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Interference-Aware Coordinated Power Allocation in Autonomous Wi-Fi Environment

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ABSTRACT Self-managed access points (APs) with growing intelligence can optimize their own performances but pose potential negative impacts on others without energy efficiency. In this paper, we focus on modeling the coordinated interaction among interest-independent and self-configured APs, and conduct the power allocation case study in the autonomous Wi-Fi scenario. Specifically, we build a 'coordination Wi-Fi platform (CWP), a public platform for APs interacting with each other. OpenWrt-based APs in the physical world are mapped to virtual agents (VAs) in CWP, which communicate with each other through a standard request-reply process defined as AP talk protocol (ATP). With ATP, an active interference measurement methodology is proposed reflecting both in-range interference and hidden terminal interference, and the Nash bargaining-based power control is further formulated for interference reductions. CWP is deployed in a real office environment, where coordination interactions between VAs can bring a maximum 40-Mb/s throughput improvement with the Nash bargaining-based power control in the multi-AP experiments.

INDEX TERMS Coordinated interaction, Wi-Fi, OpenWrt, Nash bargaining.

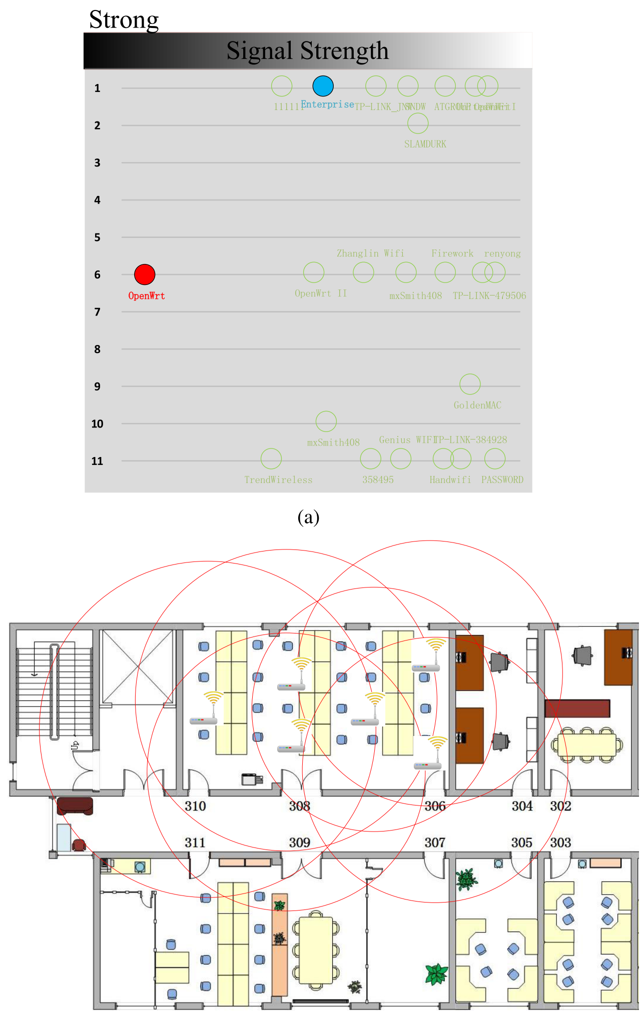
I. INTRODUCTION

Nowadays, Access Points (APs) are widely deployed in autonomous environments, which enables individual Wi-Fi-capable devices to connect Internet in a more flexible way. However, under such an autonomous circumstance, people independently deploy and configure their own APs best for their own interests and without any consideration of the adjacent APs' configurations [1]. Given complex interactions between APs in public channels, when all the co-channel autonomous APs within the same region transmit packets with their maximum powers, they can strongly interfere with each other [2], [3]. Fig. 1 demonstrates the AP deployment in an office environment. It can be observed that most of personal APs' coverage areas are overlapped together, which can pose great negative impacts on APs' performances.

Besides, in the autonomous environment, independent AP configurations can also induce great energy wastes. No matter what power settings the neighboring APs configure, one AP can acquire improved individual performances through increasing its power. Based on 802.11 protocol [4], the increased transmission power corresponds to the larger Received Signal Strength Index (RSSI) and the higher transmission rate. Meanwhile, the higher power can also enlarge one AP's coverage range to avoid hidden terminal interference as much as possible. Therefore, from the perspective of one AP, its conservative way for best Wi-Fi performances is to maximize one AP's transmission power, which is indeed the true case on commercial APs [5].

However, when all APs configure their maximum powers, both the overall performance and individual performances can be degraded. This is because each AP brings great interference to its neighboring APs, and each AP's interference is also increased by the maximum power settings of its neighboring APs. That is, each AP's conservative strategy will not lead to improved performances, but can result in performance decline because of the negative interactions between each other. Actually, lack of coordinations between self-managed APs is the principal cause for such performance degradation and additional energy consumption. When all APs can coordinately reduce their powers, they can improve their individual performances with energy efficiency [6], [7].

In this paper, we propose a coordinated management framework to solve such a low energy efficiency and high



(a)

(b)

FIGURE 1. AP Deployment in an office environment. (a) APs Seen from a Mobile Phone. (b) Office APs.

interference problem with incentive considerations. We focus on the scenario where a groups of OpenWrt based APs (wireless access points with embedded linux systems) [8][1] within some region join our designed ''Coordination Wi-Fi Platform'' (CWP). Each AP corresponds to a VA, which can configure and control the AP in the physical world. Based on an ''AP Talking Protocol'' (ATP) on CWP, a request-reply process performed by VAs, which can coordinate APs' actions, i.e., configuring traffic parameters for interference measurements or power parameters for coordinate interference reduction. Our main contributions in this paper are listed as follows. First, focusing on the autonomous Wi-Fi network, this paper aims to build CWP and ATP, the public interfaces for self-managed APs' coordinated interactions. Second, with ATP, the active interference measurement methodology is proposed for APs to monitor their physical interference environments, and a Nash bargaining power control model is further formulated and solved in a distributed manner. Besides, we deploy CWP and ATP on a small scale in an office environment, demonstrating that the active interference measurement is effective in both in-range interference and hidden terminal interference, and there is a maximum 40Mbps throughput improvement in the multi-AP experiments.

In the following of this paper, related works are presented in Section II. CWP with the active interference measurement and the power control model is proposed and implemented in Section III. Section IV evaluates the performance of active interference measurements and power control in the office environment. Section V concludes the paper.

[1] In our scenario, the APs are OpenWrt based APs, which support over 500 AP models by 96 vendors [5]. Furthermore, commercial vendors shipped more than 1.1 million OpenWrt-based APs [9].

II. RELATED WORKS

In the literature, the energy management issue in wireless networks has been studied extensively, such as cellular, WLANs and Wireless Mesh Networks (WMNs) [10]. In an earlier stage, Jones *et al.* surveyed the energy efficient protocols for wireless networks in [10]. In WLANs, a management strategy based on the resource on-demand concept was proposed in [11]. Similarly, the authors in [12] also proposed an analytical model for energy saving based on the activation of network resources on demand. Targeting on solar powered 802.11 WLAN mesh networks, Todd *et al.* in [13] showed management strategies for energy savings in North American locations. In cellular networks, the existing energy saving approaches were surveyed in [14], including the carrier aggregation, turn-off transmission mechanism, and turn-off cells during low traffic periods. In cognitive radio networks, the power control problem has also been widely studied either using game theory [16] or queuing theory [17]. Different from those existing works focusing on enterprise or centralized-deployed networks, we jointly consider an automatous Wi-Fi network scenario with energy efficiency as well as individual incentives.

Several studies analyzed power allocations in Wi-Fi scenarios. Akella *et al.* proposed a power adjustment method from the perspective of a specific AP [15]. Pelechrinis *et al.* suggested that coordinately reduced powers can improve all APs' performances with energy efficiency [7]. Mhatre *et al.* proposed a Gibbs based power control, which optimizes the overall performance without considering the individual AP performance [6]. Similarly, Murty *et al.* adjusted the APs' powers to reduce their interference in the enterprise scenario [16]. Shrivastava *et al.* developed an entropy based power control algorithm for reduced interference based on actual Wi-Fi interference measurements [17]. Different from these studies, this paper considers the power control model with incentive considerations and voluntary interference measurements. Also, such procedure is implemented on the real platform implementation.

Meanwhile, [18] and [19] sketched a simple vendor-neutral API for monitoring and measuring the interference between APs also managed by a cloud-based server. In addition, [20] presented an AP management architecture for centrally configuring APs in a large scale scenario. The project [21] aimed to build a collaborated platform within inter networks for efficient spectrum gains and reduced interference. Different from the aforementioned studies, our paper concentrates on how self-managed APs optimize their performances based on their individual perceived interference, which does not necessarily require central managements. Moreover, the on-line platform is also deployed, where self-managed APs can voluntarily perform active interference measurement between each other. It is worthy to emphasize that the central platform in our scheme does not control the APs' management, but only provides interference information between them, which can accelerate the APs' interference perceiving procedure without affecting the ultimate converged equilibrium.

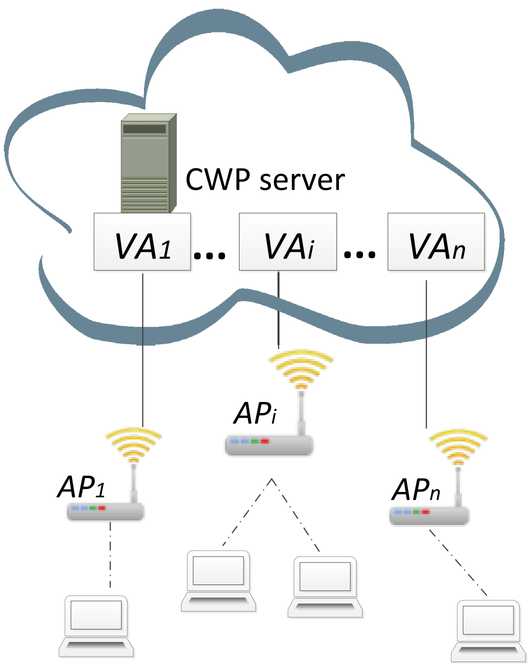


FIGURE 2. Schematic scenario.

III. COORDINATED Wi-Fi PLATFORM (CWP)

A. ARCHITECTURE

As shown in Fig. 2, CWP includes two parts: the OpenWrt based APs within a certain region (such as a building) and a CWP server for coordinated interactions between APs. Each AP connects to the CWP server through the wired broadband network, and registers as a "virtual agent" (VA) including three functions: configuring its corresponding AP, collecting and analyzing information from its corresponding AP, and interacting with the other VAs for its improved performance. In our current stage, the above functions are achieved by a series of linux expect scripts and shell scripts running on the CWP server with standard messaging, and the shell scripts running on OpenWrt based APs.

In the physical world, APs only receive commands from their VAs and act based on the commands. The coordinated interactions happen between VAs on the CWP server, which can be further divided into two parts: management modules and coordinated interaction modules as shown in Fig. 3. All the modules are implemented based on c codes, which are further invoked by a series of shell scripts running on a standard Linux server.

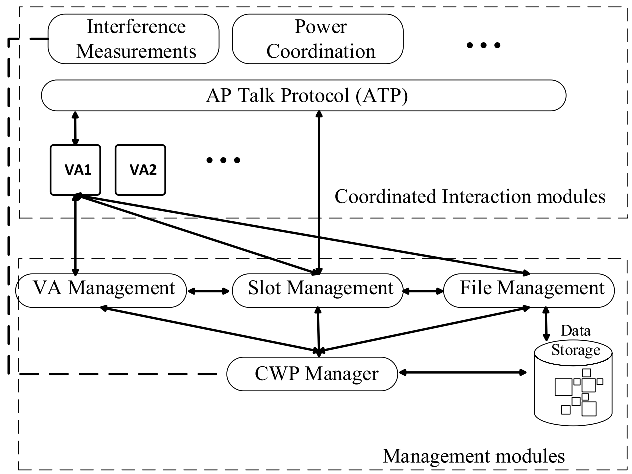


FIGURE 3. CWP framework.

Management Modules. The management modules, the core components of CWP, maintain the basic functions.

- *CWP manager* is responsible for scheduling the working process of these modules, creating the content for coordinated interactions, and allocating storage and computation resources.
- *VA Management* creates VAs. It also receives requests and responses from VAs, parses the requests and distributes them to the corresponding VAs.
- *Slot Management* works for time synchronization through the NTP protocol (in milliseconds). It divides a period of time into several slots in a coarse-grain manner such as 1 minute a slot, which sets the basic pace of communications between VAs.
- *File Management* receives and filters the experiments data performed by APs, and operates data storage in a data base (denoted by *Data Storage*). This module also manages the file access authority. In CWP, each VA can only access the files which are generated by its corresponding AP.

Coordinated Interaction Modules. The coordinated interaction modules function for the coordinated interactions between VAs such as *Interference Measurement* and *Power Control*. The specific coordinated content should be first predefined on the CWP, and be triggered by the CWP manager. The main part of the modules is "AP Talk Protocol" (ATP), which regulates a standard information exchanging process between VAs based on synchronized slots. ATP is basically a series of request-reply processes, and each VA interacts with the other VAs through sending requests and receiving responses. A VA can launch a request to the VA management module with the standard format shown as Tab. 1.

TABLE 1. Request format.

Time	Request VA	Target VA	Request content	Reply deadline

The "Time" item is the requested time in slots. The "Request VA" item is the VA who launches the talk, while the "Target VA" item is the VA who the "Request VA" requests. The "Request content" item specifies what the "Request VA" wishes the "Target VA" to do with the standard format, which is pre-defined by the user. The "Reply deadline" item is the due time before which a corresponding response from the "Target VA" is valid. Similarly, the request format is shown in Tab. 2.

TABLE 2. Response format.

Time	Response VA	Target VA	Response result

The "Response VA" item and the "Target VA" item correspond to the VA who responses a request (corresponding to the "Target VA" in the request format) and who the "Response VA" wants to reply (corresponding to the "Request VA" in the request format), respectively. The "Response result" is 1 or 0, indicating whether or not the "response VA" agrees on the request content. Whether the response result is positive depends on the preferences of "Response VA".

For simplicity, we assume that each VA can only have one request in one slot, and the ATP protocol can be summarized as follows.

1) VAs send their requests to the VA management module at the beginning of a certain slot.
2) The VA management module filters the valid requests, and sends them to the corresponding target VAs.
3) VAs generate their corresponding responses and sends them to the VA management module, which further transfers them to the corresponding VAs.
4) VAs act based on their received request contents if their responses are positive.

The above procedure is a general working flow for information exchange between VAs. All the coordinated interactions between VAs can be implemented through the ATP protocol with particular "request content". Our paper focuses on the scenario where APs help each other perform active interference measurements and power controls, which are two specific interactions between VAs. In the following, we specify the working procedure of the two above coordinated modules. The notations in the following part are also summarized in Tab. 3.

B. ACTIVE INTERFERENCE MEASUREMENTS ON CWP

1) METRIC

We consider an autonomously-managed 802.11 WLAN environment, where APs within a certain region work on the same channel. We adopt the *airtime cost* metric in [22],[2] which is used to reflect the link condition between an AP and its client in general wireless measurement scenarios [23]. Formally, let C_i denote the client set of AP_i. Then, for each AP_i and its one client $k \in C_i$, the airtime cost of AP_i's client k can be written as

$$A_{i_k} = \left\lceil \frac{B_t}{r_{i_k}} \right\rceil \frac{1}{(1 - e_{i_k})}, \tag{1}$$

where B_t is the test frame length actively transmitted from AP_i to its client k (1546 Bytes in our experiments), r_{i_k} is the bit rate in Megabytes from AP_i to its client k, and e_{i_k} is the packet loss rate. A_{i_k} reflects the average duration of successful transmitting a packet from AP_i to its client k in a satiated condition, where the transmitted traffic is approximately the channel capacity. The smaller A_{i_k} is, the better link condition between AP_i and client k is. The average airtime cost of AP_i reflects the link conditions between AP_i and its clients on average shown as

$$A_i = \frac{1}{|C_i|} \sum_{k \in C_i} \left\lceil \frac{B_t}{r_{i_k}} \right\rceil \frac{1}{(1 - e_{i_k})}, \tag{2}$$

where $|C_i|$ is the number of clients of AP_i.

2) TWO KINDS OF INTERFERENCE

Based on (1) and (2), both r_{i_k} and e_{i_k} can affect the airtime cost A_{i_k}, which corresponds to two kinds of interferences. First, the data rate r_{i_k} between AP_i and its client k depends on its Signal-to-Interference-Noise-Ratio (SINR) γ_{i_k} defined as *in-range interference*. According to the 802.11 protocol [4], with the higher SINR, AP_i can use a higher transmission rate to send packets. The relationship between γ_{i_k} and r_{i_k} can be referred to Tab. 4.

γ_{i_k} is affected by three factors: AP_i's power level, the powers of the other APs nearby AP_i, and the fading channel between AP_i and client k. Therefore, γ_{i_k} can be expressed as a function of these factors mentioned above, i.e.,

$$\gamma_{i_k} = u(g_{ik}, p_i, P_{\Lambda_{i_k}}). \tag{3}$$

g_{ik} is the channel gain from AP_i to client k. p_i, AP_i's power, is generally discretely adjusted between the minimum power $p_{i,min}$ and the maximum power $p_{i,max}$. Let Λ_{i_k} denote the AP set whose signals can be received by AP_i's client k and $P_{\Lambda_{i_k}}$ is the power set of Λ_{i_k}. A typical SINR model in the additive white Gaussian noise channel (4) shows that the smaller p_i and the greater powers of the other APs result in the greater airtime cost based on (1).

$$\gamma_{i_k} = \frac{g_{ik} p_i}{\sum_{j \in \Lambda_{i_k}} g_{jk} p_j + N_0}. \tag{4}$$

Besides, different power levels also change the coverage range of each AP, which results in different degrees of hidden terminal interference. Taking Fig. 4 for illustrations,

[2]The standard airtime cost also includes the overheads which is fixed in a certain protocol. Hence, we exclude it for simplicity.

TABLE 3. Summary of notations.

Notations	Description
r_{i_k}	the data rate between AP_i and its client k
e_{i_k}	the packet loss rate between AP_i and its client k
A_{i_k}	the airtime cost between AP_i and its client k
A_i	the average airtime cost of AP_i
C_i	the client set of AP_i
$\|C_i\|$	the number of clients of AP_i
p_i	AP_i's power
$p_{i,min}$	the minimum power of AP_i
$p_{i,max}$	the maximum power of AP_i
Λ_{i_k}	the AP set which affects the airtime cost of AP_i's client k
Λ_i	the AP set which affects the airtime cost of AP_i
P_{Λ_i}	the power set of Λ_i
g_{ik}	the channel gain from AP_i to its client k
γ_{i_k}	the received Signal-Interference-Noise-Ratio from AP_i's client k
t_b, t_e, and t_s	the requested action beginning time, the requested action ending time, and the response deadline
S_j	the requested traffic for AP_j
$A_{i_k,j}(p_i, p_j)$	the airtime cost of AP_i's client k when AP_i and AP_j work on power p_i and p_j respectively
$I_{i_k,j}(p_i, p_j)$	the interference of AP_i's client k caused by AP_j when AP_i and AP_j work on power p_i and p_j respectively
$I_{i,j}(p_i, p_j)$	the average interference of AP_i caused by AP_j when AP_i and AP_j work on power p_i and p_j respectively
$I_i(p_i, P_{\Lambda_i})$	the interference of of AP_i caused by Λ_i when AP_i and Λ_i work on power p_i and P_{Λ_i} respectively
$I_i(p_{i,max}, P_{\Lambda_{i,max}})$	the interference of of AP_i when AP_i and Λ_i work on their maximum powers respectively

TABLE 4. The relationship between SINRs and data rates.

$\gamma_{i_k}(db)$	6-7.8	7.8-9	9-10.8	10.8-17	17-18.8	18.8-24	24-24.6	24.6-
$r_{i_k}(Mbps)$	6	9	12	18	24	36	48	54

when AP_1 and AP_2 transmit traffic to their clients M_1 and M_2 with a low power level (denoted by dashed line circle), the impact of AP_1 (AP_2) on AP_2 (AP_1) is the increased interference client M_2 (M_1), which is specified in the previous subsection. If AP_1 increases its power level (denoted by solid line circle), M_2 can hear the packet transmission of AP_1, while AP_2 still cannot hear the packet transmission of AP_1. In this condition, AP_1 is the *hidden terminal* of AP_2. AP_1 could interrupt AP_2's packet transmission to M_2 when AP_1 sends packets to M_1 at the same time. Hidden terminal interference increases the airtime cost by two aspects. First, it causes packet loss which increases the packet error rate. Besides, once a packet is lost, the AP transmits the retried packet with the smallest data rate. The degree of hidden terminal interference depends on the relative positions between APs and clients, and the powers of APs. Generally, the worst case for the hidden terminal interference happens when the interferer AP_1 transmits with the maximum power, i.e. $p_{1,max}$, while the managed AP of an client transmits with the minimum power $p_{2,min}$ when the location of the client is fixed.

From the above analysis, the impact of one AP's power level on another AP are twofold. On the one hand, one AP's power configurations affect the SINR of the transmission link of another AP, which further affects the transmission rate. On the other hand, one AP's power configurations can modify its transmission range, and could become a hidden terminal and induce packet loss of another AP. Besides, it is hard for an AP to measure this impact independently. For example, one AP even cannot receive the packet from its

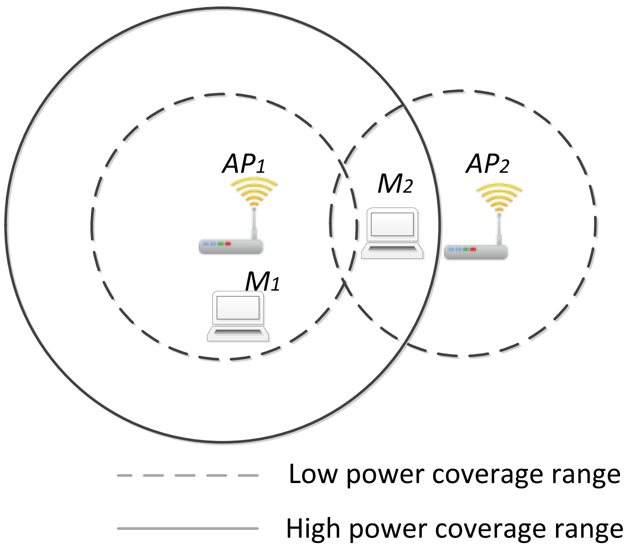


FIGURE 4. Impact of powers on hidden terminal interference.

hidden terminals. The hidden terminal interference measurement generally requires the help of its clients or the hidden terminal APs [24], [25].

3) ACTIVE INTERFERENCE MEASUREMENTS

In this part, we present how APs help each other perform active airtime cost measurement, and further calculate the interference from one AP to another AP with different powers. Assuming that VA_i wants to measure its airtime cost when its corresponding AP_i sets its power p_i and AP_j sets its power p_j. Based on ATP, VA_i first sends a request to the VA management module in a certain slot t with the format as Tab. 5.

TABLE 5. Request format for airtime cost measurements.

Time	Request VA	Target VA	Request content	Reply deadline
t	VA_i	VA_j	$(t_b - t_e, S_j, p_j)$	t_d

t_b and t_e are the requested action beginning time and the action ending time, S_j is the requested traffic of AP_j, and p_j is the power of AP_j. After the VA management module parses this request and sends it to VA_j, VA_j will check whether AP_j is available between $t_e - t_b$. If there is a client connecting AP_j, and there is no traffic from AP_j to this client in a slot, this slot can be regarded as "idle time" for AP_j.

Then, after receiving the request from the VA management module, VA_j determines whether to help AP_i perform interference measurements or not. If the corresponding time slots are free and VA_j is also willing to help VA_i, VA_j responses a positive signal (i.e. setting 1 as the "Response result" item in Tab. 2). After that, both VA_i and VA_j set the slots in $t_e - t_b$ as "busy state", which means that AP_i and AP_j do not response the other request during $t_e - t_b$.

Finally during $t_e - t_b$, VA_i measures the airtime cost of AP_i with client k and VA_j sends S_j to its certain client on p_j, which can be regarded as the airtime cost of AP_i's client k under the interference AP_j on power p_j. Based on the definition of airtime cost (1), AP_i should acquire the data rate and the packet loss rate of its transmitted packets, which can be achieved by sniffing its transmitted packets and parsing the packet headers (including data rate, packet length, and the indication whether the packet is a retried packet). In our scenario, libcap [26], a packet sniffer software, can be installed on AP_i with "monitor mode" configurations. Iperf [27] is also installed on both AP_i and AP_j, which generates UDP test packets with the fixed packet length such as 1546 Bytes. The above process can be autonomously implemented by VAs triggering the corresponding AP to run the following expect scripts:

```
/*Install libcap for packet sniffing*/
root@CWP:opkg install libcap
/*using iw to add an virtual sniffer mon0*/
root@CWP:iw dev wlan0 add interface mon0
type
monitor flags none
/*activate sniffer mon0*/
root@CWP:ifconfig mon0 up
/*activate Use Iperf to send UDP traffic*/
root@CWP:Iperf -c 192.168.1.2@root -u -b
10Mbps
```

At the end of t_e, AP_i sends the sniffed packet header to the VA management module, which further calls the CWP manager to calculate the average transmission rate (r_{i_k}), the packet loss rate (e_{i_k}), and the airtime cost $A_{i_k}(p_i, p_j)$ based on (1). With the similar airtime cost measurement methodology, AP_i can also measure its airtime cost without the interference AP_j (AP_j is idle) when AP_i works on its maximum power $p_{i,max}$ which leads to the minimum airtime cost of its client k denoted by $A_{i_k}(p_{i,max}, 0)$. Then the interference of AP_j on power p_j to AP_i's client k when AP_i is on power p_i can be written as

$$I_{i_k,j}(p_i, p_j) = A_{i_k}(p_i, p_j) - A_{i_k}(p_{i,max}, 0), \ \forall i, j, k \in C_i, \quad (5)$$

which represents the airtime cost increase from the minimum airtime cost $A_{i_k}(p_{i,max}, 0)$ ($A_{i_k}(p_{i,max}, 0)$ is the airtime cost when AP_i transmits with its maximum power and all interferers idle) to $A_{i_k}(p_i, p_j)$. The smaller $I_{i_k,j}(p_i, p_j)$ is, the less airtime cost gap with and without AP_j on p_j is, and the less interference AP_i has. In an extreme case, $I_{i_k,j}(p_i, p_j) = 0$, which represents that AP_j does not interfere with AP_i. The above airtime cost measurement can be continually performed so that AP_i can measure the interference of AP_j with different powers to its client k when AP_i is in different powers. Assuming that all APs have L discrete power levels, the "Request content" can be expressed as Tab. 6. In each item, AP_j transmits a certain amount of traffic to its client for L slots with a fixed power p_j, while AP_i sequentially configures its power levels and transmits traffic to its client k. Then the interference of AP_j with power p_j to AP_i's client k $I_{i_k,j}(p_i, p_j), \forall p_i$ can be measured by AP_i.

TABLE 6. Interference measurement request content.

$t_e - t_b(slot)$	$S_j(Mbps)$	$p_j(dbm)$
1-L	10	0
⋮	⋮	⋮
$(L-1)L+1$-$(L-1)L+L$	10	$L-1$

It is practical to perform active interference measurements for OpenWrt based APs. First, the CPU cost of capturing packets is generally less than 2%. The CPU cost for calculating airtime cost is performed on CWP, which does not have enough computation resources. In addition, the experiment files are less than 24Megabytes for each active interference measurement (the test packets are generated by 10Mbps UDP traffic, two APs have 8 power levels, and each $I_{i_k,j}(p_i, p_j)$ lasts 30 seconds). Considering that the active interference measurements are periodically implemented such as in the beginning of the deployment of APs or new APs joining CWP, the upload of the experiment file will not incur too high network bandwidth cost.

C. POWER CONTROL BASED ON NASH BARGAINING

In this part, we model the power control problem between autonomous APs under CWP with the Nash bargaining, and solve it in a distributed manner with the help of CWP.

1) OPTIMIZATION OBJECTIVE

We consider an autonomous multi-AP scenario, where n interest-independent APs ($AP_i, i = 1, 2, \ldots, n$) are willing to help each other perform interference measurements as presented in the previous section. Based on the active interference measurement result $I_{i_k,j}(p_i, p_j), \forall i, j, k \in C_i$, the interference of AP_j on power p_j to AP_i on power p_i can be expressed as the average interference of AP_i's clients

$$I_{i,j}(p_i, p_j) = \frac{1}{|C_i|} \sum_{k \in C_i} I_{i_k,j}(p_i, p_j), \quad \forall i, j. \tag{6}$$

We define that the interference of AP_i is the sum of interference that the other APs provide for AP_i shown as

$$I_i(p_i, P_{\Lambda_i}) = \sum_{j \in \Lambda_i} I_{i,j}(p_i, p_j), \quad \forall i, \tag{7}$$

where Λ_i represents the AP set which can affect the airtime cost of AP_i (such as APs providing in-range interference and hidden terminal interference for AP_i), and P_{Λ_i} is the power set of the APs in Λ_i. $I_i(p_i, P_{\Lambda_i})$ can reflect the degree of interference caused by the other APs, The smaller $I_i(p_i, P_{\Lambda_i})$, the better performance AP_i has.[3] Therefore, AP_i's optimization objective can be

$$\begin{aligned} \min_{p_i} \quad & I_i(p_i, P_{\Lambda_i}); \\ & p_{i,min} \le p_i \le p_{i,max}; \\ & p_{j,min} \le p_j \le p_{j,max}, \quad \forall j \in \Lambda_i. \end{aligned} \tag{8}$$

AP_i optimizes (8) by adjusting its power p_i. As presented in the previous section, in an non-cooperative environment, the optimal choice of AP_i is to transmit packets with its maximum power levels. In this condition, the strategies of all the APs form the Nash equilibrium (NE), where each AP_i will not have a smaller I_i by unilateral reducing its power. Let $P_{\Lambda_{i,max}}$ denote that all the APs who affect AP_i's interference work on their maximum powers. Then, $AP_i's$ interference in NE can be expressed as $I_i(p_{i,max}, P_{\Lambda_{i,max}})$. However, they can communicate with each other, and simultaneously decrease their individual powers for improved performances. That is, with the help of CWP, each AP decreases its power level for decreasing the interference to the other APs, while its own interference can be also decreased by the power reduction of the other APs.

With consideration on both utilization and fairness, we choose to use the cooperative game theory to solve the coordinated power control problem. In a cooperative game, two or more players enter the game with their individual utilities and act with each other for a win-win solution. Specifically, the players' individual utilities (cost) constitute a coordinated utility (cost) in certain form and all the players optimize this coordinated utility. The classic coordinated utility in cooperative game theory is Nash bargaining [28], which is the serial product of all the individual utilities. It can be proved that Nash bargaining can guarantee that all players acquire the maximum payoff (the minimum cost in our scenario) with fair concerns. The Nash bargaining power control problem can be modeled as

$$\begin{aligned} \max I = & \prod_i (I_i(p_{i,max}, P_{\Lambda_{i,max}}) - I_i(p_i, P_{\Lambda_i})); \\ & I_i(p_{i,max}, P_{\Lambda_{i,max}}) - I_i(p_i, P_{\Lambda_i}) \ge 0, \quad \forall i; \\ & p_{i,min} \le p_i \le p_{i,max}, \quad \forall i. \end{aligned} \tag{9}$$

$I_i(p_{i,max}, P_{\Lambda_{i,max}})$ is AP_i's interference in NE which is a fixed value and can be measured by AP_i's active interference measurement procedure. $I_i(p_{i,max}, P_{\Lambda_{i,max}}) - I_i(p_i, P_{\Lambda_i})$ is the interference reduction after power control. The larger $I_i(p_{i,max}, P_{\Lambda_{i,max}}) - I_i(p_i, P_{\Lambda_i})$ is, the greater interference is reduced. So (9) is compatible with the optimization objective (8) of individual APs.

Besides, the optimization in (9) is the continued product of each AP's interference reduction from that in NE. It is possible that $(I_i(p_{i,max}, P_{\Lambda_{i,max}}) - I_i(p_i, P_{\Lambda_i})) < 0$ and their products are also maximum, which is not the feasible solution. Therefore, we add a constrain to prevent it. Meanwhile, standalone optimizing I can result in the sacrifice of some link performance for optimizing the overall performance of an AP. For example, assuming that AP_i has two clients k_1 and k_2, and client k_1 has a larger distance with AP_i than that of k_2. AP_j is the hidden terminal of AP_i, and can only result in the airtime cost increase of k_2. In this condition, if AP_i and AP_j cooperatively decrease its power levels, AP_j is no longer the hidden terminal of k_2, and the overall airtime cost of AP_i is decreased. However, the decrease power of AP_i can also decrease AP_i's signal strength arriving at k_1, which results in the decrease transmission rate of k_1. If the degradation exceeds a certain threshold and results in an unbearable interference for k_1, even through the cooperation improves the overall performance of AP_i, it is still not practical. Hence, we add the constraint that the power control should also guarantee the performance of each link.

Specifically, let $I_{i_k,th}$ denote the interference threshold for AP_i's client k. If the interference of AP_i's client k in NE exceeds $I_{i_k,th}$, then AP_i will not increase the interference of AP_i's client k, which can be expressed as

$$\begin{aligned} & I_i(p_i, P_{\Lambda_i}) \le I_i(p_{i,max}, P_{\Lambda_{i,max}}), \\ & \text{if } I_i(p_{i,max}, P_{\Lambda_{i,max}}) \ge I_{i_k,th}, \quad \forall i, k \in C_i, \end{aligned} \tag{10}$$

Then, the coordinated power control problem can be formulated as

$$\begin{aligned} \max I = & \prod_i (I_i(p_{i,max}, P_{\Lambda_{i,max}}) - I_i(p_i, P_{\Lambda_i})); \\ & I_i(p_{i,max}, P_{\Lambda_{i,max}}) - I_i(p_i, P_{\Lambda_i}) \ge 0, \quad \forall i; \\ & I_i(p_i, P_{\Lambda_i}) \le I_i(p_{i,max}, P_{\Lambda_{i,max}}), \\ & \text{if } I_i(p_{i,max}, P_{\Lambda_{i,max}}) \ge I_{i_k,th}, \quad \forall i, k \in C_i; \\ & p_{i,min} \le p_i \le p_{i,max}, \quad \forall i. \end{aligned} \tag{11}$$

The result of NBS (Nash Bargaining Solution) achieves the Pareto optimality. The physical meaning of the Pareto optimality is that there exists no other operating point that

[3] $I_i(p_i, P_{\Lambda_i})$ does not represent the overall interference AP_i suffers from. In practice, even through the interferers of AP_i are all active, its accumulated impact is not the sum of their individual interference on AP_i. However, it is rightful to reduce $I_i(p_i, P_{\Lambda_i})$ for providing better performances for AP_i.

can lead to superior performance for one transmitter without degrading the performance of the others. In practice, the power levels are discretely adjusted. it is difficult to derive the closed-form expressions of NBS. The optimization problem above has to be numerically solved. Therefore, we propose a distributed bargaining procedure on CWP.

2) DISTRIBUTED SOLUTION

The overall optimization objective can be expressed as a series of airtime cost reduction of different APs shown as

$$\begin{aligned} I(p_1, \ldots, p_i, \ldots, p_n) &= (I_1(p_1, P_{\Lambda_1}) - I_1(p_{1,max}, P_{\Lambda_{1,max}})) \ldots \\ &\quad (I_n(p_n, P_{\Lambda_n}) - I_n(p_{n,max}, P_{\Lambda_{n,max}})). \end{aligned} \tag{12}$$

The NBS can be found by using the gradient descent method as follows:

$$\begin{aligned} p_1(t+T) &= p_1(t) + \lambda[I(p_1(t), \ldots p_n(t)) \\ &\qquad - I(p_1(t)-1, \ldots p_n(t))]; \\ &\vdots \\ p_i(t+T) &= p_1(t) + \lambda[I(p_1(t), \ldots p_i(t), \ldots, p_n(t)) \\ &\qquad - I(p_1(t), \ldots p_i(t)-1, \ldots, p_n(t))]; \\ &\vdots \\ p_n(t+T) &= p_1(t) + \lambda[I(p_1(t), \ldots p_n(t)) \\ &\qquad - I(p_1(t), \ldots p_n(t)-1)]. \end{aligned} \tag{13}$$

where T is the updating period, λ is the adjustment step size which can be set as 1, and $[I(p_1(t), \ldots p_i(t), \ldots, p_n(t)) - I(p_1(t), \ldots p_i(t)-1, \ldots, p_n(t))]$ is the approximated partial derivatives of $I(p_1(t), \ldots p_i(t), \ldots, p_n(t))$ in a discrete form. Note that $I(p_1, \ldots, p_i, \ldots, p_n)$ should be partially decided by each VA based on (12).

The bargaining procedure can be presented as follows. First, Each VA_i initializes its corresponding AP's power with its maximum power level ($p_i(0) = p_{i,max}$), and submits its interference $I_i(p_{i,max}, P_{\Lambda_{i,max}})$ in NE to the VA management module. In step t, each VA_i should also submit its airtime cost $I_i(p_1(t), \ldots, p_i(t), \ldots, p_n(t))$ and $I_i(p_1(t), \ldots, p_j(t) - 1, \ldots, p_n(t)), \forall j$ to the VA management module. Then, the VA management module distributes the above airtime cost to all the VAs, and each VA calculates its $p_i(t+T)$ based on (12) and (13). When $p_i(t) = p_i(t+T), \forall i$, the algorithm ends. The above bargaining procedure is summarized in AL. 1.

There are some practical issues about the above algorithm that deserve to be explained. First, the above bargaining result is compatible with the constraint proposed in the problem (10). In practice, each VA can set its interference reduction as 0 if its constraint is not satisfied, which means that the VA refuses to bargain for improved performance with its link performance sacrifice. Second, the bargaining procedure is based on the active interference measurements of APs, which can be performed during a period of time. Then, the power control procedure can run on the CWP server, which does not require APs to frequently change their powers. Thirdly, although the bargaining procedure needs the information exchanging by the VA management module, it does not provide the centralized control for the APs. Actually, the result is only decided by all the APs, and CWP provides a bargaining platform for their data exchanges.

Algorithm 1 Distributed Method

Input:
The power range for each AP: $p_i \in [p_{i,min}, p_{i,max}], \forall i$.
Output:
The power of each AP : p_i.

Initial the power level $p_i(0) = p_{i,max}, \forall i$.
$VA_i, \forall i$ submits $I_i(p_{i,max}, P_{\Lambda_{i,max}})$ to the VA management module.
while $\exists i, p_i(t+T) \neq p_i(t)$ **do**
  Each VA calculates $I_i(p_1(t), \ldots, p_i(t), \ldots, p_n(t))$ and $I_i(p_1(t), \ldots, p_j(t)-1, \ldots, p_n(t))$, and submits them to the VA management module.
  The VA management module distributes $I_i(p_1(t), \ldots, p_i(t), \ldots, p_n(t)), \forall i$ and $I_i(p_1(t), \ldots, p_j(t) - 1, \ldots, p_n(t)), \forall i$ to all VAs.
  Each VA adjusts the power level of its corresponding AP based on (12) and (13).
end while

We further discuss the incentives of APs joining CWP. In the interference measurement stage, one AP is voluntary to help the other APs measuring interference by sending the required traffic, which does not disclose the interference information. As the reward, this AP can measure the interference from its each neighboring AP on itself. That is, joining CWP can help each AP to acquire its surrounding interference environment without disclosing private interference information. In the power allocation stage, the Nash bargaining based power adjustment is performed in a distributed manner, where each AP can iteratively lower its power for reduced interference. One AP can cease power reduction once its interference cannot be further reduced. Therefore, joining CWP can help each AP to obtain improved Wi-Fi performance compared with that when it configures the maximum power. Based on the above characteristics, we advocate that CWP provides incentives for interest-independent APs to join it.

IV. COORDINATED Wi-Fi PERFORMANCE EVALUATION

In this section, we implement CWP and evaluate the performance of the active interference measurement and the Nash bargaining power control algorithm in an office environment. As shown in Fig. 5, 4 APs are distributed in different locations, where AP_3 connects two clients and each of the other APs connects one client.

A. ACTIVE INTERFERENCE MEASUREMENT EVALUATION

The active interference measurement experiments are conducted between AP_1 with M_1, AP_2 with M_2, and AP_3 with M_3. The experiment parameters are shown in Tab. 7.

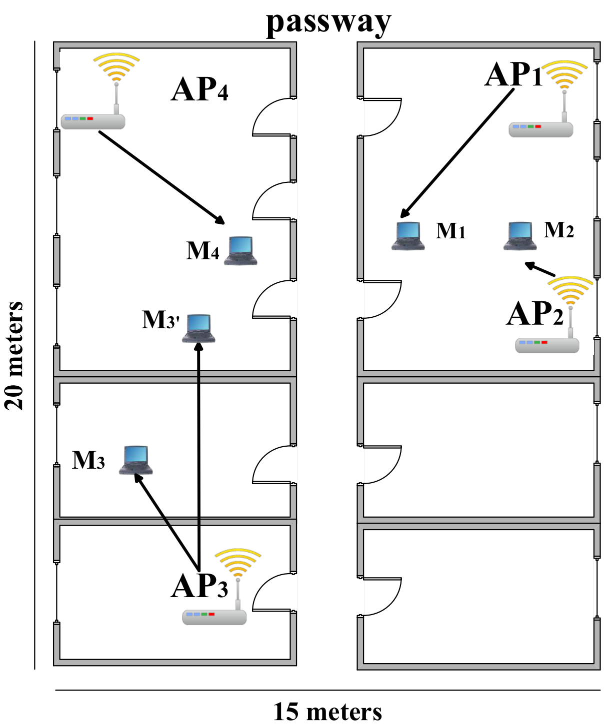


FIGURE 5. Experiments on an office environment.

TABLE 7. Experiment parameters.

AP	Netgear 4500
Protocol	802.11n
Channel	11 in 2.4G
Power	0dbm-21dbm with 3 dbm as interval
Traffic	10Mbps

OpenWrt APs [29] are used in the experiment, whose traffic parameters can be flexibly configured. All the APs reside in channel 11 in 2.4G and operate in 802.11n protocol. Each AP sends 10Mbps UDP traffic to its each connected client. The transmission power each AP is discretely configured between 0dbm-21dbm with 3dbm as the adjustment interval. Given that the wireless environment is stochastic, each experiment scenario runs 30 times, each time lasting 30 seconds [2].

We first consider the impact of powers on the APs when they can sense each other. The power of AP_1 is 15dbm which is fixed during the experiment. The power of AP_2 is adjusted from 0dbm to 21dbm with 3dbm as the interval. Fig. 6(a) shows the impact of AP_2's power on the airtime cost of the link between AP_1 and M_1. As the increase of AP_2's power from 0dbm to 21dbm, AP_1's airtime cost increases by about two times on average. This is because AP_1 receives higher interference, so AP_1 reduces its data rate. Because AP_1 and AP_2 can sense each other, the packet loss of AP_1 does not obviously increases, which is presented in Fig. 6(c).

Then we consider the impact of hidden terminal interference on the airtime cost. As shown in Fig. 6(b), when AP_3 transmits with a smaller power (9dbm), M_1 cannot hear the packet transmission of AP_3, and there is weak in-range interference from AP_3 to M_1. When AP_3 increases its power level, M_1 can receive AP_3's packet which cannot be received by AP_1. In this condition, its increases the packet loss rate of the link between AP_1 and M_1 (as shown in Fig. 6(c)), which greatly affects the corresponding airtime cost. By comparing Fig. 6(b) and Fig. 6(a), we find that the hidden terminal interference has a greater negative impact on airtime cost than in-range interference. First, it interrupts the packet loss, inducing retried packets, which can be converted to the increased airtime cost. Besides, after a packet is lost, the retried packet is generally transmitted in a very slow data rate (i.e. 2Mbps) based on the rate adaption in 802.11 protocol [4]. Therefore, the higher packet loss rate also results in the decreased transmission rate on average.

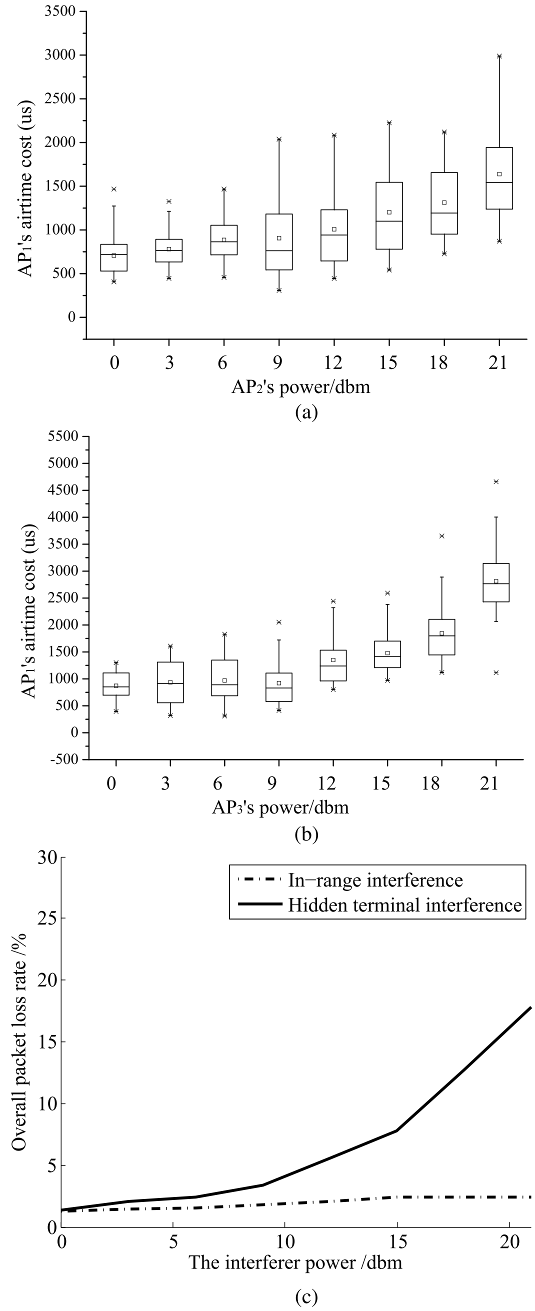


FIGURE 6. Active interference measurements. (a) In-range interference. (b) Hidden terminal interference. (c) Packet loss rate.

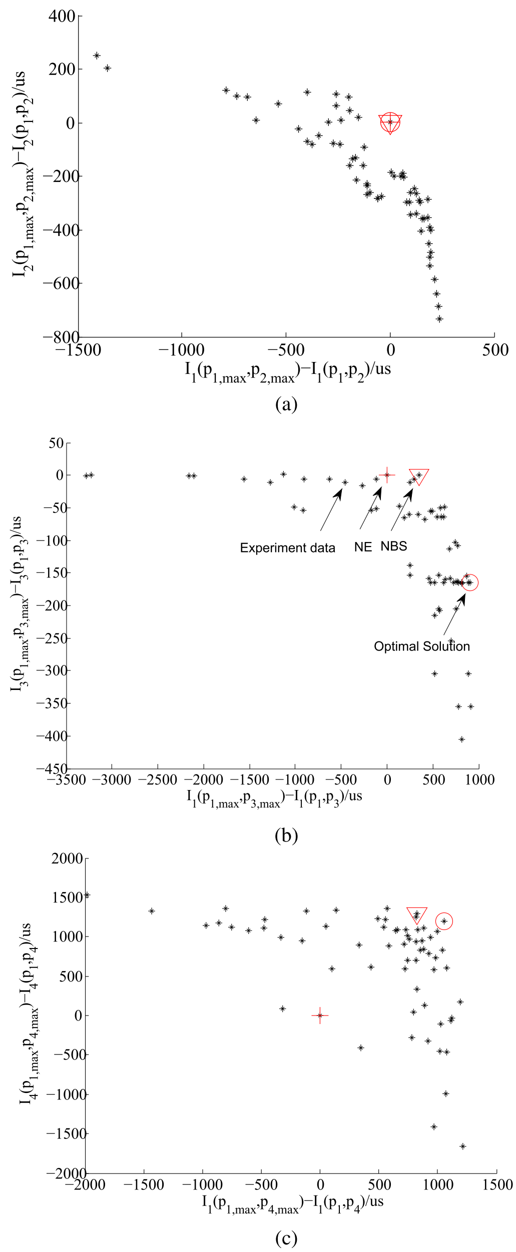


FIGURE 7. Nash Equilibrium v.s. nash bargaining solution in different scenarios. (a) AP_1 and AP_2. (b) AP_1 and AP_3. (c) AP_1 and AP_4.

B. PERFORMANCE OF POWER CONTROL BASED ON NASH BARGAINING

We evaluate the performance of power control in different conditions in Fig. 7, where the Nash equilibrium (NE), the Nash bargaining solution (NBS), and the optimal solution are drawn when AP_1 performs power control with AP_2, AP_3, and AP_4, respectively. The input of Nash bargaining procedure is the average airtime cost of the 30 experiment runs. In Fig. 7(a), there are only AP_1 and AP_2 which can sense each other, and the NE (denoted by "+"), the NBS (denoted by "▽"), and the optimal solution (denoted by "◯") are overlapped. First, the overlap of NE and NBS means that bargaining takes no effects. That is, coordinated power configurations for the two APs are also those when they configure best for themselves. This is because that AP_1 and AP_2 are very close, and one AP's reduced power will not exchange for a higher SINR caused by the power reduction of the other AP. Therefore, it is also globally optimal when two APs both work on their highest powers.

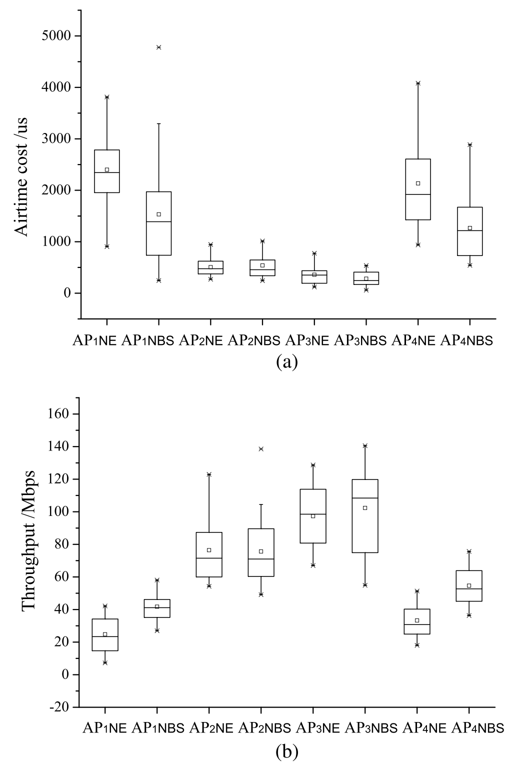


FIGURE 8. Performance evaluations with AP_3 connecting only M_3. (a) Airtime cost reduction. (b) Throughput improvement.

We further consider the scenario where AP_3 is the unilateral hidden terminal of AP_1 as shown in Fig. 7(b). In NE, both AP_1 and AP_3 transmit with its largest power. The interference of AP_1 is quite large due to its hidden terminal interference, while M_3 is almost not affected by AP_1 because AP_1 is not the hidden terminal of AP_3, while AP_3 is the hidden terminal of AP_1. In this condition, although AP_3 can slightly increase its interference for greatly improved overall performance, there is no such incentives for AP_3 to do so. Hence, there is a large distance between the NBS and the optimal solution. In practice, when AP_1 and AP_3 bargain with each other for the power control based on AL. 1, AP_3 will refuse to decrease its power levels because that will increase the interference of AP_3 itself. Therefore, NBS is very close with NE, which represents that the cooperation bring little performance improvements for overall performances.

Fig. 7(c) shows the NE and NBS in the scenario where AP_1 and AP_4 are mutually hidden terminals to the other AP. If AP_4 works on a smaller power, both AP_1 and M_1 will not hear AP_4 and the in-range interference is also quite weak. As the increase of AP_4's powers, M_1 can hear AP_4 and AP_1 cannot receive AP_4, which induces the packet loss of AP_1. Similarly, AP_1 has the same impact on AP_4. Both APs can adjust their powers for great influencing the interference of the other APs,

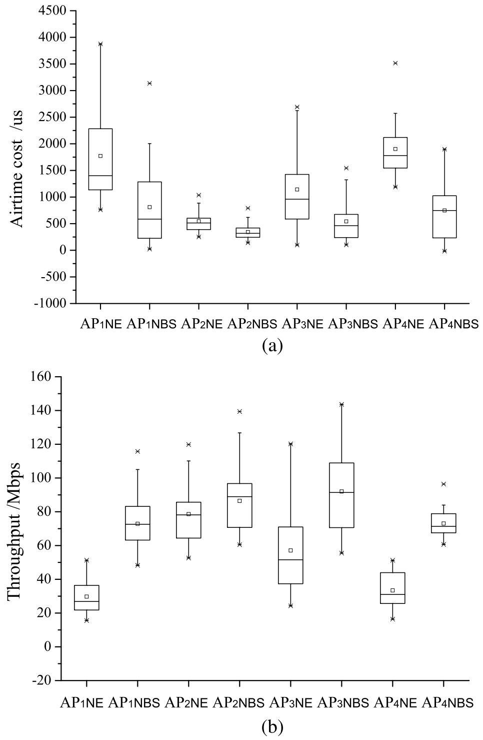


FIGURE 9. **Performance evaluations with AP_3 connecting M_3 and M_3'. (a) Airtime cost reduction. (b) Throughput improvement.**

and they have similar bargaining statuses. Therefore, their interference can be greatly reduced when they simultaneously decrease their powers. Also, the NBS is close to the optimal solution.

C. PERFORMANCE EVALUATIONS IN MULTI-AP SCENARIOS

In this part, we evaluate the airtime cost and the throughput before and after power control, respectively. Fig. 8 shows the airtime cost and throughput of APs in NBS and NE when AP_3 has only M_3 connecting to it. In this condition, the performances of AP_2 and AP_3 are generally controlled by themselves, and their reduced powers will not bring performance improvements for themselves. Therefore, they will not reduce their powers levels in the power control procedure. Besides, AP_1 and AP_4 are mutually hidden terminals in NE and AP_3 is the hidden terminal of both them. Although AP_1 and AP_4 can decrease their powers for alleviating hidden terminal interference between each other (from 21dbm to 12dbm), AP_3 still poses hidden terminal interference on them. So their average throughput is still not improved a lot.

As shown in Fig. 9, if there is another client $M_{3'}$ connecting AP_3, then AP_1 and AP_4 are also the hidden terminal of AP_3, and determines the performance of M_3'. In this condition, there is motivations for AP_3 to decrease its power levels for improved performance of the link between AP_3 and $M_{3'}$. When AP_3 reduces its powers from 21dbm to 9dbm, it poses a smaller hidden terminal interference on AP_1 and AP_4, so that both AP_1's and AP_4's airtime cost are reduced greatly after power control with about 40Mbps throughput increase on average after power controls. Meanwhile, the power reduction of AP_1 and AP_4 from 21dbm to 9dbm also brings performance improvements for AP_3.

V. CONCLUSIONS

In this paper, we advocate that Access Points (APs) can autonomously and coordinately interact with each other. With this vision, we take a case study in the autonomous Wi-Fi scenario, and build Coordination Wi-Fi Platform (CWP) for self-managed APs to interact with each other. AP Talk Protocol (ATP), a common information exchange procedure for APs, is proposed, which can help self-managed APs perform coordination interactions such as active interference measurements and power control. Based on ATP on CWP, APs can acquire its own interference caused by the other APs when they configure different powers, and further coordinate their powers for improved performance with incentive considerations. The deployment of CWP in an office environment demonstrates that in-range interference and hidden terminal interference both increase the airtime cost, and there is a maximum 40Mbps throughput improvement in the multi-AP experiments with the Nash bargaining based power control with energy efficiency.

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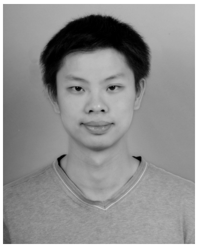

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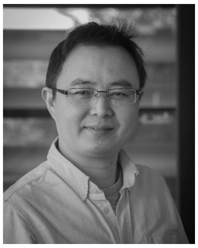

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