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# MOBILITY MANAGEMENT OF UNICAST SERVICES FOR WIRELESS ACCESS IN VEHICULAR ENVIRONMENTS

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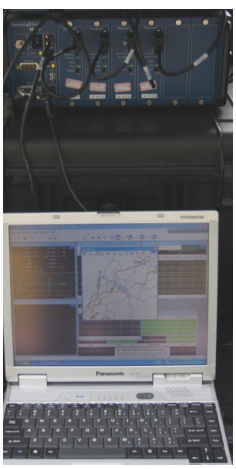

The authors propose a location estimation-based mobility management mechanism by utilizing positioning systems (e.g., GPS) for a WAVE system deployed in highway environment with a large volume of high-speed vehicles.

## ABSTRACT

Wireless Access in Vehicular Environments (WAVE) provides seamless and interoperable services for vehicles. In WAVE, the WAVE Short Message Protocol (WSMP) provides broadcast services but does not define unicast/multicast services that require mobility management to track the locations of the vehicles. To resolve this issue, this article proposes a location estimation-based mobility management mechanism by utilizing positioning systems (e.g., GPS) for a WAVE system deployed in highway environment with a large volume of high-speed vehicles. Performance study indicates that under the same paging cost, our approach can reduce 40–90 percent of the network traffic as compared with the traditional cellular mobility management approach.

## INTRODUCTION

Wireless Access in Vehicular Environments (WAVE) defined by IEEE provides seamless and interoperable services for vehicles [1, 2]. WAVE is a multichannel system that consists of one control channel (CCH) and multiple service channels (SCHs). The CCH is used to transmit WAVE management messages and WAVE short messages (WSMs). An SCH is used to exchange user information, including IP data packets and WSMs.

A WAVE device can be a roadside unit (RSU) or an onboard unit (OBU). The RSUs are stationary in operation and usually permanently mounted along the roadside. They connect to each other through a network (e.g., an intranet). In contrast, the OBU may operate in movement and is usually mounted on a vehicle. An RSU is called the *WAVE provider* that offers services (e.g., traffic information announcements). An OBU is a *WAVE user* that accesses the RSU's services.

Most research studies on WAVE have been based on ad hoc configurations [3]. In the infrastructure configuration, the existing WAVE protocol provides broadcast services. For unicast/multicast services, the WAVE system must track the locations of the OBUs. Mobility management has not been defined in the WAVE specifications, which may directly follow the existing mechanism used in cellular networks [4–6]. In this mechanism, all RSUs are statically partitioned into several location areas (LAs). When an OBU moves from the coverage of one LA to another, it needs to register to the new LA, which may not be appropriate for an environment with a large volume of high-speed vehicles. If an OBU moves very fast, it is likely to leave the coverage of the LA before the registration procedure is complete. To resolve this issue, we propose an approach that dynamically groups RSUs into an LA by exploiting the characteristics of vehicle movements. Specifically, we utilize positioning systems (e.g., GPS) to reduce the registration messages sent from the OBU to the network, and still accurately track the locations of the OBUs. The proposed mechanism is implemented in the medium access control (MAC) layer. The network layer protocol (e.g., Internet Protocol) is not involved. Note that dynamic LA assignment is an issue that has been investigated since 1990 [7]. Based on the incoming call arrival rate and the user mobility, such a mechanism dynamically adjusts the LA size to minimize the net cost of paging and location update. Different from these traditional solutions, the network estimates the users' locations in our approach. The novelty is that the OBU knows if the error of the network's estimation is too large. If so, a registration is issued to provide the precise location information.

This article is organized as follows. We describe the basic mobility management (BMM) mechanism for the WSM-based unicast service. We propose the location estimation-based mobility management (LEMM) mechanism. We conduct a performance study of WAVE mobility management, which indicates that the LEMM significantly outperforms the BMM.

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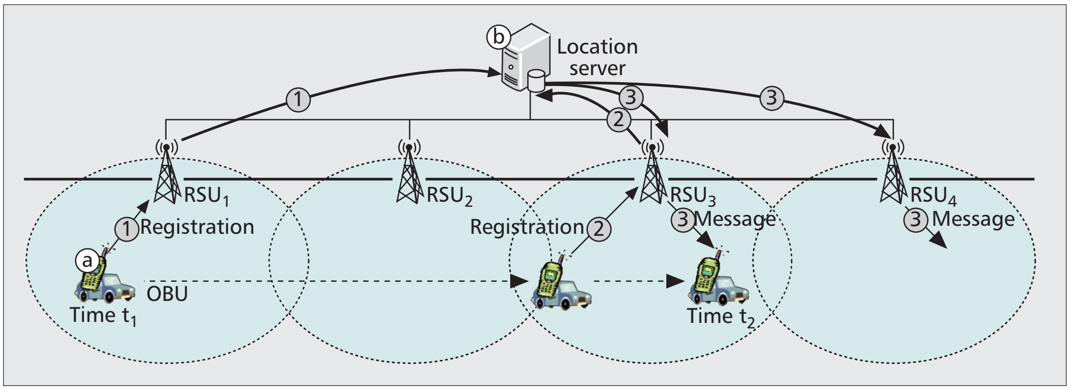


**Figure 1.** *Basic mobility management (BMM) mechanism.*

Different from these traditional solutions, the network estimates the users' locations in our approach. The novelty is that the OBU knows if the error of the network's estimation is too large. If so, a registration is issued to provide the precise location information.

## WAVE Short-Message-Based Unicast Services

The WAVE Short Message Protocol (WSMP) utilizes WSM for data delivery and WAVE service advertisement (WSA) for control signaling [1, 2]. Each WAVE service is identified by a provider service identifier (PSID). In WAVE, the broadcast services are appropriately supported. However, the unicast services are not defined. In [8], we described how unicast can be supported in WAVE, and the details are re-iterated here for the reader's benefit.

Suppose that the PSID for the unicast service is $ID_{UC}$. In this service, each OBU is identified by its MAC address. To send a message to a specific OBU, the WAVE system needs to track the location of that OBU. Following the standard 3GPP mobility management mechanism for cellular network (referred to as BMM) [9], the RSUs are partitioned into several LAs. Each LA consists of one or more RSUs and is identified by an LA Identity (LAI) [4]. In Fig. 1, assume that $RSU_1$ and $RSU_2$ are grouped in location area $LA_1$, and $RSU_3$ and $RSU_4$ are grouped in $LA_2$.

An OBU (Fig. 1a) moves to different LAs from time to time. The WAVE system needs to know the LA of the OBU so that the WSMs can be delivered to the OBU through the RSUs in that LA (instead of being broadcasted to all RSUs). Mobility management of an OBU can be achieved by introducing a network node called the *Location Server* (Fig. 1b). This server connects to all RSUs in the WAVE system, and maintains the mappings between RSUs and LAs. This article assumes that the location server and the RSUs communicate through the WAVE protocol over a managed IP network. (i.e., an intranet; in our current implementation, the RSU and Location Server actually interact through *Session Initiation Protocol* [4]). To activate the unicast service, both the OBU and the RSU need to individually perform the initialization procedure as illustrated in Step A.1 of Fig. 2.

**Step A.1** The OBU records the PSID of the unicast service (i.e., $ID_{UC}$). If the RSU supports the unicast service $ID_{UC}$, it allocates radio resources of a service channel for this service.

After initialization, the service announcement procedure is performed in Steps A.2 and A.3. In this procedure, the RSU broadcasts its LAI, which is used by the OBU to identify the location area it resides.

**Step A.2** The RSU periodically broadcasts a WSA to the OBUs. In this WSA, the source address (SA) is the RSU's MAC address ($MAC_{RSU}$) and the destination address (DA) is the broadcast MAC address FF:FF:FF:FF:FF:FF, the PSID is $ID_{UC}$. It also contains the LAI and the SCH number for $ID_{UC}$. The LAI is encapsulated in the Provider Service Context (PSC) field associated with $ID_{UC}$.

**Step A.3** When the OBU enters the coverage of the RSU, it listens to this WSA. If the OBU has subscribed to service $ID_{UC}$, it identifies the SCH for this service, which is indicated in the WSA. When the OBU enters a new location area, the LAI specified in the WSA is different from the stored LAI, and the OBU performs the registration procedure described below.

In Fig. 1, the OBU moves from a location area to $LA_1$ (through $RSU_1$) at time $t_1$ (Fig. 1) and Steps A.4 and A.5 in Fig. 2 are executed.

**Step A.4** The OBU sends a registration WSM to the Location Server through path (1) in Fig. 1. The WSM includes the SA ($MAC_{OBU}$), the DA ($MAC_{RSU}$), the PSID ($ID_{UC}$), and the Data field (i.e., type "REGISTER" and $MAC_{OBU}$). The Location Server maps the $MAC_{OBU}$ to the LAI that covers the RSU, and saves this mapping in its database.

**Step A.5** The registration is successful, and the Location Server sends back a 200 OK response to the OBU through the RSU. The OBU stores the new LAI.

If the OBU leaves $LA_1$ and enters $LA_2$ through $RSU_3$, it performs another registration (path (2) in Fig. 1). To send a unicast message to the OBU at $t_2$ (when the OBU is located at $LA_2$), the Location Server requests the RSUs of $LA_2$ to deliver the message (path (3) in Fig. 1). The unicast delivery procedure is described in Steps A.6–A.8 of Fig. 2.

**Steps A.6 and A.7** The Location Server retrieves the LAI associated with the OBU's MAC address $MAC_{OBU}$, and sends a WSM to all RSUs covered by the LA. The data field of this WSM includes type "MESSAGE." These RSUs broadcast the message in their radio coverages.

We propose a location estimation-based mobility management mechanism that dynamically groups the RSUs into LAs, which effectively reduces the registration overheads. This approach assumes that an OBU is equipped with a GPS device, which is a basic requirement in most telematics services.

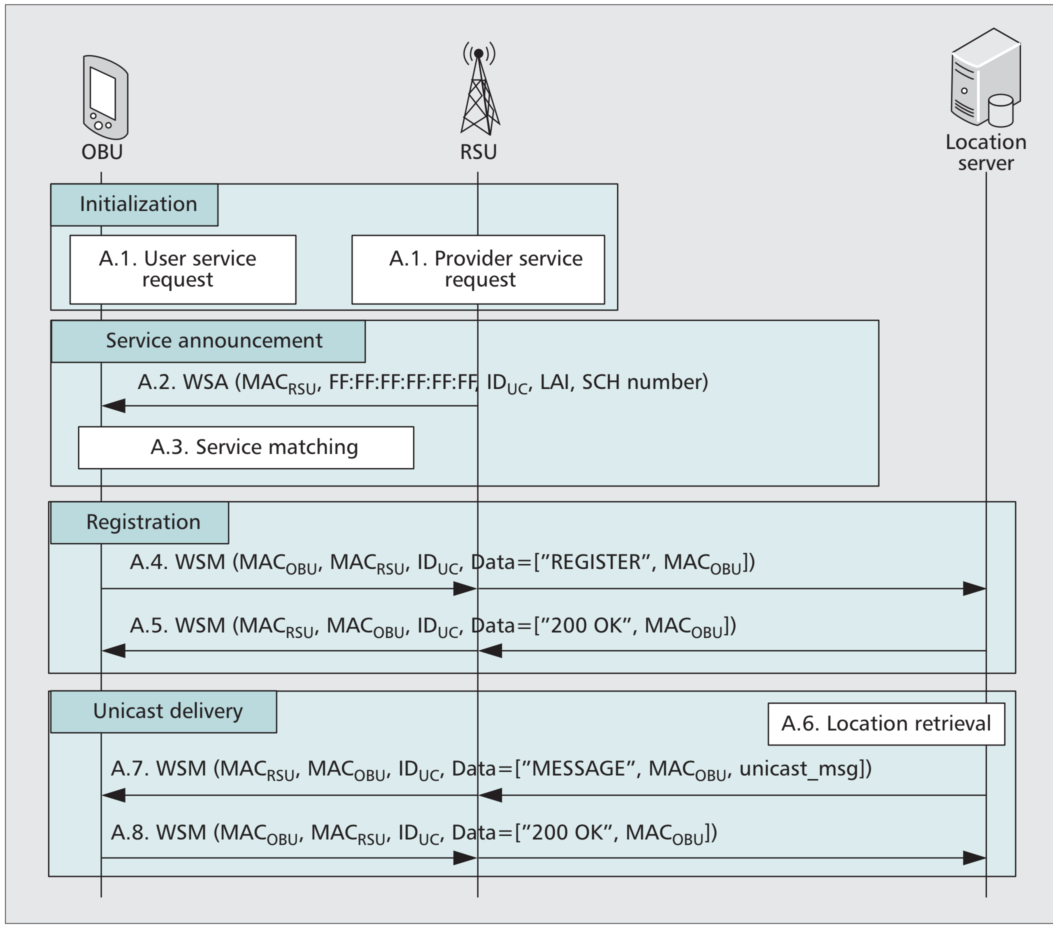


**Figure 2.** *Message flow for BMM unicast.*

**Step A.8** Suppose that the OBU is covered by a RSU with MAC address $MAC_{RSU}$. The OBU receives the WSM, and replies a 200 OK to the Location Server through this RSU which indicates that the unicast delivery is successful.

In BMM, if the LA size is small, the registration overhead may be very large in a highway environment with a large volume of high-speed vehicles. If the LA size is large (in the existing WAVE broadcast services, all RSUs are grouped in one LA), the delivery procedure will page a large number of RSUs for a single unicast WSM. Therefore, statically partitioning RSUs into LAs in advance may not capture the movement behaviors of OBUs and may result in significant registration and/or paging costs. This issue is addressed in the next section.

## Location Estimation-based Mobility Management

WAVE is typically deployed along highways where a large number of vehicles may move in relatively steady speeds and seldom change directions. In such an environment, BMM based on the standard 3GPP specification may result in poor performance (large number of registrations).

We propose a location estimation-based mobility management (LEMM) mechanism that dynamically groups the RSUs into LAs, which effectively reduces the registration overheads. This approach assumes that an OBU is equipped with a global positioning system (GPS) device, which is a basic requirement in most telematics services.

Consider the WAVE system in Fig. 1 again. In LEMM, the RSUs are not partitioned into LAs in advance. Suppose that an OBU joins in the WAVE system by entering the coverage of $RSU_1$ at time $t_1$. To report its existence to the WAVE system, it performs the first registration (path (1) in Fig. 1) as described in BMM. Unlike BMM, the OBU provides GPS-derived *movement information* (i.e., time $t$, position $l$, speed $v$, and direction $d$) to the Location Server. Note that the location $l$ is a two-dimensional Cartesian coordinate and the direction $d$ is a two-dimensional unit vector. To deliver a unicast message to the OBU, the Location Server uses the movement information to estimate the OBU's current location, and asks the RSUs who may potentially cover the OBU to deliver this message to the OBU. The message flow for LEMM is illustrated in Fig. 3. Initially, both the OBU and the RSU individually perform the initialization procedures at time $t_0$ (i.e., Step A.1 in BMM), except that the OBU also records the time $t_0$ and the location $l_0$ obtained from the GPS. Then the service announcement procedure is performed, which is the same as Steps A.2 and A.3 except that the LAI is not required in the WSA.

The registration procedure of LEMM per-

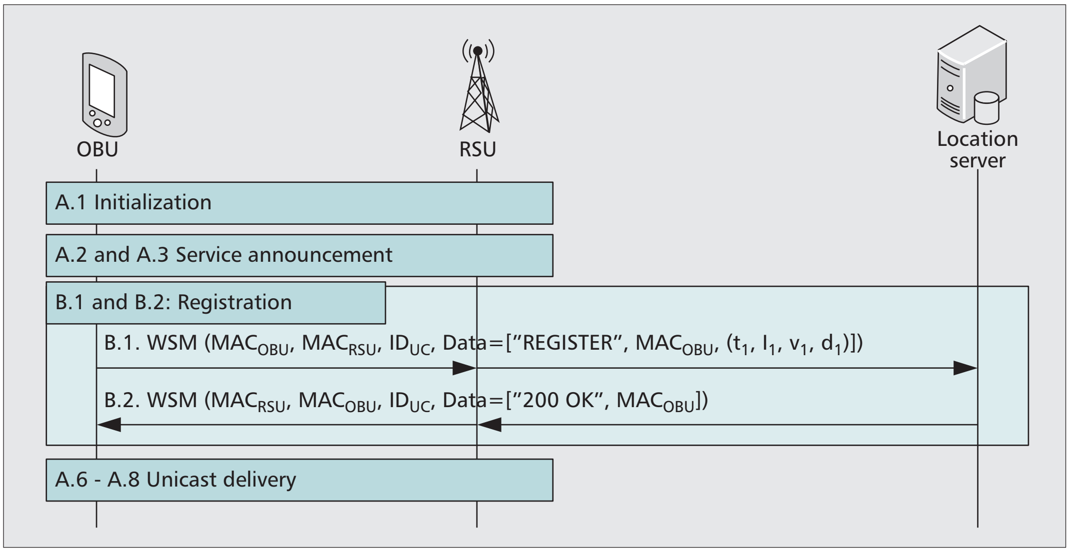


**Figure 3.** *Message flow for LEMM unicast.*

Moving jam states that in a traffic flow, a fast vehicle may be blocked by slow vehicles, and has to assume the speeds of the slow vehicles until an acceptable gap for passing is available. Then this fast vehicle will pass the slow vehicles to resume its desired speed.

formed at time $t_1$ (path (1) in Fig. 1) is described in Steps B.1 and B.2.

**Step B.1** The OBU obtains time $t_1$ and location $l_1$ based on GPS, and uses $t_1$, $l_1$ to compute its speed

$$v_1 = \frac{\left|\overline{l_0 l_1}\right|}{(t_1 - t_0)}$$

and the direction

$$d_1 = \frac{\overrightarrow{l_0 l_1}}{\left|\overline{l_0 l_1}\right|},$$

where $t_0$ and $l_0$ are the movement information measured in the last registration or at initialization. Then the OBU sends a registration WSM to the RSU. This WSM is similar to that in Step A.4 except that the movement information ($t_1$, $l_1$, $v_1$, $d_1$) is encapsulated in the data field.

**Step B.2** Upon receipt of the registration WSM, the Location Server modifies the record for $MAC_{OBU}$ with new movement information and sends back a 200 OK response to the OBU through the RSU.

If the speed and the direction of the OBU do not significantly change during period [$t_1$, $t_2$], then the movement information ($t_1$, $l_1$, $v_1$, $d_1$) is used to compute the OBU's location at time $t_2$ as

$$\hat{l}_2 = l_1 + d_1 v_1 (t_2 - t_1) \quad (1)$$

Equation 1 is used by the Location Server to estimate the OBU's location. However, if the speed or the direction of the OBU changes such that the error between the OBU's actual location $l_2$ and the estimated location computed by Eq. 1 is larger than a predefined threshold $L$, then the OBU should issue another registration, which provides new movement information to the Location Server. In this way, we can guarantee that the Location Server always estimates the OBU's location with an error smaller than the threshold $L$.

When the Location Server attempts to deliver a message to the OBU at time $t_2$, it estimates the location of the OBU by using Eq. 1 and delivers the message (path (3) in Fig. 1) as illustrated in Steps A.6–A.8 in Fig. 2. This procedure is the same as that in BMM except that at Step A.6, the Location Server retrieves the movement information of the OBU, and estimates the OBU's location $\hat{l}_2$. Then the Location Server draws a circle using $\hat{l}_2$ as the center and the threshold $L$ as the radius. It is clear that the OBU is covered by one of the RSUs overlap with this circle. Let LA* be the set of these dynamically selected RSUs, then OBU is covered by one of the RSUs in LA*.

Step B.1 merits further discussion. There are several approaches to measure the current speed in the movement information at the OBU. For example, the current speed can be the average speed of the last $x$ minutes (denoted as $v_x$), or the long-term average speed from the time of the first registration (denoted as $v_{avg}$). In this article, the current speed is computed by utilizing the *leaky-bucket integration* strategy [9] which considers $v_1$ (i.e., $x = 1$) and $v_{avg}$ with different weights. A factor $\alpha$, where $0 \le \alpha \le 1$, is introduced to adjust the weight. The current speed $v$ is estimated as

$$v = \alpha v_1 + (1 - \alpha) v_{avg} \quad (2)$$

In the right hand side of Eq. 2, the first term $\alpha v_1$ captures the near-term movement behavior while the second term $(1 - \alpha)v_{avg}$ captures the long-term movement behavior.

## Performance Modeling

This section proposes a performance model for LEMM. The model consists of two components: traffic (vehicle movement) trace generation and the mobility management simulation.

### Traffic Trace Generation

Vehicle movement data are obtained through two approaches:

**Real traffic measurement of a car moving in**

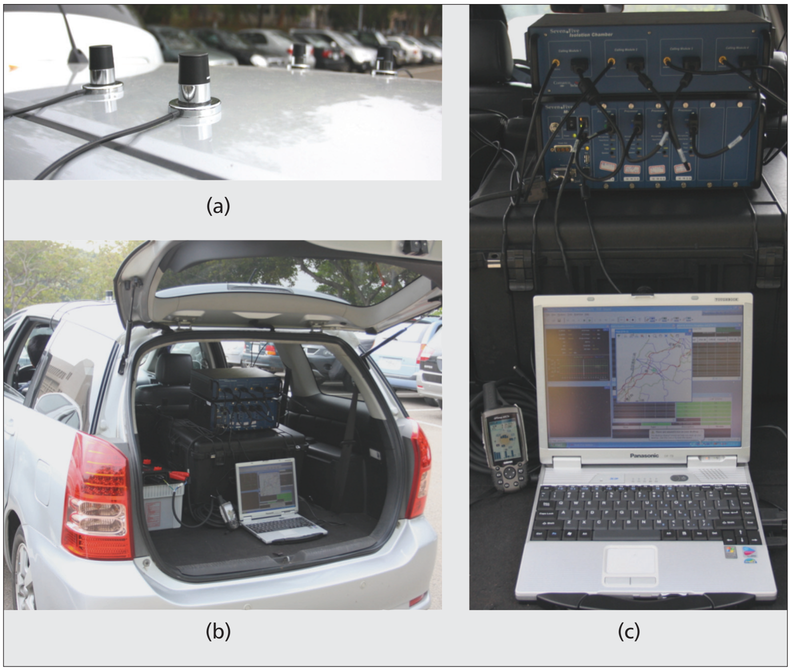

**Figure 4.** *Environment setup for the real measurement: a) antennae of the GSM handsets; b) vehicle for the real measurement; c) real measurement equipment.*

**a 70-km highway from Hsinchu to Taipei:** In this highway, the number of lanes ranges from 2 to 4. We have repeated the measurements for five times where the highway experienced medium traffic flow. The desired speed of the car was 110 km/hr (the highway speed limit in Taiwan). Figure 4 illustrates the GSM measurement environment for the real measurements that "emulates" WAVE, where a GSM base station represents a RSU, and a GSM handset in the car represents an OBU. There are 140 GSM base stations in the highway, and we actually measured the numbers of the "RSU" crossing by the SwissQual Seven.Five system. We recorded the vehicle data every second by using the Garmin GPSmap 60CSx.

**VisSim Traffic simulator that generates the vehicle movement trace files:** In VisSim simulation [8], the highway scenario is characterized by the Wiedemann 99 car-following model and the Wiedemann Psycho-Physical lane-changing model, where the vehicle speeds range from 60 km/hr to 120 km/hr, and the road length is 100 km. In each vehicle movement trace generation, up to 32,400 vehicles are injected in the road during 6 simulated hours, where the desired speed of a vehicle is uniformly randomly selected between 60–120 km/hr. The output trace file records the information of randomly selected 1000 vehicles after 2 simulated hours to eliminate the initial effect.

## Mobility Management Simulation

The mobility management simulation can be implemented by counting the numbers of LEMM registrations through the obtained traffic traces and Eq. 1. The inter-registration times can be calculated in the LEMM simulation as follows: In LEMM, a vehicle synchronizes its current location with the Location Server at a registration. When a unicast request arrives, the Location Server estimates the vehicle's location $\hat{l}_2$ by using the location information obtained in the last registration and Eq. 1. Let $l_2$ be the actual location of the vehicle. The LEMM mechanism guarantees that the error between $\hat{l}_2$ and $l_2$ is within $L$. In the LEMM simulation, it is important to find an optimal $L$ value that balances against the registration and the paging costs. Clearly, a small $L$ results in large number of LEMM registrations while a large $L$ results in large number of RSU pagings. To select an appropriate $L$ value, we build a $K$-state one-dimensional random walk (Fig. 5), where state $k$ represents that the error between $\hat{l}_2$ and $l_2$ is within $kL/K$ and $(k + 1)L/K$.

The random walk starts with state 0 when the vehicle just synchronizes with the Location Server through a LEMM registration. State $K$ is an absorbing state which means that the error threshold has been reached and the vehicle should make a LEMM registration again. Since the estimation of Eq. 1 always incurs error, it is reasonable to assume that the random walk eventually moves from state 0 to state $N$.

From a traffic trace, we compute the error between $\hat{l}_2$ and $l_2$ for every δ seconds, where δ is small enough such that the error in this time period will not exceed two states of the random walk (in our experiments, δ is 1 second). From state 0, if it takes $i$ moves to reach state $K$, then the inter-registration time interval between two LEMM registrations is $i\delta$. For every δ elapsed time, the random walk moves from state $k$ to state $k + 1$ with probability $p_k$, from state $k$ to state $k - 1$ with probability $q_k$, and remains at state k with probability $r_k = 1 - p_k — q_k$. During the LEMM simulation, we also obtained the probabilities $p_k$, $q_k$ and $r_k$ from the traffic traces. Clearly, $q_0 = r_K = p_K = q_K = 0$. In the next section, we will show, based on this random walk, how to select a sufficiently small $L$ value that results in "sufficiently" long $i$ δ.

## Moving Jam Phenomena

From the traffic traces, we observe vehicle movement phenomena called *moving jam*, which is the key to explain the performance of LEMM in the next section. Moving jam states that in a traffic flow, a fast vehicle may be blocked by slow vehicles, and has to assume the speeds of the slow vehicles until an acceptable gap for passing is available. Then this fast vehicle will pass the slow vehicles to resume its desired speed. Figure 6 plots the speed trajectories for a single vehicle (with desired speed 110 km/hr) in a 3-lane highway. The effects of moving jam on this vehicle are different for various traffic flows, and are elaborated below.

**Insignificant Moving Jam:** When the traffic flow is small (e.g., 600 veh/hr), moving jam is seldom observed and the duration of a moving jam is very short (e.g., the period 1900-2000 sec in Fig. 6a). Basically, the vehicle comfortably moves at its desired speed.

**Medium Moving Jam:** When the traffic flow is medium (e.g., 3000 veh/hr), moving jam becomes significant. In Fig. 6b, during 1900–2400 sec, for example, a moving jam occurs which forces the vehicle to move at the speed around 60 km/hr. Then this vehicle passes the slow vehicles at 2400 sec and resumes its desired speed 110 km/hr.

**Significant Moving Jam:** When the traffic flow is large (e.g., 5400 veh/hr), the moving jam occurs very frequently and the fast vehicles often move at the speeds of the slow vehicles. In Fig. 6c, the fast vehicle never reaches it desired speed (i.e., 110 km/hr).

From the above moving jam phenomena, we made two observations:

- **Observation 1:**

a) For insignificant moving jam, the variance of the vehicle speed is small (the speeds are clustered in 90–110 km/hr in Fig. 6a).

b) For medium moving jam, the speed of a fast vehicle "evenly stays" between its desired speed and the speeds of slow vehicles, and the variance of the speed is large (the speeds are clustered in 50–110 km/hr in Fig. 6b).

c) For significant moving jam, a fast vehicle is frequently limited by the slow vehicles, and the speeds are clustered in 40–80 km/hr in Fig. 6c. In this large traffic flow scenario, the variance of the speed is "small" as compared with that in medium traffic flow.

- **Observation 2:**

a) For insignificant moving jams, the variance of vehicle speed is small, and the current speed of a vehicle can be appropriately estimated by the "long-term" average speed.

b) For medium moving jam, the current speed of a vehicle must be estimated by considering the "near-term" speeds.

c) For significant moving jam, the variance of vehicle speed is "relatively" small as compared with that in medium moving jam, and the current speed is appropriately estimated by the "long-term" average speed.

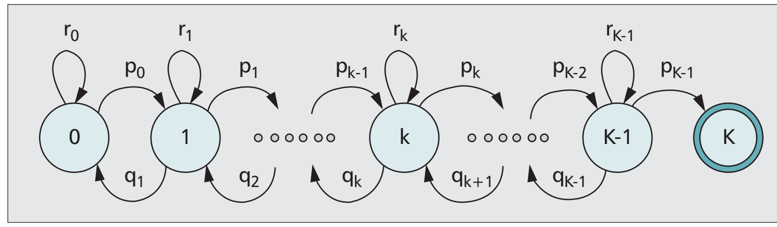


**Figure 5.** *A random walk model for selecting the threshold* L.

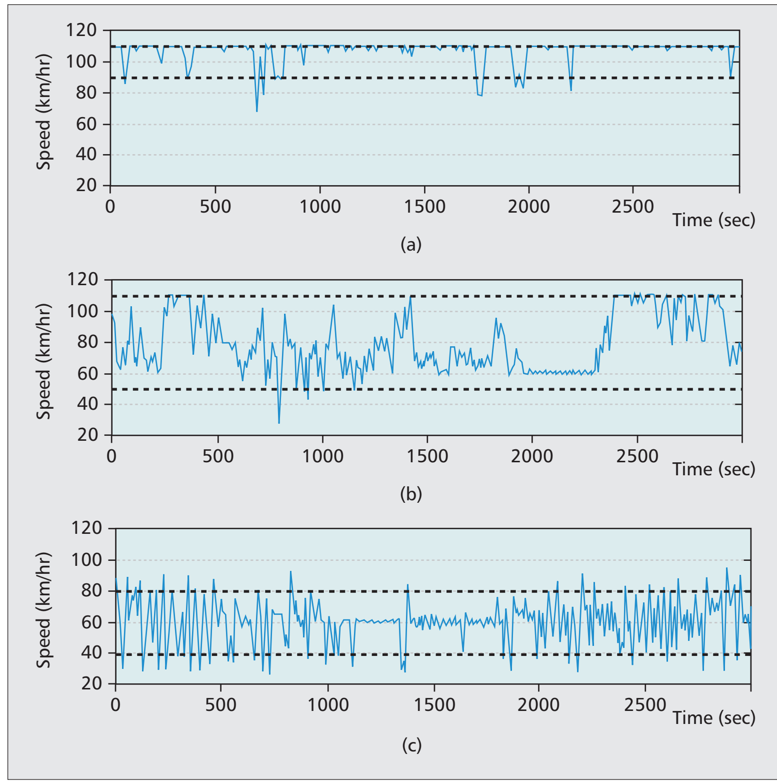


**Figure 6.** *Speed trajectories of a vehicle with desired Speed 110 km/hr in a 3-lane highway: a) traffic Flow 600 veh/hr; b) traffic flow 3000 veh/hr; and c) traffic flow 5400 veh/hr.*

## Numerical Examples

In VisSim simulation, we assume that the coverage of a RSU is $R$ km (in this article, $R$ is set to be 1), and the highway length is 100 km. Therefore, the number of the RSUs in the highway is 100/R. In BMM, if an LA covers |LA| RSUs, a vehicle always performs $100/(R|LA|)$ registrations in this highway (no matter how fast it moves). On the other hand, the registration number of LEMM is investigated through the models described earlier. Note that $R|LA| = R|LA^*| = R(|2L|+1)$. This section shows the effects of traffic flow, LEMM parameters ($\alpha$ and $L$), and the number of lanes in the highway. The output measure is $N_{LE}$, the expected number of LEMM registrations of an OBU (a vehicle).

**Effect of Traffic Flow:** Figure 7 plots $N_{LE}$ with different traffic flows in a 3-lane highway where the LEMM threshold $L = 1$ km. (i.e., $R|LA| = 2L+1 = 3$ km). From Observation 1(a) and (c), the variances of vehicle speed are small when the traffic flow is small (e.g., 600 veh/hr) or very large (e.g., 5400 veh/hr). When the variance of speed is small, an OBU does not need to update the movement information frequently in LEMM. On the other hand, when the traffic flow is medium (e.g., 3000 veh/hr), the variance of speed is large (Observation 1 (b)), and $N_{LE}$ in this scenario is larger than when the traffic flow is large or small. In Fig. 7, $N_{LE}$ increases and then decreases as the traffic flow increases.

**Effect of the LEMM Parameter $\alpha$:** Observation 2 (a) and (c) indicate that when the traffic flow is either very small or large, the current speed of a vehicle is dominated by long-term movement behavior, and Eq. 2 yields better speed estimation when $\alpha = 0$. On the other hand, Observation 2 (b) indicates that when the traffic flow is medium, the near-term movement behavior has to be taken into consideration. In Fig. 7, the optimal $\alpha$ value in equation (2) for a medium traffic flow is 0.5 (when the traffic flow is 3000 veh/hr) and 0.2 (when the traffic flow is 4200 veh/hr). Selection of an appropriate $\alpha$ value can be done by the Location Server or the OBU.

**Effect of the Number of Lanes:** Figure 8 plots $N_{LE}$ against the number of lanes in the highway and the traffic flow per lane. The figure indicates that medium moving jam phenomenon is observed at smaller traffic flow for a highway with smaller number of lanes. For example, the maximum $N_{LE}$ occurs at 600 flow/lane for 2 lanes, at 1000 flow/lane for 3 lanes, and at 1200 flow/lane for 4 lanes. Also, for the same flow/lane, the LEMM registration number decreases as the number of lanes increases.

**Effects of *L*:** In the random walk of Fig. 5, it is clear that $p_k$ is the transition probability that increases the error between $\hat{l}_2$ and $l_2$. Figure 9 plots $p_k$ against $k$ for the traffic trace from real measurement where $L = 5$ km. The figure indicates that the $p_k$ curves have several local minimums. For example, for $\alpha = 0.1$, $p_{19}$ is a local minimum. We found that if we select the threshold as (20/50) $L$ instead of $L$, the inter-registration time is reduced from 945.4 seconds to 588 seconds (i.e., reduced by18.7 percent), while the size of the location area (and thus the paging cost) is significantly reduced by (50–20)/50 = 60 percent. Similarly, for $\alpha = 0.8$, $p_{28}$ is a local minimum. If we select the threshold as (29/50) $L$ instead of $L$, the inter-registration time is reduced from 1357.8 seconds to 1181.8 seconds (i.e., reduced by 13 percent), while the paging cost is significantly reduced by (50–29)/50 = 42 percent. In other words, the random walk model suggests that $K$ (and thus $L$) should be selected such that $p_{K-1}$ is a local minimum.

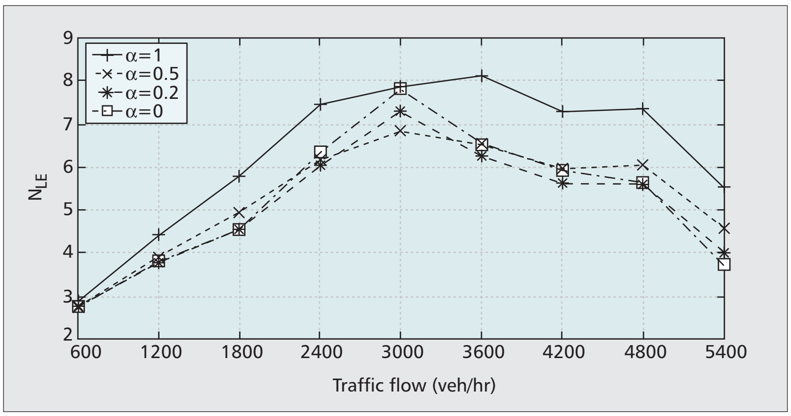


**Figure 7.** *Effects of the traffic flow and* α *on* $N_{LE}$ *(3 Lanes,* L = *1 km).*

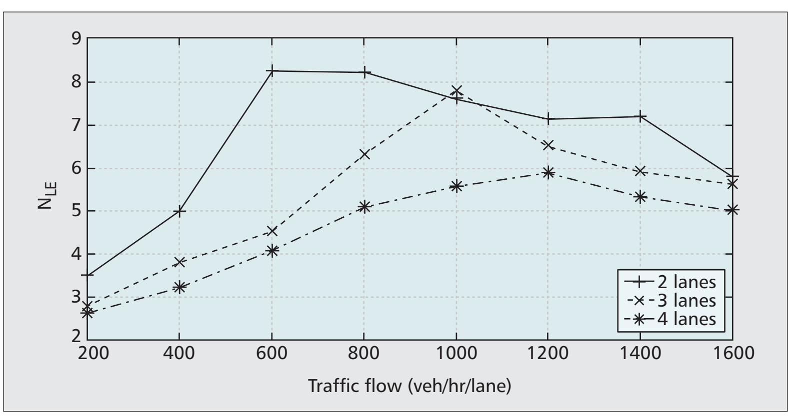


**Figure 8.** *Effect of the number of lanes on* $N_{LE}$ *(*L = *1 km,* α = *0).*

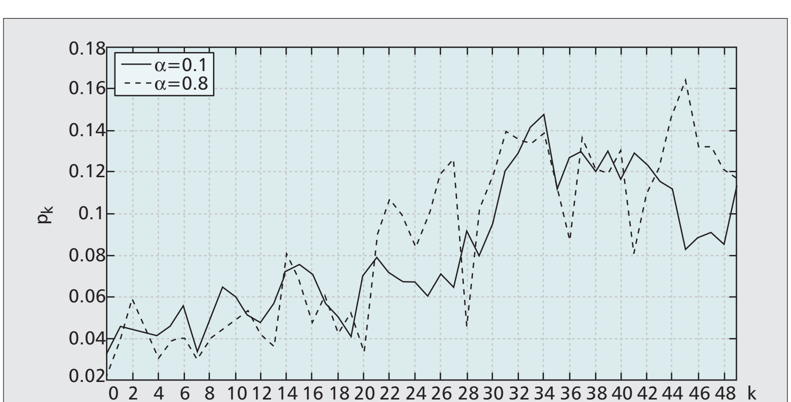


**Figure 9.** *Transition probabilities* $p_k$ *for LEMM simulation (the traffic trace is generated from the highway measurement).*

**Improvement of LEMM over BMM:** Figure 9 plots the improvement of LEMM over BMM, which is defined as the percentage of registrations saved under the condition $|LA| = |LA^*|$ (i.e., under the same paging cost). It is clear that for BMM with the location area size $|LA|$, the expected number of BMM registration for an OBU can be easily calculated as $N_B = \lfloor 100/|LA| \rfloor$. The improvement of LEMM over BMM is defined as

$$\text{Improvement (\%)} = (N_B - N_{LE})/N_B$$

Figure 10 shows that LEMM significantly outperforms BMM. For example, when $L = 1$ (i.e., $|LA| = |LA^*| = 3$ and $N_B = 33$), the improvement of LEMM over BMM ranges from 78 percent to 92 percent. For various $L$ values in our experiments, we observe at least 75 percent saving of registration message delivery.

**Consistency between VisSim and Measurement**: Figure 11 plots the inter-registration time against α. The ■ curve is computed from the average of five real measurements. The ▲ curve is obtained from VisSim simulation of a 3-lane highway with desired vehicle speeds 100–110 km/hr and the traffic flow 3000 veh/hr. The curves indicate that the $N_{LE}$ trend of our highway measurement is consistent with that derived from VisSim. In this highway measurement, the average improvement of LEMM over BMM ranges from 43 percent to 56 percent.

## Conclusions

The WAVE short message protocol adequately provides broadcast services for vehicles (OBUs) through RSUs. To support unicast services, the WAVE system must track the locations of the OBUs, which is not defined in the WAVE specifications. WAVE mobility management may directly follow the existing mechanism used in cellular networks. However, this mechanism may not work in highways where the vehicles move very fast and the traffic volume is large. To resolve this issue, we proposed the location estimation-based mobility management (LEMM) that utilizes GPS to reduce the registration messages sent from an OBU to the network. The performance study indicated that LEMM can significantly reduce the registration overhead by 43–91 percent as compared with the traditional cellular mobility management approach at the same paging cost. Furthermore, LEMM does not need to partition the RSUs into LAs in advance, which effectively reduces the RSU configuration management cost. In future work, we will conduct further analysis regarding the processing load, failure recovery mechanism, and complexity of the calculations performed by the Location Server. We will also extend our research to support efficient wireless data access in the vehicular environments [10].

## Acknowledgment

Chi-Ling Chen's assistance in processing the traffic data is highly appreciated. The authors also express sincere thanks to the Wireless Communications Lab., Chunghwa Telecom Co. Ltd. (CHT), the Institute of Transportation, Ministry of Transportation and Communications (MOTC), and the Department of Transportation Technology and Management, National Chiao Tung University (NCTU) for their precious instruments, simulation programs and valuable advice on this article.

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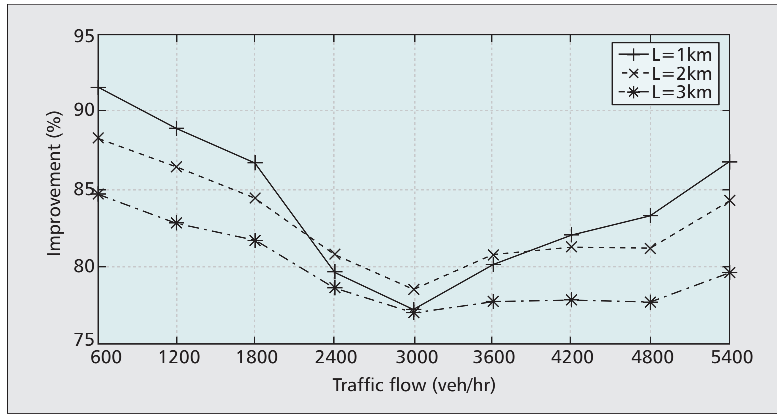


**Figure 10.** *Improvement of LEMM over BMM (3 Lanes, $\alpha = 0$).*

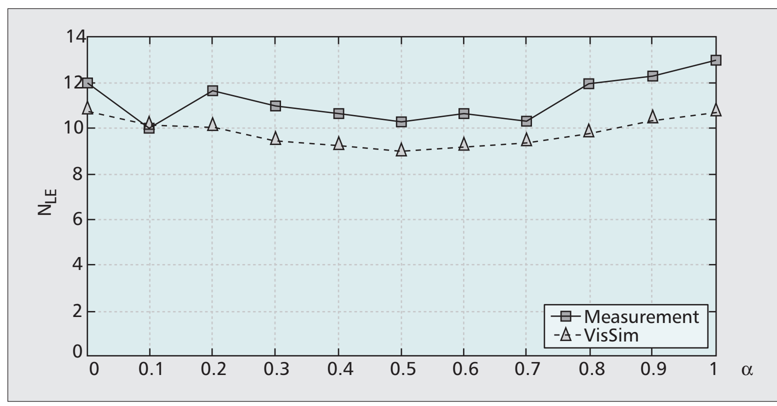


**Figure 11.** *Comparison of VisSim and measurement (L = 1 km).*