V-Handoff: A Practical Energy Efficient Handoff for 802.11 Infrastructure Networks

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***Abstract*—Wireless local area networks (WLANs) are currently among the most important technologies for wireless access. Because of its higher data rate and lower monetary cost compared with cellular networks, mobile users are likely to choose Wi-Fi when they are using mobile applications. However, keeping continuous connectivity with access points (APs) may require frequent handoffs, which may consume much energy in the handoff process. Unfortunately, most of the existing work only focused on reducing the handoff delay of IEEE 802.11-based handoffs and many handoff approaches may even increase the energy consumption of mobile nodes (MNs) in order to reduce the handoff latency. In this paper, we introduce *virtual handoff* (V-handoff), an energy efficiency-based handoff protocol via generating virtual access points (VAPs) in the corresponding physical access points (PAPs). The main idea of our proposed V-handoff protocol is to create an evenly spaced periodic schedule of beacon periods for all the VAPs in one *virtual AP grid*. To the best of our knowledge, this is the first paper that investigates the application of the wireless virtualization technique in MN's handoff energy efficiency. Simulation results show that our proposed V-handoff protocol can significantly reduce the MN's handoff energy consumption and the average handoff delay compared with IEEE 802.11-based full scanning and selective scanning handoff protocol.**

I. INTRODUCTION

With the rapid popularization of wireless local area networks (WLANs) and the dramatic expansion of demands on mobile applications, such as social networking applications, navigation applications and multimedia entertainment applications, it is essential to conserve energy when applications and services are used in resource constrained mobile nodes (MNs).

WLAN is being deployed densely and widely in many supercities because of its higher data rate and lower installation cost compared with cellular networks. For example, Manhattan, the most densely populated borough of New York City, is shown that up to 90% of its area has been covered by the signal of public Wi-Fi hotspots provided by Xfinity Ltd. and Timer Warner Cable Ltd. or other carriers. Citizens who walk around this area could keep connecting their MNs to the Wi-Fi continuously. However, connecting to the Wi-Fi incessantly consumes much energy on the side of MNs. In addition, MNs have to handoff frequently, since MNs must associate with another available 802.11 access point (AP) to preserve seamless connectivity when they move outside the range of one AP.

A lot of work has been done to improve the performance of handoffs. Over the past decade, many researchers focused on reducing the MAC layer handoff latency. For example, Selective Scanning [1], [2] can effectively reduce the scanning delay which constitutes the largest portion (over 90% [3]) of the total handoff latency by reducing the number of channels to scan during a handoff based on a channel selection strategy. Selective scanning can be used in different application scenarios, such as directional handoff [4] and cellular traffic offloading [5]–[8]. SyncScan [9], another approach for reducing the scanning delay, showed that by synchronizing the beacon broadcasting time of all APs using the same channel, MNs can scan every channel periodically, which simplifies the scanning process and reduces the overall handoff latency. However, all of existing handoff protocols did not consider the energy efficiency of MNs during the handoff process. Many approaches may even increase the energy consumption of MNs in order to reduce the handoff latency. In fact, MN's energy efficiency could be extremely worse in the area with low-dense or ultra-dense APs. In the area with low-dense APs, MNs have to keep scanning the channels to find an available AP to reassociate with, while in the area with ultra-dense APs, MNs may make frequent handoffs to maintain their connections and scan much more frequently for obtaining the fresh information of nearby APs. Although some other proposed methods [10] considered saving MNs' energy via selecting the best radio interface (e.g. WLAN or 3G) or AP, the energy efficiency of the handoff protocol itself was not considered in prior work.

In addition, virtual access point (VAP), a concept to manage WLANs flexibly by separating the functions of an AP and the hardware of an AP using virtualization techniques, is a new research direction for optimizing WLANs [11]. A VAP is generated by a physical access point (PAP). For instance, [12] proposed that VAPs could be used for improving throughput via shutting down some PAPs which are not frequently used while maintaining the function of those PAPs by creating the corresponding VAPs in a PAP. However, to the best of our knowledge, none of the existing papers investigate the application of the wireless virtualization technique in MN's handoff energy efficiency.

Unlike previous work, we focus on how to save an MN's energy in the handoff process. In this paper, a fresh concept, *virtual handoff* (V-handoff), and a novel energy efficient WLAN handoff protocol are proposed based on the virtualization technique. Our approach does not require any modification to IEEE 802.11 handoff protocol. It is incrementally deployable and requires only minor modifications to existing implementations. In addition, it can coexist with other *traditional handoff* (T-

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handoff) protocols in WLAN environments. Simulation results show that our proposed protocol can improve the energy efficiency of MNs during a handoff process and reduce the handoff latency in any AP density scenario compared to the existing handoff protocols.

The rest of this paper is organized as follows. In Section II, we describe how existing 802.11 handoff mechanisms consume MN's energy and show our measurement results for energy cost in a traditional handoff process. In Section III, our proposed handoff protocol and its energy consumption model are introduced. Simulation results and analyses are shown in Section IV, followed by the conclusions in Section V.

II. PROBLEM STATEMENT

In this section, we explain how existing IEEE 802.11 handoff protocol consumes energy in the whole handoff process and show our measurements for an MN's energy consumption in each handoff phase.

In conventional 802.11-based handoff protocol, once an MN triggers a handoff, it must identify the set of proximate candidate APs via explicitly scanning each channel (11 channels in 802.11b and 802.11g) for potential APs. This scan can be completely passive — the MN switches to each candidate channel and listens for periodic beacons generated by APs (typically every 102 ms [9]). Passive scan reduces the energy consumption in a handoff process since MNs do not have to broadcast any packet to detect nearby APs. However, the delay incurred by this approach can be quite long since the phase of beacon intervals is constant and an MN must therefore wait the full interval on each channel.

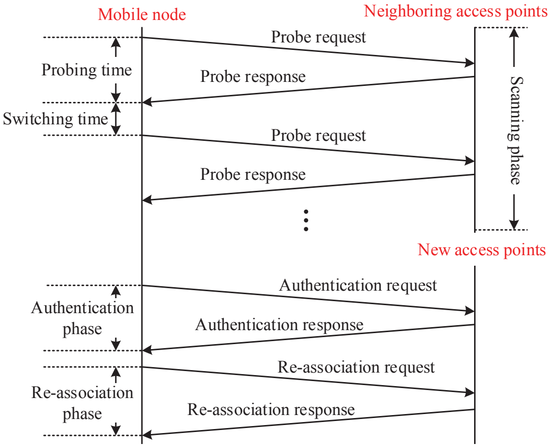


Fig. 1. A timing chart of the 802.11 handoff procedure.

To reduce this delay, most 802.11 implementations utilize the active scan approach — MNs actively broadcast probe requests on each available channel to force APs to respond immediately. This approach decreases the scanning delay. Ignoring the negligible components, the idealized delay of this active scanning approach is

$$\sum_{c=1}^{NumChannels} (1-P(c))Min + P(c)Max, \qquad (1)$$

where $P(c)$ is the probability of one or more APs operating in channel c, and Min, Max are minimum and maximum channel waiting time, respectively [9]. Minimum channel waiting time represents the amount of time to wait for the first probe response from an AP before declaring that the channel is empty, and maximum channel waiting time represents the amount of time to collect additional APs' probe responses after the MN has already received a response within minimum channel waiting time.

TABLE I
POWER CONSUMPTION MEASUREMENTS FOR THE WI-FI INTERFACE OF MOTOROLA NEXUS 6

	Measured current	For example
Broadcast send	360 mA	Probe Request $[Pb_{(rq)}]$
Broadcast receive	71 mA	Beacon
Point-to-point send	404 mA	Auth. Request $[Au_{(rq)}]$ Association Request $[As_{(rq)}]$
Point-to-point receive	176 mA	Auth. Response $[Au_{(rp)}]$ Probe Response $[Pb_{(rp)}]$ Association Response $[As_{(rp)}]$
Idle state	7.9 mA	
Power supply	4.2 V	

However, by utilizing the active scan, the energy consumption of MNs in the whole handoff process is increased because of sending a lot of probe requests in every available channel. As depicted in Fig. 1, the handoff process in 802.11 networks has three phases — each with its own energy consumption.

In addition, we conduct a measurement study of the energy consumption during a handoff process. We use KEYSIGHT N6705B [13] for powering the Motorola Nexus 6 cell phone which is the test MN with removed battery, and measuring the power consumption of the phone. Airpcap Nx [14] is used for monitoring the handoff process of the test phone via capturing the communication packets in the MAC layer. We then analyze these captured packets in the Wireshark software. We show the measurement results in Table I which summarizes the costs of sending or receiving certain type of packets in a handoff process. These values may vary with different wireless network interface cards. Fig. 2 shows the current trace for the Wi-Fi interface of the Motorola Nexus 6 in our measurement. The three large spikes in the figure are variation curves during channel scanning periods. Each spike represents one scanning for all the available channels.

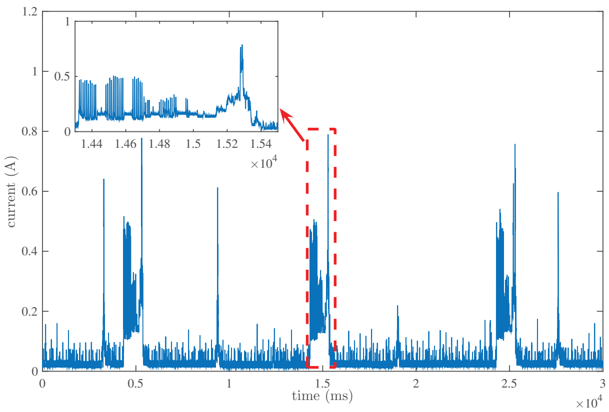


Fig. 2. The current trace for Wi-Fi interface of Motorola Nexus 6. The small window depicts the current trace of scanning all available channels.

We calculate the energy consumption of a scanning process (the test phone scanned 11 channels in 2.4 GHz) via

$$E_{scanning} = \int_{t_1}^{t_2} V I_{scan} \, dt, \tag{2}$$

where V is the power supply of the test phone, as shown in Table I, and I_{scan}, t_1, and t_2 are measured current, scan starting time, and scan ending time, respectively. The energy consumption of scanning all 11 channels in 2.4 GHz that we calculated based on (2) is 1.33 Joule.

In addition, according to Fig. 1, the total energy consumption in an 802.11-based handoff process is

$$E_{handoff} = E_{scanning} + E_{auth} + E_{re-association}, \tag{3}$$

where $E_{scanning}$, E_{auth}, and $E_{re-association}$ are the energy consumption of the three phases illustrated in Fig. 1. E_{auth} and $E_{re-association}$ can be calculated in a similar way as E_{scan} in (2). By using the measured current values in Table I, we obtain that a successful handoff with one scanning attempt consumes approximate 1.5 Joule, which may dramatically increase if MNs attempt to scan channels more than once, e.g., in the low-dense AP area, or have to handoff frequently, e.g., in the ultra-dense AP environment. Consequently, the scanning phase constitutes the largest portion, over 88% according to our measurements, of the handoff energy consumption.

Therefore, improving the handoff energy efficiency is significantly crucial and will help MNs survive longer within the WLAN environment.

III. PROPOSED PROTOCOL

This section describes our proposed V-handoff protocol in detail. First, we present assumptions and the protocol design. Next, we define the energy consumption model.

A. Assumptions

In this paper, we consider N PAPs and K MNs coexist in an L×L area. PAPs are regularly distributed within the area and randomly select a channel from M channels (e.g., $M = 11$ in the 2.4 GHz band). Each PAP has a circular transmission range with a radius of r_c and a constant handoff trigger for MNs with a radius of r_{trig} ($0 < r_{trig} < r_c$). The distance between two PAPs is d_{PAP}. For a certain PAP, nearby PAP that satisfies $d_{PAP} \leq 2{\times}r_{trig}$ is a candidate for virtualizing and we define that these two PAPs have *efficient overlapping area*.

Firstly, we assume that each PAP has at least one candidate for virtualizing in every possible user moving direction which depends on the terrain. This is a practical scenario in the area where APs are deployed densely, such as university campus, business center, and shopping mall. For example, EPIC, a building located on the Charlotte Research Institute campus of UNC-Charlotte, with a length of 95.7 meters and a width of 77.9 meters, is deployed with around 43 individual Wi-Fi APs inside the whole building. The average distance between two APs is less than 30 meters in each available user moving direction, while nowadays, in most cases, an AP has a range around 50 meters with receivable signal strength indoors and 100 meters outdoors, which satisfies $d_{PAP} \leq 2{\times}r_{trig}$ in each direction.

Secondly, since each VAP shares the same radio with the PAP that the VAP is embedded in, VAPs transmit and receive data packets via the same channel with the corresponding PAP. We also assume that MNs know the information of VAPs, e.g., the operating channel and beacon broadcasting time, that they will potentially connect with via the approach we introduce in Section III-C.

B. Overview of the Proposed Protocol

The main idea of our approach is to extend the signal coverage of an AP by generating several VAPs in its overlapping PAPs. These VAPs obtain the same MAC layer information (e.g., beacon, MAC address, and SSID) with the extended AP, named *copied physical access point* (CPAP). The PAPs that generate these VAPs are called *host physical access points* (HPAPs). Those VAPs and the CPAP compose an access point grid, named *virtual access points grid* (virtual AP grid). MNs in a virtual AP grid, instead of making the traditional means of handoff as defined in the IEEE 802.11 standard, make a type of handoff with less energy consumption and lower latency, V-handoff, as proposed in this paper.

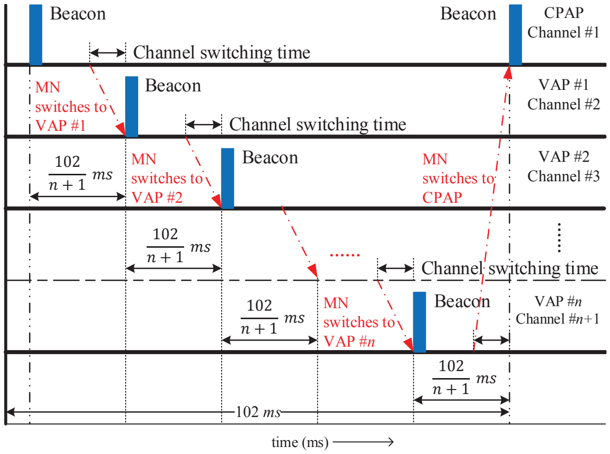


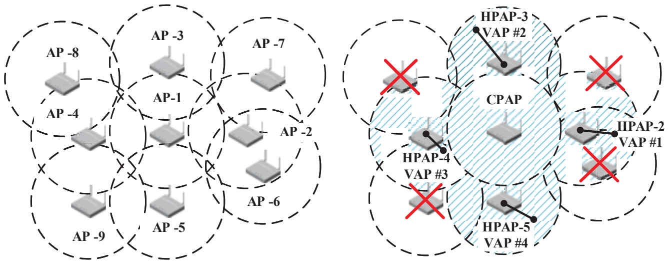
Fig. 3. Proposed beacon broadcast schedule.

At the heart of our proposed energy efficient handoff protocol is to create an evenly spaced periodic schedule of beacon periods for all the VAPs and the CPAP in a virtual AP grid. For example, in one virtual AP grid, assume the CPAP broadcasts beacons at time t, and VAP1 will do the same at time $t + \frac{BeaconInterval}{n+1}$, VAP2 will broadcast at time $t + 2\frac{BeaconInterval}{n+1}$, and so on, where n is the total number of VAPs in the virtual AP grid. Typically, the beacon interval is set to be 102 ms. Each MN associated with the CPAP or a VAP can listen to other VAPs' beacons following the beacon period schedule (as shown in Fig. 3) and connect with the VAP which is detected first. Thus, the possible handoff delays in a virtual AP grid are

$$\{t_{switch}, t_{switch} + \frac{102}{n+1}, ..., t_{switch} + (n-1)\frac{102}{n+1}\} ms, \tag{4}$$

where t_{switch} is the channel switching delay. Consequently, after triggering a handoff, an MN only needs to switch to the corresponding channels and hear beacon packets at certain time period according to the schedule. MNs do not have to send any probe requests or even authentication and association requests during the handoff process. Therefore, the energy efficiency of MNs during V-handoffs is significantly improved.

C. Single Virtual AP Grid Scenario



(a) Original AP Environment (b) Completion of VAP Selection

Fig. 4. An example of VAP selection.

First of all, we consider the single virtual AP grid scenario. For the AP that wants to expand its signal coverage, it should first select a certain number of APs which have overlapping areas with it to be the candidates for virtualizing. The main rule for choosing neighboring physical APs as virtualized candidates is to select the AP with the strongest received signal strength (RSS) at each direction (e.g., North, South, East and West). Fig. 4 shows an example of VAP selection. By virtualizing APs with the strongest RSS at each direction, the overlapping area between the CPAP and VAPs can be maximized, thus increasing the probability of MNs from the CPAP entering the range of VAPs (i.e., increasing the probability of MNs making V-handoffs).

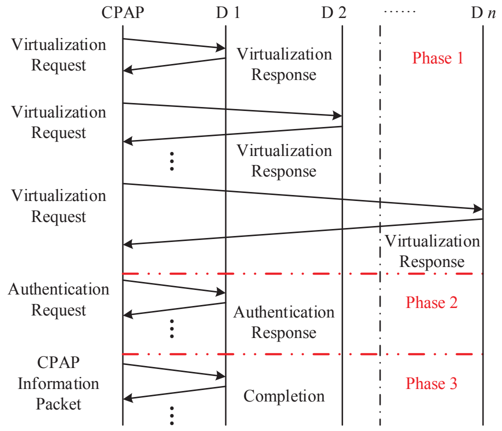


Fig. 5. A timing chart of the virtual AP grid setup procedure.

Based on the above VAP selection rule, the procedure of setting up a virtual AP grid is shown in Fig. 5. Firstly, the physical access point, CPAP, that attempts to establish a virtual AP grid broadcasts *virtualization request* packets at each direction successively. This is a practical scenario since directional antennas have been increasingly adopted in WLANs nowadays. APs in one direction that can receive this virtualization request, meaning that they are close to the CPAP, will respond *virtualization response* messages. After the CPAP receives responses, it will select the APs to be virtualized based on the VAP selection rule and then send back a *virtualization authentication request* message. Then, each selected AP replies a *virtualization authentication response* packet, which indicates the completion of the VAP selection phase. The CPAP then sends its MAC layer information (e.g., beacon, SSID, MAC address), the number of VAPs that will be generated in this virtual AP grid, and a unique ID for each VAP to HPAPs. The number of VAPs and their IDs represent the broadcasting beacon periods for the corresponding VAPs. For example, if a HPAP receives an ID m and the number of VAPs n, it indicates that the VAP generated in this HPAP will broadcast its beacons at time $m\times\frac{BeaconInterval}{n+1}$ periodically. After generating VAPs, HPAPs send *completion* messages to the CPAP. Then, a virtual AP grid is created.

D. Multiple Virtual AP Grids Scenario

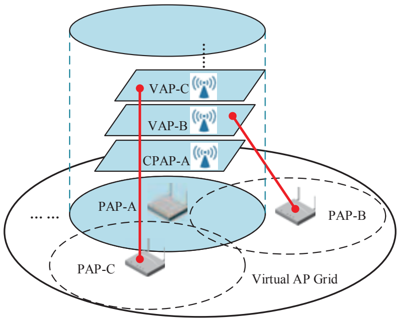


Fig. 6. The multiple virtual AP grids scenario.

Next, we consider the multiple virtual AP grids scenario. In the multiple virtual AP grids scenario, each PAP can be a CPAP, which indicates that multiple different VAPs will co-exist in a PAP, as illustrated in Fig. 6. An MN roaming between two virtual AP grids performs the T-handoff.

In addition, in our proposed protocol, both V-handoff and T-handoff have the same value for handoff trigger, but V-handoff has a higher priority than T-handoff. In other words, an MN triggered to perform a handoff should detect the existence of VAPs nearby first. However, V-handoff may cause additional handoff delay if the detection of VAPs fails. One simple way to avoid this is to have differentiated triggers for V-handoff and T-handoff. However, from the point of view of the handoff energy efficiency and the protocol complexity, using the same trigger is better.

E. Energy Consumption

Now, we calculate the energy consumption of traditional handoffs with active scanning,

$$E_{trad}=E_s\frac{N_{s-ch}}{N_{ttl-ch}}+E_{auth}+E_{re-asciation}, \qquad (5)$$

where E_s is the energy consumption of scanning all of channels, N_{ttl-ch} represents the total number of available channels, and N_{s-ch} is the number of scanned channels. In addition, based on the proposed virtual handoff protocol, the energy consumption is

$$E_{virtual}=E_{sw-ch}N_{sw-ch}+E_{listen}N_{beacon}, \qquad (6)$$

where N_{sw-ch} (20 μJ [15]), E_{sw-ch}, E_{listen} and N_{beacon} represent the times of switching channels, the energy consumption of channel switching, the energy consumption of receiving a broadcast packet (e.g., beacon), and the number of beacons received, respectively. All of these energy consumption values can be obtained using Table I and the calculation method explained in Section II. In addition, in (5), the energy consumption of channel switching is covered in E_s. Therefore, by comparing these two equations, we can see that performing a V-handoff consumes much less energy than a T-handoff.

IV. PERFORMANCE EVALUATION

In this section, We evaluate the performance of the proposed V-handoff protocol. We first analyze the impact of the number of VAPs in a virtual AP grid on the handoff performance, including handoff energy efficiency and handoff delay. Then, simulation results are presented to illustrate our contributions to decreasing the handoff energy consumption and delay.

A. Analysis

Based on our proposed V-handoff protocol, intuitively the more VAP generated, the larger signal coverage the CPAP obtains. For example, as shown in Fig. 7, the signal coverage of the CPAP with 8 VAPs is increased by around 50% compared with the CPAP with 4 VAPs. Therefore, by expanding the CPAP's signal coverage, the energy efficiency of MNs can be improved because of the reducing of the times for performing T-handoffs. However, the total number of VAPs that a CPAP can obtain has limitations. On one hand, because generating a VAP requires the HPAP has overlapping area with the CPAP, there is an upper-limit on the extended coverage for a CPAP. Thus, it is not efficient to generate overmuch VAPs in a virtual AP grid. On the other hand, MNs may switch channels to detect beacons broadcast by different VAPs. Thus, the minimal gap in time between two beacons that broadcast by different VAPs has to be larger than the MN's channel switching delay, i.e., $\frac{102}{n+1} \geq t_{switch}$. For example, $t_{switch} = 5$ ms, the maximal number of VAPs in a virtual AP grid is 19.

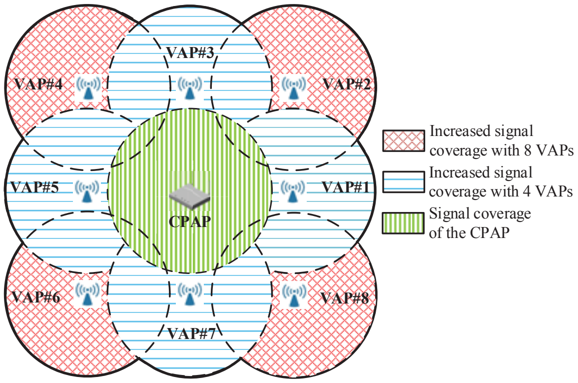


Fig. 7. The effect of the number of VAPs on the CPAP extended signal coverage.

B. Simulation Setup

In our simulation, N APs are regularly distributed in a square area. K MNs move randomly within the area following the Random Waypoint model. At startup, the operating channels of APs are randomly allocated. The values of simulation parameters are listed in Table II in detail. In order to analyze the performance of V-handoffs on energy efficiency and handoff latency, we choose two other handoff protocols, selective scanning [1] and 802.11-based full channel scanning handoff protocol to make a comparison with V-handoff. In addition, selective scanning is selected as the approach for MNs' handoff among different virtual AP grids.

TABLE II
SIMULATION PARAMETERS

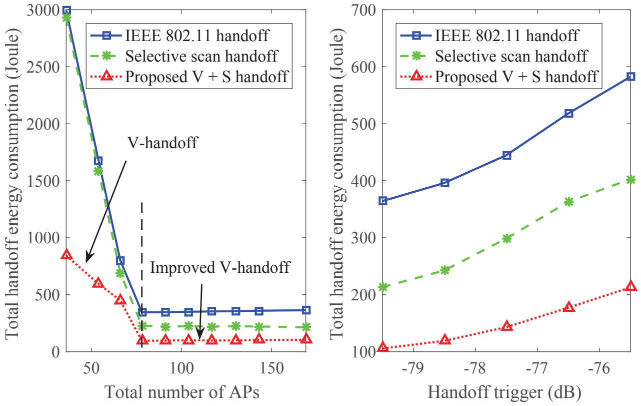
Parameters	Value	Unit
Number of channels	11	
Radius of the AP transmission range	100	m
Side length of the simulation area	840	m
Total simulation time	20000	s
Authentication delay	10	ms
Association delay	10	ms
MaxChannelTime	30	ms
MinChannelTime	10	ms
Channel switching time	5	ms
Random Waypoint: Moving speed of MNs	1-2	m/s
Number of MNs	500	
f_{vh}	2	
T_f	100	ms

C. Simulation Results

Now, we present our simulation results to demonstrate the performance of our proposed V-handoff protocol. Fig. 8 depicts the handoff energy consumption results of the three handoff protocols under different total number of APs, and different handoff triggers, as shown in Fig. 8(a) and 8(b), respectively. It is shown that our proposed V-handoff protocol outperforms both 802.11-based full scanning protocol and selective scanning protocol in terms of lower handoff energy consumption of the MN. It can decrease the energy consumption of handoffs by over 70% and 50% compared with 802.11-based protocol and selective scanning protocol, respectively. In addition, when the total number of APs is smaller than 78 (as shown in Fig. 8(a)), the MN's handoff energy consumption keeps in a high level. This is because when the total number of APs is small, the MN has to scan longer for detecting beacons from nearby APs, which consumes a lot of energy. Fig. 8(b) shows that the total handoff energy consumption increases as the MN's handoff trigger increases. This is because the increase of the handoff trigger leads to a larger number of handoffs and thus, the MN's total handoff energy cost increases.

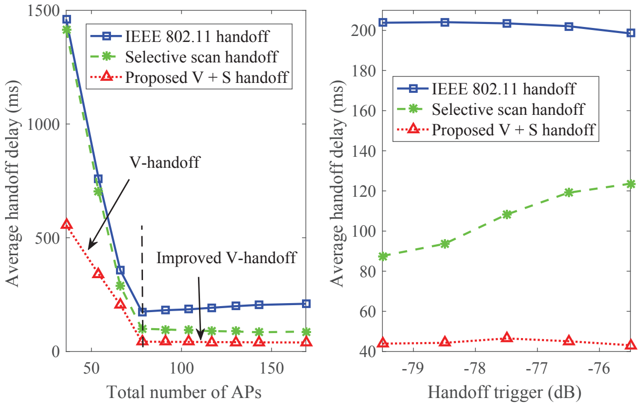
Fig. 9 shows the handoff latency of the three handoff protocols under different total number of APs, and different handoff triggers, as shown in Fig. 9(a) and 9(b), respectively. We can see that the proposed V-handoff protocol reduces the handoff delay by around 75% and 55% compared with 802.11-based full scanning and selective scanning protocol, respectively. Additionally, it is shown that the average handoff delay of selective scanning protocol increases as the MN's handoff trigger increases. However, the average handoff delay of the proposed V-handoff protocol does not change significantly when the handoff trigger increases.

Fig. 10 shows the impact of the number of VAPs in a virtual AP grid on the V-handoff performance, including the energy consumption and handoff delay. It is shown that the virtual



(a) Constant handoff trigger -79.5dB (b) Constant number of APs 169

Fig. 8. Evaluation of the handoff energy consumption.



(a) Constant handoff trigger -79.5dB (b) Constant number of APs 169

Fig. 9. Evaluation of the handoff latency.

AP grid with 8 VAPs outperforms the virtual AP grid with 4 VAPs in terms of lower total handoff energy consumption and average handoff delay, which is consistent with our analysis in Section IV-A.

V. CONCLUSION

In this paper, the MN's handoff energy efficiency is investigated. An energy efficiency-based V-handoff protocol is proposed under practical scenarios. In addition, based on the analysis of the ping-pong effect in a handoff process, an improved V-handoff protocol is also proposed to mitigate the ping-pong effect in V-handoffs, while the energy efficiency is not compromised. V-handoff is incrementally deployable and requires only minor modifications to existing implementations. Simulation results show that our proposed V-handoff protocol reduces the MN's handoff energy consumption by around 70% and 50% compared with IEEE 802.11-based full scanning and selective scanning protocol, respectively. Meanwhile, V-handoff protocol decreases the average handoff delay by around 75% and 55% compared with IEEE 802.11-based full scanning and selective scanning protocol, respectively.

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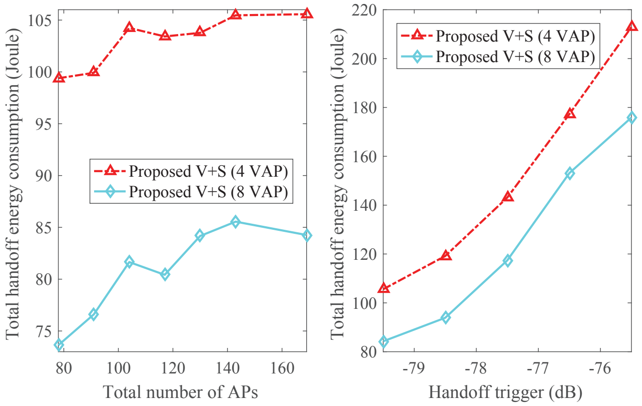
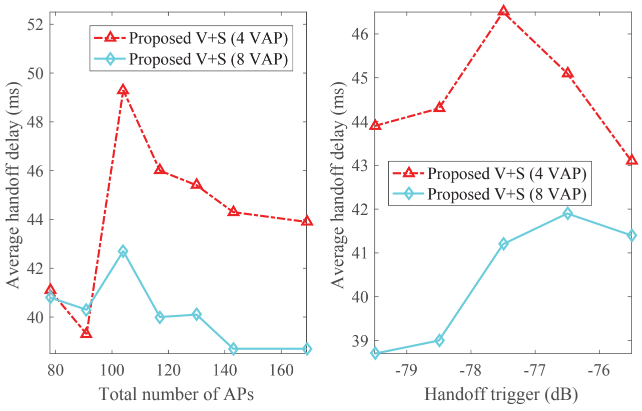


(a) Constant handoff trigger -79.5dB (b) Constant number of APs 169



(c) Constant handoff trigger -79.5dB (d) Constant number of APs 169

Fig. 10. Evaluation of the number of VAPs in a virtual AP grid

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