Design of a Fast Location-Based Handoff Scheme for Vehicular Networks

by

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Abstract

IEEE 802.11 is an economical and efficient standard that has been applied to vehicular networks. However, the long handoff latency of the standard handoff scheme for IEEE 802.11 has become an important issue for seamless roaming in vehicular environments, as more handoffs may be triggered due to the higher mobility of vehicles.

This thesis presents a new and fast location-based handoff scheme particularly designed for vehicular environments. With the position and movement direction of a vehicle and the locations of the surrounding APs, our protocol is able to accurately predict several possible APs that the vehicle may visit in the future and to assign these APs different priority levels. APs on higher priority levels will be first scanned. Once a response to scanning from an AP is received, the scanning process ends immediately. A blacklist scheme is also used to exclude those APs that showed no response to the scanning during previous handoffs. Thus, time spent on scanning APs is supposed to be significantly reduced. The simulation results show that the proposed scheme attains not only a lower prediction error rate, but also a lower MAC layer handoff latency, and that it has a smaller influence on jitter and throughput; moreover, these results show that the proposed scheme has a smaller total number of handoffs than other handoff schemes.

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List of Publications Related to Thesis

Refereed Papers

- Mohammed Almulla, Yikun Wang, Azzedine Boukerche, Zhenxia Zhang: A Fast Location-based Handoff Scheme for Vehicular Networks. In *IEEE ICC'13*, pages 57 - 61, June 2013.
- Mohammed Almulla, Yikun Wang, Azzedine Boukerche, Zhenxia Zhang: Design of a Fast Location-based Handoff Scheme for IEEE 802.11 Vehicular Networks. *IEEE Transactions on Vehicular Technology*, (submitted).

Contents

List of Tables

List of Figures

Glossary

Access Point (AP): a device that allows wireless devices to connect to a wired network, and are usually used in WLANs.

Global Positioning System (GPS): a space-based satellite navigation system that can provide location and time information.

Handoff: a.k.a. handover, the process of transferring ongoing communications from one wireless device to another.

Internet Protocol (IP): the principal communications protocol in the Internet protocol suite for connections across any set of interconnected networks.

Intelligent Transport Systems (ITS): the transportation systems that utilize synergistic technologies and systems engineering concepts to achieve safer, more coordinated, and smarter transport networks.

Media Access Control (MAC): a sublayer of the data link layer in the seven-layer Open Systems Interconnection model of computer networking, which provides addressing and channel access control mechanisms.

Mobile Node (MN): a device whose location and connected devices may frequently be changed in a wireless network.

Network Simulator 2 (NS2): a discrete event simulator targeted at networking research.

Received Signal Strength (RSS): the magnitude of the radio signal which can be used for the signal receiver to calculate the distance the signal has traveled.

Roadside Unit (RSU): a device that can provide connections to infrastructure, and which acts as an access point or a base station.

Signal-to-noise Ratio (SNR): the ratio of signal power to the background noise power.

Voice over IP (VoIP): the communications protocols or technologies involved in the delivery of voice communications and multimedia sessions over Internet Protocol (IP) networks.

Wireless Local Network (WLAN): a local area network in which a device is linked through a wireless connection using IEEE 802.11 standards.

Chapter 1

Introduction

Vehicular networks have attracted much attention from researchers and have sparked a wide discussion over the recent years. The importance and potential impact of vehicular networks have been confirmed by the rapid growth in research involving car manufacturers, government departments, and academia [46]. In this chapter, a brief introduction to vehicular networks and related technologies will be presented. The latency issue caused by handoffs and the outline of the proposed solution to this problem will then be discussed.

1.1 Background

1.1.1 Vehicular Networks

Vehicular networks fulfill the need of the general public to be connected anytime and anywhere; furthermore, vehicular networks have become one of the areas in wireless networks to receive the greatest amount of attention and have become the focus of many projects [9, 11, 55]. They provide infrastructure supports to intelligent transportation systems (ITS) and mobile entertainment environments. ITS improves the

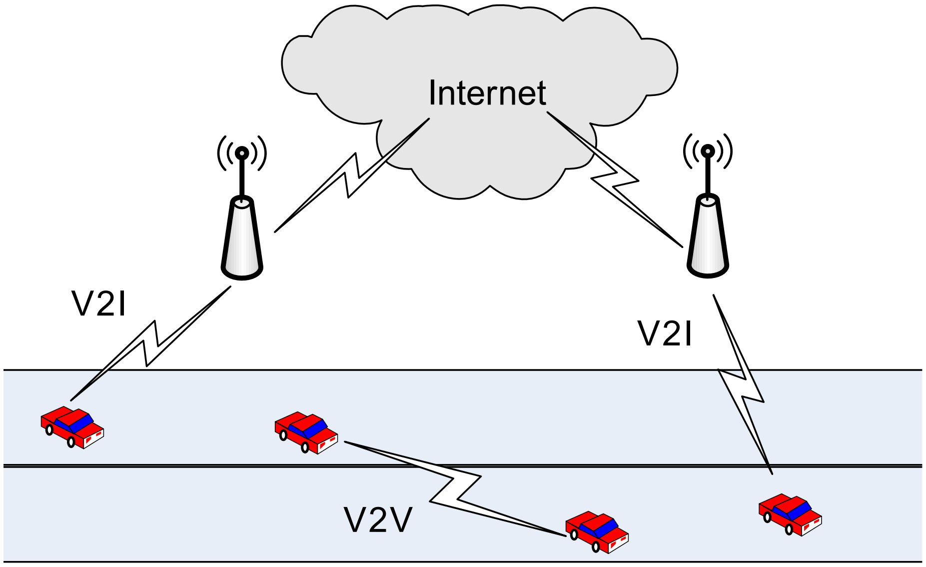


Figure 1.1: A vehicular networking scenario

safety of driving and make transport networks more coordinated by reporting traffic congestion, road conditions, car accidents, *etc.* [4]. Mobile entertainment environments include online video or music streaming and computer games, which require high-throughput network connectivity. As sensors for wireless sensor networks [5], vehicles also provide an ideal platform for vehicular sensor networks [14, 32], and may perform tasks such as monitoring urban environments, images or video of streets and checking for the presence of toxic chemicals.

In vehicular networks, there are basically two types of communications as shown in Figure 1.1: the communications among vehicles are called vehicle to vehicle (V2V) communications, and the communications between vehicles and roadside units (RSUs) are called vehicle to infrastructure (V2I) communications [17]. Vehicles communicate with each other in an ad-hoc mode for V2V communications. A network can involve solely V2V or V2I communications, or a mixture of the two types of communications.

There are various wireless communications technologies available for vehicular networks, such as Wireless Local Networks (WLANs), cellular technologies, WiMAX [25], and so on. Most modern WLANs are based on IEEE 802.11 [23] standard, which is one of many standards for the physical layer and media access control (MAC) layer which provides connections for wireless networks. It achieves low cost, yet also high bandwidth connections, and it is convenient to configure and deploy. With such strengths, it is enjoying great popularity among assorted wireless network technologies. In IEEE 802.11 based vehicular networks, access points (APs) act as RSUs and mobile nodes (MNs) are actually vehicles. Cellular technologies, however, are more expensive than WLANs currently. The bandwidth of both second and third generation cellular technology is considerably lower. Even though the fourth generation technology increases bandwidth greatly for data service, the cost is still very high for multimedia data.

Two standards, which are a result of the modification of IEEE 802.11, are designed particularly for vehicular networks. Dedicated short-range communication (DSRC) [20] is a variation of the IEEE 802.11a protocol, and the more recent IEEE 802.11p [24] is based on DSRC. They both operate in the licensed ITS band of 5.9GHz and are able to support broadband wireless services. The transmission range of IEEE 802.11p and DSRC is expanded up to $1000m$, but IEEE 802.11g was used for simulation in this work.

1.1.2 GPS in Vehicular Networks

An increasing number of vehicles are equipped with Global Positioning System (GPS) devices for the purpose of navigation. The expense of a GPS device is very small compared to that of a vehicle, so adding a GPS device to a car does not increase the price of the car noticeably. GPS is a means of obtaining location information for geographic protocols [3], which takes advantage of the location information of nodes to provide higher efficiency and scalability for various types of wireless networks. Besides, GPS may provide location information for some location-sensitive information in vehicular networks. Some examples of these protocols are discussed below.

In wireless environments, it is expected that geographic protocols will become important elements for the development of these networks. GPS devices are able to provide generally more accurate location information for geographic routing protocols [19]; thus, they have the advantage of the capability to cope with the challenging tasks resulting from high dynamics and quickly changing topology. Some examples of geographic routing protocols are proposed in the literature [30, 34, 35]. Greedy Perimeter Stateless Routing (GPSR) [30] is one of the best known geographic routing protocols. In GPSR, an intermediate node normally forwards a packet to its neighbor that is geographically closest to the destination of the packet, and this is the so-called greedy forwarding algorithm. Such protocols usually reduce the number of hops in routing.

Another possible use of GPS devices is geocasting, which is a method of delivering packets to nodes within a certain geographic area. Protocols described in [27, 26], for instance, include modifications to the Internet by integrating geographic coordinates into the Internet Protocol. Packets are sent to all nodes within a geographic area. GPS is adopted by this protocol to provide location information.

Some applications in vehicular networks require location awareness, because both the data gathered from vehicles and the data consumed by vehicles are location-dependent. For ITS, information regarding traffic congestions, road conditions and accidents must contain location information to make such information meaningful. When a vehicle encounters an emergency, for example, malfunctioning brakes [47, 44], only its neighbors need to receive alerts, because such alerts are irrelevant to vehicles far away. Vehicles with wireless communications capabilities are attractive targets for advertisements. Instead of traditional billboards on the roadside, AdTorrent [13]

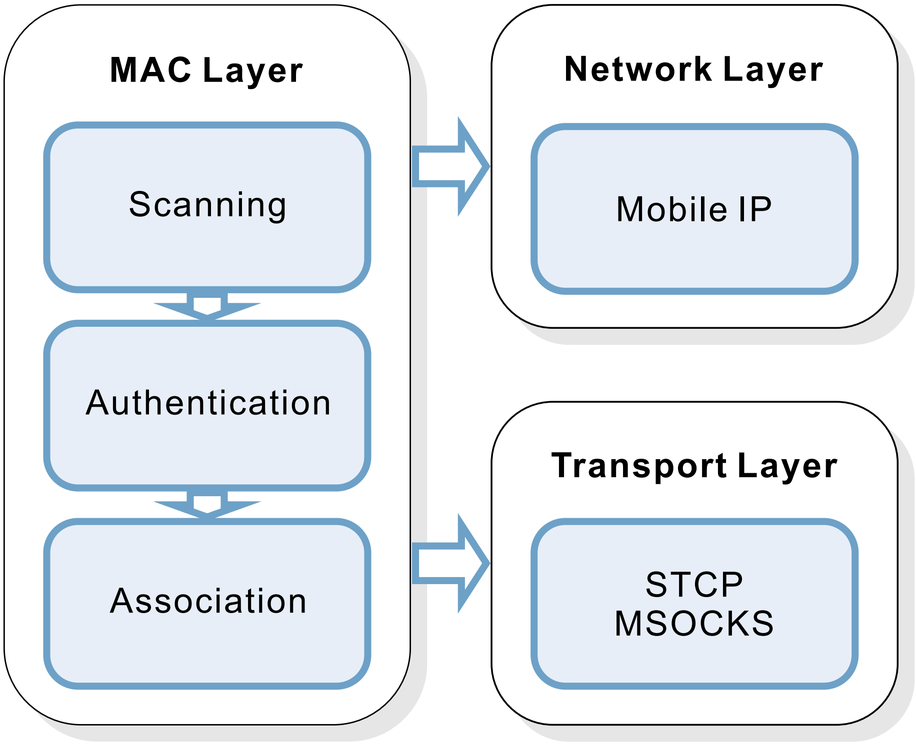


Figure 1.2: Handoff and mobility management process

delivers commercial advertisements to vehicles in a certain area with digital billboards.

In conclusion, it is obvious that utilizing the geographic information is beneficial to building scalable and efficient protocols in vehicular environments, and GPS devices are a good solution for providing the required geographic information. As GPS devices can serve many purposes for vehicular networks, it is not a demanding request for the proposed location-based scheme to utilize the GPS to provide location information.

1.1.3 Handoff and Mobility Management

When an MN migrates out of the coverage of one AP, it must switch its connection to a different AP. The process of switching APs is called a MAC layer handoff or handover. This process interrupts ongoing communications temporarily. The time

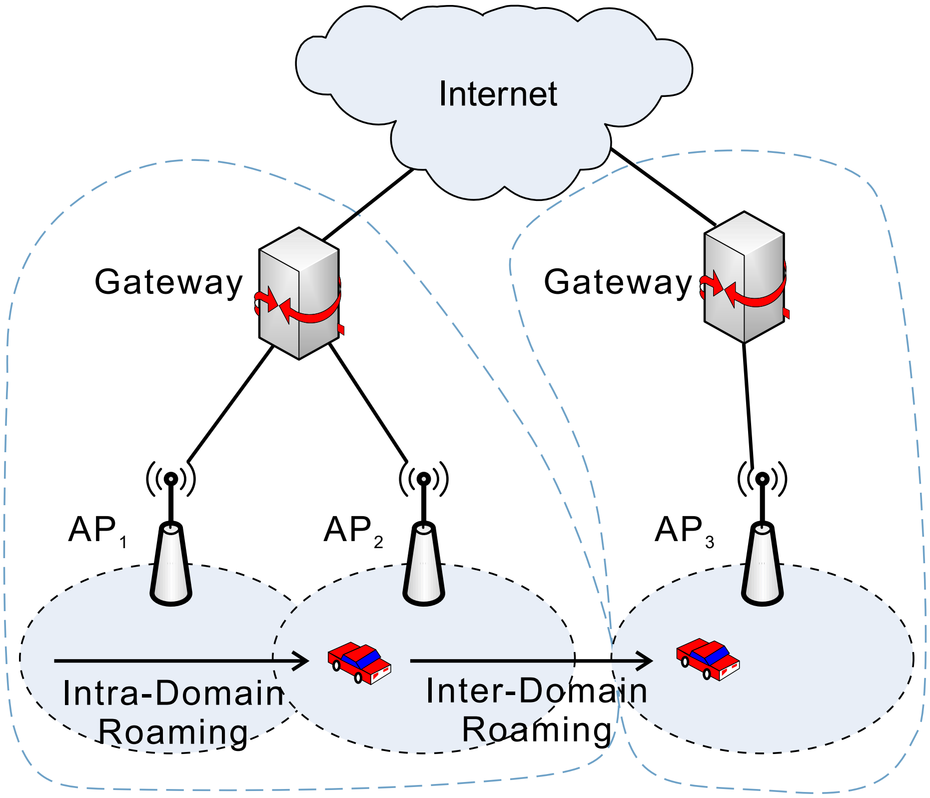


Figure 1.3: Intra-domain roaming and inter-domain roaming

spent completing a handoff process is called handoff latency, which causes delay, jitter or package loss to the network. There are basically three phases in an IEEE 802.11 handoff process: scanning, (re)authentication and (re)association, as shown in Figure 1.2.

The MAC layer handoff is only one part of mobility management; higher layers may also be involved [12, 1]. In terms of network layer, if a handoff does not involve a change of domains, the handoff process is defined as an intra-domain roaming. Otherwise, it is called an inter-domain roaming, as illustrated in Figure 1.3. Mobile IP [50, 51] is a well-known standard for mobility handling using tunnel technology in the network layer. Without Mobile IP, the IP address of the mobile device would be changed after a handoff; thus, all previous connection is lost. Mobility management is also implemented in the transport layer. For example, Stream Control Transmission Protocol (STCP) [60] gives native support for multiple addresses per host, and some protocols use proxy-based approaches, such as MSOCKS [37].

These mobility management schemes in the network layer and the transport layer are likely to introduce even more latency, but this thesis is concentrated on the MAC layer handoff.

1.2 Problem Statement

Despite the advantages of IEEE 802.11, such as low cost, scalability, ease of maintenance and deployment, this standard has difficulty supporting high mobility scenarios, such as vehicular environments. This is because it was originally designed mainly for indoor use and for static or low-speed MNs. The transmission range of this protocol is limited, compared with cellular technologies. Due to the limited transmission range, vehicles at higher movement speeds inevitably generate more handoffs than traditional MNs. Therefore, the handoff latency should be minimized to support smooth roaming in vehicular networks so as to guarantee quality of service for users.

For active scanning in IEEE 802.11 standard, real world data shows that the delay of the scanning phase ranges from $200ms$ to $400ms$ for most experimented devices, which accounts for more than 90% of the overall latency [40]. By contrast, the next two phases cause much less delay, usually below $10ms$.

The total delay in such a handoff process is so prominent that it significantly deteriorates user experience, especially when users are using some real-time applications, such as VoIP, video conferencing and online gaming. As for VoIP, the handoff latency should be less than $50ms$ [28] to ensure seamless roaming. When a user is using Skype [59] for a video talk with friends, significant jitter caused by handoffs would harm the quality of video. Online gaming is also delay sensitive, as no players like to lose control of his or her character in the game due to a sudden disconnection with the game server.

In urban areas, it is possible that the new AP may be located on roads that intersect with the road where the vehicle is travelling. If such an AP is chosen, radio signals between the AP and the vehicle will inevitably travel through buildings. As this may result in higher path loss and shadow fading effects to electromagnetic waves, the signals may be seriously deteriorated.

1.3 Research Outline

The objective of this thesis is to design an efficient location-based handoff scheme to support smooth roaming in vehicular environments.

In the proposed scheme, each vehicle is aware of its location and movement direction from a GPS receiver, together with the working channel and location information of all surrounding APs; thus, the fitness for the future handoff of these APs can be evaluated with our algorithms based on acquired geographic information. Those APs, which have a higher probability for being located in the future path of the vehicle, are selected to be scanned first. If the vehicle receives a response from the AP being scanned, it will not be necessary to scan remaining channels, and subsequent handoff procedures, authentication and association, will be executed immediately. In this way, the latency of the MAC layer handoff is significantly reduced.

Admittedly, the inaccuracy of the GPS may cause incorrect AP selections, but it can be remedied in vehicular environments. This is because GPS error is relatively small, when compared with the high velocity and vast movement range of vehicles. Moreover, if the vehicle cannot establish a connection with an AP being scanned, this AP will be recorded with a blacklist scheme, and it will not be scanned in the future under similar circumstances.

1.4 Contributions

First, a scheme that achieves high prediction accuracy in the selection and evaluation of APs is proposed in this thesis. The scheme is designed for vehicular networks, so some of the constraints of vehicular mobility pattern can be used to increase the prediction accuracy. The inaccuracy of the GPS does not harm the prediction accuracy seriously. Prediction accuracy is fundamental to the reduction of handoff latency, because fewer APs will be scanned, if the prediction is correct.

Secondly, the handoff latency of this scheme is significantly reduced, because fewer channels are scanned. If the prediction is correct, only one AP will be scanned. Extensive simulation experiments are run to determine the scanning delay of this scheme, and comparisons with other schemes are performed to demonstrate the advantages of our scheme. The handoff latency is minimized by our scheme so that user experience with some real-time applications, such as VoIP or video gaming, is improved.

Thirdly, this scheme is designed to select those APs that may be able to maintain a stable connection with the vehicle after a handoff. To sustain a long-term communication, the AP should be located in the future path of the vehicle, namely on the same road as the vehicle. In this way, radio signals between the AP and the vehicle does not travel through buildings and thus the quality of signals is improved.

Lastly, this scheme is able to reduce the total number of handoffs. The probability of turning at an intersection is smaller than that of maintaining the original direction, for most vehicles travelling in cities. If a vehicle is moving toward an AP after a handoff and keeps moving straight, this AP can provide the vehicle with the longest connection duration. Therefore, fewer handoffs are needed and handoffs occur less often.

1.5 Thesis Organization

This thesis presents our research on a new and fast handoff scheme, and it is organized as follows:

- Chapter 1 introduces the research background, the usefulness of this work, the research objective and the contributions of this thesis.
- Chapter 2 provides a review of related work on various handoff mechanisms. This chapter emphasizes those schemes that aim at reducing the handoff latency of MAC layer handoff.
- Chapter 3 presents a detailed description of the proposed scheme, which includes four schemes: a turn detection scheme, an AP selection scheme, a prioritized scanning scheme, and a blacklist scheme.
- Chapter 4 provides simulation results and some discussion on the performance of this scheme. The proposed scheme is also compared with others here.
- Chapter 5 summarizes the thesis and suggests future works.

Chapter 2

Related Work

Related work on handoff schemes is reviewed in this chapter. First, the standard handoff scheme of IEEE 802.11 is described. As stated before, the scanning phase consumes most of the time in the handoff latency, so many schemes with improved scanning phases are devised to solve this bottleneck. Advantages and disadvantages of these methods are discussed in the second part. Handoff decision schemes for IEEE 802.11 networks are reviewed and compared with those for cellular networks in the third of this chapter.

2.1 Standard Handoff Scheme

As discussed before, there are basically three phases in a handoff process: scanning, (re)authentication and (re)association. Traditionally, the scanning phase includes two types: passive scanning and active scanning. During passive scanning, each MN periodically changes its channel to monitor beacon frames sent by the surrounding APs to collect information of them. As for active scanning, each MN sends out probe request messages proactively to every channel and waits for responses from APs.

As for active scanning [23], if the channels to be scanned include all legitimate

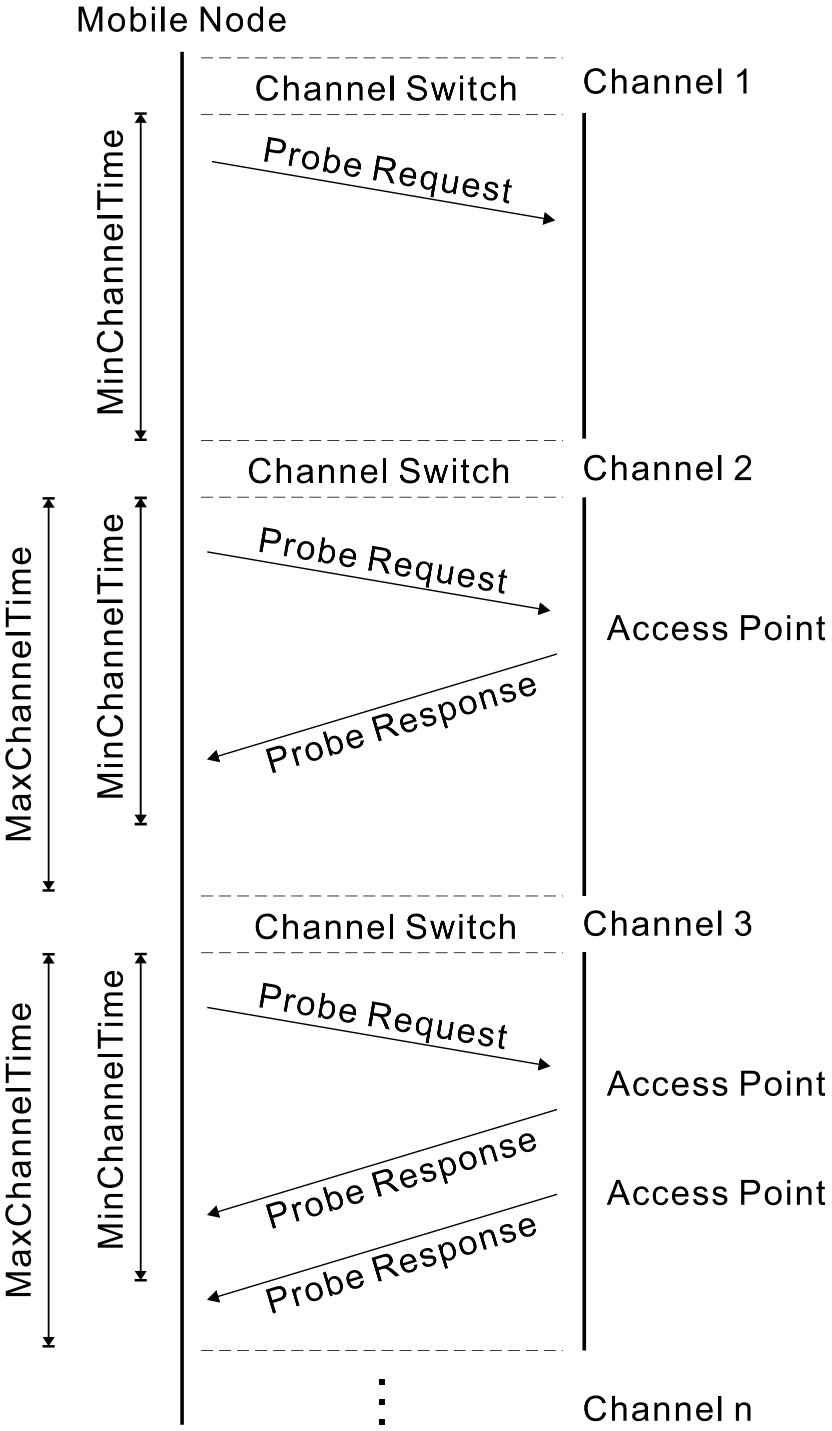


Figure 2.1: The full-scan scheme in IEEE 802.11

channels, the scheme is called the full-scan scheme. There are a total of 11 legitimate channels in North America, but they may not be all used in a network. The scanning delay or probe delay is mainly affected by three parameters: the number of used channels, $MinChannelTime$ and $MaxChannelTime$. Whenever an MN broadcasts a probe request message on a certain channel, it will initialize a timer. If the medium is detected as idle before $MinChannelTime$ expires, the MN can conclude there is no AP working on this channel and can switch channels to scan the next channel. Otherwise, the MN will deem that there are some MNs working on this channel, and then it will set a new timer to $MaxChannelTime$ and wait for more time. The MN will continue to scan other channels, whether it receives a probe response message or not, when $MaxChannelTime$ expires. Channel switch and transmission overhead (CS&T) also introduce more delay to the scanning process. Figure 2.1 illustrates the standard scanning and waiting scheme.

Every time a probe response is received by an MN, the received signal strength (RSS) of the corresponding AP is measured and the information of the AP together with its RSS is stored. Once all channels are scanned, the MN will then select the AP with the strongest RSS to start the following phases: (re)authentication and (re)association.

Assuming there are N channels in a scenario, the length of scanning delay is between $N \times (MinChannelTime + CS\&T)$ and $N \times (MaxChannelTime + CS\&T)$. One way to reduce the scanning delay is to cut the number of channels N to be scanned. In Figure 2.1, for example, it is obvious that waiting time is wasted on scanning Channel 1, which no AP uses. Besides, optimizing the settings of $MinChannelTime$ and $MaxChannelTime$ is also capable of improving probe delay. As scanning delay is the main source of handoff latency, many protocols focus on improvements on the scanning strategy. Some of these strategies are reviewed in the following section.

Table 2.1: Summary of schemes with optimized scanning parameters

Solution	**Parameter Settings**
A. Mishra *et al.* [40]	$MinChannelTime = 6.5ms$ and $MaxChannelTime = 11ms$
H. Velayos *et al.* [63]	$MinChannelTime = 1ms$ and $MaxChannelTime = 10.24ms$
R. Pazzi *et al.* [48]	$MinChannelTime$ and $MaxChannelTime$ are adaptive

2.2 Enhancement of the Scanning Phase

The schemes with improved scanning phases are divided into four categories; they are schemes with optimization of scanning parameters, reduction of scanned channels, cooperative scanning and the pre-scan strategy. Examples in these categories are discussed separately in this section.

2.2.1 Optimization of Scanning Parameters

As discussed before, $MinChannelTime$ and $MaxChannelTime$ have an influence on scanning delay. If the values are too high, unnecessary waiting time is wasted. On the other hand, an MN may not have enough time to receive all probe responses from APs, if the values are too low. Three strategies addressing this issue are reviewed and summarized in Table 2.1.

After lots of comparative tests on various combination of devices, A. Mishra *et al.* recommended that the proper values of $MinChannelTime$ and $MaxChannelTime$

should be 6.5ms and 11ms, respectively [40]. In the proposed scheme, the parameters suggested by A. Mishra *et al.* are used.

H. Velayos *et al.* [63] analyzed the link-layer handoff process based on the IEEE 802.11b standard and also conducted many experiments. They found that scanning delay can be reduced by 20%, if using active scanning with its timers $MinChannelTime$ and $MaxChannelTime$ set to 1ms and 10.24ms. Besides, they also suggested that 60ms could be an adequate beacon interval for passive scanning. Pre-authentication was also implemented, but their measurements indicate that the reduction in the total handoff delay is not significant with pre-authentication, because the original authentication process does not take a long time.

R. Pazzi *et al.* [48] proposed an algorithm in which these parameters are dynamically adjusted based on previous scanning information and the response messages received during current scanning. $MinChannelTime$ for a certain channel will decreased, if no AP works on this channel during the previous scanning; otherwise, it will be increased. $MaxChannelTime$ is adapted based on the RSS of the frames received within $MinChannelTime$. This scheme satisfies the requirements of real-time applications under their simulation environments.

2.2.2 Reduction of the Number of Channels

The reduction of the number of channels needed to be scanned is another way to shorten the scanning delay. This kind of solution usually can reduce handoff latency sharply, but the cost is that it requires information of APs prior to a handoff. Therefore, some extra databases or caching mechanisms are usually needed to provide such information. The drawback is that keeping the information of APs up-to-date may pose challenge to the scalability of the network. A summary of schemes reviewed in this part is presented in Table 2.2.

Table 2.2: Summary of schemes with fewer channels

Solution	**Strategy**	**Other Features**
A. Mishra *et al.* [41] M. Shin *et al.* [57]	neighbor graphs	accelerated context transfer
S. Shin *et al.* [58]	channel masks	caching mechanism for APs
Y. Liao *et al.* [33]	scanning in groups	N/A
C. Tseng *et al.* [62]	location-based	pre-authentication
S. Mellimi *et al.* [38]	location-based	two antennas

In [57], neighbor graphs (NG) or non-overlapping graphs are established to store information regarding adjacency relationships among APs. An example of the neighbor graph is shown in Figure 2.2. With the NG algorithm or NG-pruning algorithm, one MN needs only to scan channels adopted by adjacent APs. This approach saves time wasted in scanning channels that no adjacent AP uses. Neighbor graphs are also used to accelerate context transfers by updating the cache of neighbor APs before handoffs [41]. Thus, handoff latency due to reassociation is significantly reduced.

For selective scanning, S. Shin *et al.* [58] introduced a data structure, channel mask, to determine which channels will be scanned. They used the selective scanning algorithm to ensure that only a selected subset of channels will be scanned in future handoffs. MNs only scan non-overlapping channels (1, 6 and 11) and channels used by previous responding APs after a full scan. The channel of the previously connected AP will not be scanned, because the probability of an adjacent AP on the same channel of the current AP is very small. Combined with caching mechanism for storing information of surrounding APs in the previous handoffs, the latency attains

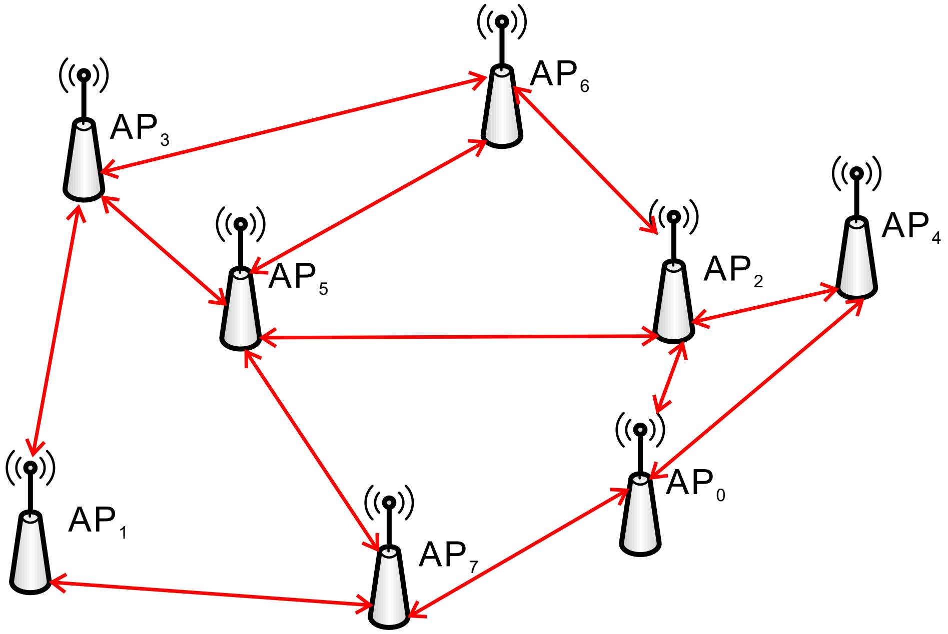


Figure 2.2: An example of the neighbor graph

further reduction.

Y. Liao *et al.* [33] proposed a smooth handoff scheme. Instead of consecutively scanning all channels at one time, the MN in this scheme divides channels into several groups, and scans the groups one by one. After one group of channels are scanned, the MN stops scanning and resumes normal data transmission. After a while, the MN continues to scan channels in the next group. Once all channels are scanned, the MN can decide on channel selection. This method does not reduce the total number of channels to be scanned, but it can achieve lower packet loss ratio and smaller jitter.

GPS receivers are nowadays becoming a common component of electronic devices; thus, some schemes select APs based on the position information of both APs and MNs provided by GPS receivers. The location of an MN is acquired from its own GPS receiver, and a location server is also introduced to supply coordinates of the APs. A location-based scheme was proposed by C. Tseng *et al.* [62]. If an AP is located within a certain range of movement direction of the MN, it will be included

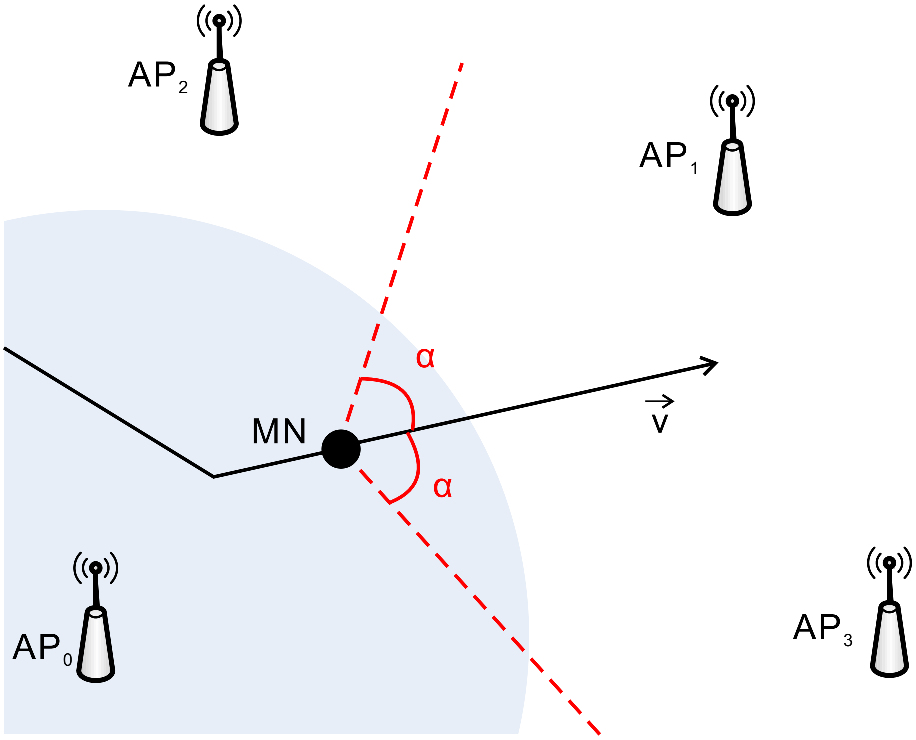


Figure 2.3: A scenario of the location-based scheme

in a candidate list as a potential AP for handoff. For example, AP_1 and AP_3, in Figure 2.3, are within the range and are thus added to the list. Whenever a handoff occurs, only the channels of APs on the list will be scanned. After deriving possible future APs, the MN initiates IEEE 802.1X pre-authentication to reduce the delay of authentication.

In another scheme [38], information on the surrounding APs is retrieved by an additional antenna. The next most favorable AP for an MN is decided upon by a continuous calculation of the distance between the MN and its surrounding APs. The MN favors the AP with the maximum rate of change in that distance. The additional antenna also enables the MN to achieve seamless handoff. The drawback of this solution is that adding extra equipment is not quite economical.

2.2.3 Cooperative Scanning

Another solution to accelerate the scanning process is to make use of other devices in the network in a cooperative way. Both MNs and APs can be used as cooperative devices for this purpose. An AP can gather the information of other APs, while an MN can provide other MNs with its knowledge of surrounding APs.

A fast handoff scheme by avoiding probe wait (FHAP) [7] is a fast handoff scheme that takes advantage of inter-AP communications. After an MN sends a probe request message, it then switches to the next channel immediately without waiting for response messages. The AP that has received the probe request sends a response to the previous AP using IAPP (Inter-Access Point Protocol) [21] or a protocol of a vendor, rather than sending it to the MN via the wireless channel. The previous AP is the AP that the MN is associated with before this handoff. The MN is then connected with the previous AP again and gathers the probe responses through it. The waiting time of $MinChannelTime$ or $MaxChannelTime$, as discussed above, is therefore avoided.

In a protocol developed by Z. Zhang *et al.* [49, 69], each MN will broadcast an advertisement message in a certain range, after it successfully selects a new AP. In this way, the MNs within the range are able to have the knowledge of APs in this area. If the RSS of one of these AP meets some quality requirements, those MNs that need a handoff can associate with this AP. Otherwise, these MNs will scan those APs that these MNs are aware of. Since only channels used by those APs are scanned, the scanning delay is therefore reduced.

2.2.4 Pre-scan Strategy

Despite the schemes using assorted techniques to shorten the scanning phase, the scanning phase can be executed before a handoff is triggered. Such schemes are usually

Table 2.3: Summary of schemes with pre-scan strategy

Solution	**Strategy**	**Advantages**
SyncScan [54]	synchronized scanning	
AdaptiveScan [67]	different scanning frequency for different channels	reduced overheads
DeuceScan [6]	partial scanning and spatiotemporal graph	better AP selection for vehicular networks
QualityScan [66]	consideration of traffic load of APs	load balancing for vehicular networks
make-before-break [53]	an extra transceiver for scanning	elimination of delay in all phases of handoff
APFH [7]	FHAP [7] for pre-scan	increase in throughput on the wireless channel

able to remove the scanning delay completely, but they increase system complexity and introduce overheads. Some of these schemes are reviewed in this section and a summary is shown in Table 2.3.

SyncScan [54] is one such protocol that can sharply reduce handoff latency. APs are synchronized to send out beacons at fixed times so that an MN can switch to other channels at the same time to check the signal strength of a certain AP. Continuing this process, the MN will have complete knowledge of surrounding APs in advance and then will select the AP with the strongest signal, whenever a handoff is required. SyncScan does add some complexities, as time synchronization is required, which can be achieved by NTP (Network Time Protocol) [39]. The main issue, however, is that high throughput cannot be achieved, because the working channel of the MN periodically changes all the time and the delay of CS&T is introduced at every channel switch.

Overheads caused by the pre-scan scheme pose a challenge to the overall performance of the network, and several schemes are aimed at reducing the overheads. AdaptiveScan [67] scans all channels at the beginning. After that, the MN divides channels into three groups based on RSS. Channels with lower RSS are scanned less frequently. However, once the RSS of a channel from a lower RSS group exceeds the weak RSS of a channel in a higher RSS group, this channel will be moved to the higher RSS group and replace the channel with the weakest RSS. Once a handoff is needed, the MN will try to connect to the strongest channel with the highest RSS. If the handoff fails, the MN will continue to try to scan from strong channels to weak channels.

These two approaches are not particularly designed for vehicular networks. DeuceScan [6] implements a similar pre-scan scheme for vehicular environments. The vehicular nodes probes all channels first and then it constructs a spatiotemporal graph to record the RSS of each AP and only probes channels of neighbor APs in the following pre-scan operations. Variations of the RSS imply possible movement directions of the vehicle. During a handoff, this scheme tends to select the AP, the RSS of which is increasing, so as to avoid wrong decisions. QualityScan [66] does not select the next AP based only on RSS. AP controllers are set up in this scheme to collect current load information of APs and to predict future network traffic. In this way, it allows load balancing and enhancement of performance for vehicular networks.

In a make-before-break handoff scheme [53], the pre-scan scheme is also implemented, but this scheme equips each MN with two transceivers. A two-card dynamic algorithm is devised to switch the two transceivers. The pre-scanning is thus done by the extra transceiver, while the other transceiver maintains a normal connection with the AP. Not only scanning, but also reauthentication and reassociation can be performed before handoff. Thus, this scheme is able to realize a soft handoff.

In Adaptive Preemptive Fast Handoff (APFH) [7], the MN may also send probe requests prior to a handoff, and the FHAP is adopted as the scanning strategy to reduce overheads and to increase throughput on the wireless channel. The MN will not start pre-scan, unless the RSS of the currently serving AP drops below a defined threshold.

2.3 Handoff Decision Schemes

Handoff decision schemes are concerned with making decisions on the timing of a handoff and the selection of a new channel. The handoff in current cellular networks requires interaction between base stations (BSs) and mobile stations (MSs), and prioritization is often involved in handoff decision schemes [56]. As each BS has limited number of channels for users, the differentiated priority of handoff can improve user experience. For example, no one likes ongoing phone call to be interrupted [10]. For a person who is making a phone call, his or her cell phone has higher priority for a handoff than those phones that are in standby status.

In IEEE 802.11 networks, however, the handoff decision in the standard scheme is made by the MN alone, and each AP only operates on one channel. Prioritization is therefore too difficult to be implemented. Handoff decision schemes without prioritization for both cellular networks and IEEE 802.11 networks will be reviewed in this section.

Table 2.4: Summary of handoff timing decision algorithms

Solution	**Decision Criteria**	**Applied Condition**
WaveLAN [36]	relative SNR measurement with a fixed hysteresis	IEEE 802.11 networks
H. Zhu *et al.* [70]	relative RSS measurement with a GPS-based adaptive hysteresis	cellular networks
H. Velayos *et al.* [63]	three consecutively failed retransmissions	IEEE 802.11 networks
PAHO [18]	the prediction of timing with GPS location information	vertical handoffs

2.3.1 Handoff Timing Decision

If the handoff prioritization is not involved, the timing of a handoff is mainly based on RSS for most algorithms [52, 68]. These algorithms can be generally divided into two categories: absolute RSS based algorithms and relative RSS based algorithms. Some of these algorithms are summarized in Table 2.4.

Absolute RSS based schemes are the simplest ones, which use one threshold for the RSS of the currently serving AP. In IEEE 802.11 networks, if the RSS of an AP drops below a certain threshold and stable communications cannot be sustained, a handoff process will be initiated. Relative RSS based schemes are usually unsuitable for IEEE 802.11 networks, unless an MN is equipped with two transceivers like schemes described in [15, 53], or the pre-scan strategy is used for the network. It is because the MN cannot keep monitoring the RSS of other adjacent APs, while it maintains communications with its currently serving AP in a traditional way.

However, relative RSS based schemes are easy to implement in cellular networks. A simple way is to initiate a handoff, when the RSS of the serving BS falls below a threshold value and it becomes smaller than the RSS of another BS. This method is simple, but it will cause repeated handoffs between two BSs, though it is better than absolute RSS based ones. The problem of repeated handoffs is called the ping-pong effect, which is caused by the temporary fading of the signals from both the stations [52].

To prevent the ping-pong effect, hysteresis is added to the comparison of the RSS to avoid unnecessary handoffs when the current connection quality is still satisfactory [52]. For this purpose, a fixed hysteresis is used by Lucent WaveLAN [36]. The signal-to-noise ratio (SNR) changes instead of the RSS changes between two APs are measured. Only if the difference in the SNR existing between the serving BS and a new BS is larger than a predetermined threshold, will a handoff be triggered.

The hysteresis can also be an adaptive value, many adaptive handoff algorithms were proposed so as to improve handoff performance [31, 64, 65]. An adaptive handoff algorithm for cellular networks was proposed by H. Zhu *et al.* [70]. Apart from accelerating the scanning process, a GPS device is utilized for the determination of the hysteresis in this work. The distance between a mobile station and a serving BS is calculated to determine a dynamic hysteresis value. The hysteresis value is used to judge whether the signal strength of a new BS, compared with the currently serving BS, is strong enough to trigger a handoff. Simulation results show that the algorithm intelligently reduces the probability of unnecessary handoffs.

RSS is not the only metric for handoff decisions. In [63], a handoff is incurred, whenever the retransmission of a package fails three times consecutively. Other reasons for dropped packets, such as collisions and fading, are ruled out in this way, and the ping-pong effect is thus alleviated. We also adopt this criteria in the proposed scheme.

The GPS is utilized for handoff decision in the position aware vertical handoff decision algorithm (PAHO) [18]. This algorithm is able to predict when an MN is about to move out of the coverage area of the serving BS, based on the velocity and the position information of the MN. The MN can consequently decide on the best timing to initiate a handoff between heterogeneous networks, and it will choose the nearest BS when it is time to execute a handoff.

2.3.2 Channel Selection

In current cellular networks, an MS measure the RSS of the surrounding BSs and report to those BSs. The network then makes the channel selection decision based on the RSS information received from the MS. Besides, the network may also take into account the actual channel availability and the network load information [56], while making handoff decisions.

By contrast, an MN in the 802.11 networks makes the handoff decision without the participation of APs. As each AP dose not have multiple channels and several adjacent APs may work on a same channel, channel availability is not an important problem. The selection of a new channel is actually about selecting a new AP for this kind of networks. Most schemes select a new AP solely based on the RSS of APs, but other metrics are also used. QualityScan [66], for instance, considers load balancing for vehicular networks. Some location-based schemes [18, 38] utilize the location information of the MN and its surrounding APs to select a suitable AP for a handoff. In SyncScan [54], SNR is measured to determine a handoff; moreover, the changes in signal quality, rather than a single sample during a handoff, are constantly monitored with this scheme. With more samples, the measurement becomes more accurate. These features thus enable better handoff decisions with SyncScan.

2.4 Summary

In this chapter, the standard IEEE 802.11 handoff scheme is first introduced. Unlike cellular networks, the scanning phase of the IEEE 802.11 handoff is the major obstacle for the smooth roaming of MNs. Recent improvements to the scanning strategy in literature are discussed. Tuning some scanning parameters helps to decrease scanning delay in some schemes. Other schemes utilize previous scanning results or location information of APs and the MN, such that the number of channels required to be scanned is reduced and so is the scanning delay. Those pre-scan schemes are capable of eliminating nearly all of the probe delay, but the major drawback is the overheads caused by the pre-scan process. Only DeuceScan [6] and QualityScan [66], among above methods, are originally designed for vehicular networks, but other methods may possibly be applied to vehicular networks without a significant decrease in their performance.

The Handoff decision on the timing of a handoff and the selection of a new channel is also discussed. Fewer schemes focus on this problem in IEEE 802.11 networks than in cellular networks, as the handoff process in IEEE 802.11 networks is more simple. From these schemes, it is found that the GPS and the pre-scan strategy contribute to making better handoff decisions.

Chapter 3

Location-Based Handoff Scheme

In this chapter, the proposed handoff process is described. The proposed scheme includes the following two schemes for predicting several potential APs for handoffs: they are a turn detection scheme and an AP selection scheme. Our scheme also has a prioritized scanning scheme for replacing the standard scanning scheme and a blacklist scheme for avoiding undesirable APs discovered in previous handoffs.

3.1 Prediction of APs

The turn detection scheme and AP selection scheme for AP prediction are location-based, using GPS to provide location information. The turn detection scheme is a necessary part, because it assists the AP selection scheme in the acquisition of the correct movement information of the vehicle. The detailed algorithms of the two schemes are described in this section. To ensure that these two schemes function properly, some prerequisites must be satisfied during the deployment of APs, which will be presented first in this section.

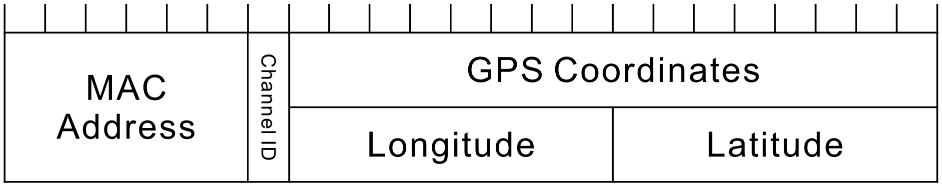


Figure 3.1: Required information of an AP

3.1.1 Prerequisites

During the deployment of APs, a database storing the GPS data of all APs must be built. This is feasible because the location information of all APs is necessary for maintenance, and GPS data serve as a possible reference for location information. All adjacent APs of every AP can be either automatically or manually determined. For example, an adjacent AP can be determined by the distance between two APs: if the distance is shorter than twice the maximum transmission range of all APs, then this AP is an adjacent AP. Every AP should be informed of required data concerning its adjacent APs, including a MAC address, an operating channel ID, and GPS coordinates.

Every AP is assumed to be placed at the intersection of two roads so that vehicles on both roads can achieve good communication without having radio signals pass through buildings. Preferably, there is an AP at each intersection, but it is not economical, because one AP usually covers more than one block. The length of each block is around $100m$ on average, while the outdoor transmission ranges of IEEE 802.11a standard and IEEE 802.11p standard are both above $100m$.

Whenever a vehicle establishes a connection with a new AP, it receives a message containing the information of all adjacent APs. For each AP, we use 6 bytes to store the MAC address and 1 byte for the Channel ID. Only longitude and latitude data are used, and they are both formatted as double precision float point numbers, which

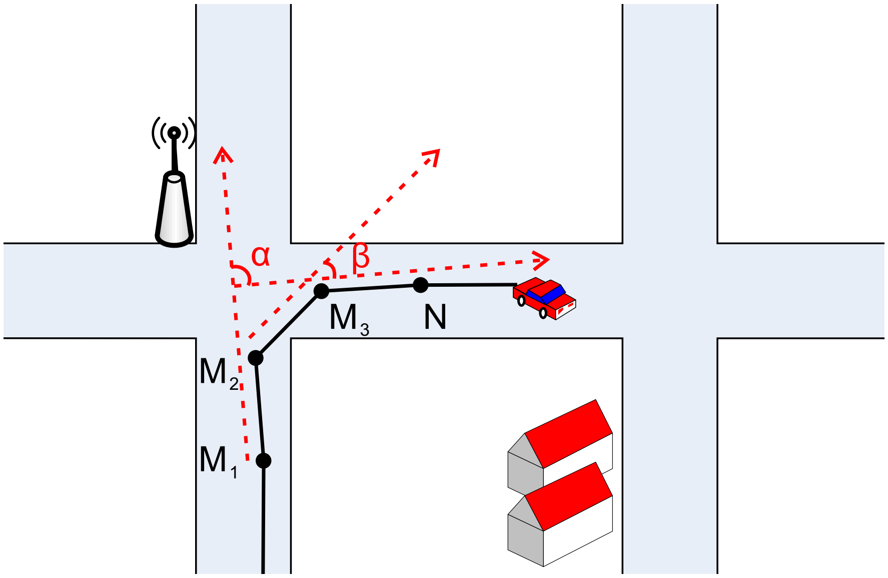


Figure 3.2: A scenario of the turn detection scheme

take 8 bytes each. The information of each AP is illustrated in Figure 3.1. Therefore, one adjacent AP takes 23 bytes in total to store the required information. Though the maximum size of one MAC Service Data Unit in IEEE 802.11 vary according to different systems, one MAC frame should be sufficient to contain the information of all adjacent APs.

3.1.2 Turn Detection Scheme

This turn detection scheme is an indispensable part of our scheme. The next scheme, AP selection scheme, requires two locations of a vehicle to determine its movement direction: a beginning location with coordinate vector $\mathbf{s}$ and an end location. If both locations belong to the same road, the vehicle movement direction calculated by these locations will correctly indicate the current direction of the vehicle and probably also indicate the orientation of this road, assuming that the road is straight. With the direction known, the APs ahead on this road can be selected by the next scheme.

Table 3.1: Notations used in the turn detection scheme

Notation	**Description**
$\mathbf{s}$	the vector of the beginning vehicle location
$\mathbf{n}$	the vector of the current vehicle location
$\mathbf{M}$	the queue storing vectors of the three latest vehicle locations
$\mathbf{m}_1$, $\mathbf{m}_2$, $\mathbf{m}_3$	elements in $\mathbf{M}$
α	the angle of previous moving direction change
β	the angle of latest moving direction change
Th_d	the minimum distance between the current and the previous location
Th_{cos}	the maximum value of $\cos\alpha$ and $\cos\beta$ for a detected turn

However, if the vehicle turns at an intersection, these locations will belong to different roads and thus the acquired direction will be neither that of the vehicle direction nor that of the road orientation. Consequently, the beginning location must be updated for the next scheme, whenever a vehicle turns.

The turn detection scheme is used to detect vehicle turns and to update the beginning location for the AP selection scheme. Once a turn is confirmed, the beginning location $\mathbf{s}$ is required to be changed to the current location $\mathbf{n}$. The detailed process of this scheme is presented in Algorithm 3.1 and notations used in the algorithm are shown in Table 3.1.

In this scheme, the current location $\mathbf{n}$ is updated every second. A queue $\mathbf{M}$ is created to store coordinate vectors of the three latest locations of the vehicle. It has a maximum size of three elements, which are labeled as $\mathbf{m}_1$, $\mathbf{m}_2$, and $\mathbf{m}_3$. $\mathbf{m}_1$, $\mathbf{m}_2$, and $\mathbf{m}_3$ are the respective first, second, and last elements in $\mathbf{M}$, if there are three elements

Algorithm 3.1 Turn detection scheme

```
if distance between n and $\mathbf{m}_3 > Th_d$ then
    if M contains $\mathbf{m}_1$, $\mathbf{m}_2$ and $\mathbf{m}_3$ then
        if $\cos\beta < Th_{cos}$ or $\cos\alpha < Th_{cos}$ then
            $\mathbf{s} \leftarrow \mathbf{n}$
            remove the first two elements in M
        end if
        push n to M
        remove the first element in M
    else if M contains $\mathbf{m}_2$ and $\mathbf{m}_3$ then
        if $\cos\beta < Th_{cos}$ then
            $\mathbf{s} \leftarrow \mathbf{n}$
        end if
        push n to M
    else if M contains $\mathbf{m}_3$ then
        push n to M
    end if
else if M is empty then
    push n to M
    $\mathbf{s} \leftarrow \mathbf{n}$
end if
```

in the queue. The new element is always appended as the last element in the queue. If this queue is full, whenever a new location is enqueued, the first element must be removed.

This queue is updated only if the distance between the current location and the previous one is larger than a threshold Th_d or if the queue **M** is empty. This is because GPS data are not accurate, and the measurement of the vehicle direction will be very inaccurate, if the distance between those two locations is too small.

As shown in Figure 3.2, α and β are two angles that indicate direction changes of the vehicle in the past several seconds. After the GPS device is initialized or a turn is detected, the number of elements in $\mathbf{M}$ is one or zero. In this situation, no angle is formed and thus no turn detection is executed. If the number equals two, only one angle β will be calculated and assessed. If the queue $\mathbf{M}$ is full, both angles will be evaluated.

For the measurement of changes in movement direction, cosine values of both α and β are calculated as follows:

$$\cos\alpha = \frac{(\mathbf{n} - \mathbf{m}_3) \cdot (\mathbf{m}_2 - \mathbf{m}_1)}{\|\mathbf{n} - \mathbf{m}_3\| \|\mathbf{m}_2 - \mathbf{m}_1\|} \tag{3.1}$$

$$\cos\beta = \frac{(\mathbf{n} - \mathbf{m}_3) \cdot (\mathbf{m}_3 - \mathbf{m}_2)}{\|\mathbf{n} - \mathbf{m}_3\| \|\mathbf{m}_3 - \mathbf{m}_2\|} \tag{3.2}$$

When $\cos\alpha$ or $\cos\beta$ is smaller than the threshold Th_{cos}, indicating that α or β exceeds a certain angle, the vehicle is deemed to be steered at a crossroad and the beginning location $\mathbf{s}$ must be changed. The selection of the value of Th_{cos} requires a trade-off: if the threshold is too low, some real turns may be omitted by this scheme; on the other hand, if it is too high, some nonexistent turns may have been wrongly detected.

When the number of elements in $\mathbf{M}$ is three, two cosine values are calculated so that more real turns can be correctly detected. If a turn is not a sharp one like the example shown in Figure 3.2, the aforementioned two-fold calculation algorithm is capable of successful detection: if the vehicle fails to detect a turn at location $\mathbf{m}_3$, because β is not large enough, it is more likely to detect the turn at the next location $\mathbf{n}$ due to a larger angle α.

However, this calculation using two cosine values may possibly cause the already detected turns to be detected again. To prevent this, whenever a new turn is detected

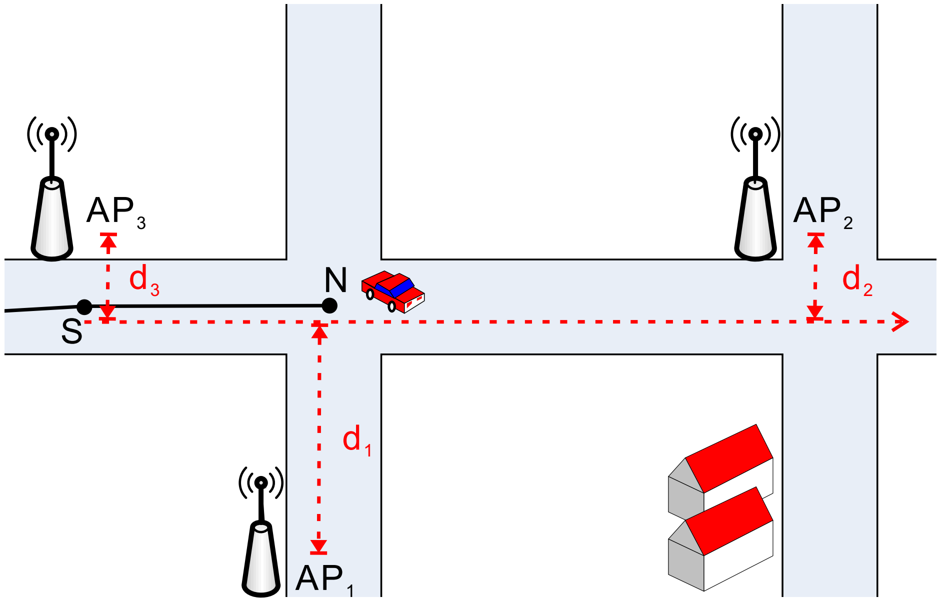


Figure 3.3: A scenario of the AP selection scheme

and there are three elements in the queue $\mathbf{M}$ in the meantime, $\mathbf{m}_1$ and $\mathbf{m}_2$ of $\mathbf{M}$ must be removed so that this scheme will be executed in the future under the following condition: $Num = 1$. A turn can be detected, only if $Num > 1$. Thus, a new turn is likely to be detected in the future, after at least two vehicle locations have been recorded since the last detected turn of the vehicle.

GPS devices are used for turn detection in this work, but electrical compasses may be also capable of detecting turns. Using an electrical compass introduces extra cost for this hardware, but most of the computation cost of the turn detection scheme is saved by the electrical compass. As for the accuracy of direction measurement, it is difficult to compare these two types of devices.

3.1.3 AP Selection Scheme

As stated before, the vehicle location is updated every second. Whenever retransmission of a package fails three times consecutively, the AP selection scheme is triggered.

Table 3.2: Notations used in the AP selection scheme

Notation	**Description**
$\mathbf{s}$	the vector of the beginning vehicle location
$\mathbf{n}$	the vector of the end (current) vehicle location
R	the maximum transmission range
N	the number of the adjacent APs to the vehicle
AP_i	one element in the adjacent AP list
d'_i	the distance between the vehicle and AP_i
d_i	the distance between the vehicle directional vector and AP_i
$\mathbf{a}_i$	the vector of the location of AP_i
pv_i	the priority value of AP_i
A	the slope in the adaptive threshold
B	the intercept in the adaptive threshold

In this way, the so-called ping-pong handoffs happen much less frequently [63]. The scenario is shown in Figure 3.3 and notations used in the algorithm are shown in Table 3.2.

Once this scheme is triggered, the current location $\mathbf{n}$ becomes the end location. With the beginning location $\mathbf{s}$, determined by the previous scheme, and the end location $\mathbf{n}$ of the vehicle, a vector is formed for the following steps. The scheme shown in Algorithm 3.2 is capable of distinguishing APs on the same road as the vehicle from those APs on different roads, with distances between APs and the vector.

Assume that there are N adjacent APs in the list provided by the currently serving

Algorithm 3.2 AP selection scheme

```
Require: adjacent AP list is not empty and $\mathbf{n} \neq \mathbf{s}$
for each AP$_i$ do
    $d'_i \leftarrow$ distance between the vehicle and AP$_i$
    if $d'_i < R$ then
        if $d_i <$ the adaptive threshold then
            if the vehicle becomes closer to AP$_i$ then
                $pv_i \leftarrow d'_i$
                add it to the list of AP candidates
            else
                $pv_i \leftarrow d'_i + R$
                add it to the list of AP candidates
            end if
        else if the vehicle becomes closer to AP$_i$ then
            $pv_i \leftarrow d_i + 2R$
            add it to the list of AP candidates
        end if
    end if
end for
sort the list of AP candidates based on their priority values
```

AP, and that the coordinate vector of AP$_i$ is $\mathbf{a}_i$. Among all APs, only the AP within the maximum transmission range R of the vehicle is likely to be selected for further calculation. The distance from the selected AP$_i$ to the vector specified by $\mathbf{s}$ and $\mathbf{n}$ is:

$$d_i = \frac{|\det(\mathbf{n} - \mathbf{s}\ \mathbf{n} - \mathbf{a}_i)|}{\|\mathbf{n} - \mathbf{s}\|} \tag{3.3}$$

where det( ) denotes a determinant.

If d_i is smaller than a certain threshold, then AP$_i$ is deemed to be on the same road. For this approach, an adaptive threshold is adopted, which is presumed to be in linear relationship to the distance between the vehicle and AP$_i$. This distance is denoted as d'_i, which equals to $\|\mathbf{n} - \mathbf{a}_i\|$. The adaptive threshold for AP$_i$ is:

$$\text{Adaptive threshold} = A \cdot d'_i + B \tag{3.4}$$

In the linear relationship, the slope and the intercept are denoted as A and B respectively, and their values will be determined by an optimization algorithm through experiments. The rationale is that inaccuracy of vehicle advancement direction, caused by inaccuracy of the GPS data, results in a higher deviation in d_i of distant APs than in d_i of close ones. Therefore, close APs are judged by a lower threshold so as to exclude more APs on other roads, while distant APs are evaluated by a higher threshold so as to include more APs on the same road. For example, AP$_2$ and AP$_3$ are better choices than AP$_1$ in Figure 3.3.

Among APs on the same road as the vehicle, our approach favors the AP that the vehicle is moving toward. It is determined by the changes in the distance between the vehicle and the AP: a decrease in this distance suggests that the vehicle is becoming closer to AP$_i$. In this situation, the priority value pv_i of such an AP is set to d'_i. For an AP that the vehicle is moving away from, pv_i is set to the sum of d'_i and R. For example, pv_2 of AP$_2$ is lower than pv_3 of AP$_3$ in Figure 3.3. Among those APs that are on the same road, this approach also favors the AP that is closer to the vehicle, as its priority value is either d'_i or $d'_i + R$. It is because the threshold defined above is more strict for closer APs, and therefore, they are more likely to be on this road.

As for APs not on this road, only those APs, for which the distance to the vehicle is decreasing, are added to the list of AP candidates, and their priority values depend on d_i values. In this way, those APs that are close to the vehicle will be scanned first, as they usually can provide better RSS.

At last, this list of AP candidates is sorted based on their priority values. The

Table 3.3: Optimal parameters for the adaptive threshold

Maximum Transmission Range	A	B
$250m$	0.333	14.1
$500m$	0.141	20.4
$750m$	0.079	25.2

lower the priority value is, the higher the possibility of this AP being a good candidate for a handoff is. Therefore, those APs of lower priority values are put first in the list so that they will be probed first in the next step: prioritized scanning.

3.1.4 Determination of the Parameters

Genetic algorithm, a well-known and widely-used global optimization algorithm, was implemented to search for optimal values of the parameters for the adaptive threshold, A and B, so that a minimum prediction error rate of the scheme can be achieved. Three scenarios were devised for simulations, where the maximum transmission range R of each scenario is $250m$, $500m$ and $750m$. The optimal values of A and B in three situations are shown in Table 3.3.

In every scenario, there are five APs within the transmission range of the vehicle. Among those APs, two APs are on the same road as the vehicle, and the other three APs, as interference APs, are on other roads. Projected to the road where the vehicle travels, the location of these APs are randomly distributed along this road, but the distances from this road to the interference APs are both $100m$. For settings of genetic algorithm, the population of chromosomes is 20 and the number of generations is 80. Constraints for the variables are that $A \times R + B$ is smaller than $100m$, *i.e.*,the presumed minimum length of every block.

The accuracy of GPS is influenced by the surrounding environments of a vehicle and the quality of the equipped GPS receiver, so it has different accuracy levels. For different accuracy levels, values of A and B also differ. The values of A and B in the table are a result of a trade-off between different values resulting from different GPS accuracy levels. The length of each block is presumed to be $100m$ for the experiments. In reality, the AP selection scheme can be more accurate for larger blocks, and it can be less accurate for smaller blocks.

3.2 Prioritized Scanning Scheme

Once the list of AP candidates is generated, the vehicle can proceed to start the next step: prioritized scanning. The detailed algorithm is shown in Algorithm 3.3, which contains two parallel procedures. Procedure 1 is a probe-and-wait procedure, which is similar to the full-scan method described in the previous section. We also use those two parameters, $MinChannelTime$ and $MaxChannelTime$, for waiting timers. The $MinChannelTime$ timer is started immediately after the vehicle switches its radio channel and sends a probe request. If the receiver is not idle during $MinChannelTime$, the vehicle will continue receiving such messages until the $MaxChannelTime$ timer expires.

Unlike scanning from Channel 1 to Channel 11 in the full-scan scheme, a vehicular node in our scheme first switches its working channel to the same channel as the AP of the lowest priority value, and it sends a probe request to that AP. Then, it scans other APs with higher priority values (a lower higher priority value indicates higher priority for our scheme). The probe request is sent directly to the MAC address of the AP, rather than broadcasted on the channel of the AP, because the vehicle is aware of its MAC address. On the other hand, other APs working on the same channel as the selected AP are prevented from receiving probe request messages.

Algorithm 3.3 Prioritized scanning scheme

```
Require: the list of AP candidates is not empty
Procedure 1:
for AP of lowest $pv_i$ to AP of highest $pv_i$ do
    send a probe request to AP$_i$
    start probe timer and keep monitoring the channel
    while True do
        if the receiver is idle until $MinChannelTime$ expires then
            break
        end if
        if $MaxChannelTime$ expires then
            break
        end if
    end while
end for
Procedure 2:
if receive a probe response from AP$_i$ then
    stop scanning and start authentication
    break
end if
```

After sending a probe request to an AP, the transceiver of the vehicle keeps checking whether a probe response message from that AP has been received in Procedure 2. If such a message has been received, meaning that the prediction of the AP selection scheme is probably correct, the prioritized scanning will be ended, and reauthentication and reassociation will begin. If the prediction is good enough, a valid probe response message may be received at the first time of probing. As a result, the scanning delay is significantly decreased because only 1 channel is scanned, instead of 11 channels in the full-scan scheme.

If the list of AP candidates is empty, however, this scheme cannot be performed. Such an incident usually occurs when the vehicle is just started and has not established any connection with any AP. In this situation, the traditional full-scan scheme is implemented for scanning.

3.3 Blacklist Scheme

The prediction does not always produce correct results, especially when the accuracy of the GPS is undesirable. A blacklist scheme is needed to exclude some APs that may be mistakenly selected as high priority for scanning. It is an optional scheme; our location-based handoff scheme can work without it.

This scheme contains two parts: adding a blacklisted AP and checking the blacklists. If the blacklist scheme is enabled, the prioritized scanning is performed with a list of AP candidates after removal of several blacklisted APs. Additionally, the scanning procedure might contain a step to update blacklists. The procedure of the altered scanning scheme is presented in Figure 3.4.

3.3.1 Adding a Blacklisted AP

The AP need to be scanned is denoted as AP_i, and the AP that the vehicle is previously connected to before a handoff is denoted as AP_j. During prioritized scanning, if a vehicle does not receive a probe response from an AP_i, AP_i will be then appended to the blacklist belonging to an AP_j. In the meantime, the current location of the vehicle will be also recorded, and it is denoted as $\mathbf{l}_{ij}$. This is because blacklists are effective only if the vehicle is located within a range around that location. For example, when the vehicle is travelling on Road A one day, if it receives no probe response from an AP during a handoff, this AP is consequently blacklisted. At a later time, if

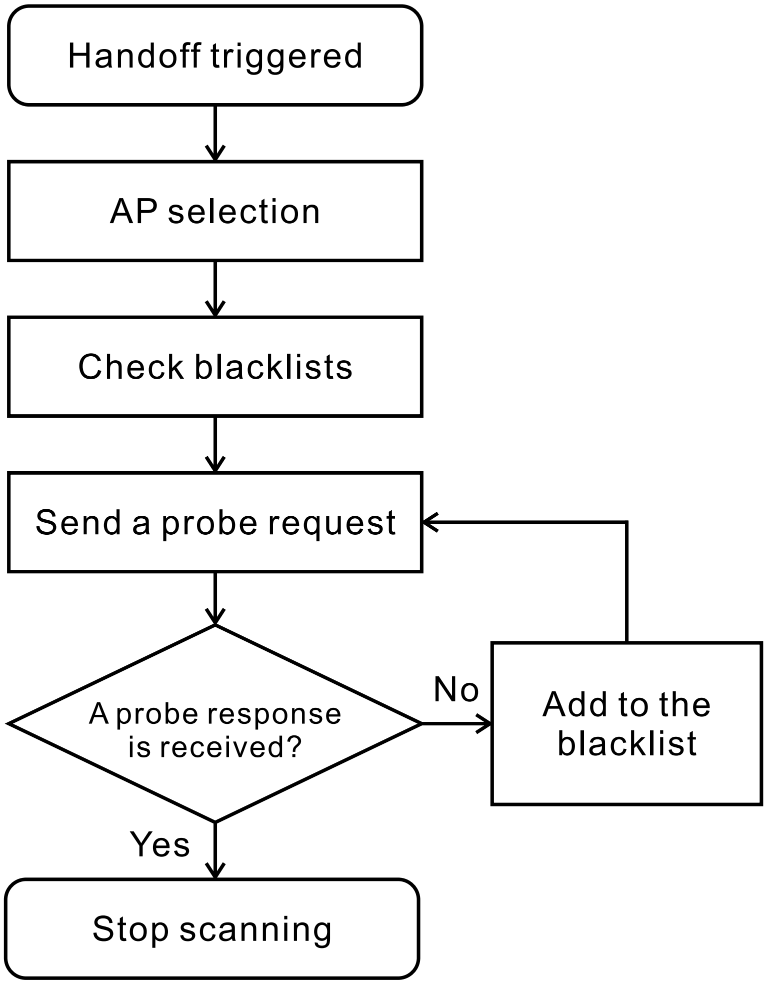


Figure 3.4: Procedure of the scanning scheme with blacklists

the vehicle moves to Road B, on which the previously blacklisted AP is coincidentally located, this AP can be a good one for a possible handoff. With this approach, this AP will not be regarded as a blacklisted AP for this time.

Each blacklisted AP has one entry on the blacklists. Each entry has a limited lifetime in order to remove redundant entries and to reduce the size of the whole blacklist. A lifetime counter for each blacklisted AP is used for this purpose. The counter of a newly added blacklisted AP is set to an initial value. If a blacklisted AP has not been used for a long time, it will be deleted.

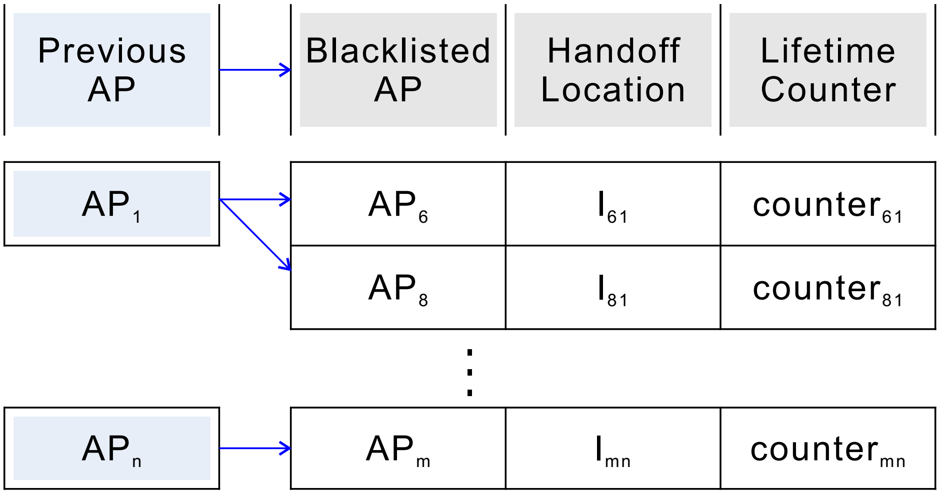


Figure 3.5: An example of the blacklists

An example of the data structure of the blacklists is shown in Figure 3.5. The blacklist of AP_1 has two entries and the blacklist of AP_n has one entry. Each entry contains one blacklisted AP, whose MAC address is used as its identifier, the location of the vehicle at a previous handoff, and a lifetime counter for this entry.

3.3.2 Checking the Blacklists

Given that the list of AP candidates has been formed, each AP candidate will be checked to determine whether it has been blacklisted with the method shown in Algorithm 3.4. The data structure of the blacklists mentioned above is devised to accelerate the searching process of blacklisted APs. With this form of the blacklists, a small subset of all blacklisted APs, in which all the APs belong to the same AP_j as the previously connected AP, can be easily selected. Only blacklisted APs from this subset are evaluated. This subset is denoted as $\mathrm{blacklist}_j$. The event that a candidate AP_i of the vehicle exists in $\mathrm{blacklist}_j$ is called a “hit”. The MAC address of AP candidates is used to identify whether a certain AP exists.

For each “hit”, if the distance between the current location $\mathbf{n}$ and the previous

Algorithm 3.4 Checking blacklists

```
Require: the list of AP candidates is not empty
get blacklist$_j$ belonging to the previously connected AP$_j$
for each candidate AP$_i$ do
  if AP$_i$ exists in blacklist$_j$ then
    if $\|\mathbf{n} - \mathbf{l}_{ij}\| < Th_{blacklist}$ then
      remove AP$_i$ from the list of AP candidates
      $\mathbf{l}_{ij} \leftarrow (\mathbf{n} + \mathbf{l}_{ij})/2$
    else
      $counter_{ij} \leftarrow counter_{ij} - 1$
      if $counter_{ij} = 0$ then
        remove AP$_i$ from blacklist$_j$
      end if
    end if
  end if
end for
if the list of AP candidates is empty then
  restore the original list of AP candidates
  empty blacklist$_j$
end if
```

location $\mathbf{l}_{ij}$, stored in the blacklist entry, is smaller than a threshold $Th_{blacklist}$, it is a "good hit"; this AP will be removed from the list of AP candidates, and then the recorded location will be updated to the mean of $\mathbf{n}$ and $\mathbf{l}_{ij}$. Otherwise, it is a "bad hit" and this AP will be kept. For "good hits", it is possible that this AP was wrongly blacklisted. If all AP candidates are excluded from the list due to the operations above, the original list of AP candidates will be restored. Besides, the blacklist for this AP$_j$ will be emptied, because it is impossible to distinguish which blacklisted AP has been wrongly added.

For a “good hit”, the lifetime counter remains unchanged. For a “bad hit”, however, the counter is subtracted by one. Once the lifetime counter of a blacklisted AP becomes zero, this entry will be removed.

3.4 Summary

This chapter has introduced the proposed location-based handoff scheme. This scheme requires all APs to know their geographic locations so that the AP selection scheme is able to generate a list of AP candidates for a handoff based on movement information of the vehicle and location information of the APs. The turn detection scheme assists the AP selection scheme in the acquisition of the correct movement direction of the vehicle. With the list of AP candidates, APs on the list are probed in ascending order of their priority values with the prioritized scanning scheme. In the end of this chapter, the blacklist scheme is described, which may exclude, if necessary, undesirable APs discovered during previous handoffs from the list of AP candidates.

The proposed handoff scheme is supposed to reduce the handoff latency, and thus to support some real-time applications. The simulation results, which demonstrate the performance of the scheme, are presented in the next chapter.

Chapter 4

Simulation Results

Due to the inaccuracy of GPS, the prediction of APs could be erroneous. Prediction accuracy of the turn detection scheme and the AP selection scheme is illustrated in the first section, as it has an influence on scanning delay. Next, the proposed scheme is compared with other schemes in regards to prediction accuracy and scanning delay. Simulation results on throughput, jitter and the number of handoffs are also presented and discussed in this chapter.

4.1 Prediction Accuracy

4.1.1 Accuracy of GPS

Prediction accuracy of the proposed scheme is examined in this section. The prediction errors are mainly a result of the GPS inaccuracy, but the performance levels of the GPS Standard Positioning Service (SPS) have been gradually increasing over the past two decades. The distance between a GPS satellite and a receiver allows for an accuracy of 7.8 meters at a 95% confidence level even in the worst cases [61]. Actual accuracy for users depends on weather conditions and GPS receiver qualities. As for some high-quality GPS SPS receivers, real-world data collected by the Federal Aviation Administration show that the horizontal error is below $2.2m$ at a 95% confidence level [16].

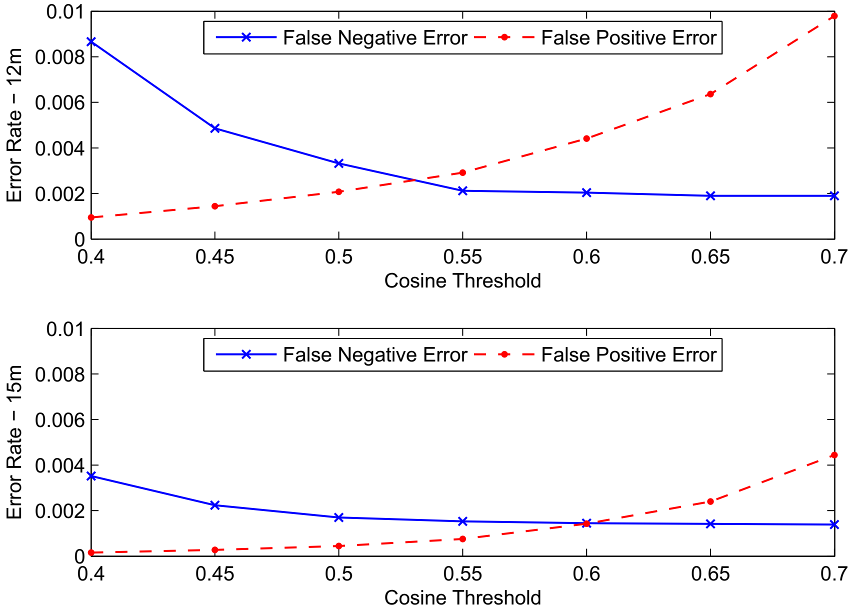
In our experiments, we assume the horizontal error is Rayleigh distributed and conduct experiments on two GPS accuracy levels. The error is below $5m$ at a 95% confidence level for the first level, which means the standard deviation $\sigma = 2.04$. And, the error is below $10m$ for the second level, which means $\sigma = 4.08$. Accordingly, longitude error and latitude error are both assumed to be normally distributed with the same value of σ.

4.1.2 Accuracy of Turn Detection Scheme

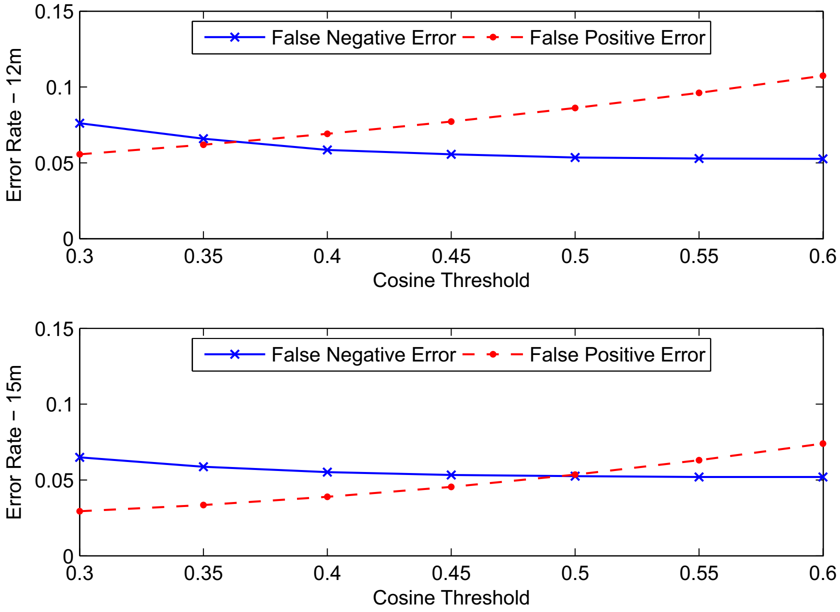
Error rate of the turn detection scheme includes two parts: the false positive error that indicates the probability of falsely detected turns when a vehicle travels in straight lines, and the false negative error that indicates the probability of undetected turns when a vehicle actually turns at road intersections.

For the false negative error rate shown in Figure 4.1, the turn detection scheme is simulated in a situation where all the angles of vehicle turns are 90°. The experiments are conducted under two different GPS accuracy levels: $\sigma = 2.04$ and $\sigma = 4.08$. In Figure 4.1(a), Th_d is $12m$ for the upper figure, and it is $15m$ for the lower figure. It is the same with Figure 4.1(b).

The angles of road intersections are not all right angles. Figure 4.2 illustrates the false negative error rate of 60° turns and 120° turns, on the condition that $\sigma = 2.04$. Compared with right angled turns, the false negative error rate of 60° turns is higher than that of right angled turns, while the false negative error rate of 120° turns is lower. The false positive error rate is the same under the same GPS accuracy, because this error rate is experimented upon in a scenario where the vehicle moves

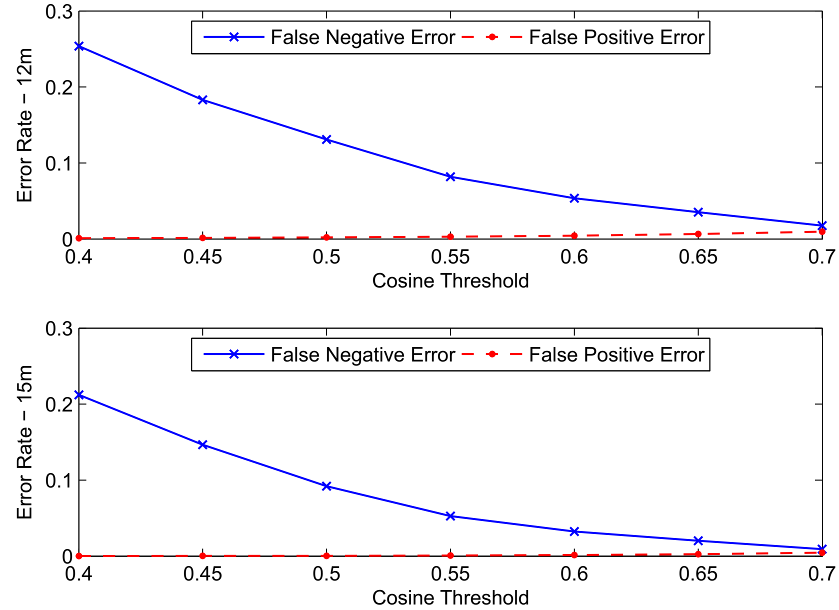


(a) $\sigma = 2.04$

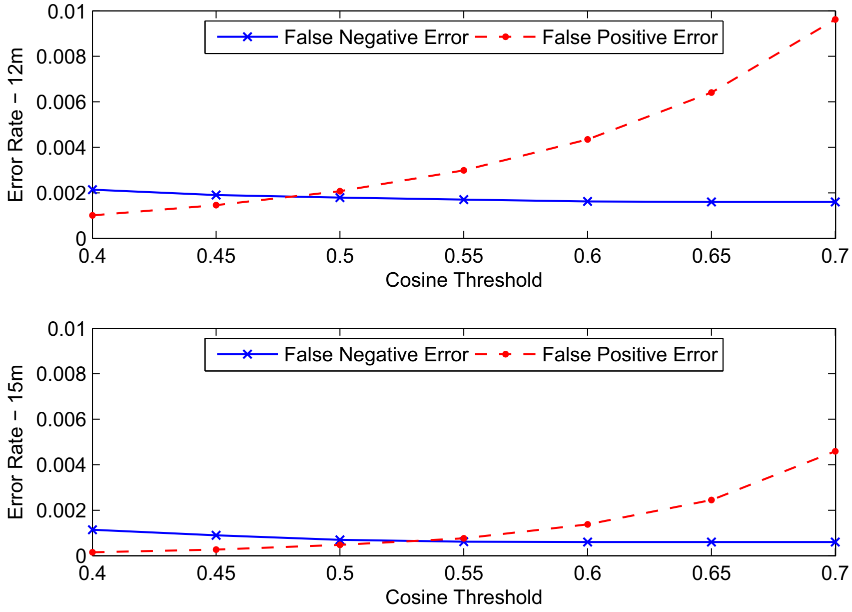


(b) $\sigma = 4.08$

Figure 4.1: Detection error rate of right angled turns



(a) $\sigma = 2.04$, $angle = 60°$



(b) $\sigma = 2.04$, $angle = 120°$

Figure 4.2: Detection error rate of non-right angled turns

on a straight road.

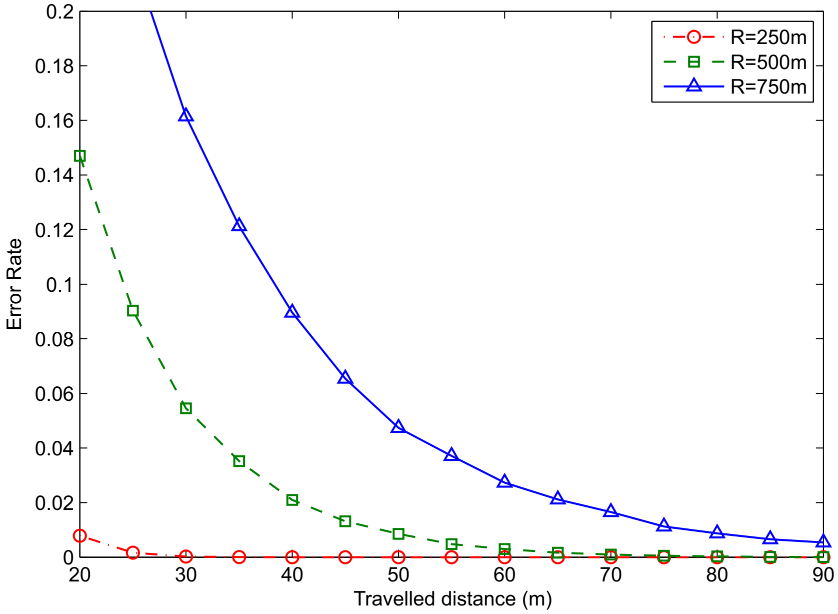
In Figure 4.1 and Figure 4.2, it is obvious that the error rate becomes lower under better GPS accuracy. When Th_d increases from $12m$ to $15m$, both kinds of error rate both decrease. If Th_d is too high, however, the vehicle cannot detect the turns immediately, which may harm the accuracy of the AP selection scheme. As the cosine threshold Th_{cos} grows, or in other words, as the corresponding angle for the threshold lessens, the false positive error increases and the false negative error decreases. As a trade-off, the intersection of the two error rate lines may suggest a preferred value for Th_{cos}.

4.1.3 Accuracy of AP Selection Scheme

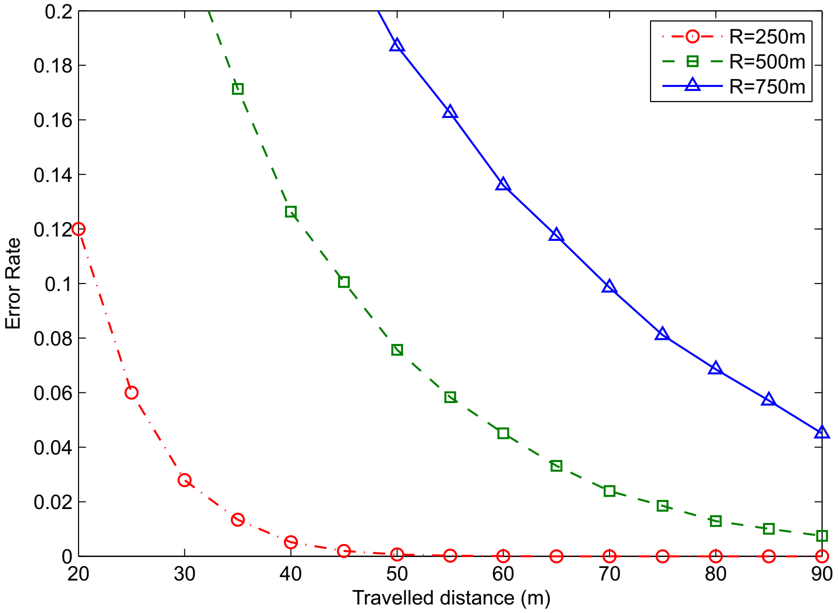
As for the AP selection scheme, three scenarios were used for simulations, where the maximum transmission range R is $250m$, $500m$ and $750m$, respectively. In each scenario, there are six APs within the transmission range of the AP connected to the vehicle before a handoff. Among those APs, two APs are on the same road as the vehicle, and the other APs, operating as interference APs, are on other roads.

The relationship between the error rate and the travelled distance of the vehicle, in the two GPS accuracy levels, is illustrated in Figure 4.3. The error rate in this figure is the probability that the first AP on the list of AP candidates is not the true first AP. In other words, the first AP will not be placed as the first one on the list, if the GPS is absolutely accurate. The travelled distance is the distance between those two locations $\mathbf{s}$ and $\mathbf{n}$, namely, the distance that the vehicle has moved since its last turn. Both Figure 4.3(a) and Figure 4.3(b) reveal that better GPS accuracy results in better prediction accuracy.

Figure 4.4 demonstrates the probability that not only the first AP on the list of AP candidates but also the second one is not the true first AP. Even though under



(a) $\sigma = 2.04$



(b) $\sigma = 4.08$

Figure 4.3: Error rate of the first AP selection

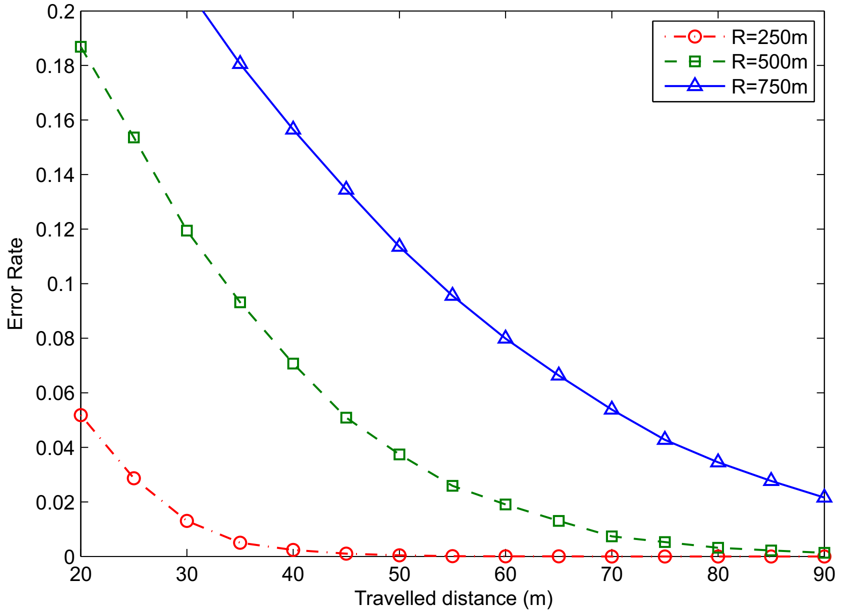


Figure 4.4: Error rate of the second AP selection

worse GPS accuracy, the error rate in Figure 4.4 is similar to that in Figure 4.3(a), and it is lower if compared with Figure 4.3(b), in which the GPS accuracy is the same as that in Figure 4.4. Therefore, if the first instance of scanning fails during prioritized scanning, it is very likely that an AP will respond to the probe request from the vehicle during the second round of scanning.

In Figure 4.3 and Figure 4.4, the error rate becomes relatively high when the transmission range expands, but vehicles usually can achieve a longer travelled distance in this situation. The higher error rate in this situation is thus compensated for, since a longer travelled distance can result in a lower error rate.

4.1.4 Comparison of Prediction Accuracy

Error rate of the proposed AP selection scheme is compared with a prediction method proposed by S. Mellimi *et al.* [38] in four different scenarios in Figure 4.5. Because

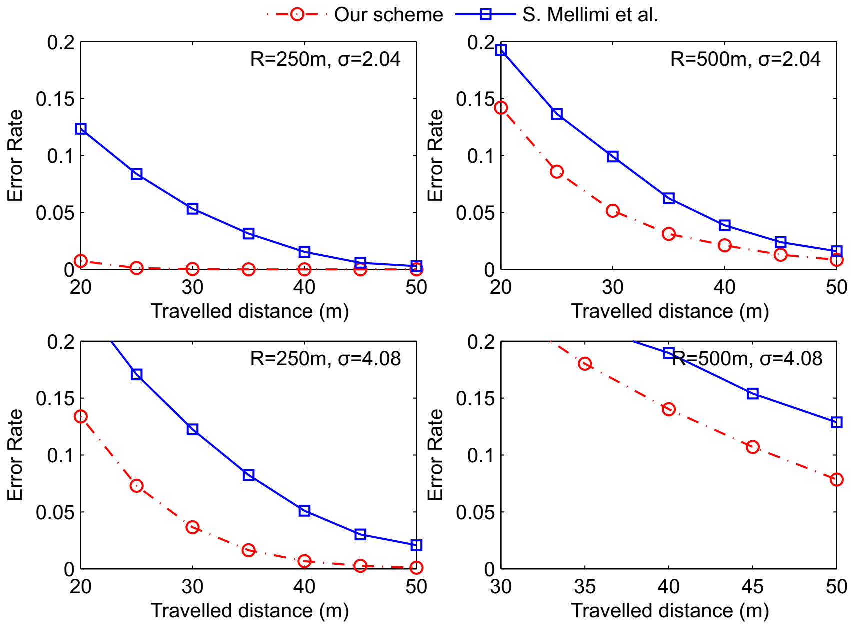


Figure 4.5: Comparison of the error rate of AP selection

that method does not include a turn detection strategy and thus uses the direction of velocity, which is updated in a relatively short time interval, it cannot achieve a travelled distance as long as the one in our scheme. The longest travelled distance experimented with is consequently set to $50m$. Our scheme shows better prediction accuracy in all these scenarios, and it can perform even better, if the travelled distance grows.

4.2 Handoff Latency

4.2.1 Scanning Delay of the Proposed Scheme

Scanning delay, as discussed before, is the major cause of handoff latency. In this section, the scanning delay of our scheme is evaluated with simulation results from the Network Simulator - ns2 (Release 2.35) [45]. Simulation parameters are shown in Table

Table 4.1: Parameters of the wireless network

Parameter	**Value**
Wireless Protocol	IEEE 802.11g
Transmission range	$250m$
MaxChannelTime	$11ms$
MinChannelTime	$6.5ms$
Transmission overhead	$0.1ms$
Channel switch delay	$5ms$
The number of channels	11
Bandwidth	11Mbps
Propagation model	2-Ray Ground Reflection

Table 4.2: Parameters of the simulation scenarios

Parameter	**Highway**	**Urban**
Vehicle speed	$80km/h$	$50km/h$
Scenario size	$2000m \times 20m$	$1000m \times 1000m$
Simulation time	$10 \times 300s$	$10 \times 300s$

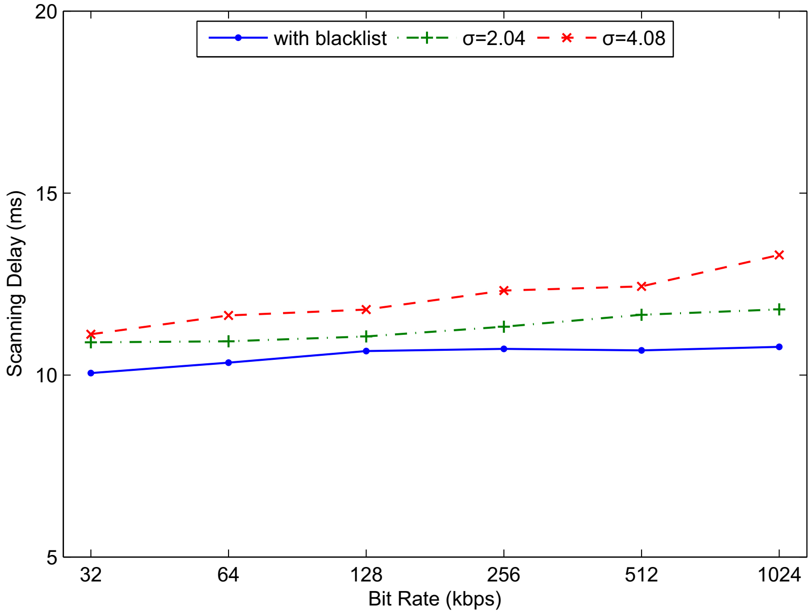
4.1. The bit rate of background traffic, generated from a constant bit rate generator (CBR) over UDP, ranged from 32kbps to 1024kbps. The simulation duration was $300s$ for each time. Because ns2 does not support multiple wireless channels, channel switch delay, around $5ms$ [43] was added to the timers for scanning, after the working channel of the vehicle was switched. An urban scenario and a highway scenario were developed to measure the scanning delay, and parameters of these two scenarios are shown in Table 4.2. The vehicles moved at different speeds along a straight road in the highway scenario. The road networks in the urban scenario were a grid-like network; the dimension of each block was set to $100m \times 200m$.

The scanning delay of the proposed scheme in various traffic loads and GPS accuracy levels is presented in Figure 4.6. For the two lines labeled as "$\sigma = 2.04$" and "$\sigma = 4.08$" in the figure, the blacklist scheme was not used for the simulations. For the line labeled as "with blacklist", the standard deviation σ of the GPS error is 4.08. The average scanning delay grows slightly with the increase of traffic loads in both scenarios. When GPS accuracy deteriorates, the scanning delay does not suffer from significant increase. This is because predictions are very accurate in both GPS accuracy levels on condition that transmission range remains $250m$. Using the blacklist scheme decreases the scanning delay slightly in the highway scenario, but it is observed that the blacklist scheme shows more prominent advantages in the urban scenario, where the network topology is more complex, making it more difficult to select a proper AP to scan first.

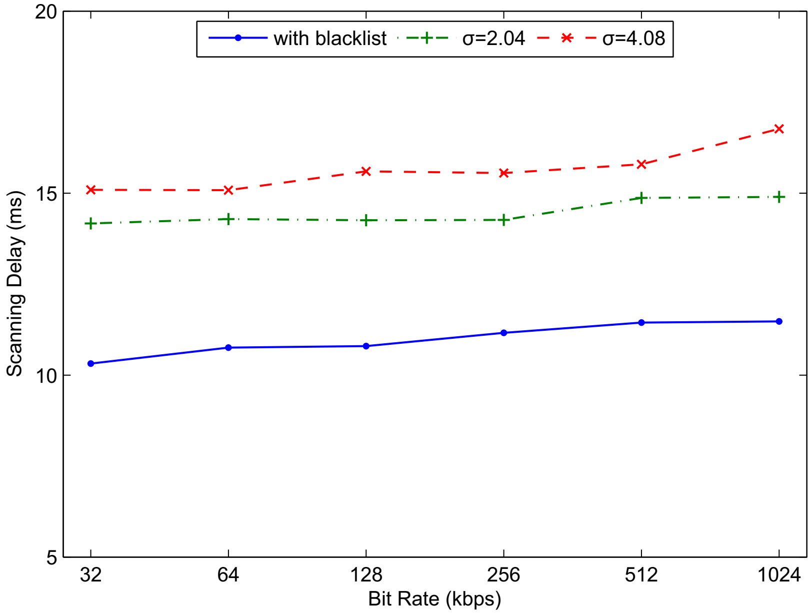
4.2.2 Comparison of Scanning Delay

As shown in Figure 4.7, both the average and the 95% confidence interval of the scanning delay of our scheme were compared with other schemes. Those schemes are the full-scan scheme, another location-based fast handoff (LBFH) scheme [62] and the neighbor graph (NG) scheme [57]. GPS error was below $5m$ in both highway and urban scenarios, and the blacklist feature was not enabled for our scheme. Other settings in the comparison remain the same as shown in Table 4.1 and Table 4.2.

Similar to Figure 4.6, the scanning delay of these four schemes is also higher in the more complex urban scenario. The full-scan scheme requires more time to complete

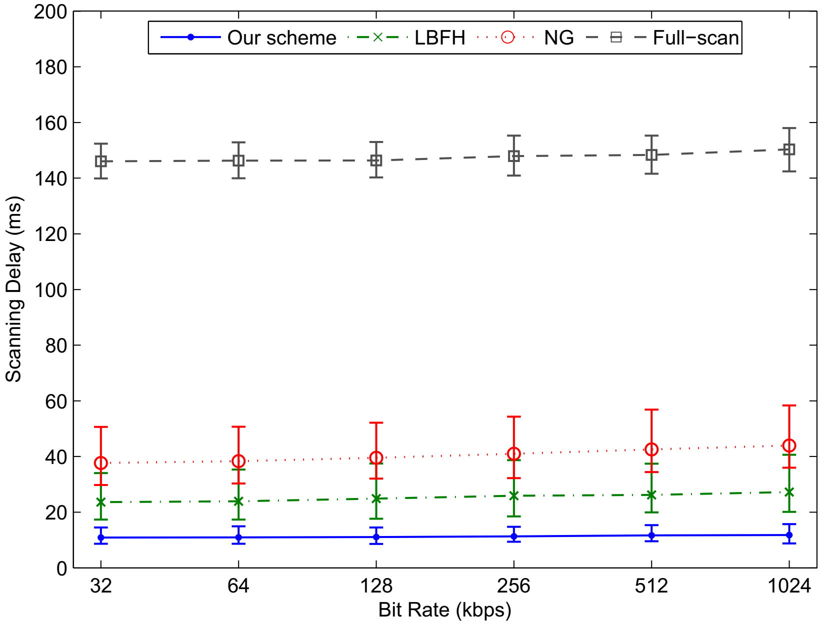


(a) Highway scenario

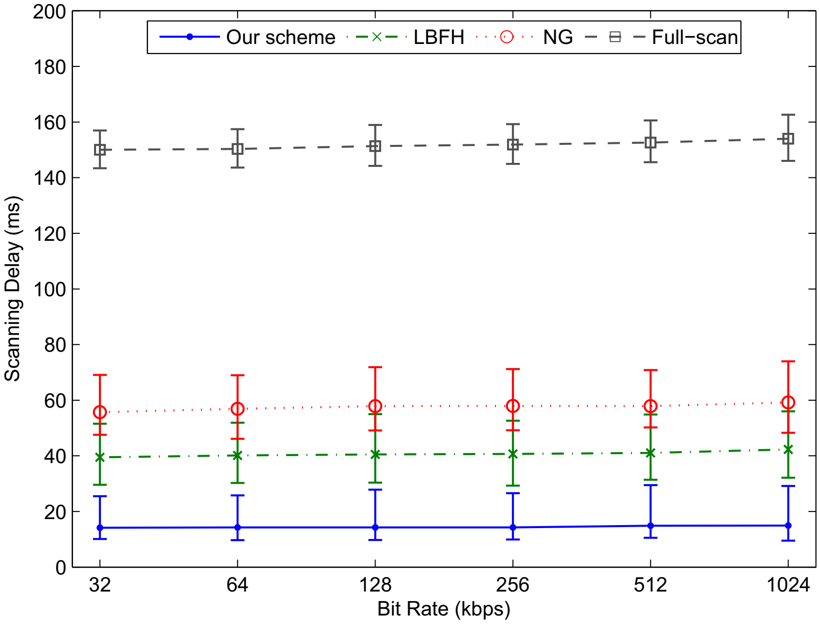


(b) Urban scenario

Figure 4.6: Scanning delay of the proposed scheme

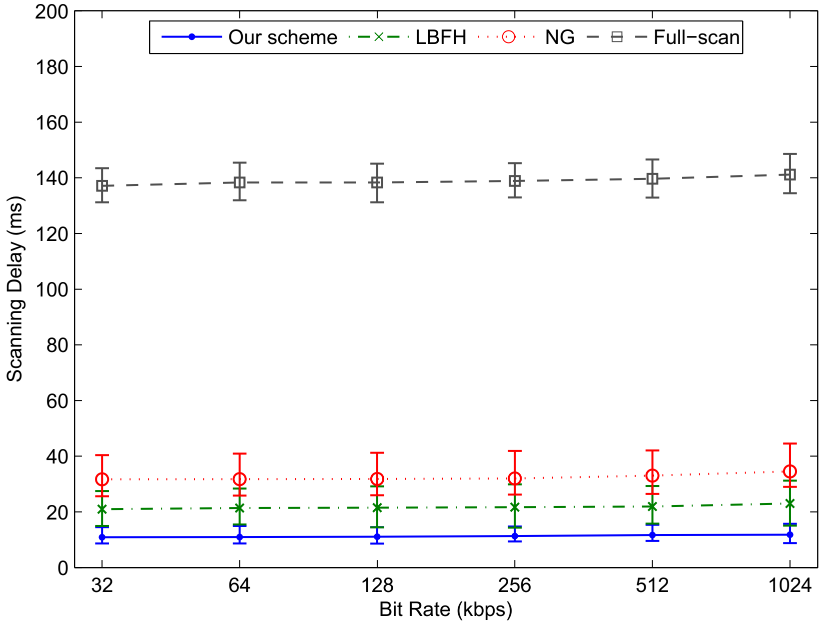


(a) Highway scenario

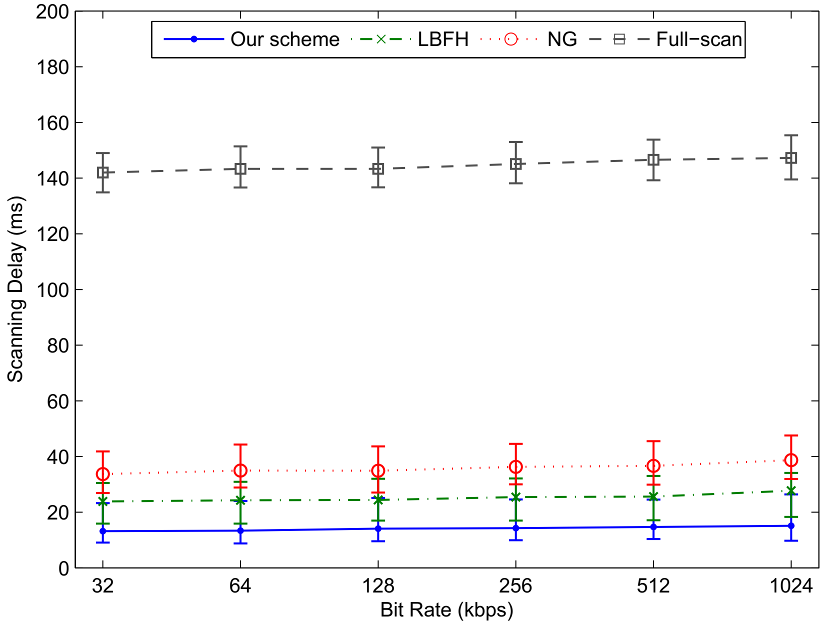


(b) Urban scenario

Figure 4.7: Comparison of scanning delay (11 channels)



(a) Highway scenario



(b) Urban scenario

Figure 4.8: Comparison of scanning delay (3 channels)

the scanning phase than others, as it scans all 11 channels. The confidence interval of the delay of the LBFH scheme and the NG scheme is relatively high, because the number of channels to be scanned might be different each time. The LBFH scheme achieves lower delay, because it only scans channels used by an AP in one direction, namely the movement direction of the vehicle, rather than all channels of adjacent APs, as in the NG scheme. Among these schemes, our approach realizes the lowest delay in both scenarios, for it scans fewer channels: it usually only scans 1 or 2 channels. As a consequence, the average of the scanning delay of our scheme remains at around $15ms$.

There are 11 channels available for use in IEEE 802.11 networks in North America, but only 3 of them are non-interfering channels: they are Channel 1, 6 and 11. In previous experiments, all of the 11 legitimate channels were assigned to APs. For the experiment results shown in Figure 4.8, only the 3 non-interfering AP channels were used. Because there are fewer channels to be scanned, the scanning delay of the LBFH scheme and the NG algorithm decreases in contrast to the results in Figure 4.7. The decrease is slight in the highway scenario, but it is quite prominent in the urban scenario. The scanning delay of the full-scan scheme is also shortened, as the waiting time after a probe request is more likely to reach $MaxChannelTime$ for those used channels. There is not too much change in the scanning delay of our scheme.

The scanning delay of these schemes were also evaluated in two scenarios from real road networks. A part of Ontario Highway 417 near Ottawa, the length of which is roughly $6000m$, was extracted from OpenStreetMap [8], a free online map database. Similarly, a small part of Ottawa urban road networks was also extracted from OpenStreetMap. The size of the chosen area is about $1800m \times 1800m$. The data of the road networks were then converted into a file acceptable to Simulation of Urban Mobility (SUMO) [2]. SUMO allows to simulate how a number of vehicles moves through a

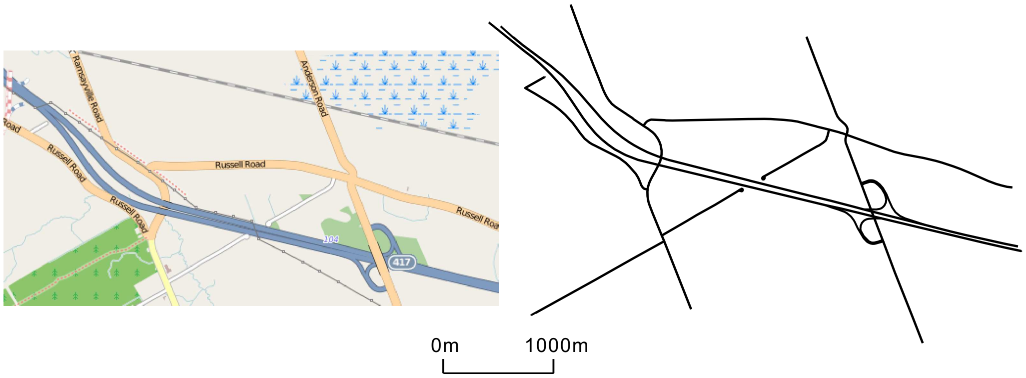
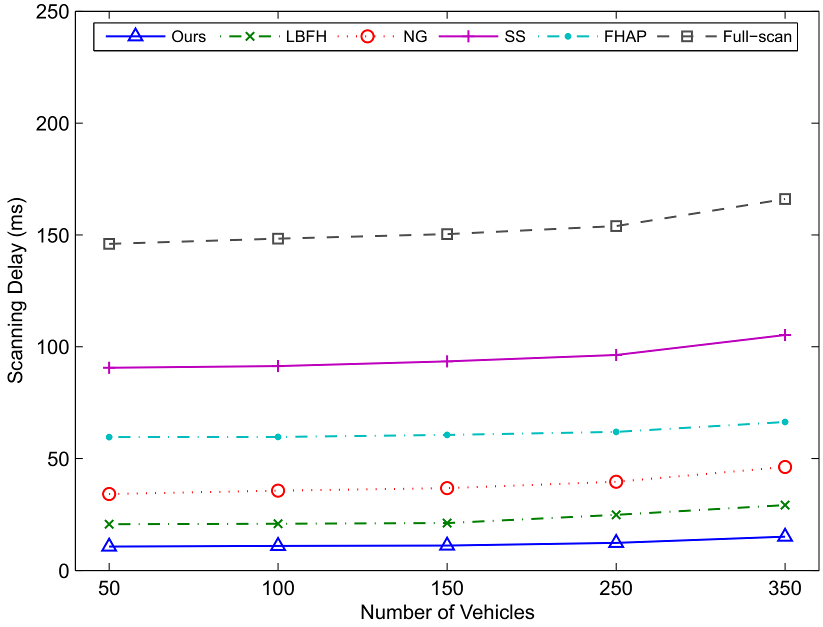


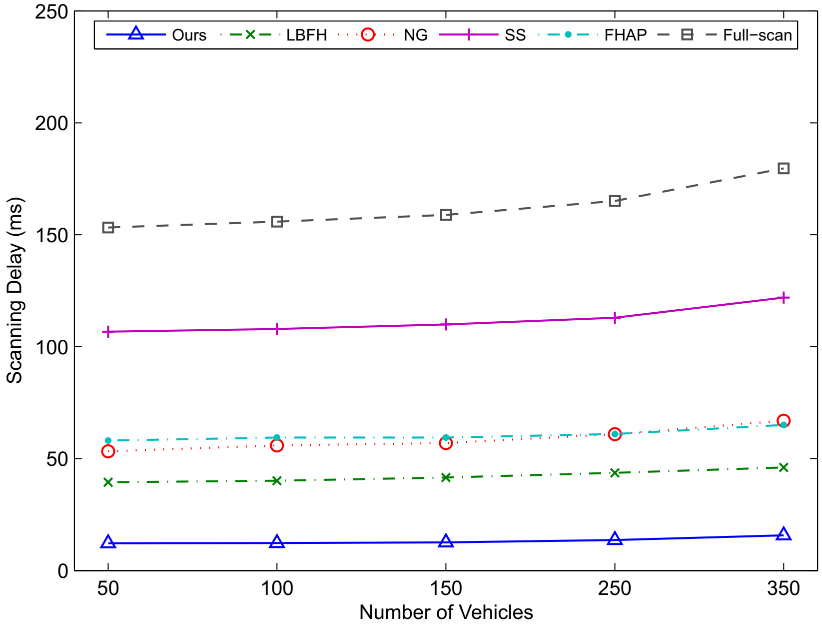
Figure 4.9: A part of Ontario Highway 417

Figure 4.10: A part of Ottawa road networks

given road network. The source positions and the destination positions of the vehicles were randomly generated, and these vehicles moved along the shortest routes between the source and the destination positions. With this file, SUMO automatically generated a file containing vehicle movement traces for ns2. SUMO can recognize different road types, and the speed limits of these road types are thus different. Thus, all vehicles in a SUMO generated scenario moves at the speed below the corresponding

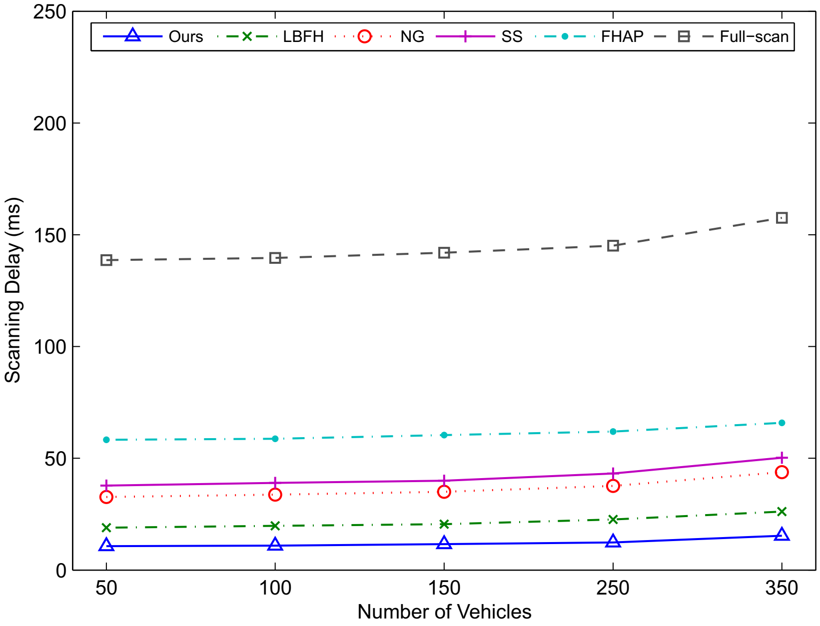


(a) Highway 417 scenario

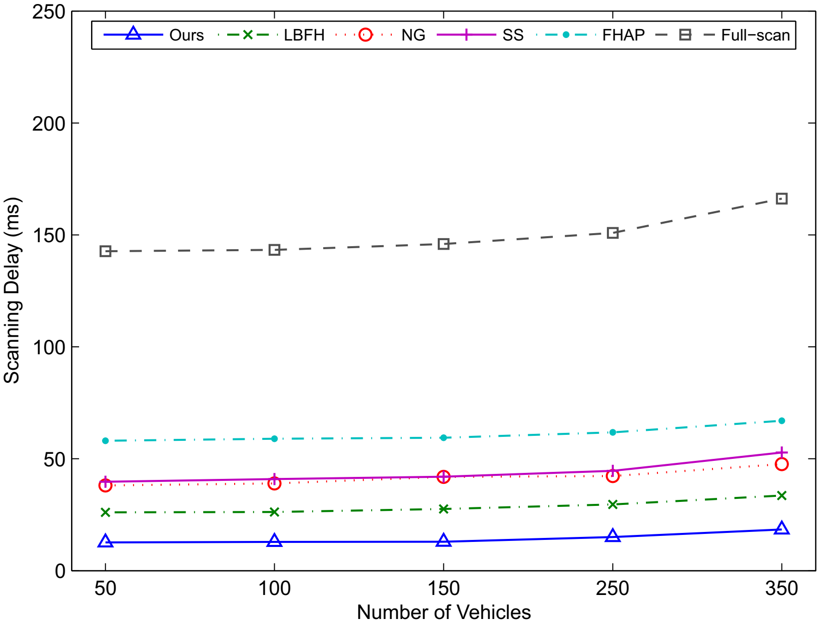


(b) Ottawa urban scenario

Figure 4.11: Comparison of scanning delay (11 channels)



(a) Highway 417 scenario



(b) Ottawa urban scenario

Figure 4.12: Comparison of scanning delay (3 channels)

Table 4.3: Summery of the compared schemes

Scheme	**Scanned channels**	**Location information requirement**	**Prior AP information requirement**	**Real-time application support**[a]	**Scanning delay**
Full-scan	All				High
SS[58]	Selected				Unstable
NG[57]	Selected		√	Partially	Medium
FHAP[7]	All				Medium
LBFH[62]	Selected	√	√	√	Low
Ours	Selected	√	√	√	Low

[a] Total handoff latency is required to be less than $50ms$ for VoIP

speed limit.

Figure 4.9 shows this selected part of the Ontario Highway 417, which was used as the Highway 417 scenario for the following simulations in ns2. The part of the Ottawa urban area is shown in Figure 4.10, and it was for the Ottawa urban scenario. In both figures, the real maps are on the left, and the extracted road networks are on the right. There are more than 30 APs operating in the areas.

Figure 4.11 illustrates the average scanning delay of our scheme, the full-scan scheme, the LBFH scheme, the NG scheme, the selective scanning (SS) scheme [58] and the FHAP scheme [7] in the Highway 417 scenario and the Ottawa urban scenario, when 11 AP channels were used. Figure 4.12 shows the delay when only Channel 1, 6 and 11 were used. The bit rate of communications between every vehicle and the APs was 64kbps; besides, the simulation duration was $500s$ for each time. The number of vehicles passing the areas was increased from 50 to 350. The scanning delay in the two figures generally shows obvious increase, as the number of vehicles reaches 350. The delay of the selective scanning scheme decreases prominently, because it prefers to scan those 3 channels. As for the FHAP scheme, the scanning delay shows no significant changes in the four figures. The performance of other schemes in these scenarios is similar to that in the previous highway and urban scenario. The characteristics of all compared schemes are summarized in Table 4.3.

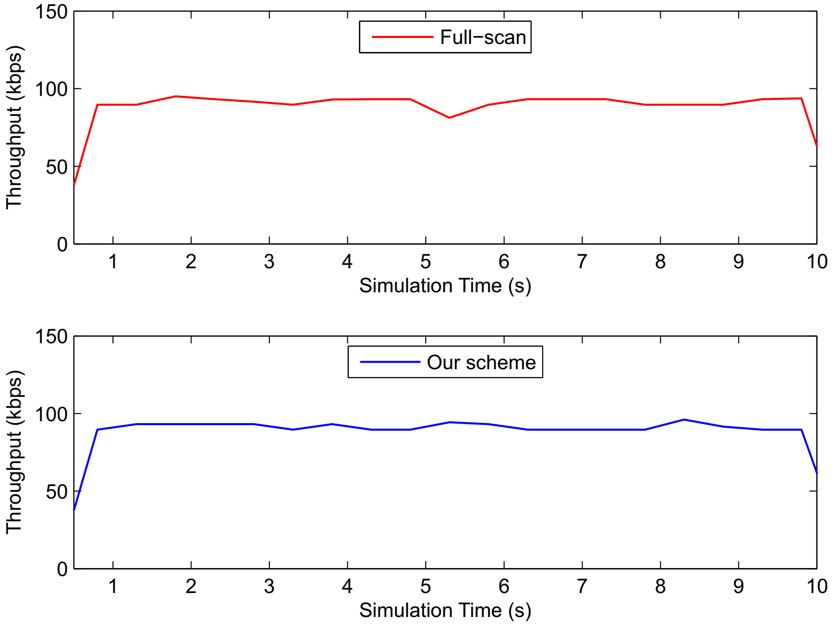
4.3 Comparison of Other Evaluation Metrics

In this section, various simulation results of throughput, jitter and the number of handoffs are presented and discussed. The comparison between our scheme and the full-scan scheme are shown to demonstrate the advantages of our scheme. For the following simulations using our scheme, the GPS accuracy level was set on $\sigma = 2.04$ and the blacklist feature was not enabled.

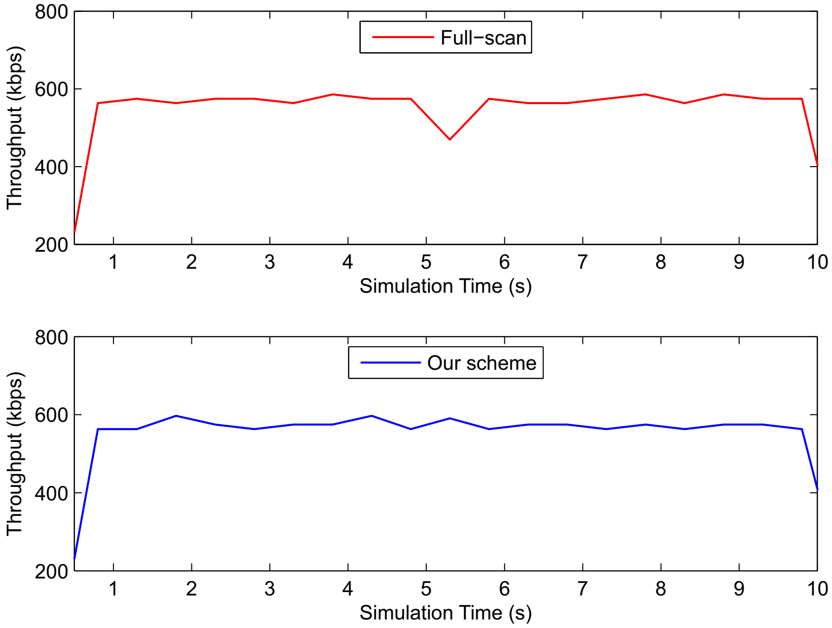
4.3.1 Throughput

A VoIP communication between two vehicles was established to examine the influence of our handoff scheme on real-time applications. To simulate the G.711 encoded/decoded VoIP stream [29], CBR traffic was established between two vehicles. One vehicle sent a 160byte UDP packet to the other one every $20ms$. The bit rate of background traffic was 512kbps. Besides, open system authentication, a built-in module in ns2, was adopted for the (re)authentication phase. Other settings of the simulation environment were the same as in the previous experiments, as shown in Table 4.1.

The influence of the full-scan scheme and our scheme on throughput is compared,



(a) Data bit rate: 80kbps



(b) Data bit rate: 512kbps

Figure 4.13: Comparison of handoff influence on throughput

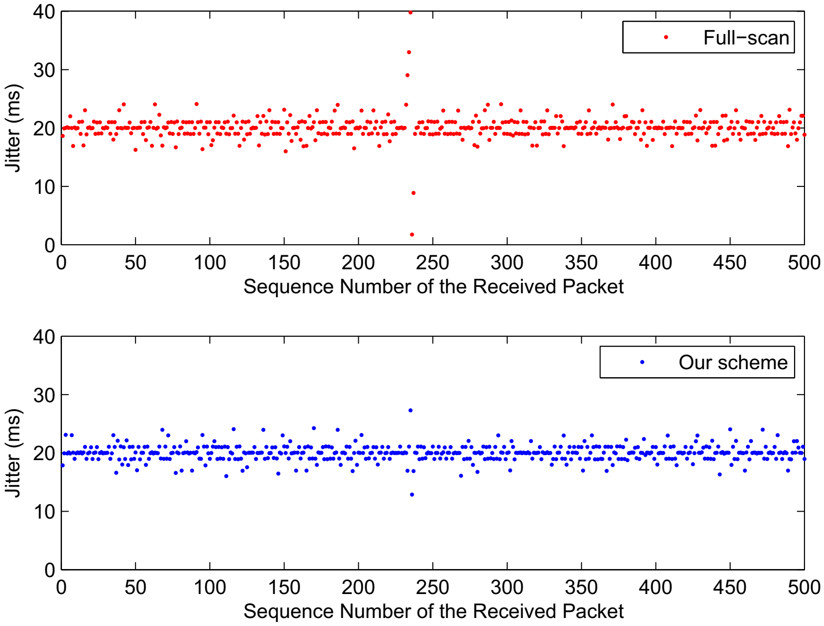


Figure 4.14: Comparison of handoff influence on jitter

as shown in Figure 4.13(a). During the 10s simulation time, a handoff was manually triggered at 5s to test both schemes. A significant drop of throughput can be observed when using the full-scan scheme, while there is no discernible change with respect to the throughput when using our scheme. Since the bit rate of this VoIP stream is low, the data bit rate was increased to 512kbps in another experiment, the results of which are presented in Figure 4.13(b). The influence of handoff on throughput in this figure is more significant when compared with Figure 4.13(a).

4.3.2 Jitter

Apart from throughput, the handoff process also affects jitter. The full-scan scheme and our scheme are compared in the same simulation environment as the experiments for Figure 4.13(a) in order to evaluate handoff influence on the jitter of VoIP stream. The jitter of 500 received data packets of the VoIP stream is presented in Figure 4.14.

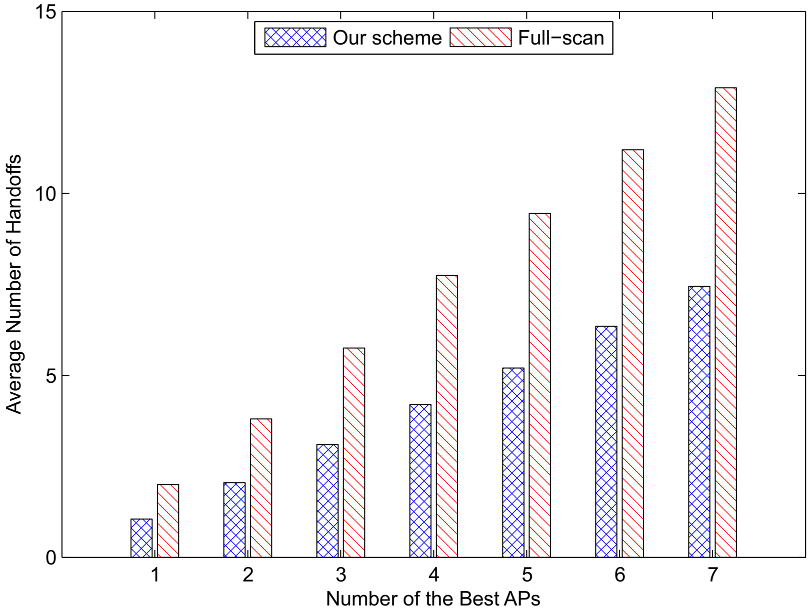
Most frames are able to arrive at the destination in time, and the jitter is around $20ms$. During the communication interruption caused by the handoff, more dots in the upper figure deviate greatly from $20ms$. This means that more frames will suffer from larger jitter, if the full-scan scheme is adopted.

4.3.3 The Number of Handoffs

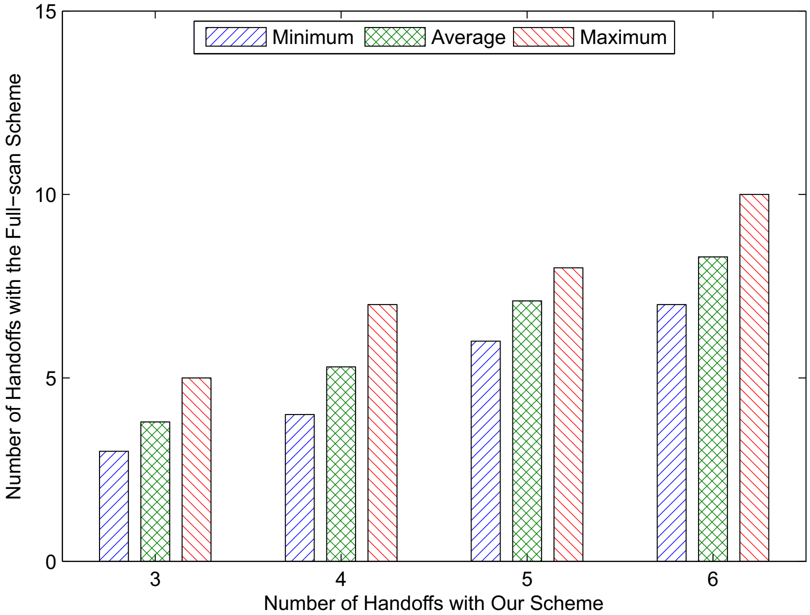
In addition, the proposed scheme is supposed to reduce the total number of handoffs by selecting APs that can provide relatively longer services for a vehicle. To prove this, a highway scenario was devised, where there were several best APs on the same road as the vehicle and some APs on other roads acting as interference APs. The distance from interference APs to the road ranged from $100m$ to $150m$. A VoIP stream was also established between two vehicles. One vehicle did not move, while the other vehicle moved along the road. The number of handoffs triggered by the moving vehicle was then recorded, after it passed by all the best APs.

Figure 4.15(a) illustrates the difference in the average number of handoffs triggered with our approach and with the full-scan scheme, which chooses the AP with the highest RSS for a handoff. As the number of the best APs passed by increases from one to seven, the average number of handoffs of our scheme remains almost the same as the number of the best APs, while the number of the full-scan scheme suffers from more pronounced increases. In a word, our scheme usually succeeds in selecting the best APs and thus reduces unnecessary handoffs, as long as the vehicle maintains its direction.

The number of handoffs was also calculated in the same urban scenario used in the previous experiment. There were 100 vehicles moving in the area of $1000m^2$ for this experiment; these vehicle traveled in different routes. The experimental results show that the number of handoffs triggered with our approach ranges between 3 and



(a) Highway scenario



(b) Urban scenario

Figure 4.15: Comparison of the number of handoffs

6. For the vehicles following the same routes but using the full-scan scheme, however, the number of handoffs are higher in general. The relationship between the number of handoffs with the full-scan scheme and that with our approach is presented in Figure 4.15(b). The average, the minimum and the maximum of the number of handoffs with the full-scan scheme in different circumstances are all shown in this figure.

4.4 Summary

In this chapter, the performance of the proposed scheme is evaluated through extensive experiments and through comparisons with other handoff schemes. The overall prediction error rate of both the turn detection scheme and the AP selection scheme is low. This means that the order and the contents of the list of AP candidates are reliable. With this list, the handoff latency is significantly shortened by the prioritized scanning scheme, because sending out the probe message for only one or two times is usually enough to find a suitable AP. In comparison with other schemes, our scheme achieves the lowest scanning delay in the highway scenario, the urban scenario and the real-world scenario of Ottawa road networks. A real-time application, VoIP, is also simulated in order to prove that our scheme is able to satisfy real-time requirements. Other evaluation metrics, such as jitter, throughput and the average number of handoffs, are all improved with our scheme.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In urban areas or on highways, the mobility patterns of vehicles are limited by roads and streets. By utilizing such constraints and GPS receivers, the AP suitable for a handoff can be accurately predicted with a proper method. In this thesis, an efficient location-based handoff scheme designed for vehicular networks is described. This scheme combines two related prediction schemes. The first one, the turn detection scheme, ensures that the two locations collected for calculation of vehicle movement direction are on the same road. The second one, the AP selection scheme, is devised to rate APs within the transmission range of a vehicle; APs on the potential path of a vehicle are given higher priority, as they will maintain a long and stable connection with the vehicle. The prioritized scanning is then started, which scans APs in ascending order of priority values. Once an AP responds, the scanning will be stopped. The scanning delay is reduced in this way. Besides, a blacklist scheme is designed to further reduce scanning delays by eliminating previous prediction errors, which can also reduce the scanning delay.

Simulation results reveal that overall prediction error rate of the proposed scheme is low. As a consequence, handoff latency is significantly shortened due to the optimization of the most time-consuming scanning phase. In the comparisons with other schemes, our scheme demonstrates the lowest scanning delay in both highway and urban scenario and it is able to support real-time applications such as VoIP. Because of the decrease in handoff latency, the influence of handoffs on jitter and throughput is relieved. Moreover, the average number of triggered handoffs also attains reduction with our method.

5.2 Future work

5.2.1 Other Applications with the Prediction Algorithms

The goal of the proposed scheme is the accurate prediction of an AP that is not only on the same street as the vehicle but also in the direction the the vehicle is moving. The AP can be replaced by other types of objects or the location of an event. In ITS, information on traffic congestions, accidents or other emergencies are location sensitive [4]. For example, if a vehicle is moving directly to the location of an emergency event, the driver of this vehicle should be given the highest level of alertness. However, a vehicle that is moving away from this location or on a different road, even if it is close to the location, does not need a red alert, because the emergency is unlikely to affect the vehicle.

Instead of traditional billboards on the roadside, digital billboards in the vehicular networks may be used to deliver advertisements. As for this type of application, advertisements of hotels, restaurants, theaters or shopping centers that are on the possible future path of a vehicle should be displayed in a prominent place on the screen, because it is easy for the driver to go to these places.

5.2.2 Possible Improvements to the Proposed Scheme

Due to the high prediction accuracy of the proposed scheme, it is possible for the vehicle to start a pre-authentication process with the AP of the highest priority before a handoff, and the authentication delay could be reduced in this way. Like the location-based handoff scheme proposed by C. Tseng *et al.* [62], a vehicle can initiate the IEEE 802.1X pre-authentication process, specified in IEEE 802.11i [22], in order to reduce the delay caused by authentication operations.

GPS SPS is presumed to provide location information in this thesis, and it has different accuracy levels under different circumstances. Combined with augmentation systems, GPS is able to achieve a higher level of accuracy today; these enhanced systems limit positioning errors within a few centimeters. As such, a vehicle can begin authentication with a new AP of the highest priority, without the prioritized scanning, if the GPS accuracy is good enough.

This work is only concerned with the MAC layer handoff in IEEE 802.11 networks, but a handoff may happen between heterogeneous wireless networks in vehicular environments. Various cellular networks have already covered most areas in cities nowadays. If there is no AP of a WLAN network within the transmission range of a vehicle, for example, the vehicle may initiate a vertical handoff and switch its connection to a cellular base station. The mechanism for such a vertical handoff [42] may be a promising research field for future work.

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