DeuceScan: Deuce-Based Fast Handoff Scheme in IEEE 802.11 Wireless Networks

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***Abstract*—The IEEE 802.11 standard has enabled low-cost and effective wireless local area network (WLAN) services. It is widely believed that WLANs will become a major portion of the fourth-generation cellular system. The seamless handoff problem in WLANs is a very important design issue to support the new astounding and amazing applications in WLANs, particularly for a user in a mobile vehicle. The entire delay time of a handoff is divided into probe, authentication, and reassociation delay times. Because the probe delay occupies most of the handoff delay time, efforts have mainly focused on reducing the probe delay to develop faster handoff schemes. This paper presents a new fast handoff scheme (i.e., the DeuceScan scheme) to further reduce the probe delay for IEEE-802.11-based WLANs. The proposed scheme can be useful to improve wireless communication qualities on vehicles. A spatiotemporal approach is developed in this paper to utilize a spatiotemporal graph to provide spatiotemporal information for making accurate handoff decisions by correctly searching for the next access point. The DeuceScan scheme is a prescan approach that efficiently reduces the layer-2 handoff latency. Two factors of stable signal strength and variable signal strength are used in our developed DeuceScan scheme. Finally, simulation results illustrate the performance achievements of the DeuceScan scheme in reducing handoff delay time and packet loss rate and improving link quality.**

***Index Terms*—Fast handoff, fourth generation (4G), IEEE 802.11, spatiotemporal, wireless local area networks (WLANs).**

I. Introduction

THE IEEE 802.11 standard [3] has enabled low-cost and effective wireless local area network (WLAN) services. It is widely believed that WLANs will become a fundamental technology and an important portion of the fourth-generation (4G) cellular system. The recent successful deployment of WLANs in numerous hotspots has justified the fact that WLAN technology will play a key role in wireless data transmission. Small mobile portable devices in a wireless data service environment provide ubiquitous data services for real-time applications, e.g., mobile voice over IP [1] and mobile video conferencing. If a user is in a mobile vehicle, a handoff procedure is frequently applied between different WLAN access points (APs). The user suffers the handoff latency problem for the real-time multimedia application. This is important in the development of a fast handoff mechanism. Efforts will be made in this paper to develop a fast handoff protocol. This result will be useful to improve wireless communication qualities on vehicles.

For the IEEE 802.11 Medium Access Control (MAC) operation [3], the "handoff" function occurs when a mobile host (MH) seamlessly changes its connection from one AP to another. There are many related works [5]–[7], [21] and new approaches [8], [19] that have reduced the handoff latency. Mishra *et al.* [11] defined the handoff process as occurring in two distinct logical steps (i.e., discovery and reauthentication) and classified the entire handoff latency into three delays (i.e., probe, authentication, and reassociation delays). The probe delay always occupies the largest proportion of the entire handoff latency, and finding ways to reduce the probe delay is the main issue.

In the IEEE 802.11 standard, the scan function is used in the discovery phase to help an MH find potential APs with which to reassociate, and a full scan that probes 11 channels is implemented when an MH enters the handoff process. The time cost of a full scan to probe 11 channels is high. That is, a high probe delay is incurred due to the full scan of probing 11 channels. Improving the scan operation can significantly reduce the handoff latency. To improve the handoff latency, many existing handoff schemes [9], [10], [12]–[18], [20] have been proposed. All the existing results can be divided into fast handoff schemes in the discovery phase (by reducing the probe delay) and in the reauthentication phase (by reducing the reassociation and authentication delays).

We review the existing fast handoff schemes that seek to reduce the reassociation and authentication delays. Mishra *et al.* [12] described the use of a special data structure called the *neighbor graph*, which temporarily captures the mobility topology of an MH. The neighbor graph uses a cache approach. The APs in the neighbor graph are the candidate handoff APs. The cache miss problem exists if a real handoff AP is not the candidate handoff AP from the neighbor graph. In addition, the signaling and data overhead is significantly increased if there are a large number of neighbor APs. Mishra *et al.* [13] also used neighbor graphs to reduce the authentication time. To improve the neighbor graph scheme [13], Pack *et al.* [15] proposed a *selective neighbor caching* scheme for a fast handoff in IEEE 802.11 wireless networks. This approach only propagates an MH's context to the selected

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TABLE I
COMPARISON OF THE EXISTING FAST HANDOFF PROTOCOLS

Methods / Properties	IEEE 802.11 standard [3]	neighbor graph [17]	selective scan [18] cache hit	selective scan [18] cache miss	SyncScan [16]	location-based approach [20]	DueceScan
pre-scan	no	no	no		yes	no	yes
probe action	full scan	partial scan	no	partial scan	no	no	no
handoff time	slow	medium	fast	medium	fast	fast	fast
direction	no	implicitly	no		no	yes	implicitly
location device	no	no	no		no	yes	no
memory usage	1	$O(n \times M)$	$O(n)$		$O(N)$	$O(N \times M)$	$O(n \times M)$

neighbor APs by considering handoff frequencies between APs. When a context transfer is needed, neighbor APs with handoff probabilities that are equal to or higher than a predefined threshold value are selected. Pack and Choi [14] proposed a fast handoff scheme based on a mobility prediction in public WLAN systems. These multiple APs are selected by a prediction algorithm called the *frequent handoff region* selection algorithm, which takes into account the users' mobility patterns and service classes. There are other research results in an MH's context transfer in the link and IP layers [9] from the viewpoint of multilayer designs.

The existing fast handoff schemes that seek to reduce the probe delay are described as follows. Table I gives the comparisons of existing fast handoff mechanisms for reducing the probe delay, where the "prescan" means that an MH scans all or a part of the channels for neighboring APs, the "probe action" denotes which scan function is used during a handoff process, the "handoff time" describes the total delay time for the entire handoff process, the "direction" indicates whether an MH knows the actual direction or not, the "location device" shows if an MH needs extra location-provider devices, and the "memory usage" illustrates how memory spaces are needed for a handoff protocol. First, Li *et al.* [10] proposed a reliable active scanning (RAS) scheme for IEEE 802.11 MAC layer handoffs. It efficiently increases the reliability of channel scanning, particularly in a noisy environment. Although the RAS scheme really decreases the handoff delay time in an IEEE 802.11 WLAN, the handoff latency is still high. This is because the RAS scheme only reduces the retransmission probability when scanning each channel but does not decrease the number of scanned channels. Therefore, in this paper, we did not compare our results with the RAS scheme. Observe that the idea of a neighbor graph was already used to reduce the reassociation and authentication delays by Mishra *et al.* [12]. Shin *et al.* [17] also presented a new scheme for improving the probe delay of IEEE 802.11 handoffs using neighbor graphs. This scheme reduces the total number of probe channels (using a partial scan) and the total time spent waiting for each channel and uses neighbor graphs to capture the mobility topology of an MH; hence, it needs a large amount of memory to record the mobility information. On the other hand, the effectiveness of this scheme is low if there are many neighbor APs nearby the currently connecting AP. Shin *et al.* [18] developed a fast handoff procedure using a *selective scanning* algorithm. By using a dynamic channel mask in the selective scanning algorithm, scanning a subset of all (11) the channels (called a partial scan) can be used as a generic solution. However, cache missing in the cache-based scheme is a fatal problem for the handoff. More recently, Ramani and Savage [16] have developed a practical fast handoff called SyncScan for the IEEE 802.11 infrastructure networks. This scheme is a low-cost technique for continuously tracking nearby base stations by synchronizing short listening periods. By executing a prescan in advance, SyncScan omits the probe delay and slashes the entire handoff delay. Efforts are made in this paper to develop a new prescan scheme. In addition, Tseng *et al.* [20] presented a location-based fast handoff for IEEE 802.11 networks. This location-based fast handoff approach utilizes the MH's current location from a designated server to make the correct handoff decision. However, an extra hardware device, i.e., a location provider (such as a Global Positioning System), must be available and attached to each MH.

This paper presents a new fast handoff scheme (i.e., the DeuceScan scheme) to further reduce the probe delay for IEEE-802.11-based WLANs. A spatiotemporal approach is developed in this paper, which utilizes a spatiotemporal graph to provide spatiotemporal information for making accurate handoff decisions by correctly searching for the next AP. The DeuceScan scheme is a prescan approach that efficiently reduces the layer-2 handoff latency. Two factors of signal strength and variation of signal strength are used in our developed DeuceScan scheme. Finally, the simulation results illustrate the performance achievements of the DeuceScan scheme in reducing the handoff delay time and the packet loss rate, and improving the link quality, compared to existing fast handoff schemes.

The rest of this paper is organized as follows. Section II illustrates the basic ideas of the DeuceScan scheme. Section III presents the DeuceScan protocol. A simulation analysis is presented in Section IV. Section V summarizes the results.

II. PRELIMINARY AND BASIC IDEAS

Before describing the basic idea of our protocol, the time complexity of memory usage of the existing protocols and our approach is discussed as follows. Some notations are defined. N is the number of all neighboring APs, and a convex polygon (called a region) is formed by N APs, where an MH is in a convex polygon (a region). n is the number of selected neighboring APs when the partial number of APs is considered in some existing handoff protocols, where $n < N$. M is the number of regions during a moving path. A moving path is

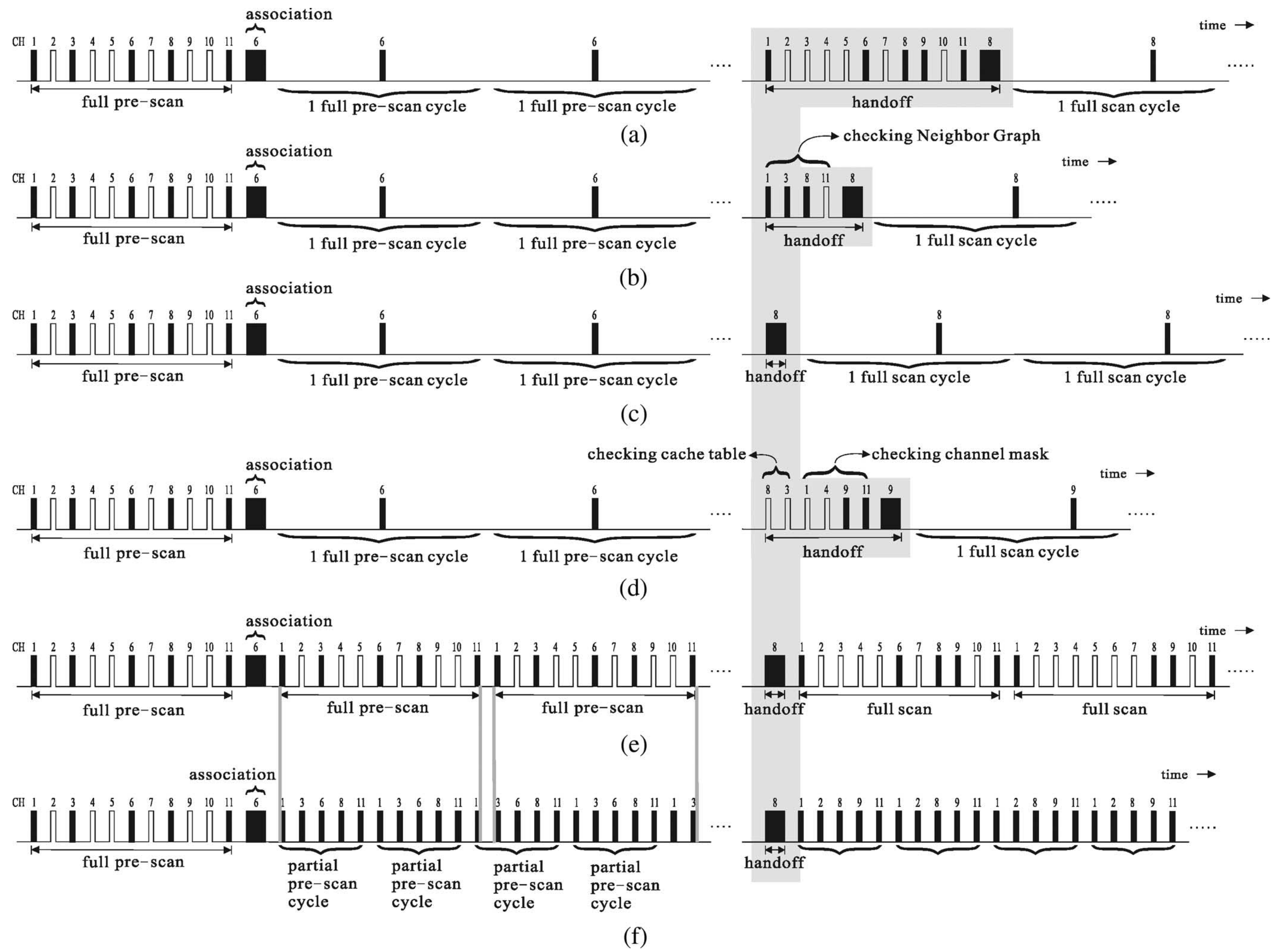

Fig. 1. Probe activities of (a) IEEE 802.11 infrastructure network, (b) neighbor graph, (c) selective scan with cache hit, (d) selective scan with cache miss, (e) SyncScan, and (f) DeuceScan.

connected by a series of M distinct regions. However, an MH may roam again to a previously visited region.

Table I summarizes the time complexity of the memory usage of the IEEE 802.11 standard [3], the neighbor graph scheme [17], the selective scan scheme [18], the SyncScan scheme [16], the location-based approach [20], and our DeuceScan scheme. The IEEE 802.11 standard [3] keeps one record for a currently associated AP, and the time complexity of memory usage is $O(1)$. The neighbor graph scheme [17] is a cache-based scheme and keeps all moving history information, and the time complexity of memory usage is $O(n \times M)$. With the partial scan operation, the selective scan scheme [18] does not keep the moving history information, and the time complexity of memory usage is $O(n)$. When an MH enters a new region, the selective scan scheme needs to perform again the full scan operation. The SyncScan scheme [16] is a prescan scheme and does not keep the moving history information, and the time complexity of memory usage is $O(N)$. Therefore, the SyncScan scheme must perform the full scan operation if an MH roams to a new region. The location-based approach [20] needs an extra location device and more memory spaces to record the moving history information, and the time complexity of memory usage is $O(N \times M)$. Our DeuceScan scheme is a partial prescan scheme and keeps the moving history information, and the time complexity of the memory usage of our scheme is $O(n \times M)$. Consequently, our DeuceScan scheme offers slightly more memory space to acquire low handoff latency.

As described earlier, the probe delay occupies most of the handoff latency. This paper aims to develop a new approach to reduce the probe delay. In the following, we compare all existing fast handoff schemes, which mainly reduce the probe delay, as illustrated in Fig. 1. They are the neighbor-graph-based scheme [17], the selective-scanning-based scheme [18], the SyncScan scheme [16], and our DeuceScan scheme. A detailed comparison is given in Fig. 1.

To compare the above fast handoff schemes, we initially created a handoff scenario based on the IEEE 802.11 standard [3]. Let CH_i denote channel i. First, the IEEE 802.11 standard [3] performs a full scan operation during the handoff procedure. As shown in Fig. 1(a), it scans channels CH_1, CH_3, CH_6, CH_8, and CH_{11}, which have active APs by the full scan operation. Initially, the MH selects and associates with one of the APs (in CH_6) with the maximum received signal

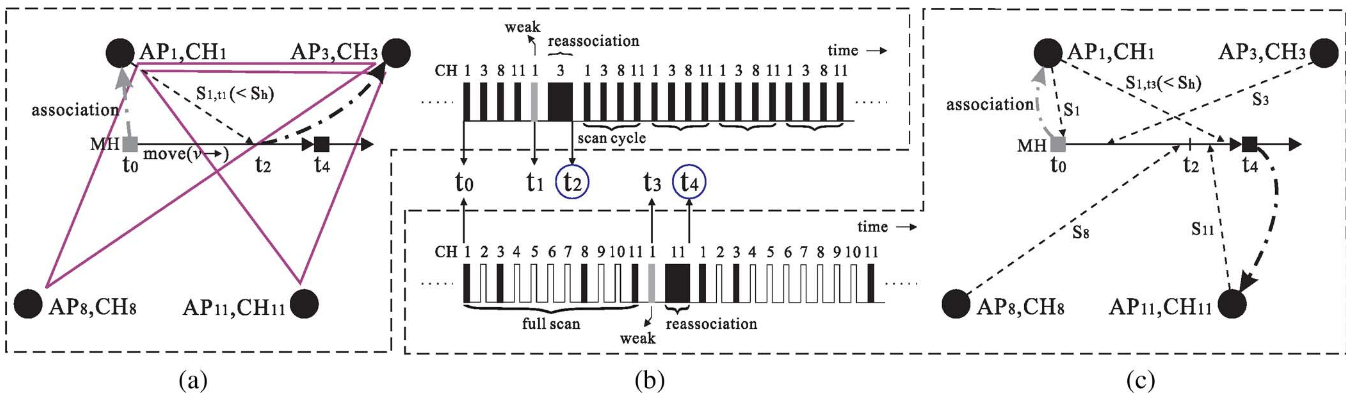

Fig. 2. DeuceScan versus SyncScan. (a) DeuceScan ($\alpha = 1, \beta = 2$). (b) Time slot sequences. (c) SyncScan.

strength (RSS). The MH received the beacon that is transmitted by the serving AP at a fixed time interval. When the MH intends to initiate a handoff, it again performs the handoff procedure and the full scan operation. From the scanning results, the MH is handed off to the next AP in CH_8.

With the same handoff scenario as shown in Fig. 1(b), the neighbor-graph-based scheme [17] only scans all neighbor APs. Compared to the full scan operation used in the IEEE 802.11 standard [3], this obviously reduces the latency of channel scanning since a partial scan operation is used. With the same handoff scenario, Fig. 1(c) and (d) shows the selective-scanning-based scheme [18] with cache hit and cache miss, respectively. There is no probe delay for the selective-scanning-based scheme with the cache hit. However, the selective-scanning-based scheme with the cache miss needs a long probe delay because some channels need to be rescanned. Observe that under the same handoff scenario as illustrated in Fig. 1(e) and (f), the SyncScan scheme [16] and our DeuceScan scheme do not require a probe delay during the handoff process. This effect is very similar to the result of the selective-scanning-based scheme with cache hit. This indicates that the SyncScan and DeuceScan schemes are prescan approaches. It is easy to see that one more partial prescanning operation can be done in the time period of one full prescanning operation. Efforts are made in this paper to exploit the advantage of the partial prescanning operation to develop an effective fast handoff scheme.

The DeuceScan scheme follows the same assumptions as the SyncScan scheme [16], i.e., that time synchronization is required between APs to allow the MH to arrange the scanning order of the APs, and that the MH can receive beacons from the APs. This paper can be done using the network time protocol service over the Internet [2].

An example is given in Fig. 2 to illustrate the differences between the SyncScan scheme [16] and our DeuceScan scheme. Let $\mathrm{RSS}_{t_j}^{\mathrm{AP}_i}$ denote the RSS in which an MH received a signal with the RSS from AP_i at time t_j. As illustrated in Fig. 2(a), with the DeuceScan scheme, an MH is associated with AP_1 in CH_1 at time t_1 and receives $\mathrm{RSS}_{t_1}^{\mathrm{AP}_1}$. Assuming that $\mathrm{RSS}_{t_1}^{\mathrm{AP}_1} < \mathrm{RSS}_{\mathrm{threshold}}$, it should perform the handoff procedure and reassociate to AP_3 in CH_3 at time t_2. With the same moving pattern and speed using the SyncScan scheme, the MH also associates with AP_1 in CH_1 at time t_1, as shown in Fig. 2(c). However, it must wait for at least one cycle of the full scanning (in the prescan step) until time t_3 to determine if $\mathrm{RSS}_{t_3}^{\mathrm{AP}_1} < \mathrm{RSS}_{\mathrm{threshold}}$. Therefore, the MH executes the handoff procedure and reassociates with AP_{11} in CH_{11} at time t_4, where $t_2 < t_4$. This implies that the DeuceScan scheme is a partial prescanning operation and that the SyncScan scheme is a full prescanning operation. Due to the possibility of $t_2 < t_4$, the handoff sensibility of the DeuceScan scheme is better than that of the SyncScan scheme, particularly when the moving speed v of the MH is high. This effect is discussed in Section IV.

The DeuceScan scheme is constructed using the ideas of a *spatiotemporal graph* and the *deuce process*. We introduce the basic ideas of the spatiotemporal graph and the deuce process as follows.

A. Spatiotemporal Graph

Since the DeuceScan scheme is a cache-based scheme, each MH possesses its own individual spatiotemporal graph to cache useful information. The spatiotemporal graph is composed of a series of triangles, where each triangle is established at a different time and location. A triangle is constructed by three APs (AP_{i_1}, AP_{i_2}, and AP_{i_3}), and an MH, respectively, receives $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}}$, $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}}$, and $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}}$ from AP_{i_1}, AP_{i_2}, and AP_{i_3} at time t_i, such that there is no $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_j}}$ that exists to satisfy $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_j}} > \min\{\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}}, \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}}, \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}}\}$, where $j \neq \{1, 2, 3\}$. This implies that the MH receives the largest strength signals from AP_{i_1}, AP_{i_2}, and AP_{i_3}. From the spatiotemporal viewpoint, the MH is located in the area of triangle ∇ at time t_i, which is denoted ∇_{t_i}. An example is given in Fig. 3 in which AP_1, AP_8, and AP_{11} form ∇_{t_1} at time t_1, and AP_1, AP_3, and AP_{11} form ∇_{t_2} at time t_2. Observe that if only two available APs exist in a region, our scheme can be correctly performed by logically simultaneously letting the second AP to be the second and third APs. In the following, we only discuss the case when the number of neighboring APs ≥ 3.

Observe that the full prescanning operation needs to be performed if an MH enters a new location that it has not traversed before. After performing the full prescanning operation, the

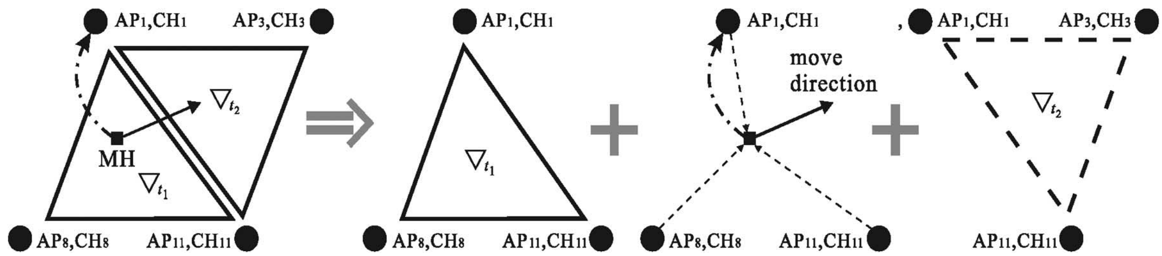

Fig. 3. Example of a spatiotemporal triangle list.

MH can identify ∇_{t_i} at the new location. Assume that the MH enters a different location at time t_{i+1}. Then, $\nabla_{t_{i+1}}$ must be constructed, where $\nabla_{t_i} \neq \nabla_{t_{i+1}}$. However, it is possible for the condition of $\nabla_{t_i} = \nabla_{t_{i+1}}$ to exist when no handoff has occurred. For simplicity, we consider the case of $\nabla_{t_i} \neq \nabla_{t_{i+1}}$. As mentioned before, an MH keeps a spatiotemporal triangle list $= \{\nabla_{t_1}, \nabla_{t_2}, \ldots, \nabla_{t_i}, \nabla_{t_{i+1}}, \ldots, \nabla_{t_j}\}$ at time t_j. A handoff occurs from times t_i to t_{i+1}. In addition, if an MH reenters an already traversed location whose spatiotemporal triangle is ∇_{t_i}, the MH can extract its spatiotemporal triangle ∇_{t_i} from $\{\nabla_{t_1}, \nabla_{t_2}, \ldots, \nabla_{t_i}, \nabla_{t_{i+1}}, \ldots, \nabla_{t_j}\}$ since the location information of AP_{i_1}, AP_{i_2}, and AP_{i_3} is already stored in the spatiotemporal triangle list, where AP_{i_1}, AP_{i_2}, and AP_{i_3} form the triangle ∇_{t_i}. Then, a partial prescanning operation is performed by only scanning AP_{i_1}, AP_{i_2}, and AP_{i_3}. Our scheme offers a high hit ratio by utilizing the spatiotemporal property. If a new triangle ∇ does not exist in the spatiotemporal triangle list, this indicates that the MH has not traversed the current location before; therefore, a new triangle ∇ is constructed by a full scanning operation. This new triangle ∇ is added to the spatiotemporal triangle list. When the handoff occurs, the MH tries to reassociate with a suitable AP from the other two APs in the current spatiotemporal triangle (besides the serving AP). As mentioned before, our DeuceScan scheme is a partial prescan scheme and keeps the moving history information; therefore, the time complexity of the memory usage of our scheme is $O(n \times M)$. This way, it avoids having to perform the full scanning operation in the handoff procedure, which significantly reduces the handoff latency. An example is given in Fig. 3 to illustrate that an MH keeps a spatiotemporal triangle list $= \{\nabla_{t_1}, \nabla_{t_2}\}$, where AP_1, AP_8, and AP_{11} form ∇_{t_1} at time t_1, and AP_1, AP_3, and AP_{11} form ∇_{t_2} at time t_2.

B. Deuce Process

The key idea of our DeuceScan scheme is the deuce process. The first important property of the deuce process is the partial prescanning operation. As described before, one additional partial prescanning operation can be done in the time period of one full prescanning operation, as shown in Fig. 1(f). Given $\alpha + 3$ APs, $\mathrm{AP}_{i_1}, \mathrm{AP}_{i_2}, \mathrm{AP}_{i_3}, \ldots, \mathrm{AP}_{i_{\alpha+3}}$, the main operation of the deuce process is to keep the same result of $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ for β consecutive times, where $\alpha \geq 0$, $\beta \geq 1$, and the total number of channels $\geq \alpha + 3$. If we can keep the consecutive β's to have the same result of $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ from time t_j to $t_{j+\beta-1}$, then the accurate and stable signal results can be obtained, where $j \leq i \leq j + \beta - 1$. In addition, it is possible to perform one more partial prescanning operation within the time period of a full prescanning operation. That is, we can obtain more useful and accurate information in the same time period.

One other advantage of the deuce process is to provide fault-tolerant capability. The main idea of the deuce process is to keep the result of $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ for β times. If a handoff decision is made at time t_i, we can make the correct decision from all the accumulated results before time t_i. For example, as shown in Fig. 4(b), the handoff decision can be done at time t_i based on three identical results of $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_6}$. A further example is shown in Fig. 4(c), where the handoff decision is made at time t_i based on two identical results of $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_6}$, although the second time, the result differs: $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_6}$. This paper achieves a fault-tolerant capability. This result is very useful for an MH making the correct handoff decision when moving at a high speed, particularly on vehicles.

III. DeuceScan Scheme: Deuce-Based Fast Handoff Scheme

This section develops the deuce-based fast handoff scheme, i.e., the DeuceScan scheme, by utilizing the spatiotemporal graph to provide a new partial prescanning operation. The probe delay time accounts for most of the overall handoff latency. The DeuceScan scheme is developed to significantly reduce the probe delay time and the handoff latency.

A. Deuce Procedures

Before describing the DeuceScan scheme, two deuce procedures with stable and variable signal strengths are described as follows.

1) Deuce Procedure With Stable Signal Strength: The deuce procedure aims to obtain stable and accurate information of the RSS in a short time for an MH in spatiotemporal triangle ∇_i. This stable information helps the MH make the correct decision when changing the spatiotemporal triangle from ∇_i to ∇_{i+1}. In the following, we present the deuce procedure with stable signal strength, which is denoted $D_s(\alpha, \beta)$, where

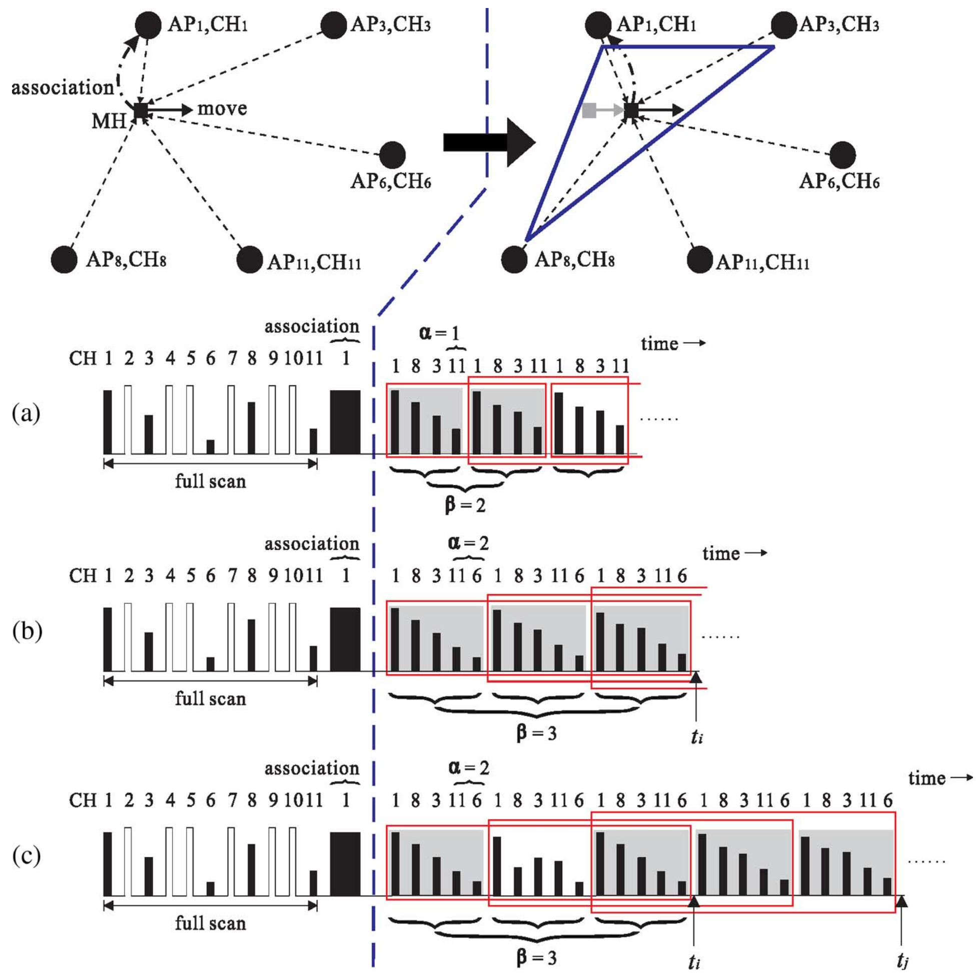

Fig. 4. Examples of (a) $D_s(1, 2)$, (b) $D_s(2, 3)$, and (c) $D_s(2, 3)$.

α is the extra number of scanning (partial prescanning) APs, and β is the consecutive number of scan cycles. A scan cycle is the delay time that is required to scan $\alpha + 3$ APs (with each AP being in a different channel). Each successive β scan cycle forms a deuce window. Observe that $D_s(\alpha, \beta)$ is a partial prescanning procedure. The use of extra α APs is to provide fault-tolerant capability, and it offers extra scanning chances if the next handoff AP is not in spatiotemporal triangle ∇_i. In addition, β is used to improve the accuracy of the candidate list of potential handoff APs. Basically, the larger the value of α, the higher the fault-tolerant capability, and the larger the value of β, the higher the accuracy of the candidate list of handoff APs. Before applying $D_s(\alpha, \beta)$, the MH initially performs a full scanning operation to select and associate an AP with the maximum RSS. After associating with an AP, then $D_s(\alpha, \beta)$ is performed as follows. $D_s(\alpha, \beta)$ produces an accurate candidate list of handoff APs.

D1) The MH only prescans $\alpha + 3$ APs, $\mathrm{AP}_{i_1}, \mathrm{AP}_{i_2}, \mathrm{AP}_{i_3}, \ldots, \mathrm{AP}_{i_{\alpha+3}}$, where $\alpha + 3$ is less than the total number of channels. The MH received $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}}, \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}}, \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}}, \ldots, \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ from $\mathrm{AP}_{i_1}, \mathrm{AP}_{i_2}, \mathrm{AP}_{i_3}, \ldots, \mathrm{AP}_{i_{\alpha+3}}$ at time t_i.

D2) Given a scan cycle (by scanning $\alpha + 3$ APs), the MH performs the prescan function by scanning $\mathrm{AP}_{i_1}, \mathrm{AP}_{i_2}, \mathrm{AP}_{i_3}, \ldots, \mathrm{AP}_{i_{\alpha+3}}$ to maintain a stable deuce window. A deuce window is said to be stable if it keeps the same order of signal strengths for all $\alpha + 3$ APs within β scan cycles. Without loss of generality, assume that $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$. The deuce window is stable if $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ is maintained for all β scan cycles.

D3) If the deuce window is stable, the MH confirms that the current spatiotemporal triangle ∇_i is composed of AP_{i_1}, AP_{i_2}, and AP_{i_3}. Then, go to D2 to continuously perform the prescan function before executing the actual handoff procedure.

D4) If a handoff decision must be made at time t_i and if the deuce window is unstable, then the current spatiotemporal triangle ∇_i is composed of AP_{i_1}, AP_{i_2}, and AP_{i_3}, where the results of $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_1}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ occur most frequently among β scan cycles. Otherwise, go to D2 to continuously perform the prescan function to wait for the next stable deuce window.

An example of $D_s(\alpha,\beta)$ is given in Fig. 4. Fig. 4(a) shows the case of $D_s(1,2)$, which maintains $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}}$ for two scan cycles. Fig. 4(b) illustrates the case of $D_s(2,3)$, which maintains $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_6}$ for three scan cycles. Finally, Fig. 4(c) illustrates the case of $D_s(2,3)$, which maintains $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_6}$ for three consecutive scan cycles. As shown in Fig. 4(c), the second scan cycle has a different result. It may wait for the next three consecutive scan cycles with the same result at time t_j. Observe that it may make the handoff decision at time t_i with the most same result of $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_6}$, although the second scan cycle has a different result.

2) Deuce Procedure With Variable Signal Strength: The RSS cannot judge the moving intention for an MH. The variable signal strength is used to acquire the information of moving intention to accurately make the handoff decision. We also consider the variation of the signal strength for the deuce procedure. We define the variable signal strength as follows. An AP receives $\mathrm{RSS}_{t_i}^{\mathrm{AP}}$ and $\mathrm{RSS}_{t_{i-1}}^{\mathrm{AP}}$ at times t_i and t_{i-1}, respectively. The *variation in the variable signal strength* or *signal variation* is denoted $\Delta_{t_i}^{\mathrm{AP}} = \mathrm{RSS}_{t_i}^{\mathrm{AP}} - \mathrm{RSS}_{t_{i-1}}^{\mathrm{AP}}$. If $\Delta_{t_i}^{\mathrm{AP}} > 0$, then $\Delta_{t_i}^{\mathrm{AP}}$ denotes the approach rate of an AP from times t_{i-1} to t_i. If $\Delta_{t_i}^{\mathrm{AP}} < 0$, then $\Delta_{t_i}^{\mathrm{AP}}$ is the departure rate of an AP from times t_{i-1} to t_i. If the deuce window is stable, it means that the MH approaches or leaves the AP. Observe that the main goal of the deuce procedure with variable signaling strength is to provide the accurate moving intention information by using approach and departure rates.

Consider three APs (AP_{i_1}, AP_{i_2}, and AP_{i_3}) for which we can estimate $\Delta_{t_i}^{\mathrm{AP}_{i_1}}$, $\Delta_{t_i}^{\mathrm{AP}_{i_2}}$, and $\Delta_{t_i}^{\mathrm{AP}_{i_3}}$ from times t_{i-1} to t_i. Without loss of generality, if $\Delta_{t_i}^{\mathrm{AP}_{i_1}}$, $\Delta_{t_i}^{\mathrm{AP}_{i_2}}$, $\Delta_{t_i}^{\mathrm{AP}_{i_3}} > 0$, and $\Delta_{t_i}^{\mathrm{AP}_{i_1}} > \Delta_{t_i}^{\mathrm{AP}_{i_2}} > \Delta_{t_i}^{\mathrm{AP}_{i_3}}$, then the approach rate is $\mathrm{AP}_{i_1} > \mathrm{AP}_{i_2} > \mathrm{AP}_{i_3}$. Similarly, if $\Delta_{t_i}^{\mathrm{AP}_{i_1}}$, $\Delta_{t_i}^{\mathrm{AP}_{i_2}}$, $\Delta_{t_i}^{\mathrm{AP}_{i_3}} < 0$, and $|\Delta_{t_i}^{\mathrm{AP}_{i_1}}| > |\Delta_{t_i}^{\mathrm{AP}_{i_2}}| > |\Delta_{t_i}^{\mathrm{AP}_{i_3}}|$, then the departure rate is $\mathrm{AP}_{i_1} > \mathrm{AP}_{i_2} > \mathrm{AP}_{i_3}$. The use of departure and approach rates provides an accurate moving intention information to make the handoff decision. In the following, the deuce procedure $D_v(\alpha,\beta)$ with signal variation is given based on the departure and approach rates.

- D1') The MH only prescans $\alpha+3$ APs, $\mathrm{AP}_{i_1}, \mathrm{AP}_{i_2}, \mathrm{AP}_{i_3}, \ldots, \mathrm{AP}_{i_{\alpha+3}}$, where $\alpha+3$ is less than or equal to the total number of channels. The MH estimates $\Delta_{t_i}^{\mathrm{AP}_{i_1}}, \Delta_{t_i}^{\mathrm{AP}_{i_2}}, \Delta_{t_i}^{\mathrm{AP}_{i_3}}, \ldots, \Delta_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ from $\mathrm{AP}_{i_1}, \mathrm{AP}_{i_2}, \mathrm{AP}_{i_3}, \ldots, \mathrm{AP}_{i_{\alpha+3}}$ at time t_i.
- D2') Given a scan cycle (by scanning $\alpha+3$ APs), the MH performs the prescan function by scanning $\mathrm{AP}_{i_1}, \mathrm{AP}_{i_2}, \mathrm{AP}_{i_3}, \ldots, \mathrm{AP}_{i_{\alpha+3}}$ to maintain a stable deuce window. A deuce window is said to be stable if the same order of signal variations for all $\alpha+3$ APs is maintained for β scan cycles. Without loss of generality, there are three cases shown as follows.
  - Case 1. If $\Delta_{t_i}^{\mathrm{AP}_{i_1}} > \Delta_{t_i}^{\mathrm{AP}_{i_2}} > \Delta_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \Delta_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}} > 0$, then the deuce window is stable if the same result of $\Delta_{t_i}^{\mathrm{AP}_{i_1}} > \Delta_{t_i}^{\mathrm{AP}_{i_2}} > \Delta_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \Delta_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ is maintained for all β scan cycles, where $\Delta_{t_i}^{\mathrm{AP}_{i_\kappa}}$ denotes the approach rate of the MH to AP_{i_κ}, $1 \le \kappa \le \alpha+3$.
  - Case 2. If $0 > \Delta_{t_i}^{\mathrm{AP}_{i_1}} > \Delta_{t_i}^{\mathrm{AP}_{i_2}} > \Delta_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \Delta_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$, then the deuce window is stable if the same result of $\Delta_{t_i}^{\mathrm{AP}_{i_1}} > \Delta_{t_i}^{\mathrm{AP}_{i_2}} > \Delta_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \Delta_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ is maintained for all β scan cycles, where $\Delta_{t_i}^{\mathrm{AP}_{i_\kappa}}$ denotes the departure rate of the MH to AP_{i_κ}, $1 \le \kappa \le \alpha+3$.
  - Case 3. If $\Delta_{t_i}^{\mathrm{AP}_{i_1}} > \Delta_{t_i}^{\mathrm{AP}_{i_2}} > \Delta_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \Delta_{t_i}^{\mathrm{AP}_{i_\gamma}} > 0$ and $0 > \Delta_{t_i}^{\mathrm{AP}_{i_{\gamma+1}}} > \Delta_{t_i}^{\mathrm{AP}_{i_{\gamma+2}}} > \cdots > \Delta_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$, then the deuce window is stable if the same results of $\Delta_{t_i}^{\mathrm{AP}_{i_1}} > \Delta_{t_i}^{\mathrm{AP}_{i_2}} > \Delta_{t_i}^{\mathrm{AP}_{i_3}} > \cdots > \Delta_{t_i}^{\mathrm{AP}_{i_\gamma}} > 0$ and $0 > \Delta_{t_i}^{\mathrm{AP}_{i_{\gamma+1}}} > \Delta_{t_i}^{\mathrm{AP}_{i_{\gamma+2}}} > \cdots > \Delta_{t_i}^{\mathrm{AP}_{i_{\alpha+3}}}$ are maintained for all β scan cycles, where $1 < \gamma < \alpha+3$.
- D3') If the deuce window is stable, the MH confirms that the current spatiotemporal triangle ∇_i is composed of AP_{i_1}, AP_{i_2}, and AP_{i_3}. Then, go to D2' to continuously perform the prescan function if the actual handoff procedure has not occurred.
- D4') If a handoff decision must be made at time t_i and if the deuce window is unstable, then the current spatiotemporal triangle ∇_i is composed of AP_{i_1}, AP_{i_2}, and AP_{i_3}, where the results of AP_{i_1}, AP_{i_2}, and AP_{i_3} occur most frequently among β scan cycles. Otherwise, go to D2' to continuously perform the prescan function to wait for the next stable deuce window.

Fig. 5 displays three example conditions of the deuce procedure $D_v(0,2)$ while an MH initially associates with AP_1 through channel CH_1. Fig. 5(a) illustrates that ∇_i is constructed by AP_1, AP_6, and AP_{11}, where $\Delta_{t_i}^{\mathrm{AP}_1} > \Delta_{t_i}^{\mathrm{AP}_6} > \Delta_{t_i}^{\mathrm{AP}_{11}} > 0$. Fig. 5(b) displays that ∇_i is constructed by AP_1, AP_6, and AP_{11}, where $0 > \Delta_{t_i}^{\mathrm{AP}_1} > \Delta_{t_i}^{\mathrm{AP}_6} > \Delta_{t_i}^{\mathrm{AP}_{11}}$. Finally, Fig. 5(c) shows that ∇_i is constructed by AP_1, AP_6, and AP_{11}, where $\Delta_{t_i}^{\mathrm{AP}_{11}} > \Delta_{t_i}^{\mathrm{AP}_6} > 0$, and $0 > \Delta_{t_i}^{\mathrm{AP}_1}$.

B. DeuceScan Scheme

The DeuceScan scheme (i.e., the deuce-based fast handoff scheme) is divided into two phases (i.e., constructing the spatiotemporal graph and handoff with the DeuceScan process), as described below.

1) Phase I—Constructing the Spatiotemporal Graph: Before effectively performing $D_s(\alpha,\beta)$ and $D_v(\alpha,\beta)$, a spatiotemporal graph, which is a spatiotemporal triangle list $= \{\nabla_{t_1}, \nabla_{t_2}, \ldots, \nabla_{t_i}, \nabla_{t_{i+1}}, \ldots, \nabla_{t_j}\}$, is constructed, and the spatiotemporal triangle list is obtained by applying $D_s(\alpha,\beta)$. The location information of AP_{i_1}, AP_{i_2}, and AP_{i_3} is already stored in the spatiotemporal triangle list. The procedure of

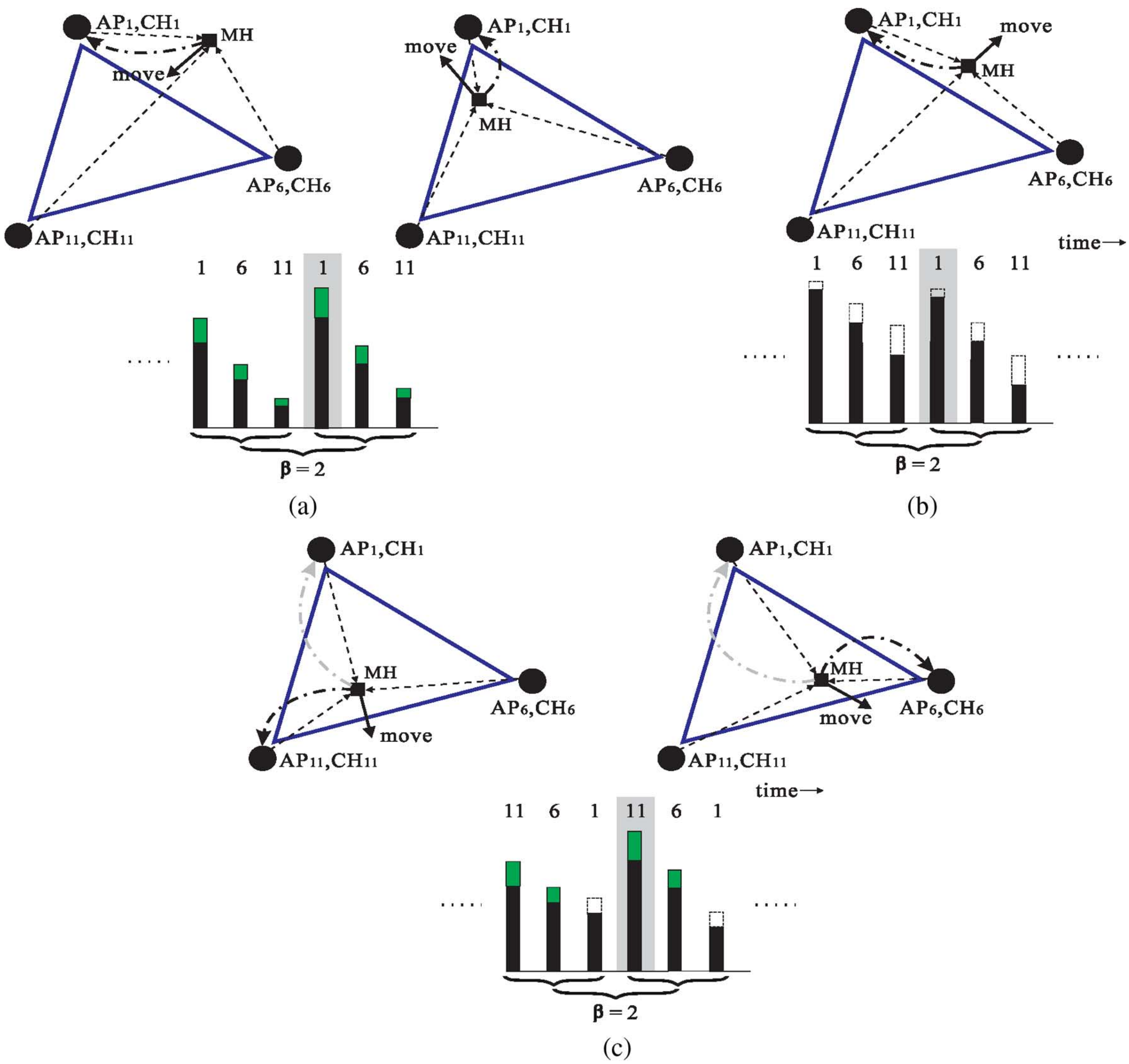

Fig. 5. Example of $D_v(\alpha, \beta)$.

constructing the spatiotemporal triangle list $= \{\nabla_{t_1}, \nabla_{t_2}, \ldots, \nabla_{t_i}, \nabla_{t_{i+1}}, \ldots, \nabla_{t_j}\}$ is given as follows.

S1) If an MH is turned on, it initially performs a full prescanning operation for all channels to associate with an AP with the strongest RSS. The MH executes $D_s(\alpha, \beta)$, where $\alpha =$ the total number of channels $- 3$. ∇_{t_1} is estimated at time t_1, and the spatiotemporal triangle list $= \{\nabla_{t_1}\}$.

S2) If an MH enters a new location at time t_i, $i > 1$, then $D_s(\alpha, \beta)$ is performed, where $\alpha =$ the total number of channels $- 3$. Then, a spatiotemporal triangle ∇_{t_i} is estimated, and the spatiotemporal triangle list $=$ spatiotemporal triangle list $\cup \nabla_{t_i}$.

S3) If an MH enters a location at time t_i, $i > 1$, and the MH is located in ∇_{t_μ}, if a spatiotemporal triangle ∇_{t_μ} already exists in the current spatiotemporal triangle list, then $D_s(\alpha, \beta)$ is performed to prepare the accurate information of candidate handoff APs, where $\alpha <$ (the total number of channels) $- 3$. Go to step S2.

Fig. 6 displays an example of constructing spatiotemporal graphs. Fig. 6(a) shows the performance of a full prescanning operation. Fig. 6(b) shows the construction of a spatiotemporal triangle ∇ by AP_1, AP_8, and AP_{11} through $D_s(1, 3)$. Fig. 6(c) illustrates that a spatiotemporal triangle ∇ cannot be constructed by $D_s(1, 3)$. In the first scan cycle, $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3}$; however, the next consecutive two scan cycles have different results of $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_{11}} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_3} > \mathrm{RSS}_{t_i}^{\mathrm{AP}_8}$. Therefore, one more scan cycle is needed to satisfy $D_s(1, 3)$, where the scan window is shifted one scan cycle.

2) Phase II—Handoff With the DeuceScan Process: After constructing the spatiotemporal triangle list $= \{\nabla_{t_1}, \nabla_{t_2}, \ldots, \nabla_{t_i}, \nabla_{t_{i+1}}, \ldots, \nabla_{t_j}\}$, the handoff procedure using the DeuceScan process is presented. Let $\mathrm{AP}_{\mathrm{cur}}$ denote the currently associated AP, and the MH receives $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{\mathrm{cur}}}$ from $\mathrm{AP}_{\mathrm{cur}}$ at time t_i. Let $\mathrm{RSS}_{\mathrm{threshold}}$ denote the threshold value of the RSS. If $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{\mathrm{cur}}} < \mathrm{RSS}_{\mathrm{threshold}}$ and $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{\mathrm{next}}} > \mathrm{RSS}_{\mathrm{threshold}}$ are received, then the handoff procedure is executed to hand over to $\mathrm{AP}_{\mathrm{next}}$.

S1) When an MH enters a new location at time t_i, the MH performs the partial prescanning procedures $D_s(\alpha, \beta)$

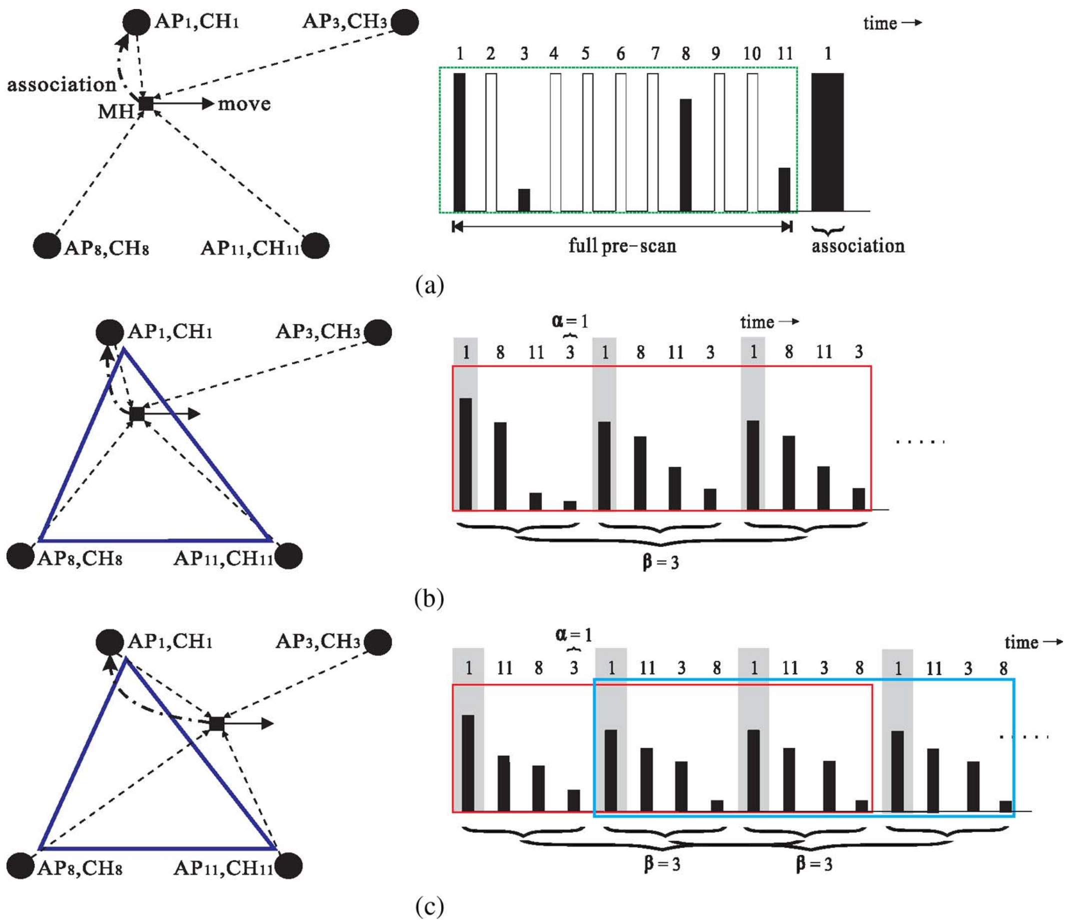

Fig. 6. Construction of spatiotemporal graphs.

and $D_v(\alpha,\beta)$ when $\mathrm{RSS}_{t_i}^{\mathrm{AP}_{\mathrm{cur}}} > \mathrm{RSS}_{\mathrm{threshold}}$ to estimate the current spatiotemporal triangle ∇_{t_i}, where, for AP_{i_1}, AP_{i_2}, and AP_{i_3}, $\mathrm{AP}_{i_1} = \mathrm{AP}_{\mathrm{cur}}$, and the candidate handoff APs are AP_{i_2} and AP_{i_3}.

S2) From the result of performing $D_s(\alpha,\beta)$, the best candidate handoff AP is AP_{i_2}, and the second best one is AP_{i_3}. If the same result is obtained when $D_v(\alpha,\beta)$ is executed, then the final best and second best handoff APs are AP_{i_2} and AP_{i_3}, respectively. Otherwise, if $|\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}} - \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}}| > \Delta_{\mathrm{threshold}}$, then the final best and second best handoff APs are AP_{i_2} and AP_{i_3}, respectively. If $|\mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_2}} - \mathrm{RSS}_{t_i}^{\mathrm{AP}_{i_3}}| \le \Delta_{\mathrm{threshold}}$, then the final best and second best handoff APs are AP_{i_3} and AP_{i_2}, respectively.

Fig. 7 shows an example of applying the DeuceScan scheme, where the currently associated AP is AP_1. Fig. 7(a) and (b) shows that $D_s(1,2)$ and $D_v(1,2)$ are performed when $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} > \mathrm{RSS}_{\mathrm{threshold}}$ at time t_i. Fig. 7(c) illustrates that if $\mathrm{RSS}_{t_i}^{\mathrm{AP}_1} < \mathrm{RSS}_{\mathrm{threshold}}$, a handoff is executed by selecting AP_{11} as the next handoff AP by performing $D_s(1,2)$ and $D_v(1,2)$. In summary, the main operation of the DeuceScan process is to make the handoff decision from the same RSS order results for the consecutive β times to significantly reduce the wrong decisions and the frequent unnecessary handoffs.

IV. Performance Analysis

A simulation is done by using the NCTU-NS simulator [4] to simulate the performance of our DeuceScan scheme with all the existing fast layer-2 handoff schemes [3], [16]–[18]. In the following simulation, the DeuceScan scheme is compared with the SyncScan scheme [16], the IEEE 802.11 standard (STD) [3], the neighbor-graph-based scheme (NG) [17], and the selective-scanning-based scheme with the cache mechanism (SSC) [18]. As mentioned before, the DeuceScan and SyncScan schemes [16] are prescanning protocols, whereas all the other protocols are not.

In this simulation, we assumed that the network topologies are randomly generated by the NCTU-NS network simulator [4]. All APs are randomly distributed in a 1000×1000 m^2 region. The mobility model in this simulation is the adopted "random waypoint" model [22]. The mobility characteristics are determined by two parameters, i.e., speed and pause times, where the speed ranges from 5 to 30 m/s, and the pause time ranges from 1 to 10 s in our simulation. The other system parameters are listed in Table II.

The performance metrics to be observed are the following:

- *handoff latency:* the time period between an MH changing its association from the current associated AP to another one;

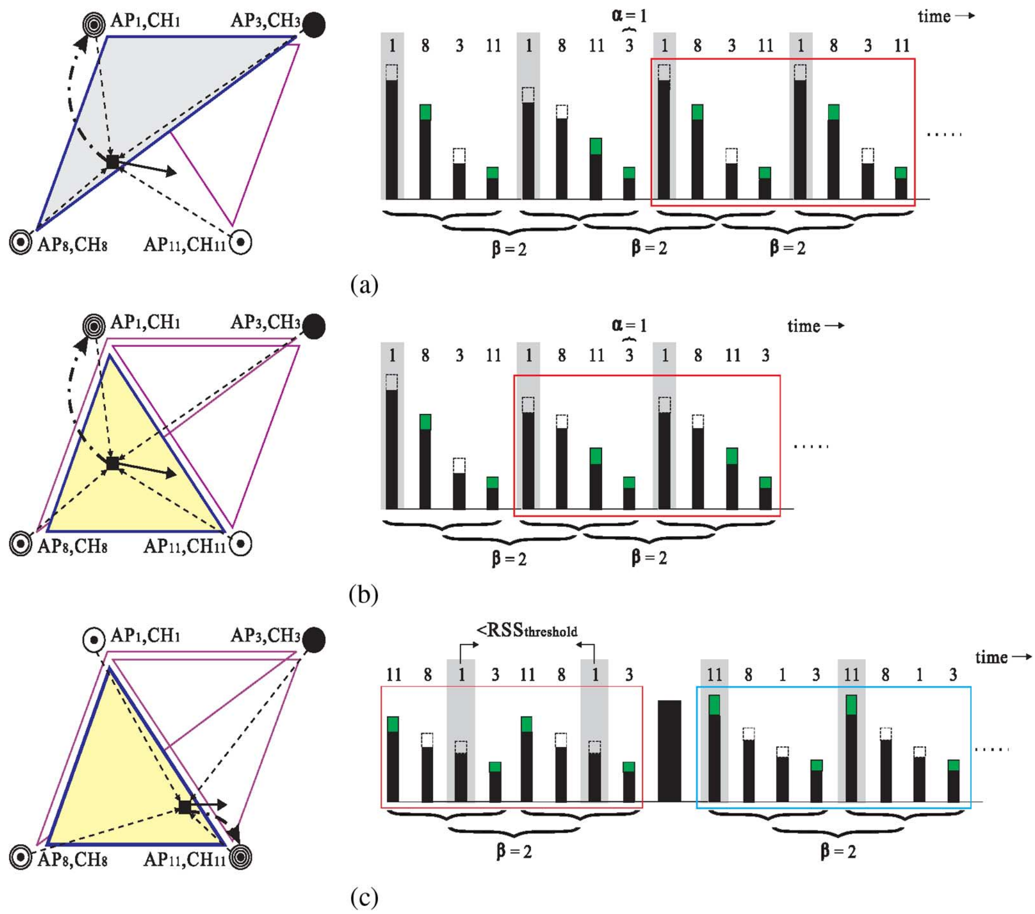

Fig. 7. Applying the DeuceScan scheme.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Number of mobile hosts	500
Number of access points	100∼200
Network region	1000 m ×1000 m
Radio propagation range	100 m
Mobility of mobile hosts	5∼30 m/s
Pause time of mobile hosts	10 sec

- *packet loss:* the total number of packets that are lost during the handoff procedure for an MH;
- *link quality:* the average RSS of an MH for a period of time.

An effective fast handoff scheme is achieved by having low handoff latency, low packet loss, and high link quality during the handoff operation for an MH. In the following, we illustrate the performance achievements of handoff latency, packet loss, and link quality of our DeuceScan scheme.

A. Determination of α and β

We first describe the effects of the handoff success ratio (HSR) and the handoff latency under various values of α and β. The HSR is defined as the ratio of an MH successfully handing off from a previous AP to a next AP, where the next AP is selected from the candidate APs. The candidate APs are determined and predicted by the detection mechanism of the existing handoff protocols. It indicates that an MH possibly hands off to a next AP that is not a candidate AP.

To illustrate the influence of the HSR, various combinations of the values of α and β were considered to observe the influences as follows. Fig. 8(a) illustrates the HSR versus various moving speeds (ranging from 0 to 30 m/s), where $0 \leq \alpha \leq 3$, and β is fixed at 1. It is observed that the curve $\alpha = 0 < \alpha = 1 < \alpha = 2 < \alpha = 3$. This implies that the larger the number of α is, the higher the HSR will be. For each curve, it was observed that when the moving speed is high, the HSR is slightly decreased. We observed the same results in Fig. 8(b)–(d) for the simulation results of the HSR versus moving speeds (ranging from 0 to 30 m/s), where $0 \leq \alpha \leq 3$, and β is fixed at 2, 3, and 4, respectively. It was observed that the HSR drops as β decreases from all the corresponding curves in Fig. 8. Consequently, the HSR drops as α and β decrease. On the other hand, we investigate the influence of handoff latency under various combinations of the values of α and β. Fig. 9(a) gives the simulation results of handoff latency versus various values of α (ranging from 0 to 7), where $1 \leq \beta \leq 4$, and the moving speed is fixed at 5 m/s. It is observed that the curve $\beta = 1 < \beta = 2 < \beta = 3 < \beta = 4$. This implies that the greater the number of β is, the higher the handoff latency will be under a low moving speed. For each curve, it was observed that the greater the number of α, the higher the handoff latency.

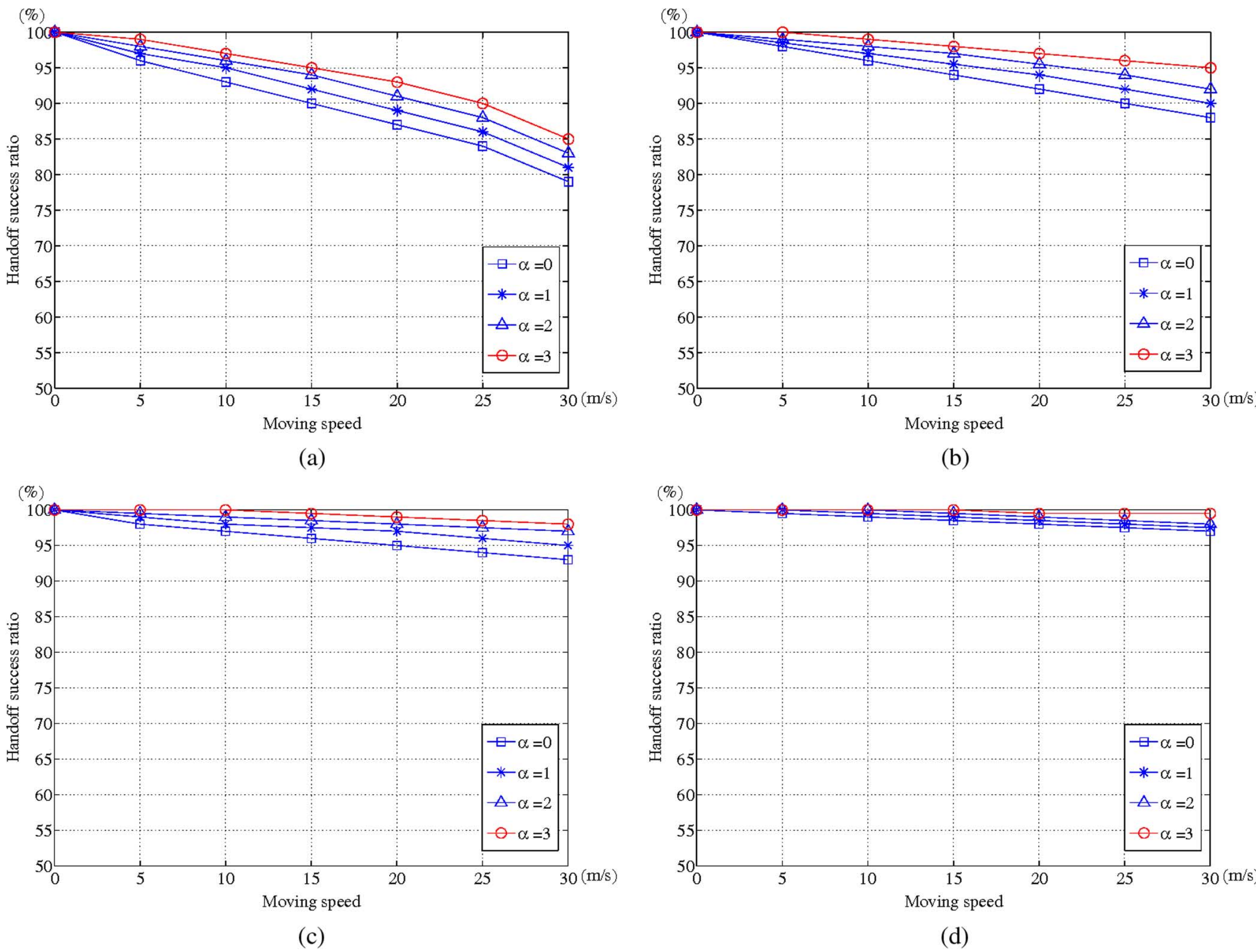

Fig. 8. Performance of the HSR versus moving speed.

We have similar results in Fig. 9(b) and (c) for the simulation result of handoff latency versus various values of α (ranging from 0 to 7), where $1 \leq \beta \leq 4$, and the moving speeds are fixed at 15 and 30 m/s, respectively. However, if α is fixed at 1, and $\alpha + 3 = 4$, then it is observed that the handoff latency $\beta = 2 < \beta = 1 < \beta = 3 < \beta = 4$ under medium and high moving speeds.

This is because when an MH uses more β scan cycles, it improves the predictive accuracy of candidate APs but incurs a larger handoff latency. Therefore, $(\alpha, \beta) = (1, 2)$ has the smallest handoff latency under medium (15 m/s) and high (30 m/s) moving speeds. From our simulation result, this justifies that (1, 2) will be the best choice for (α, β).

B. Handoff Latency

The entire handoff latency is classified into three delays, i.e., probe, authentication, and reassociation delays [11]. Ramani and Savage [16] developed a new fast handoff called the SyncScan scheme for IEEE 802.11 infrastructure networks. This scheme is a low-cost technique for continuously tracking nearby base stations by synchronizing short listening periods at the client with periodic transmissions from each base station [16]. Prescan means that the probe operation is continuously performed before the handoff procedures. By executing a prescan in advance, SyncScan omits the probe delay and slashes the entire handoff delay. SyncScan is a prescan scheme. The main idea is that the probe operation is executed before initiating the handoff operation. This implies that the probe delay is slashed. Observe that the handoff latency of the prescan scheme is only calculated by authentication and reassociation delays. Our work is a prescan scheme and follows the same handoff latency calculation, system model, and assumption from SyncScan [16]. In our scheme, the time cost of searching the appropriate spatiotemporal triangle and calculating the variables of the radio signal strength is not included in the handoff latency. This is because these operations can be performed before initiating the handoff operation, and this time cost is overlapped with the time period during the prescanning procedure.

The performance of the handoff latency versus the different values of α and β of $D_s(\alpha, \beta)$ and $D_v(\alpha, \beta)$ is discussed as follows. In our simulation, we let $D(\alpha, \beta)$ represent the deuce procedures $D_s(\alpha, \beta)$ and $D_v(\alpha, \beta)$. The performance effects of handoff latency versus moving speed under different values of α and β are illustrated in Fig. 10(a). In general, the higher

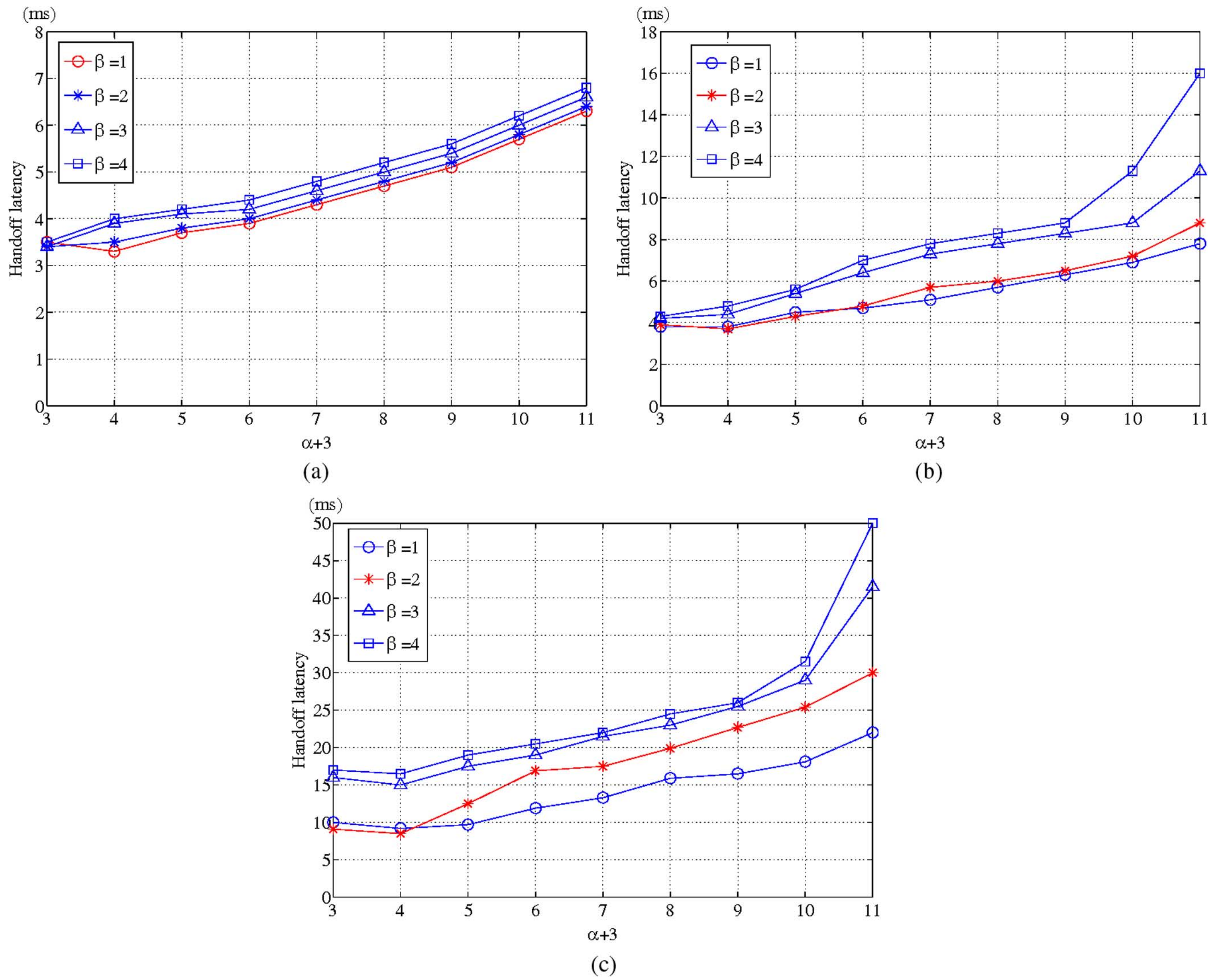

Fig. 9. Performance of handoff latency versus various numbers of $\alpha + 3$.

the moving speed of an MH, the higher the handoff latency. Fig. 10(a) shows the handoff latency of $D(1, 2) < D(2, 2) < D(1, 3) < D(3, 2) < D(2, 3)$. This is because the larger the deuce window size, the higher the handoff latency. The increased number of extra scanning APs increases the handoff latency time. However, the increased number of extra scanning APs and the large deuce window size can effectively acquire accurate handoff information with fault-tolerant capability. It is reasonable to adopt $D(1, 2)$ for the following performance discussion.

Given a fixed $D(1, 2)$, we discuss the performance of handoff latency versus moving speed in Fig. 10(b) and (c). The higher the speed of an MH, the longer the handoff latency. Fig. 10(b) illustrates the handoff latency of STD > NG > SSC > DeuceScan. This is because STD, NG, and SSC have to scan all channels during the handoff procedure. This verifies that the performance of the prescanning protocol (DeuceScan) is better than that of the nonprescanning protocols (STD, NG, and SSC) for significantly reducing the probe delay time. Fig. 10(c) shows that the handoff latency of SyncScan is larger than that of DeuceScan. This result verifies that our prescanning scheme (DeuceScan) has a lower handoff latency than that of the existing prescanning scheme (SyncScan) because our scheme is a partial prescanning scheme. The DeuceScan scheme has a shorter handoff delay than that of the SyncScan scheme under a high moving speed because of the partial prescanning property.

We investigated the performance of the handoff latency versus the number of neighbor APs for $D(1, 2)$. Moreover, we studied the performance of the handoff latency versus the number of neighbor APs, as shown in Fig. 10(d) and (e). In general, the greater the number of neighbor APs, the higher the handoff latency. Fig. 10(d) shows the handoff latency of STD > NG > SSC > DeuceScan under a fixed moving speed. The STD always performs the full scanning operation during the handoff; hence, the handoff latency of the STD steadily increases as the number of neighbor APs increases. However, the NG performs a partial scanning operation during the handoff, and the handoff latency greatly increases as the number of neighbor APs approaches 17. When the SSC experiences a

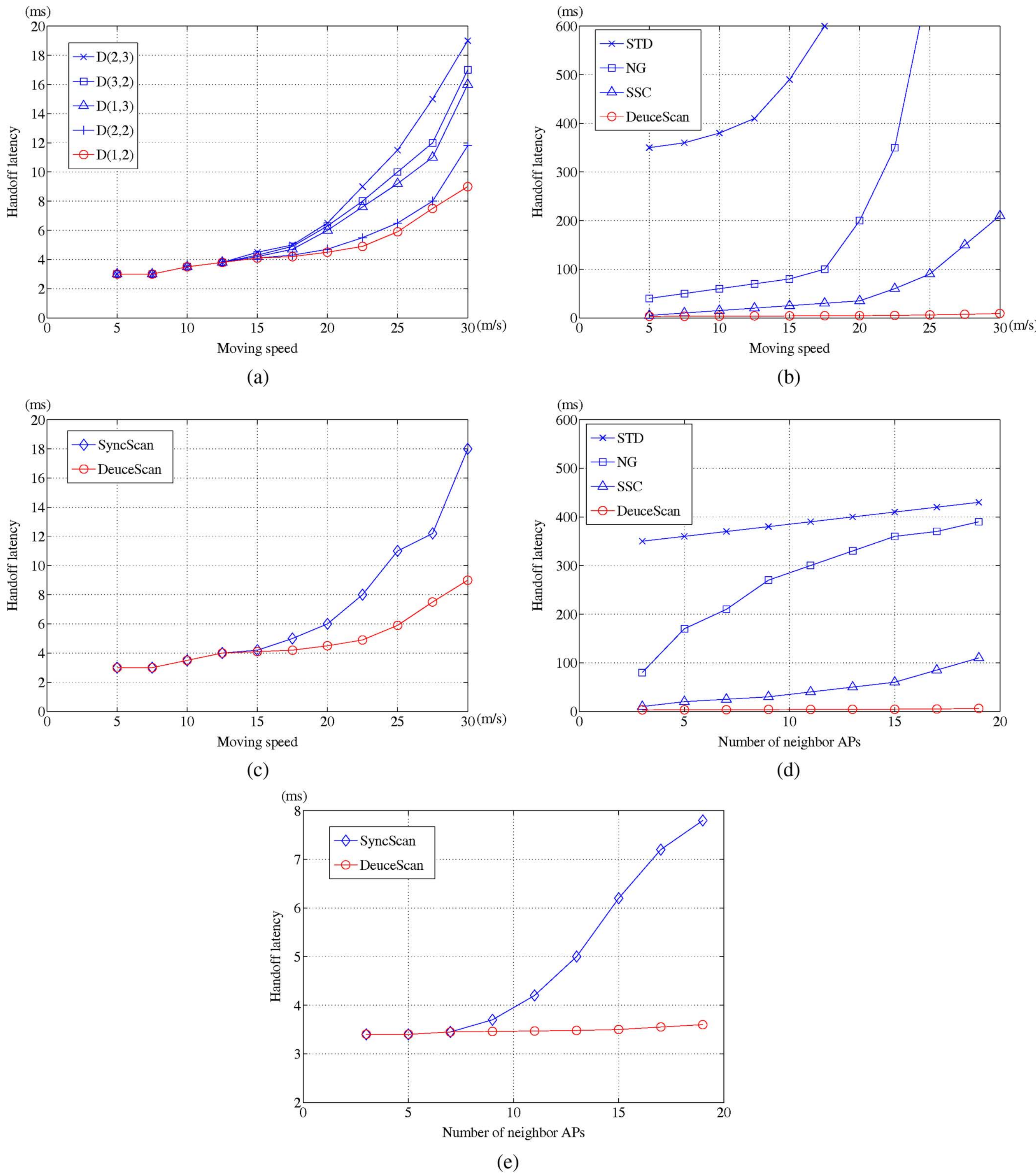

Fig. 10. Performance of handoff latency.

cache miss, the average handoff latency significantly increases. Fig. 10(e) shows that our DeuceScan scheme was not affected by the number of neighbor APs since a fixed number of APs ($\alpha + 3$ APs) is selected; however, the SyncScan scheme was affected by the number of neighbor APs since a full prescanning operation is performed.

C. Packet Loss

The performance effect of packet loss versus moving speed under different values of α and β is illustrated in Fig. 11(a). In general, the higher the moving speed of an MH, the higher the packet loss. Fig. 11(a) shows the packet loss of $D(1,2) < D(2,2) < D(1,3) < D(3,2) < D(2,3)$. The reason is given

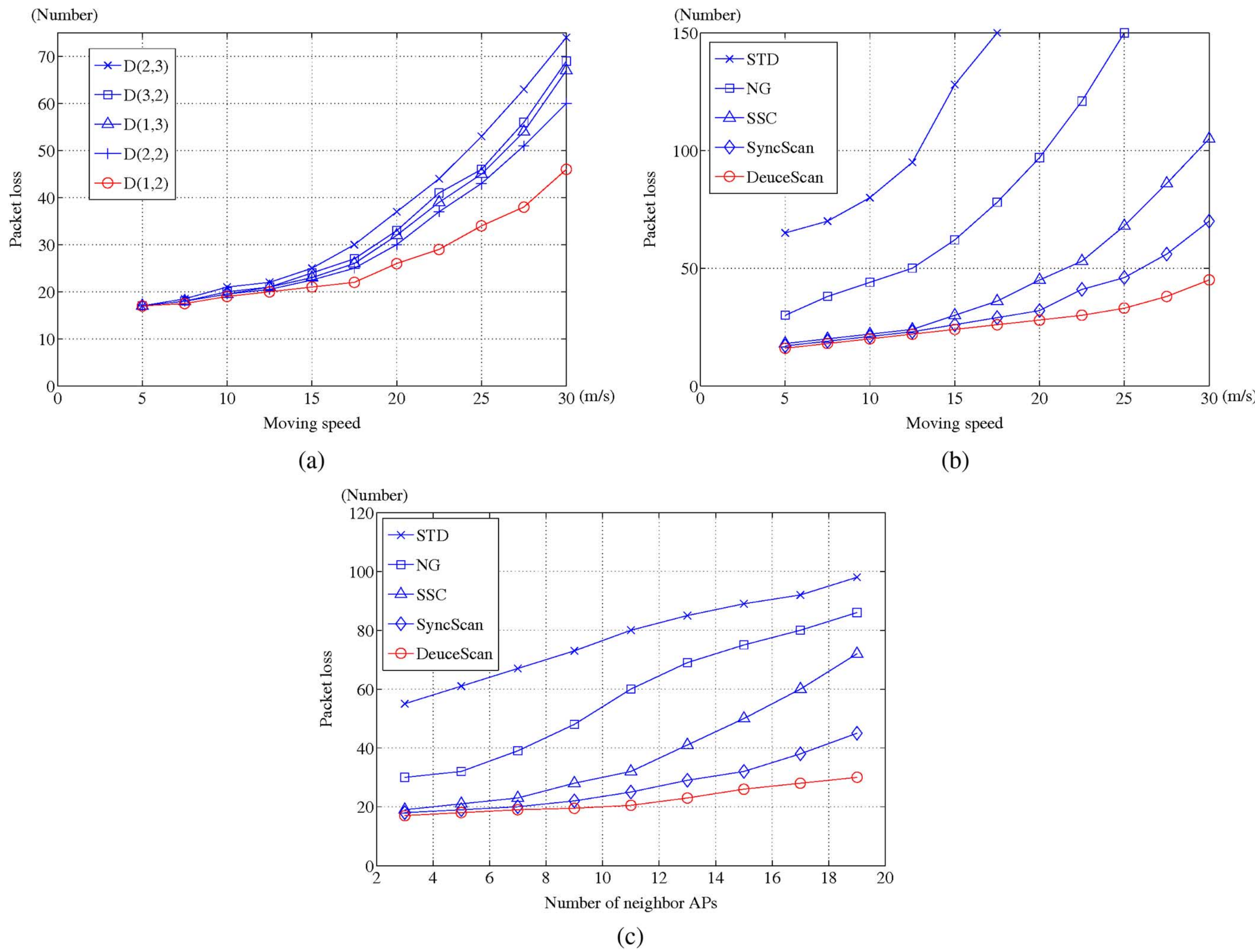

Fig. 11. Performance of packet loss.

in Section IV-A. It is verified that the higher the handoff latency, the greater the packet loss. Fig. 11(b) shows the packet loss of STD > NG > SSC > SyncScan > DeuceScan versus the moving speed. Fig. 11(c) shows the packet loss of STD > NG > SSC > SyncScan > DeuceScan versus the number of neighbor APs. The greater the number of neighbor APs, the greater the packet loss.

D. Link Quality

The performance effect of link quality versus moving speed under different values of α and β is illustrated in Fig. 12(a). Generally, the higher the moving speed of an MH, the lower the link quality. Fig. 12(a) illustrates the link quality of $D(1,2) > D(2,2) > D(1,3) > D(3,2) > D(2,3)$. The reason is given in Section IV-A. An MH with a better link quality implies that a good communication quality is maintained over a wireless environment. When $\mathrm{RSS}_{t_i}^{\mathrm{AP_{cur}}} < \mathrm{RSS}_{\mathrm{threshold}}$, the MH executes a handoff procedure to be reassociated with the next AP with the best and most stable signal strengths. If the handoff latency is low, an MH can seamlessly hand off to a new AP, and the time duration of an MH stays at a low signal strength for a short period of time.

Fig. 12(b) illustrates the performance of link quality versus moving speed. Basically, the SyncScan and DeuceScan schemes maintain a high link quality because the prescanning operation is adopted. DeuceScan has a better link quality than SyncScan because of the partial prescanning operation. Fig. 12(c) simulated a handoff situation to illustrate the differences in link quality between the DeuceScan and SyncScan schemes. After a handoff occurred in time $t = 20$ s, if the MH's moving speed is high, it possibly hands off to different APs by applying different schemes. Therefore, the MH hands off to AP_3 using the DeuceScan scheme but hands off to AP_{11} using the SyncScan scheme. In addition, the MH using the DeuceScan scheme has a better link quality due to its lower packet loss.

In summary, a true layer-2 fast handoff scheme (i.e., DeuceScan) achieves low handoff latency, low packet loss, and high link quality, particularly with a high moving speed.

V. Conclusion

In this paper, we have presented a new fast handoff protocol called the DeuceScan scheme to efficiently reduce the layer-2 handoff delay for IEEE-802.11-based WLANs. To consider

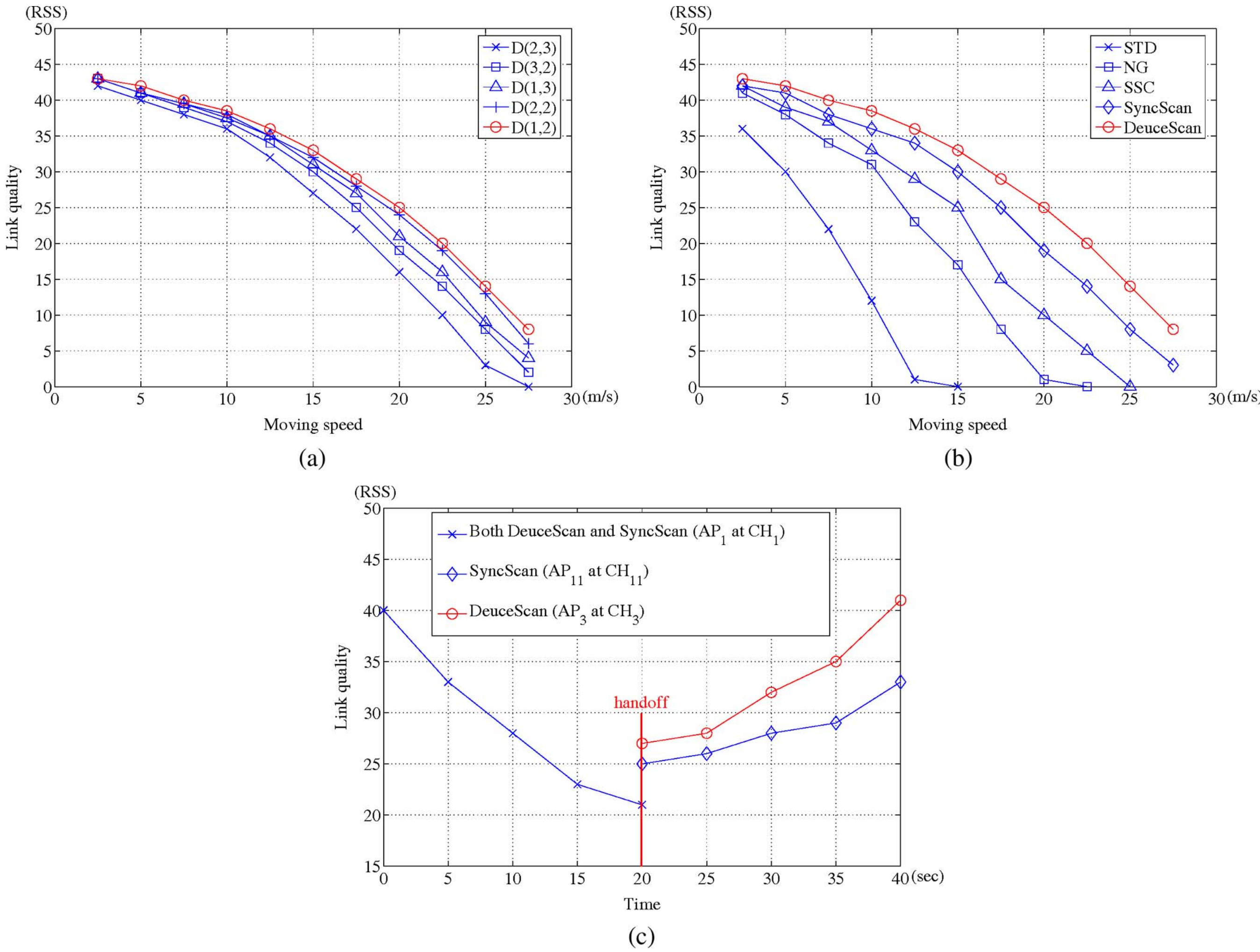

Fig. 12. Performance of link quality.

the partial prescanning operation, a spatiotemporal approach is developed in the DeuceScan scheme to utilize a spatiotemporal graph for accurately and correctly making the handoff decision. Our proposed scheme is very useful in improving the wireless communication qualities on vehicles by utilizing the moving intention information. To provide the moving intention information, two factors of stable signal strength and variable signal strength are used in our developed DeuceScan scheme. In addition, our DeuceScan scheme has a fault-tolerant capability to significantly reduce wrong decisions and frequent unnecessary handoffs. The simulation results illustrated the performance achievements compared to existing fast handoff protocols. Future work involves developing a fast handoff protocol in IEEE 802.16e for fixed broadband wireless access systems.

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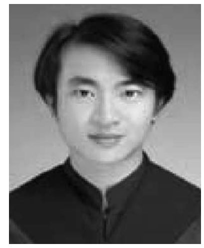

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