur due to co-channel interference (asynchronous interference) or collisions (synchronous interference). In order to effectively mitigate the interference for spatial reuse, the causes of packet loss should be differentiated and corresponding network parameters (Physical Carrier Sensing (PCS) threshold, transmit power (TXPW) and contention windows size) tuned accordingly. Such loss differentiation ability is not supported by current IEEE 802.11 networks; we devised a novel, zero over-the-air overhead, robust yet accurate method of estimating the probability of collision and interference, respectively. In this work, we investigate how to use differentiated Packet Error Rate (PER) to mitigate asynchronous interference for increasing spatial reuse. Motivated by analysis, a *joint* transmit power and PCS threshold self-adaptation algorithm based on loss differentiation is proposed. Heuristics that address node starvation and fairness are also incorporated within the above (aggregate throughput maximization) framework to allow a flexible suite of approaches to network tuning.

Elaborate simulations show that such joint adaptation algorithm can increase both total throughput and worst link throughput in HD WLAN greatly compared with PCS only adaptation without loss differentiation.

Key words: IEEE 802.11, physical carrier sense, transmit power control, loss differentiation, High Density WLAN, contention window size, adaptation

1 Introduction

The convenience of wireless networking has led IEEE 802.11 to emerge from the individual home (the market for which it was initially targeted) to large-scale deployments in environments covering medium to large enterprises, apartment complexes and housing developments, and public area hot-spots. Such networks comprise a large number (10s-100s) of Access Points (AP) that are separated by a few meters on average [1], forming a multi-cell network serving a large number of clients (100s – 1000s).

In such High-Density (HD) 802.11 networks, coverage is less of a design concern because of the ubiquitous deployment of APs. Rather, spatial reuse via effective interference mitigation becomes the primary challenge to improve total network throughput. Packet losses due to both co-channel interference (asynchronous interference) and collisions (synchronous interference) need to be considered in the design of any effective interference mitigation scheme [1].

With network-level coordination, physical carrier sensing (PCS) with a tunable threshold has been proven to be efficient for managing mutual interference from simultaneous co-channel transmissions in an 802.11 network [2] [3] [4]. Here, each node samples the energy level in the medium and initiates channel access only if the received signal strength is no higher than the PCS threshold. It was shown that an optimal PCS threshold achieves a trade-off between the amount of spatial reuse and the PER due to hidden terminals, thereby improving the overall network throughput [4].

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[1] In this work, we implicitly assume background noise is negligible since the HD WLAN is a interference-limited network.

While PCS with a common variable threshold has been shown to yield better aggregate throughput, methods for optimizing PCS thresholds at run-time by *individual self-adaptation of each node without network-level coordination* are yet to be developed. It is reported in [3] that allowing each node to adapt its PCS threshold according to its own PER could lead to severe fairness problem, i.e. some links might starve. The reason lies in packet loss due to hidden terminals, which can be further divided into two cases: interference *prior* to or *after* arrival of signal packet. No matter how small a PCS threshold used by a node, it can only detect the former but not the latter. Therefore, in PCS self-adaptation, the links may still experience severe packet loss when hidden terminals initiate transmissions after signal packets. Instead of PCS threshold adaptation, tuning transmit power (TXPW) can be an effective antidote in such cases. Therefore, *joint transmit power and PCS threshold self-adaptation* will be a focus in this paper for balancing the trade-off between the amount of spatial reuse and link PER.

Design of such self-adaptation algorithms requires real-time measurement of PER, interference energy level and timing. The timing of asynchronous interference relative to reference signal is important since it will be used in the determination of interference mitigation methods. In HD-WLANs, the probability of collisions (packet loss due to synchronous interference) is significant, because of potentially simultaneous transmissions in the same slot. Any adaptation scheme for spatial reuse that does not consider these collisions will lead to lower-than-optimal aggregate throughput or even diverge in extreme conditions, as we reported in [6].

However, in the design of adaptation algorithm for spatial reuse in HD WLAN, determining the *cause* of the packet loss by differentiating measured link PER into those resulting from asynchronous interference and synchronous interference, respectively, is one of the primary challenges. The above is particularly difficult because in ACK-based systems, the transmitter only knows success/failure but not the cause of loss. Moreover, to the best of our knowledge, differentiating the timing of interference relative to useful signal has rarely been exploited. In [14], we contributed a novel method to distinguish and estimate the PER due to collision and asynchronous interference with different timing relative to signal packets. This method only needs minor modifications to the IEEE 802.11 standard [28] and does not incur any over-the-air overhead such as RTS/CTS.

Based on the differentiated PER, a run-time self-adaption algorithm, which can jointly adapt both transmit power and PCS threshold, is proposed to improve spatial reuse in HD WLAN. In the novel algorithm, each node adapts its own parameters based on its own local measurements, without the overhead due to information exchanges. Furthermore, the algorithm does not need any topology information and can be widely used in most 802.11 networks, such as HD infrastructure and ad-hoc (mesh) networks.

In summary, the main contributions of this work are:

1. (1) an analytical model and resultant sufficient conditions for mitigation of asynchronous interference by joint tuning transmit power and PCS threshold;
2. (2) *first* joint self-adaptation algorithm for transmit power and PCS threshold based on differentiated packet loss

The rest of the paper is organized as follows. We summarize related work in Section 2 and briefly review the proposed method for differentiating packet loss in Section 3. In Section 4, we show how to exploit the differentiated packet loss information for joint adaptation of transmit power and PCS threshold via analysis. Sufficient conditions to minimize different types of interference are found. Motivated by the analysis, a heuristic joint adaptation algorithm based on loss differentiation is proposed in Section 5 and then evaluated by simulations in Section 6. Finally, we conclude the paper in Section 7.

2 Related Work

2.1 Related work of loss differentiation

There have been several attempts to distinguish the cause of packet loss in wireless networks. For example, [9] relied on request-to-send/clear-to-send (RTS/CTS) exchange in 802.11 for differentiation. However, RTS/CTS suffers from inefficiency and contributes to fundamental limitations in spatial reuse [2] [8]. In [10], all nodes broadcast their transmission time for the failed transmissions, which contributes to additional communication and processing overhead. In [12], a novel loss differentiation MAC was proposed based on the assumption loss due to link errors has a good chance to receive the header correctly while collisions do not. However, it required a new MAC frame (NACK) thereby compromising compatibility with existing IEEE 802.11 standard. In addition, when the asynchronous interference arrives prior to reference signal, the header of signal will be corrupted. In our previous work [6], we found *the loss probability due to interference is insensitive to CWmin (min. contention window size) in HD mesh network* and proposed a run-time method to estimate the probability of collision and interference by using large CWmin without any MAC or Physical layer modification of 802.11 specifications. In [13], the probability of collision was first estimated as the proportion of busy slots due to transmissions by other nodes; then the probability of channel error was found by assuming that the above two classes of errors are statistically independent. However, no timing information of the interference relative to useful signal was considered in the above methods. Exploiting the capture effect was proposed in [11] for loss differentiation. Although the method could detect interference *prior* to or *after* arrival of signal packet in some cases, it requires significant re-design of the 802.11 receiving chain.

2.2 Related work of spatial reuse for HD-WLAN

Recent research efforts have been dedicated to enhancing spatial reuse to improve network capacity of HD-WLANs. They fall into three major categories: PCS threshold adaptation, transmit power control (TPC) and joint PCS adaptation and TPC. PCS adaptation adjusts the energy level that a transmitter uses to assess channel state prior to channel access while TPC adjusts the actual power emitted onto the RF channel.

Zhu et al. [2] derived the optimal PCS threshold that maximizes the aggregate one-hop throughput for a regular topology given a minimum required SINR (Signal to Interference and Noise Ratio); an adaptive PCS threshold algorithm was suggested based on periodic measurement of PER and evaluated on a real test-bed in [3]. Yang et al. [5] proposed an analytical model to address the impact of MAC overhead on the optimal PCS threshold, considering (bandwidth independent) overhead due to PHY header, slot time, etc., and bandwidth dependent overhead caused mainly by collisions. The analytical approach of [4] provided the most concrete guidance for the optimal PCS threshold for single rate networks: it found that setting the threshold such that the interference range equals the carrier sense range is a good, robust initialization. In [6], we showed that any good PCS adaptation scheme for spatial reuse should also consider collisions, otherwise it will lead to lower-than-optimal aggregate throughput.

Besides reducing power consumption, TPC approaches have also been applied for increasing spatial reuse. An additional control channel was used in by Monks et al. [16], Wu et al. [15] and Muqattash et al. [17] to increase concurrent transmissions around the receiver. Single channel solutions for TPC were provided in [18] and [19]. In [18], a node increases its transmit power when successive packet loss are detected, and decreases it when the number of continuous successful transmissions exceeds a threshold. Muqattash et al. [19] used an access window to allow for a series of RTS/CTS exchanges prior to data transmissions so that neighboring nodes can determine the optimal transmit power based on the information provided in the RTS and CTS packets to maximize spatial reuse. Akella et al. [20] proposed a power control algorithm called PERF that reduces transmit power as long as the links between an AP and all its clints can maintain the highest datarate. However, most of the above TPC schemes (except [18] [20]) require additional hardware or signalling overhead. In addition, all these studies do not consider the effect of PCS threshold on the network capacity even though it is a major determinant of spatial reuse.

There are only a few studies considering the joint impact of both transmit power and PCS threshold so far. In [23], Kim et al. showed that in the case that the achievable channel rate follows the Shannon capacity, spatial reuse depends only on the ratio of the transmit power to PCS threshold. In [24], Yang et al. investigated the impact of transmit power and PCS threshold on network throughput via Markov Chain model. However, both the analysis in [23],[24] assumed a common transmit power and PCS threshold for the whole network. Fuemmeler et al. [21] [22] showed that the product of the transmit power and the PCS threshold should equal a constant for maximizing spatial reuse. The authors also proposed a practical protocol to implement their solution and evaluated it by ns2 [27] simulation. However, the issue of starvation of individual nodes while maximizing throughput was left unaddressed. Recently, [25], found a similar result to [21] for determining sufficient conditions for starvation-free power control. However, both algorithm complexity and control message overhead in this adaptation algorithm are much higher than ours. Moreover, the most significant difference between this work and [21][25] is that our algorithm provides clear insight into the distinct roles of transmit power and PCS adaptation in balancing throughput gains (maximizing spatial reuse) while avoiding node starvation.

3 Loss Differentiation and Estimation

There are mainly three categories of interference based on the timing relation between desired and interference signals, which are illustrated in Fig. 1:

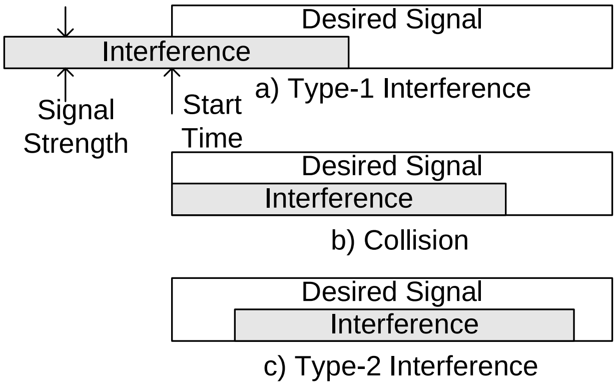

Fig. 1. Illustration of three types of interference. The height of each rectangle represents the signal strength of a packet.

(1) **Collision (Synchronous Interference)**: the interference signal that starts at the same slot as the desired signal.
(2) **Type-1 Interference**: the interference signal that arrives *prior* to the desired signal.
(3) **Type-2 Interference**: the interference signal that arrives *after* the arrival of the desired signal.

Note that packet losses caused by both type-1 interference and type-2 interference are typically known as *hidden terminal problem* in the literature.

Estimation: In [14], we proposed a novel method to distinguish and estimate PER due to different types of interference exploiting *timing of arrival* relative to desired signal. For convenience, the events that collision, type-1 interference and type-2 interference arrive, will be denoted by **C**, **I1** and **I2** respectively. We seek to estimate PER due to C, I1 and I2 individually, defined as

- p_c: the packet loss rate due to C.
- p_1: the packet loss rate due to I1.
- p_2: the packet loss rate due to I2.

Clearly, the above estimators presume effective loss differentiation which is discussed in [14]. The core of this proposed loss differentiation method is also shown in Appendix A. In particular, $\langle p_c \rangle$,$\langle p_1 \rangle$ and $\langle p_2 \rangle$ [2] were estimated by the local measurements at transmitters using measured energy and delayed sensing. We have also shown that the PER due to I1 and I2 is insensitive to the CWmin setting, and can be used to adapt transmit power and PCS threshold jointly. CW adaptation for collision resolution according to $\langle p_c \rangle$ is not the focus of this paper and is deferred for future work.

4 Adapting PCS Threshold and Transmit Power based on Loss Differentiation

In this section, we show how the two classes of asynchronous interference in HD WLAN network can be eliminated by tuning PCS threshold and transmit power jointly. While both transmit power and PCS threshold may be used to mitigate interference, increasing transmit power is much more aggressive and must be done with care. Thus in the interference management at each link, we adapt PCS threshold first and transmit power only thereafter when desired.

We will show that

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[2] We will use $< >$ around any quantity to denote its estimate based on observed data.

(1) keeping the ratio of transmit power and PCS threshold higher than a certain threshold can fully eliminate packet loss due to I1;
(2) After packet loss due to I1 has been eliminated, fixing PCS threshold and tuning the transmit power can eliminate packet loss due to I2 on all links.

In summary, each node can fully eliminate packet loss due to I1 but not loss due to I2 by tuning PCS alone; additional transmit power adaptation is needed to eliminate packet loss due to I2. The analysis results here provide a guideline for joint PCS threshold and transmit power adaptation based on loss differentiation (LD).

4.1 Definitions

We consider a network of 802.11 nodes in either infrastructure or ad-hoc mode and assume (without loss of generality) that the units of power are appropriately scaled so that, given a source-destination pair separated by a distance of x meters, the received power from the source at the destination is given by $P_R = P \cdot g(x) = c \cdot P/x^{\gamma}$, where P is the transmit power, $g(x)$ is the path loss and γ is the path loss exponent; c is constant and equals $\frac{\lambda^2}{16\pi^2}$, where λ is the wavelength.

We now introduce several definitions.

(1) *Total received power* $P_R(i)$: We denote the total received power at a node i by $P_R(i) = c \cdot \sum_j \frac{P(j)}{d(j,i)^{\gamma}}$, where j denotes all the nodes which are transmitting at t, $d(j,i)$ is the distance between nodes j and i. Here we implicitly assume background noise is negligible since the HD WLAN is a interference-limited network.
(2) *PCS threshold* γ_{cs}: PCS threshold γ_{cs} is a tunable parameter with the property that a node i senses the channel busy if and only if $P_R(i) > \gamma_{cs}$.
(3) *SINR threshold* S_0 : The SINR threshold S_0 at a receiver is set to achieve a suitably high probability of successful packet reception. The value of S_0 will depend on the physical layer and data rate; in general, higher data rates will require a higher S_0.

4.2 Eliminating packet loss due to I1 by tuning PCS threshold

Fig. 2 shows a link with node separation x_1 and its signal and interference powers. The ratios between different power values are also shown. We denote the transmit power as P_1 and the PCS threshold as γ_{cs1} for the source. The sensed power at node A and that at node B before A initiates any transmission will be denoted as P_A and P_B, respectively.

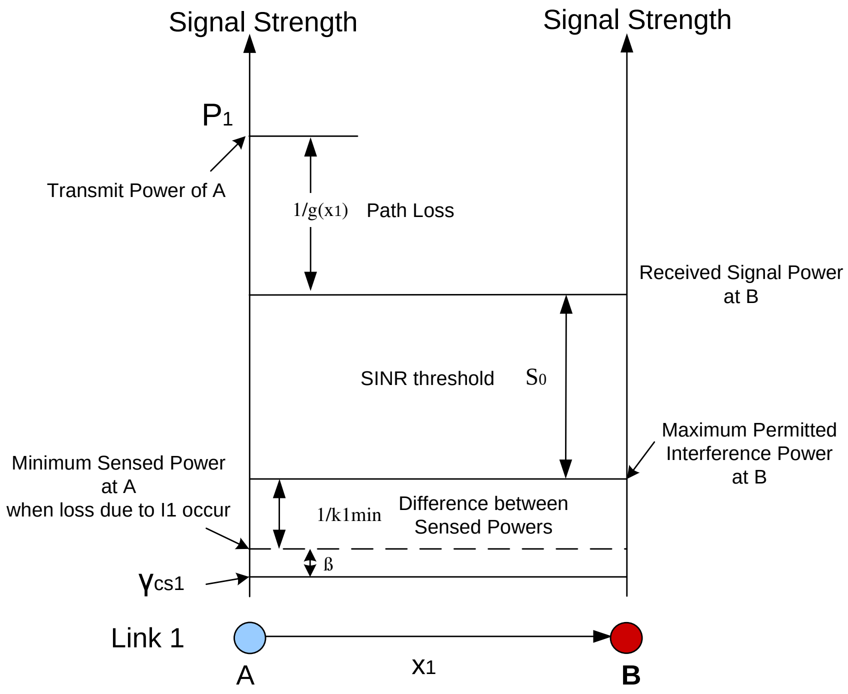

Fig. 2. One link in a HD WLAN network. The axes represents signal strength. In order to eliminate packet loss due to I1, a solution would be to decrease the PCS threshold (γ_{cs1}) of the sender so as to detect all destructive type-1 interference (higher than the dashed line in the figure) and therefore avoid unnecessary transmission attempts.

For convenience, we introduce a coefficient k to represent the ratio of P_A and P_B; it models the difference between the sensed powers of a sender and a receiver at their respective locations.

Definition:

$$K_1 = \{k_1 | P_A = k_1 P_B\}$$

$$k_{1\,\min} = \inf_{k_1 \in K_1} k_1$$

Here, because the value of k_1 is mainly determined by the locations of the active interference nodes around the link, we assume that K_1 and $k_{1\,\min}$ are independent of P_1.

Target: In order to eliminate packet loss due to I1, we need to satisfy

$$P_A \leq \gamma_{cs1} \Rightarrow \frac{P_1 \cdot g(x_1)}{P_B} \geq S_0 \tag{1}$$

where $p \Rightarrow q$ represents if p holds then q will hold.

The statement in (1) means that whenever a sender senses the channel idle and initiates a transmission, the current interference level at the receiver will not corrupt this transmission.

Simple manipulations yield a sufficient condition:

$$\frac{P_1 \cdot g(x_1) \cdot k_1}{S_0} \geq \gamma_{cs1} \;\; k_1 \in K_1 \tag{2}$$

which implies that the PCS threshold,γ_{cs1}, should be no higher than the minimum power that node A can sense when packet loss due to I1 occur (illustrated with dashed line in Fig. 2) and which is equivalent to

$$\frac{P_1}{\gamma_{cs1}} \geq \frac{S_0}{g(x_1) \cdot k_{1\,\min}} \tag{3}$$

For convenience, let's introduce another coefficient β to rewrite (3) into

$$\frac{P_1}{\gamma_{cs1}} = \beta \frac{S_0}{g(x_1) \cdot k_{1\,\min}} \tag{4}$$

where $\beta \geq 1$.

Discussion: From (3), we see that keeping the ratio of transmit power to PCS threshold higher than a certain threshold can fully eliminate packet loss due to I1. For higher data rates and longer link distance, a transmit power to PCS threshold ratio is needed. Each link can eliminate packet loss due to I1 by simply decreasing PCS threshold if PER due to I1 can be isolated. Thus packet loss due to I1 can be eliminated in a distributed manner.

4.3 Eliminating packet loss due to I2 by tuning transmit power

Fig. 3 shows two links with link separations x_1 and x_2 respectively. The transmit power of the two senders are P_1 and P_2 and their PCS thresholds are γ_{cs1} and γ_{cs2}. Assuming only one link is transmitting at the beginning, the other link is sensing the channel and make a decision for its own transmission. If Link 1 transmits first, the sensed power at node C and that at node D before C initiate a transmission will be denoted as P_C and P_D, respectively; If Link 2 transmits first, the sensed power at node A and that at node B before A initiate a transmission will be denoted as P_A and P_B, respectively. Similar to k_1 as defined earlier, we also define k_2 for link 2. Note that here P_B (or P_D) are also the aggregate interference power at the receiver of the first link after the second link transmits.

We now introduce several assumptions.

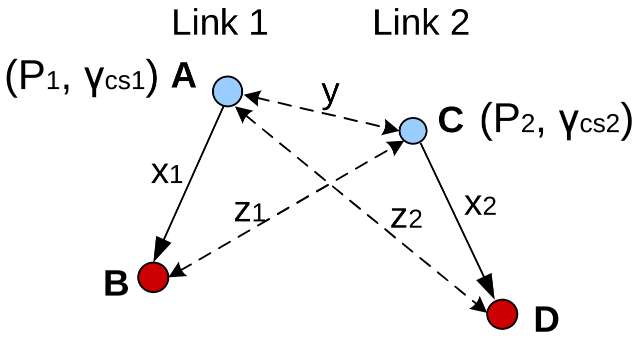

Fig. 3. Two links in a HD WLAN network

(1) *Aggregate Interference Power*: The aggregate interference power sensed is the sum of the power from *one* dominant source and interference floor P_I(from all other interference nodes) . For simplicity, the interference floor P_I is assumed to be equal at all four nodes. Thus

$$\begin{aligned} &P_A = P_I + P_2 \cdot g(y) \qquad P_B = P_I + P_2 \cdot g(z_1) \\ &P_C = P_I + P_1 \cdot g(y) \qquad P_D = P_I + P_1 \cdot g(z_2) \end{aligned} \tag{5}$$

(2) *Sufficient Condition for Eliminating Packet Loss due to I1*: we assume the ratio of transmit power to PCS threshold for each link has already been set to eliminate its packet loss due to I1. Thus

$$\begin{aligned} &\frac{P_1}{\gamma_{cs1}} = \beta_1 \cdot \frac{S_0}{g(x_1) \cdot k_{1\,\min}} \\ &\frac{P_2}{\gamma_{cs2}} = \beta_2 \cdot \frac{S_0}{g(x_2) \cdot k_{2\,\min}} \end{aligned} \tag{6}$$

where $\beta_1 \geq 1$ and $\beta_2 \geq 1$. When PCS threshold is fixed, adapting transmit power is equivalent to adapting β.

Target: In order to eliminate packet loss due to I2, we need to find the feasible range of α, s.t. the following are simultaneously satisfied

$$\begin{cases} P_A \leq \gamma_{cs1} \Rightarrow \frac{P_2 \cdot g(x_2)}{P_D} \geq S_0 & (I_2 \quad \textit{aviodance} \quad \textit{in} \quad \textit{link} \quad 2) \\ P_C \leq \gamma_{cs2} \Rightarrow \frac{P_1 \cdot g(x_1)}{P_B} \geq S_0 & (I_2 \quad \textit{aviodance} \quad \textit{in} \quad \textit{link} \quad 1) \end{cases} \tag{7}$$

where $\alpha = \frac{P_1 \gamma_{cs1}}{P_2 \gamma_{cs2}}$.

The statements in (7) mean that whenever a sender senses the channel idle and initiates a new transmission, this transmission will not corrupt an existing transmission of the other link.

Simple manipulations lead to a sufficient condition for α:

$$\begin{cases} \alpha \leq \dfrac{\frac{\beta_2}{k_{2\min}} - \frac{P_I}{\gamma_{cs2}}}{1 - \frac{P_I}{\gamma_{cs1}}} \cdot \dfrac{g(y)}{g(z_2)} = \alpha_2 \\ \alpha \geq \dfrac{1 - \frac{P_I}{\gamma_{cs2}}}{\frac{\beta_1}{k_{1\min}} - \frac{P_I}{\gamma_{cs1}}} \cdot \dfrac{g(z_1)}{g(y)} = \alpha_1 \end{cases} \tag{8}$$

Discussion:

(1) *Special case*: when $P_I \ll \gamma_{cs1}$ and $P_I \ll \gamma_{cs2}$, (8) will be reduced to

$$\alpha_1 = \frac{k_{1\min}}{\beta_1} \cdot \frac{g(z_1)}{g(y)} \leq \alpha \leq \frac{\beta_2}{k_{2\min}} \cdot \frac{g(y)}{g(z_2)} = \alpha_2 \tag{9}$$

By definition of k_1 and k_2, $k_{1\min} \cdot \frac{g(z_1)}{g(y)} = k_{1\min} \cdot \frac{P_B}{P_A} \leq 1$ and $\frac{1}{k_{2\min}} \cdot \frac{g(y)}{g(z_2)} = \frac{1}{k_{2\min}} \cdot \frac{P_C}{P_D} \geq 1$. Thus for any $\beta_1 \geq 1, \beta_2 \geq 1$, we have $\alpha_1 \leq 1 \leq \alpha_2$ and hence $\alpha = 1$ is always a solution. Thus keeping the product of PCS threshold and transmit power constant will lead to a *sufficient* condition for solving hidden terminal problems in this special case, which is consistent with the results in [21]. When interference from others can be ignored, this condition makes the PCS mechanism symmetric, i.e, the two transmitters can both detect each other.

(2) *General case*: According to (6), α can be expressed as

$$\alpha = \frac{P_1 \gamma_{cs1}}{P_2 \gamma_{cs2}} = \frac{\beta_1}{\beta_2} \frac{\gamma_{cs1}^2 g(x_2) k_{2\min}}{\gamma_{cs2}^2 g(x_1) k_{1\min}} \tag{10}$$

Increasing β_1 (β_2), the value of α_1 (α_2) will decrease (increase) respectively. Thus the feasible set of α, $[\alpha_1, \alpha_2]$, expands and it follows that for fixed γ_{cs1} and γ_{cs2}, increasing (P_1, P_2) (thus subsequently (β_1, β_2)) jointly will lead to a solution for α. Moreover, each node can find such a solution in *distributed manner* by gradually increasing their transmit power, a manner that makes self-adaptation without a central coordinator possible. For example, whenever a link, say Link 1, has significantly large PER due to I2 ($\langle p_2 \rangle$ is higher than a preset threshold), the second inequalities in (8) will not hold. Thus if Link 1 can determine PER component due to I2 from total PER, it can decide to gradually increase its transmit power (thus β_1) and eliminate packet loss due to I2.

4.4 Summary

We have shown that lowering PCS threshold can fully eliminate packet loss due to I1 and increasing transmit power with fixed PCS threshold suppresses any packet loss due to I2. We now propose a heuristic algorithm to first minimize packet loss due to I1 by PCS threshold adaptation and then packet loss due to I2 by transmit power adaptation that satisfies the sufficient conditions above.

However, since these are only sufficient and may not be necessary, the network may not achieve the highest degree of spatial reuse possible. An example of this adaptation margin will be illustrated and discussed via a simulation for ring topology in Section 6. Thus we propose an additional heuristic: the algorithm keeps on trying higher PCS threshold and lower transmit power values for each link whenever there is an adaptation margin, i.e. the PER due to I1 or I2 are insignificantly small ($\langle p_1 \rangle$ or $\langle p_2 \rangle$ is sufficiently lower than preset thresholds).

5 Joint Transmit Power and PCS Adaptation Algorithm based on Differentiated Loss

We present and evaluate a self-adaptation algorithm for joint transmit power and PCS adaptation based on loss differentiation. Fig. 4 shows the joint transmit power and PCS adaptation algorithm. The adaptations comprise three parts, i.e. **Joint Transmit Power and PCS Adaption**, **Starvation Avoidance** and **Fairness Tuning**. The first part will improve spatial reuse with guaranteed link reliability; the second can solve the temporary starvation to accelerate the convergence of transmit power and PCS threshold adaptations; and the third part is designed for (best-effort) fairness provision, which is optional and enabled only when "Fairness Enable" is set to "1".

5.1 Joint transmit power and PCS adaptation

The algorithm heuristic is motivated by the analysis in the previous section. Each transmitter will increase its transmit power or decrease its PCS threshold whenever PER due to I1 or I2 is significantly large (compared with preset thresholds); it will decrease its transmit power or increase its PCS threshold whenever PER due to I1 or I2 is significantly small. The key parameters are as follows:

- T: PCS threshold and transmit power updating interval
- M: the number of transmissions per second from a node within an updating period T
- THm_l: the targeted minimum number of transmissions per second required at any link for starvation avoidance
- p_{1min}, p_{1max}: targeted minimum, maximum $\langle p_1 \rangle$ (A range is used to avoid parameter oscillation)
- $\gamma_{min}, \gamma_{max}$: minimum, maximum PCS threshold
- p_{2min}, p_{2max}: targeted minimum, maximum $\langle p_2 \rangle$
- P_{min}, P_{max}: minimum, maximum transmit power
- δ: adaptation step for transmit power and PCS threshold

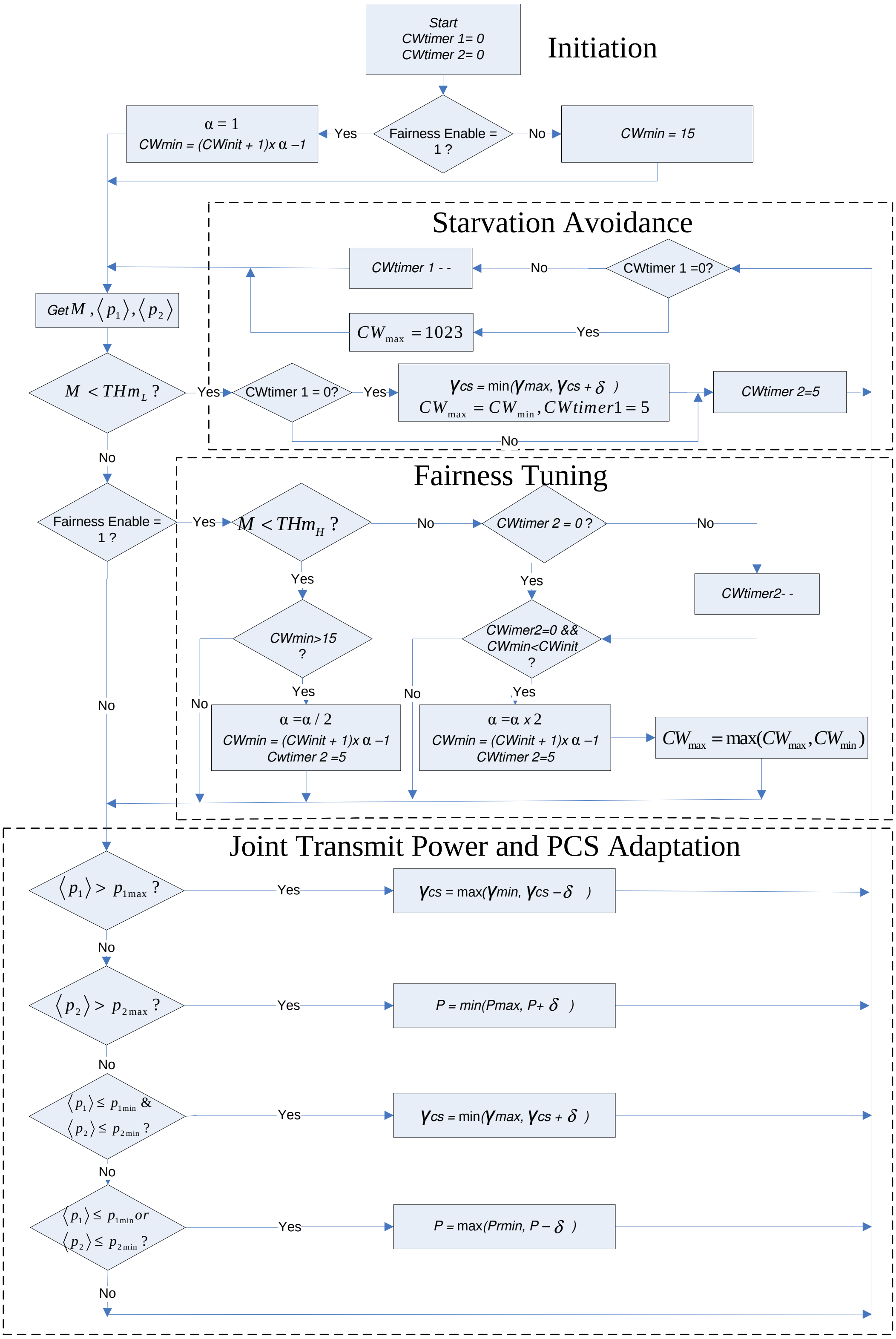

Fig. 4. Joint transmit power and PCS adaptation algorithm

Here, instead of fully eliminating packet loss due to I1 or I2, like [3], a targeted PER is proposed to balance spatial reuse and packet loss for higher throughput.

The proposed transmit power and PCS adaptation algorithm operates as follows. All nodes estimate their own p_1, p_2 and measure M in each T-interval, and then tune their own PCS threshold or transmit power for the next iteration. In all steps, at most one parameter is updated for network stability at the cost of some convergence speed, but this is an acceptable trade-off. Whenever there exists significant PER due to I1 ($\langle p_1 \rangle \geq p_{1max}$), γ_{cs} will decrease; when PER due to I2 is significantly large ($\langle p_2 \rangle \geq p_{2max}$) but without significant packet loss due to I1, transmit power P will increase. This is consistent with our strategy of minimizing packet loss due to I1 first with PCS threshold tuning and then minimizing packet loss due to I2 with transmit power adaptation.

On the other hand, the algorithm keeps on trying higher PCS threshold and lower transmit power on each link whenever PER due to I1 or I2 is insignificantly small in attempt to further increase spatial reuse. Our simulation experiences show that in many cases, increasing PCS threshold arbitrarily will force equilibrium values of transmit power and PCS threshold that are higher with little difference in PER and spatial reuse. This is undesirable as the network will consume more energy and produce more interference to the neighboring networks (due to higher transmit power) with little benefit. Thus *only* when **both** PER to I1 and I2 are insignificantly small, the algorithm will try higher PCS threshold for more spatial reuse.

Therefore, consistent with Fig. 4, adaptation rules are summarized as the following:

$$\gamma_{cs} = \begin{cases} \max(\gamma_{cs} - \delta, \gamma_{min}) & \text{if } \langle p_1 \rangle > p_{1max} \\ \min(\gamma_{cs} + \delta, \gamma_{max}) & \text{if } \langle p_1 \rangle < p_{1min} \text{ and } \langle p_2 \rangle < p_{2min} \\ \gamma_{cs} & \text{otherwise} \end{cases} \tag{11}$$

$$P = \begin{cases} \min(P + \delta, P_{max}) & \text{if } \langle p_2 \rangle > p_{2max} \text{ and } \langle p_1 \rangle \leq p_{1max} \\ \max(P - \delta, P_{min}) & \text{if } (\langle p_1 \rangle \leq p_{1min} \text{and } p_{2min} < \langle p_2 \rangle \leq p_{2max}) \\ & \text{or } (\langle p_2 \rangle \leq p_{2min} \text{ and } p_{1min} < \langle p_1 \rangle \leq p_{1max}) \\ P & \text{otherwise} \end{cases} \tag{12}$$

In order to improve the PER estimation accuracy, a relatively long updating interval T is preferred to collect a large number of samples. On the other hand, a smaller T can make adaptations converge faster. Therefore the selection of T should balance the tradeoff between convergence speed and the accuracy of estimation. In our experiments, we find that T=1-3 seconds are good values. Both adaptations here aim to be conservative while keeping the network stable; we thus recommend smaller adaptation steps with some small loss of convergence speed, i.e., $\delta = 0.25dB$. Large steps have also been tested, such as 0.5dB and 1dB that produce higher PER (than 0.25dB step) after convergence. In addition, since all the adaption was done at the transmitter side, the transmit power value is piggybacked in each data packet. This allows the receiver to subsequently use the value as its transmit power for the reverse link for ACK packets.

5.2 Starvation avoidance

Starvation Avoidance helps nodes with less transmission opportunity find its correct transmit power and PCS threshold quickly and get out of starvation state. In fact, after joint transmit power and PCS adaptation shown above, both packet loss due to I1 and I2 can be minimized, which implies that no single node can dominate and starve other nodes. Thus the starvation problems pointed out in [25] can be readily solved by joint transmit power and PCS adaptation. However, there still may be **temporary starvation** during start-up of the adaptation due to the following: i) The PCS threshold of a node is much lower than its neighbors, implying it typically senses the channel busy due to the large carrier sensing range and ii) a node experiences very high PER, leading to a very large Contention Window as a result of Binary Exponent Backoff (BEB).

In case of temporary starvation which is detected by $M < THm_l$, Starvation Avoidance algorithm will be enabled to help the node get out of the starvation state quickly. In such instances, the algorithm forces the PCS threshold to increase by δ once and disables the BEB for five intervals, controlled by $CWtimer1$. This allows the node to acquire more transmission opportunity in the next several (say 5) updating periods and further converge to an appropriate transmit power and PCS threshold. Within these several updating periods, because the M value of a node in the starvation state is usually much smaller than those of other nodes, the node will not significantly increase p_c of its neighboring nodes.

5.3 Fairness tuning

Fairness tuning is an optional but important module in the proposed algorithm. It is used to guarantee that the *worst* link throughput is higher than some preset threshold. After applying the self-adaptations of transmit power and PCS threshold, the unfairness in throughput may be still pronounced though all the links operate without packet loss due to I1 or I2. This is due to the fact that short links or the links on edge will tend to have higher PCS threshold, and therefore will have much higher throughput than long links or the links in the center. To address this problem, a self-adaptation fairness algorithm is proposed.

In the proposed algorithm, CWmin is selected as the control parameter, because CWmin setting can be independent of PCS threshold and transmit power adaptations in HD WLAN. It is due to that PER due to I1 and I2 is insensitive to the CWmin setting, as we reported in our previous work [6][14]. Thus the values of CWmin will have minor impact on PCS threshold and transmit power adaptations, which is based on loss differentiation. Other control parameters, such as Transmission Opportunity (TXOP, proposed in 802.11e), may also been used for fairness provision and will be studied in our future work. With only self-adaptation and no over-the-air information exchange, it is hard to achieve perfect fairness, i.e., uniform throughput distribution across all the network links. However, self-adaptation can still help improve fairness in a best-effort manner.

In the algorithm, we define a preset threshold, THm_h, which can be configured by the hardware vendor or an IT manager, and each link measure its own channel access probability, indicated by the number of transmissions per second M, periodically and tune its own CWmin value to ensure that M does not drop below THm_h. Fig. 4 also shows the algorithm for fairness with key parameters explained as follows:

- $THm_h(> THm_l)$: the minimum targeted number of transmissions per second required at any link for fairness, which will be set adaptively according to Quality of Service (QoS) requirement and network density.
- $CWmin$: the CWmin value used by a transmitter. Once a link's M value is higher than THm_l but lower than THm_h in any intervals, it will cut its CWmin by half.
- $CWinit$: The initial CWmin value for all transmitters, which is set to 255, 127 or 63 in the simulations. $CWinit$ is also the upper bound of CWmin and may be further adapted according to p_c, so that the probability that two transmitters will transmit at the same time is minimized. Since it is not the focus of this paper, it is left for future work.
- $CWtimer2$: once a link's M value is higher than THm_h for a number(say

5) consecutive intervals, it will double its CWmin until reaching $CWinit$.

6 Simulation Evaluations

6.1 Simulation set-up

In this section, we will evaluate the performance of the proposed solution by OPNET [26] simulation. The simulations are carried out in OPNET using the modified physical carrier sensing module developed in our previous work [4] [7]. We use the *total throughput* to measure *system capacity*, and *worst link throughput* to measure *fairness*. Altogether four groups of simulations are investigated: a) symmetric network with different link distance; b) random HD WLAN with a common link distance; c) random HD WLAN with random link distances; d) single cell network, which is a collision dominated scenario. For simplicity, all cells in each scenario are assumed to work on a single channel. Unless specified, traffics are assumed to be saturated flows with a constant packet size 1500 bytes.

In the simulations, the value of THm_l, p_{1min}, p_{1max},p_{2min} and p_{2max} are set to 20 packets/s, 0, 5%, 0 and 10% respectively. Setting p_{1min} and p_{2min} to 0 is reasonable when the true value of p_1 or p_2 is insignificant.

In this simulation study, estimation and adaptation was carried out *continuously* during the whole simulation period. However, when the algorithm is used in real HD-WLAN networks, the overhead (measurements and computing) in adaptations can be reduced by dividing the time into two segments: adaptation and normal operation. The adaptation segment is a period during when the proposed algorithm performs adaptation in real-time. For example, adaptation can be performed on a fixed schedule such as the first several minutes in each hour. After determining the suitable transmit power and PCS threshold in adaptation segment, each node will use these (fixed) values during the normal operation segment.

6.2 Simulation results and discussion

6.2.1 Symmetric network with different link distance

In this experiment, a symmetric ring network is used to investigate performance of transmit power and PCS adaptation in a distributed manner and the resulting improvement in spatial reuse compared to earlier adaptation methods such as [3]. The network consists of three concentric rings with 5m

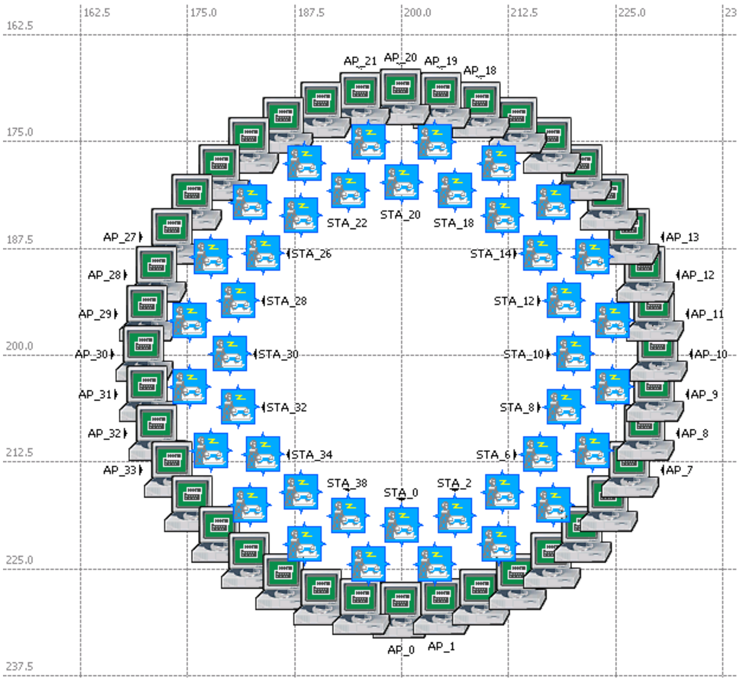

Fig. 5. Long and short links HD WLAN scenario

Table 1
Total and Worst Link Throughput (Rate 12Mbps) for Fig. 5

	Baseline	Fair(255)
Total(Mbps)	28.8	42.5
Worst(Kbps)	554	750

distance in the radius as shown in Fig. 5, where 40 sender and receiver (S-R) pairs are placed. The radius of the outside ring is set to 30 m. Each sender in the outside ring sends saturated traffic to its receiver which is located in inner rings with 5 m or 10 m distance, i.e. a total of 20 short links (5m) and 20 long links (10m) in the network. In our simulation, we use fixed 802.11a rate 12Mbps. Here, we set P_{min} = 0dBm, P_{max}=10dBm, γ_{def}= -86.8dBm [3], and γ_{max}= -66.8dBm. The receiver sensitivity is set to -66.8dBm such that the reception range was 10 m with the minimum transmit power. T is set to $3s$. Path loss exponent is set to 2. THm_h is set to 50 packets/s. In the simulation, we observe that using BEB with $CWmin$ = 15 the network will appear big unfairness, which is not a reasonable operation condition for the network. Thus fairness algorithm (CWinit is set to 255) is enabled here. The detailed discussion between enabling and disabling the fairness algorithm will be carried out later in the subsequent examples.

Here, the group of results denoted ‘Baseline’ is used as baseline performance,

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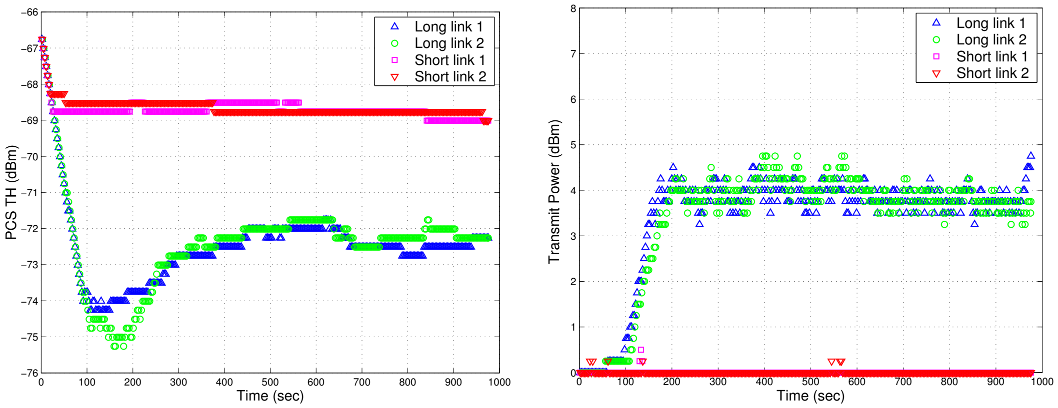
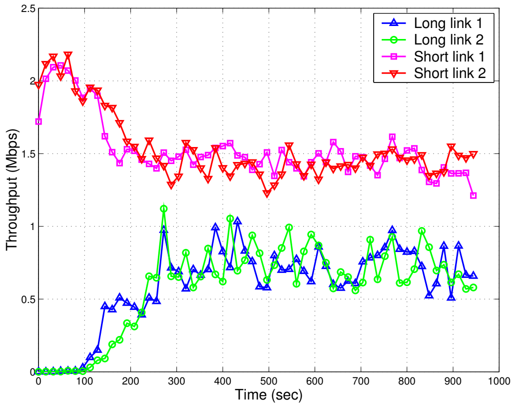
[3] γ_{def} is used for as the lower bound for determining γ_{min} in loss differentiation algorithm.



(a) PCS Threshold (b) Transmit Power



(c) Link Throughput

Fig. 6. Joint transmit power and PCS adaption in a 40-pairs ring network (Fig. 5)

where 'Baseline' means that all devices are using the same (minimum) transmit power and the same PCS threshold, configured at the optimal value obtained by scanning all the available values. 'Baseline' has already been shown to be very efficient in literature, such as [4], [3].

Fig. 6 shows the traces for PCS threshold, transmit power and throughput of two long links (AP0-STA0, AP2-STA2) and two short links(AP1-STA1, AP3-STA3), which illustrates how joint adaptation works. In the figure, long links decrease their PCS threshold from -66.8dBm to around -74dBm at 100s to minimize packet loss due to I1 first. Then they increase their transmit power from 0dBm to 4dBm during (100,200)s to minimize packet loss due to I2 after packet loss due to I1 has been eliminated to be lower than $p_{1max} = 5\%$. Therefore, at the 200th second, both packet loss due to I1 and I2 has already been minimized by joint adaptation and the per-link throughput of long links is improved from 0 to about 500kbps. Finally, after 200 seconds, long links will gradually attempt to increase their PCS threshold from -74dBm to -72.5dBm and therefore further improve their throughput to 750kbps while the throughput of short links do not decrease. This further improvement implies that after packet loss due to I1 and I2 has been minimized at the 200th second,

Table 2
Total Throughput (Mbps) for Fig. 7

Rate	Legacy	Baseline	PCS	PCS +TXPW	Fair(255)	Fair(127)	Fair(63)
54Mbps	65	113	110	113	66	82	95
36Mbps	54	143	133	141	78	99	115
18Mbps	36	152	152	165	87	112	134

there is still an *adaptation margin* and our proposed algorithm can effectively to pursuit higher spatial reuse in such adaptation margins.

To understand why our algorithm improves spatial reuse beyond the 'Baseline' case, consider that in the latter, short links have to use the same PCS threshold and transmit power as long links. However, in our algorithm, short links can seek and successfully transmit at higher rate while managing interference to others with a higher PCS threshold and a lower transmit power, with consequent higher spatial reuse. This can been see from Fig. 6 where after parameter convergence, the short links have a PCS threshold about 3.5dB higher than the short links on average; while their transmit power are 3.5dB lower that those of long links. In addition, upon introducing fairness tuning, the long links can still achieve throughput upto 750 kbps, which is even a little higher than the average per-link throughput in 'Baseline' case. Therefore, as listed in Table 1, the proposed joint transmit power and PCS adaptation with fairness enabled (denoted by "Fair(255)") improves total throughput by 48% from 28.8Mbps (CW is fixed at 255) to 42.5Mbps.

6.2.2 Random HD WLAN with a common link distance

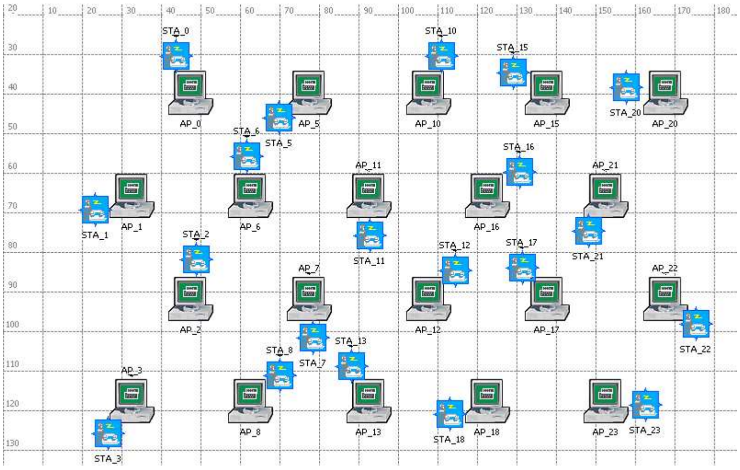
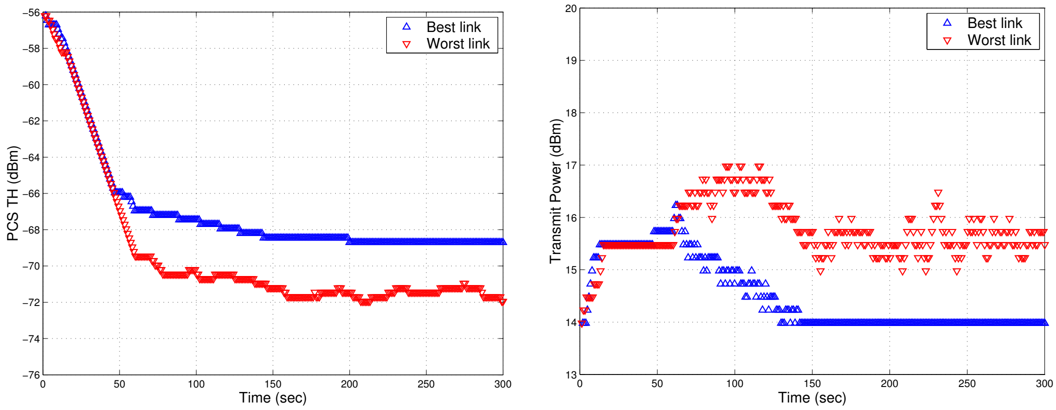


Fig. 7. Multi-cell scenario: 20 down-link pairs HD WLAN (all 10m)

In the following experiments, we investigate another HD WLAN network topology, where all links have the same distance, i.e. 10 m. We will show



(a) PCS Threshold (b) Transmit Power

Fig. 8. Joint transmit power and PCS adaption in a 20 10-meter down-link pairs HD WLAN (Fig. 7)

Table 3
Worst Link Throughput (Kbps) for Fig. 7

Rate	Legacy	Baseline	PCS	PCS +TXPW	Fair(255)	Fair(127)	Fair(63)
54Mbps	312	164	42	900	1962	2000	2180
36Mbps	572	613	111	1290	2600	2390	2260
18Mbps	871	214	201	247	2070	2140	1684

that even when link distances are identical, different transmit power and PCS threshold leads to higher aggregate throughput and better fairness due to location dependant interference variations. Fig. 7 shows the network topology where it comprises 20 co-channel cells with cell radius of 10 meters and AP-to-AP distance of 30 meters. Each cell has one AP and one client (STA), and AP are transmitting saturated UDP traffic, i.e. a total of 20 links in the network.

In our simulation, we used fixed 802.11g rates 18, 36 or 54Mbps to show our loss differentiation method and adaptation algorithm can work on various 802.11 network. Here, P_{min} = 14dBm, P_{max}=24dBm, γ_{def} = -86dBm, and γ_{max}= -56dBm. The receiver sensitivity is set to -56dBm such that the reception range is 10 m with minimum transmit power. THm_h is set to 150 packets/s and path loss exponent is the typical indoor value 3. T are set to $1s$. From now on, consistent with IEEE 802.11 specification, BEB with $CWmin$ = 15 are used for all the simulations for 802.11a and 802.11g except “Fair(x)” cases.

The baseline performance marked ‘Legacy’ means there is no transmit power control and no PCS adaptation, and all devices are using the minimum PCS threshold and the minimum transmit power [4]. We use “PCS” to indicate

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[4] Legacy stations may also use the maximum transmit power, which will produce

the solution with the proposed PCS adaptation only (all transmit power adaptation and conditions based on PER due to I2 in Fig. 4 are disabled), “PCS+TXPW” to indicate the solution with both transmit power and PCS adaptation, and “Fair(x)” to indicate the solution which combines PCS+TXPW adaptation and the fairness tuning with $CWinit = x$.

Table 2 and 3 show the results of total throughput and worst link throughput, respectively. Clearly, both “PCS” and “PCS+TXPW” achieve almost the same (or higher) performance as “Baseline” in terms of total throughput, which is much higher than “Legacy”, e.g. 4.6 times as those of 18Mbps. Furthermore, “PCS+TXPW” dramatically improves worst link throughput compared with “PCS”, e.g. 22 times as those of 36Mbps. It is also better than “Baseline” for all rates and “Legacy” for rates 36Mbps and 54Mbps. Finally, comparing “Fair(x)” and “PCS+TXPW”, worst link throughput has been greatly improved at the cost of decreasing total throughput to some level. It seems that setting $CWinit = 63$ for fairness algorithm is a good choice since the worst link throughput has been greatly improved, e.g. 7 times to rate 18Mbps, at the cost of limited degradation ($< 20\%$) in total throughput.

Fig. 8 shows the traces for PCS threshold and transmit power of the best link (AP3-STA3) and worst link (AP17-STA17) (in terms of throughput) with rate 36Mbps. After convergence at 150th second, the worst link has PCS threshold about 2.5dB lower than the best link on average, while transmit power 1.5dB higher than the best link. This is due to that even if link distances are the same, interference levels are still non-identical. Therefore transmit power and PCS threshold should be adjusted on a per-link basis, so that a link at disadvantaged location can be compensated with a higher transmit power and lower PCS threshold. It is worth remarking that some links here may begin to increase their transmit power before their packet losses due to I1 are minimized. In such a complex network, because the T2-ratio (see appendix) used to determine suitable γ_{min} for loss differentiation has not been adapted to the preferred value T_{2th} during the start-up period, some estimation errors could occur in the differentiated PER. However, such estimation errors during the start-up period have no real effect on the convergence of the proposed algorithm.

We also studied the impact of heterogenous rate assignment on the proposed algorithm. Specifically, we randomly select a link (i.e. AP3-STA3 in the example. Selecting other links had similar results) among the 20 links in Fig. 7 and let it use a different data rate (48Mbps) from others links which are all assigned to 36Mbps. As shown in Fig. 9, no matter what rate AP3 uses, both the PCS threshold and transmit power in “PCS+TXPW” scheme can converge. It indicates that with any rate assignment “PCS+TXPW” can always

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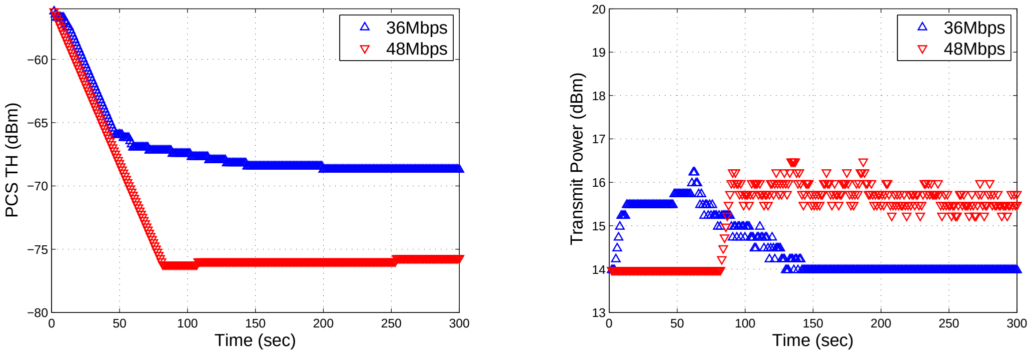
an even lower throughput.



(a) PCS threshold of AP3

(b) Transmit power of AP3

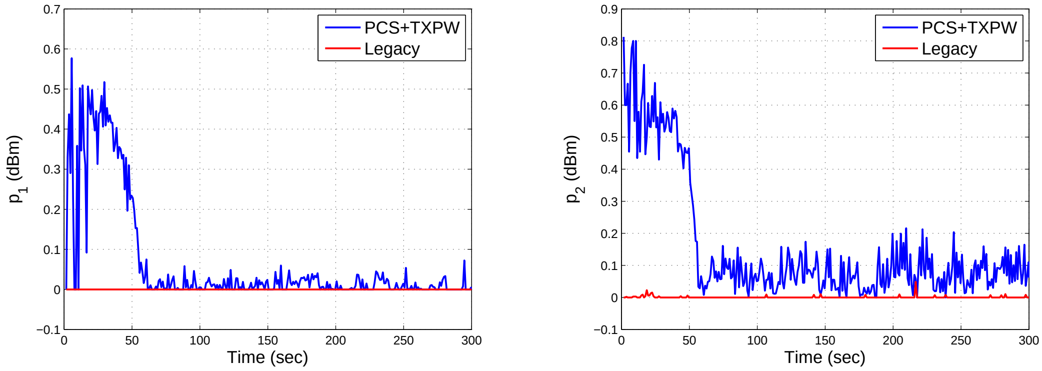
Fig. 9. Transmit power and PCS threshold of AP3 with different rate assignments in a 20 10-meter down-link pairs HD WLAN (Fig. 7). All the rest stations uses the rate of 36Mbps

Table 4
Total and Worst Link Throughput (Rate 36Mbps) for Fig. 11

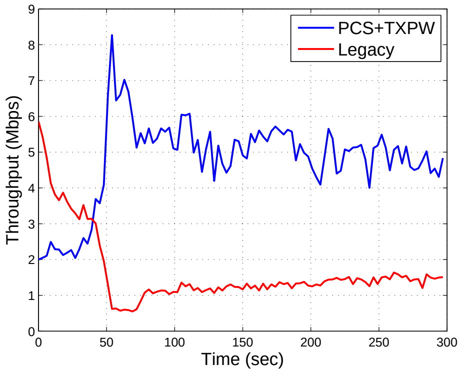
	Legacy	Baseline	PCS	PCS +TXPW	Fair(255)	Fair(127)	Fair(63)
Total(Mbps)	57	173	142	195	110	133	157
Worst(Kbps)	44	0	0	100	1230	818	312

find the suitable PCS threshold and transmit power for each link and thus the proposed algorithm potentially can work with link adaption schemes, which will be studied in the future work.

In order to evaluate the applicability of “PCS+TXPW” to real life HD environments with legacy stations, we did the following experiment. We randomly select a link (i.e. AP15-STA15 in the example. Selecting other links had similar results.) among the 20 links in Fig. 7 and let it use “PCS+TXPW” or legacy parameters (the minimum PCS threshold and the maximum transmit power) in two rounds of simulations respectively. Meanwhile all the rest stations perform “PCS+TXPW” adaptations. As shown in Fig. 9 (a) and (b), when AP15 uses legacy parameters, its p_1 and p_2 are negligible and even lower than those when the station performs adaptations. It demonstrates that the legacy stations can ‘survive’ in the co-existence cases. However, as shown in Fig. 9 (c), comparing with the case performing adaptations, AP15 with legacy parameters can only achieve about 1/4 of link throughput. It shows that stations with “PCS+TXPW” adaptation have advantage over the ones with legacy parameters, because the former can use much higher PCS threshold and thus be more aggressive in acquiring channel access.



(a) PER due to I1 of AP15 (b) PER due to I2 of AP15



(c) Throughput of Link AP5-STA15

Fig. 10. Differentiated PER and throughput of AP15 with and without PCS+TXPW in a 20 10-meter down-link pairs HD WLAN (Fig. 7). All the rest stations adopt PCS+TXPW.

6.2.3 Random HD WLAN with random link distances

One more large-scale realistic network where links have random distances, i.e. uniform [5,15) m was studied. In the pervious example of identical link distances, we note that the performance of “Baseline” is still acceptable comparing with that of “PCS+TXPW”. Here, we will show that the “Baseline” case performance suffers from serious degradation in a random network. Fig. 11 shows the network topology of 20 co-channel cells with cell radius of 15 meters and AP-to-AP distance of 30 meters. Here, comparing with the previous experiment, the cell radius is enlarged to verify that the proposed algorithm can work well with a relatively large interference level. In this experiment, all traffic is bidirectional yielding 40 links. Here, P_{min} = 14dBm, P_{max}=30dBm, γ_{def} = -86 dBm, and γ_{max}= -61.3 dBm. The receiver sensitivity is set to -61.3dBm such that the reception range is 15 m with the minimum transmit power. All other parameters are the same as the previous experiment.

Table 4 shows the results of total throughput and worst link throughput for

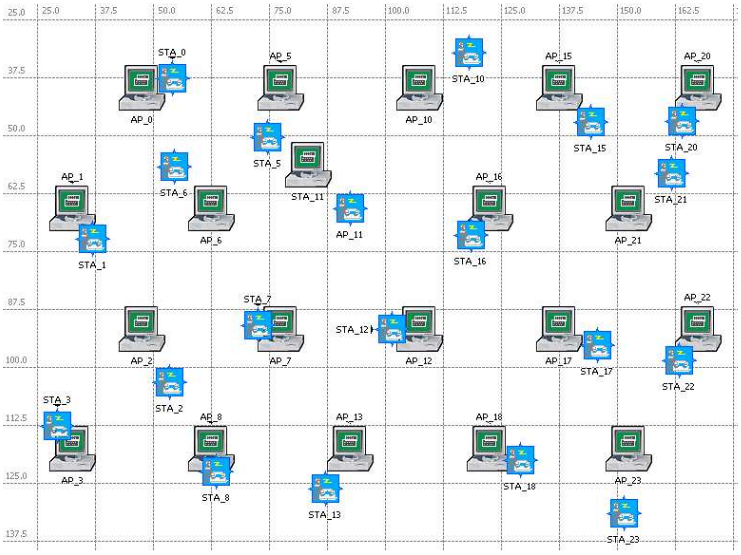
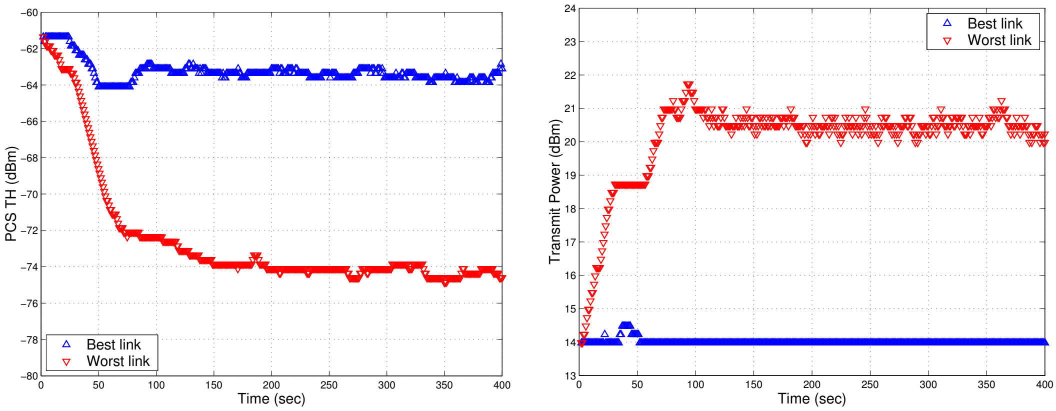


Fig. 11. Multi-cell scenario: 20 bidirectional random pairs HD WLAN

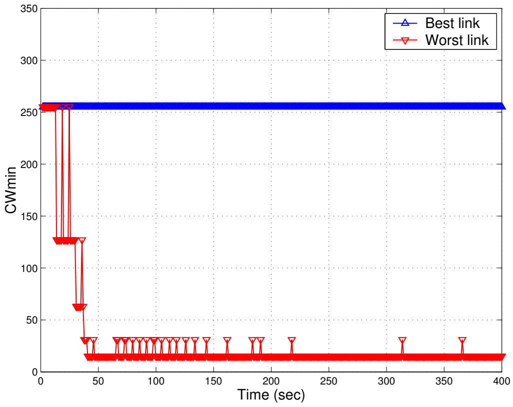
rate 36Mbps. Fig. 12 shows the traces for PCS threshold, transmit power and CWmin for the best link (AP3-STA3) and worst link (STA11-AP11) (in terms of throughput) with rate 36Mbps for "Fair(255)".

In this group of experiments, "PCS+TXPW" achieve much higher performance than "PCS","Baseline" and "Legacy" in terms of total throughput. Furthermore, "PCS+TXPW" dramatically improves worst link throughput compared with "PCS", "Baseline" and "Legacy". Moreover, in such a network with random link distances, the capacity and worst link throughput for 'Baseline' are much worse than our proposed "PCS+TXPW". This implies that transmit power and PCS threshold adaptation on a per-link basis can efficiently deal with the great diversity in interference level at each link and therefore improve spacial reuse with guaranteed link reliability. In addition, although "PCS+TXPW" can avoid starvation, its worst link throughput is just 100kbps because a much lower PCS threshold is used by the worst link. Thus in a network with diverse link distance, fairness algorithm is strongly encouraged. As shown in Fig. 12 (c), after **Fairness tuning** is enabled, CWmin of the worst link will be lower than those of other links to maintain its channel access probability. Therefore, the fairness can be greatly improved.

Fig. 13 shows the transmit power and PCS threshold distribution in the random 40-link HD WLAN after convergence with "Fair(255)". As we can see from the figure, the link with a higher transmit power tends to have a lower PCS threshold, which is consistent with the results in [21] for managing mutual interference. However, with diverse link distances, the product of transmit power and PCS threshold in our heuristic algorithm is not a constant. As shown in the lowest figure of Fig. 13, the square roots of the products expressed as $(Transmit\ power + PCS\ threshold)/2$ in dBm have differences



(a) PCS Threshold (b) Transmit Power



(c) CWmin

Fig. 12. Joint transmit power and PCS adaption with Fairness Tuning enabled in a random 40-link HD WLAN (Fig. 11)

up to 5 dB. This suggests that the sufficient condition found in [21] is not a necessary condition for managing mutual interference in HD WLAN.

Up to this point, we assumed all the traffics are saturated in the simulation, which represents the worst case in terms of interference. In the following, we will study how the adaptations perform in the case with less interference, i.e., non-saturated scenarios. In particular, we introduce Poisson traffic with different arrival rates for the random 40-link HD WLAN. As shown in Fig. 14, “PCS+TXPW” can also remain stable in non-saturated scenarios with diverse arrival rates. However, the converged values of transmit power and PCS threshold for different arrival rates vary. For a lower arrival rate, a station trends to use a lower transmit power and higher PCS threshold. When the arrival rate increases and is close to saturation conditions, both the converged transmit power and PCS threshold will also approach those of the saturated scenario. This lies in that in an environment with more interference, a station have to use a lower PCS threshold and a higher transmit power to eliminate packet loss due to I1 or I2.

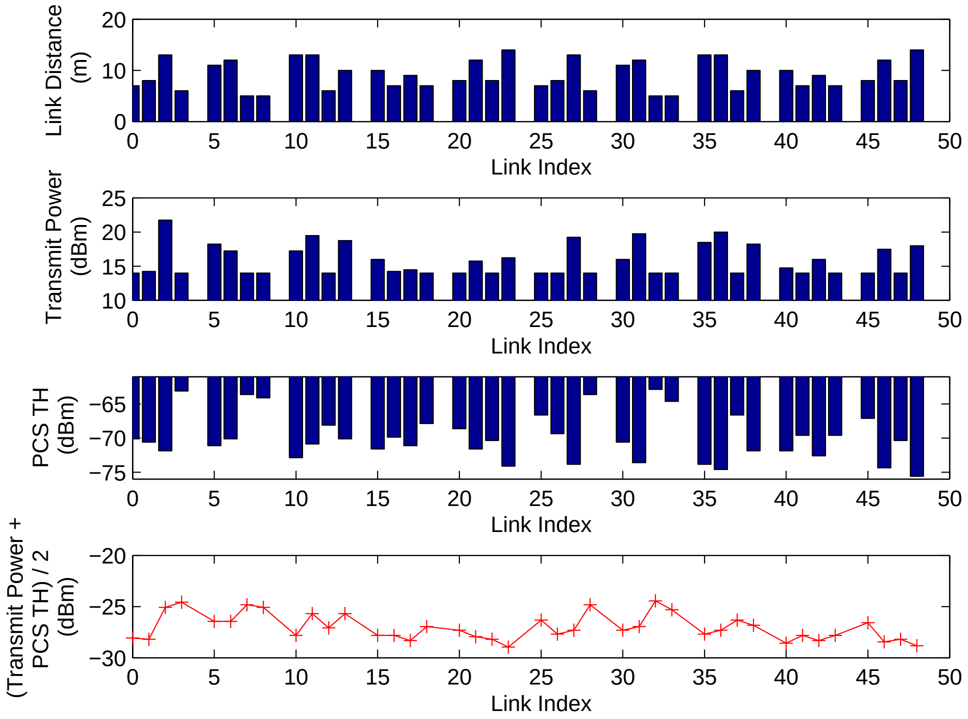
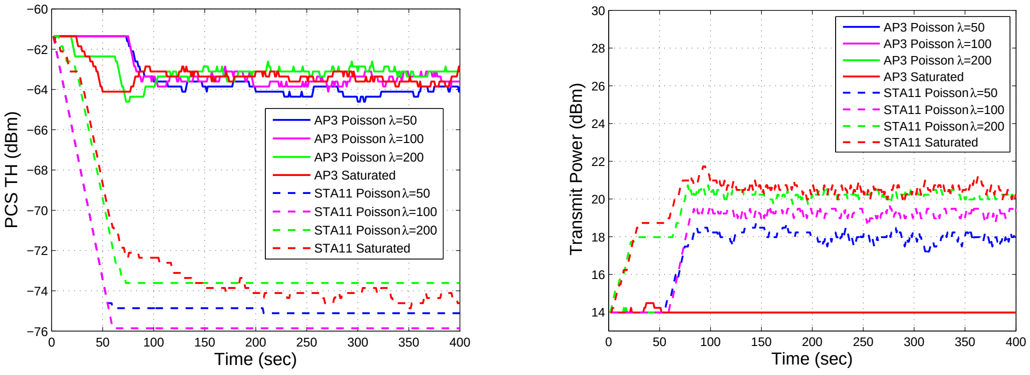


Fig. 13. Transmit power and PCS threshold Distribution in a random 40-link HD WLAN (Fig. 11) after convergence



(a) PCS threshold

(b) Transmit power

Fig. 14. Joint transmit power and PCS adaption with non-saturated traffic in a random 40-link HD WLAN (Fig. 11)

6.2.4 Single cell network

Simulations for a single cell WLAN - a collision dominated scenario - have also been investigated. The network comprises only 1 AP, but N clients(from 1 to 9). Links have random distances, i.e. uniform [5,15) m. All other parameters are the same as those in the previous experiment. The results show that “PCS+TXPW” can achieve almost the same performance as those of “Baseline” and “Legacy”. It implies that the self-adaptation algorithm can be widely used in WLAN with different scales. Due to space limitations, these results are not shown here.

7 Conclusion

In this paper, an analytical model and resultant sufficient conditions for mitigation of asynchronous interference by joint tuning transmit power and PCS threshold are investigated. Further, a practical transmitter-based solution for joint transmit power and PCS adaptation based on loss differentiation is proposed. Simulation with random multi-cell and single-cell scenario evaluated the performance of the proposed solution in terms of both total throughput and worst link throughput. It increases both total throughput and worst link throughput in HD WLAN greatly compared with the PCS adaptation only schemes. Fairness algorithm has been significantly improved by CWmin control with a small cost of total throughput.We believe that the approach propose here paves the way for further design and optimization of the 802.11 protocol stack to enable high performance high density WLANs.

Our future work will incorporate more varied scenarios including node mobility.

APPENDIX A

This appendix shows our proposed loss differentiation method in [14], which can estimate PER due to C, I1 and I2 individually.

We invoke the following key assumption: **the packet loss due to C, I1, and I2 are independent**[5], which will be used in estimating p_1 and p_2.

We assume that energy detection based carrier sensing is implemented. We introduce s, defined as the over-the-air energy observed by a node *prior* to a transmission. We denote γ_{min} as the *minimum* PCS threshold that essentially represents the noise floor [6]. If $s < \gamma_{min}$, the node assumes that there is no

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[5] Certainly, this cannot be strictly true, since given the type-1 interference exists, the contribution of type-2 interference or collisions depends on the amount of type-1 interference present.

[6] The actual PCS threshold γ_{cs} always exceeds γ_{min}.

type-1 interference (i.e. noise only) and thus the PER due to I1 is assumed negligible. For convenience, we denote the binary variable E $=\{s > \gamma_{min}\}$, which takes value E $= 1(0)$ if type-1 interference is detected (not detected). Thus packet losses for $E = 1$ may be ascribed to either I1 or I2 or C; whereas packet losses given $E = 0$ are only due to I2 or C.

The number of successful transmissions and failures in the presence and absence of type-1 interference are measured. During the measurements, each station counts its number of transmitted data packets and received ACKs within a specific time duration, T, as follows:

- t_1: number of transmissions with E=1
- f_1: number of failures with E=1
- t_2: number of transmissions with E=0
- f_2: number of failures with with E=0

The heuristics behind choice of γ_{min} can be described as follows. A low γ_{min} ensures that only collisions or type-2 interference contribute to f_2; however, small γ_{min} will also lead to a lower T2-ratio (measured by $t_2/(t_1 + t_2)$) and therefore require longer observation duration T to generate enough samples for reliable estimation, yielding the familiar trade-off between estimation accuracy and time. Thus, we set γ_{min} such that T_{2th} (T2-ratio threshold) fraction of transmissions satisfy $s \leq \gamma_{min}$ to achieve a desired operating point.

We define the following probabilities:

- p_1': the probability of packet loss due to I1, given E=1
- p : the probability of packet loss, given E=1
- $\bar{p_1}$: the probability of packet loss due to C or I2, given E=1

Using the independence assumption, we have

$$1 - p = (1 - p_1')\,(1 - \bar{p_1}) \tag{A-1}$$

where we estimate [7] p and $\bar{p_1}$ via

$$\langle p \rangle = \frac{f_1}{t_1} \text{ and } \langle \bar{p_1} \rangle = \frac{f_2}{t_2} \tag{A-2}$$

Note that we estimate the probability of packet loss due to C or I2 at E=0 using the assumption that such loss are independent of whether type-1 interference is present. Now, combine (A-1) and (A-2) to get

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[7] We use $< >$ around any quantity to denote its estimate based on observed data.

$$\langle p_1' \rangle = 1 - \frac{1 - \langle p \rangle}{1 - \langle \bar{p_1} \rangle} = 1 - \frac{1 - \frac{f_1}{t_1}}{1 - \frac{f_2}{t_2}} \tag{A-3}$$

Further, since we assume there is no packet loss due to I1 given E=0, we have

$$\langle p_1 \rangle = \langle p_1' \rangle \cdot \frac{t_1}{t_1 + t_2} = (1 - \frac{1 - \frac{f_1}{t_1}}{1 - \frac{f_2}{t_2}}) \cdot \frac{t_1}{t_1 + t_2} \tag{A-4}$$

Using the assumption that the probabilities of packet loss due to C and I2 are independent, we estimate p_2 as

$$\langle p_2 \rangle = 1 - \frac{1 - f_2/t_2}{1 - \langle p_c \rangle} = \frac{f_2/t_2 - \langle p_c \rangle}{1 - \langle p_c \rangle} \tag{A-5}$$

Note that (A-5) gives the estimate of p_2 regardless of the value of E.

Finally, we propose a simple mechanism to estimate p_c based on the fact that collisions are synchronous with the reference signal. Define a probability, q, such that **each node will delay its transmission by half slot with probability of** q. [8] This allows us to estimate p_c with little impact on the network. The nodes that delay their transmissions will then use the first half-slot to measure the on-air energy for collision detection. We measure the following two metrics at a transmitter in each interval:

- n: the number of delayed transmissions at a node;
- $m(< n)$: the number of *failed* transmissions whose energy level measured in the first half slot is higher than the PCS threshold, γ_{cs}.

Assume that N other nodes contend for the channel along with the reference node. Denote the transmission probability for node i as τ_i. The collision probability for the reference node is given by

$$p_c = 1 - \prod_{i=1}^{N} (1 - \tau_i) \approx \sum_{i=1}^{N} \tau_i \tag{A-6}$$

With the proposed delay, a transmission from node i will be detected by the reference node with the probability of $\tau_i\,(1 - q)$. Hence, the observed collision probability measured by m/n equals

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[8] A slot is 9 μs for .11a or .11g, and 20 μs for .11b. Notice even if a collision is detected, the transmission will still proceed.

$$\frac{m}{n} = 1 - \prod_{i=1}^{N} (1 - \tau_i(1-q)) \approx (1-q) \sum_{i=1}^{N} \tau_i \tag{A-7}$$

Combining (A-6) and (A-7), we get

$$\langle p_c \rangle = (\frac{m}{n})(\frac{1}{1-q}) \tag{A-8}$$

Inserting (A-8) into (A-5)

$$\langle p_2 \rangle = \left(\frac{f_2}{t_2} - \frac{m}{n}(\frac{1}{1-q}) \right) / \left(1 - \frac{m}{n}(\frac{1}{1-q}) \right) \tag{A-9}$$

In summary, (A-8), (A-4) and (A-9) give the PER due to C, I1 and I2 respectively. We will force $\langle p_c \rangle$, $\langle p_1 \rangle$ or $\langle p_2 \rangle$ to be "1", if the estimated value is higher than 1, and to be "0", if the estimated value is lower than 0.

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