Vehicular Passenger Mobility-Aware Bandwidth Allocation in Mobile Hotspots

Younghyun Kim, Haneul Ko, Sangheon Pack, *Senior Member, IEEE*, and Xuemin (Sherman) Shen, *Fellow, IEEE*

***Abstract*—In this paper, we propose a vehicular passenger mobility-aware bandwidth allocation (V-MBA) scheme in mobile hotspots. The V-MBA scheme consists of both call admission control and bandwidth adjustment functions to lower handoff vehicle service dropping probability and efficiently utilize resource of base station. Specifically, a handoff priority scheme with guard bandwidth is employed to protect handoff vehicle service. Also, bandwidth is dynamically assigned to each vehicle by exploiting vehicular passenger movement pattern that includes getting on and off events at a station. We evaluate the V-MBA scheme by developing a continuous-time Markov chain model. Simulation results demonstrate that the V-MBA scheme can guarantee low new vehicle service blocking probability and handoff vehicle service dropping probability through flexible bandwidth allocation.**

***Index Terms*—Mobile hotspots, vehicular passenger mobility-aware bandwidth allocation, call admission control, bandwidth adjustment.**

I. INTRODUCTION

WITH the popularity of smart devices, the demand for Internet access in moving vehicles is increasing [2]. Diverse wireless communication technologies (e.g., wireless fidelity (Wi-Fi), worldwide interoperability for microwave access (WiMAX), and high speed packet access (HSPA)) are available in vehicular environments. In this paper, we focus on an emerging technology for vehicular networks, mobile hotspot, which introduces an integrated architecture of wireless local area networks (WLAN) and wireless wide area networks (WWAN). Mobile hotspots can provide extended service coverage to vehicles and accommodate more passengers without excessive usage of WWAN resources [3]. As shown in Figure 1, connections between an external base station (BS) and an access point (AP) attached to a vehicle are supported by WWAN. On the other hand, vehicular passengers are connected to the AP through WLAN. While stand-alone WLANs cannot provide satisfactory quality of service (QoS) in vehicular environments due to frequent disconnections [4]–[6], the integrated WWAN-WLAN can support better mobility management [3], energy-efficient connectivity (due to low power operation of WiFi [7]), and so on.

Resource management for the WWAN link should be carefully designed for successful deployment and satisfactory service in mobile hotspots. In particular, resource management schemes in mobile hotspots should consider the vehicular passenger movement pattern (i.e., getting on/off the vehicle). In vehicular environments, the number of passengers in a vehicle[1] is variable when it arrives at or departs from a station. In other words, some passengers may get in or get off vehicles at a station. As a result, the number of passengers in vehicles can be diverse and thus it is wasteful and inefficient for each vehicle to be assigned the same amount of bandwidth units, i.e., fixed bandwidth allocation. On the other hand, a vehicle moves between two adjacent cells (i.e., handoff vehicle) or newly starts within a cell (i.e., new vehicle). Generally, handoff vehicles should have higher priority than new vehicles when they try to acquire bandwidth units from a base station (BS) since passengers feel much worse quality of service (QoS) if ongoing calls are disrupted. Therefore, a handoff priority scheme is another important issue in mobile hotspots. Although extensive works (e.g., [8], [9]) for bandwidth allocation in WWANs have been conducted in the literature, most of them focus on a single mobile user rather than a set of mobile users with vehicular passenger mobility, and therefore they cannot be directly applied to mobile hotspots. Furthermore, previous works [10]–[15] on resource management in mobile hotspots do not consider the vehicular passenger movement pattern for resource management.

In this paper, we propose a vehicular passenger mobility-aware bandwidth allocation (V-MBA) scheme consisting of call admission control (CAC) and bandwidth adjustment (BA) functions to lower both handoff vehicle service dropping probability and new vehicle service blocking probability compared with the conventional handoff vehicle priority scheme. Specifically, a portion of bandwidth units is reserved to protect handoff vehicles. After that, new vehicles and handoff vehicles are accepted or blocked by the call admission control function. On the other hand, when a vehicle's ridership is changed, a BS adjusts the allocated bandwidth units for the vehicle depending on the number of passengers (i.e., adjustment vehicle). Hence, the BS can efficiently utilize its own resource and accept more handoff vehicles and new vehicles since spare bandwidth units of each vehicle are returned by the BA function. Note

[1]Throughout this paper, vehicles mean public transportations such as bus and subway.

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Y. Kim, H. Ko, and S. Pack are with the School of Electrical Engineering, Korea University, Seoul, Korea (e-mail: {younghyun_kim, st_basket, shpack}@korea.ac.kr). S. Pack is the corresponding author).

X. Shen is with the Department of Electrical and Computer Engineering, University of Waterloo, Canada (e-mail: xshen@bbcr.uwaterloo.ca).

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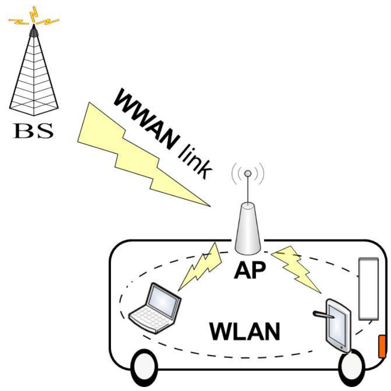

Fig. 1. Mobile hotspot architecture.

that additional bandwidth units are also provided to a vehicle when its ridership increases. By developing a two-dimensional continuous-time Markov chain (CTMC), we analyze the V-MBA scheme in terms of new vehicle service blocking probability, handoff vehicle service dropping probability, and adjustment vehicle service blocking probability. Analytical and simulation results demonstrate that the V-MBA scheme can guarantee lower new vehicle service blocking probability and handoff vehicle service dropping probability than the fixed bandwidth allocation scheme with guard bandwidth. Main contribution of this paper is two-fold: 1) this is the first work on resource management considering the vehicular passenger movement pattern in mobile hotspots; and 2) we develop the analytical model for the V-MBA scheme and validate the analytical results by extensive simulations.

The remainder of this paper is organized as follows. Section II summarizes the related works and Section III presents the system model. Section IV describes the V-MBA scheme. The analytical model based on the CTMC and numerical results are given in Sections V and VI, respectively. Finally, Section VII concludes this paper.

II. Related Work

Recently, extensive works on mobile hotspots have been conducted in the literature including performance analysis [16]–[18], security [19], [20], and proxy/gateway architecture [21]–[23]. Pack *et al.* [16] analyzed the TCP-friendly rate control protocol (TFRC) in mobile hotspots and showed that both channel condition and bandwidth of WWAN mainly affect the throughput of TFRC. In [17], the downlink and uplink throughputs were measured under various environments, i.e., high speed trains, subways, and cars, and it was shown that currently deployed mobile hotspots have poor and unstable throughput because of relatively low and fixed bandwidth in WWAN and channel contention in WLAN. Yang *et al.* [18] evaluated the packet-level performance of uplink video traffic in mobile hotspots by means of a discrete-time batch Markov-modulated process (D-BMAP) for the packet-level video traffic for the WLAN link. Taha and Shen [19] proposed a fake point-cluster-based location privacy scheme to provide location privacy for vehicular passengers within mobile hotspots. In addition, the same authors introduced secure and lightweight authentication/key agreement schemes for mobile hotspots in [20]. Pack *et al.* [21] developed a proxy cache to reduce the transmission cost over wireless links in mobile hotspots whereas Ahmed *et al.* [22] introduced a novel gateway which can support seamless switching between multiple wireless broadband technologies. Hare *et al.* [23] carried out extensive experiments and reported interesting measurement results in mobile hotspots. Specifically, user behavior and traffic usage patterns are characterized and several performance optimization techniques (e.g., caching) are discussed.

In terms of resource management in mobile hotspots, several works have been reported in the literature [10]–[15]. Niyato *et al.* [10] formulated a game-theoretic model for efficient resource allocation in an integrated WLAN/WWAN multihop relay architecture, and a bandwidth allocation scheme is introduced to maximize the utilities for the different types of connections. Song *et al.* [11] investigated WWAN bandwidth reservation with the delay constraint after analyzing the delay performance of mobile hotspots. Kim *et al.* [12] proposed a mobility-aware call admission control algorithm to maximally utilize resources with low handoff call dropping probability. Rabbani *et al.* [13] proposed a resource distribution algorithm in WLAN to provide QoS enabled connections by means of an adaptive scheduling scheme. Song *et al.* [14] proposed a call admission control scheme that limits the number of admitted calls in a mobile hotspot for guaranteed QoS. In addition, flow-level and packet-level analytical models were developed to derive the maximum number of admissible users. Song [15] proposed a bandwidth reservation scheme in order to reduce the packet delay for video applications under vehicular handover scenarios. The amount of reserved bandwidth units is estimated by the fractional Brownian motion process and the extended Markov-modulated Gamma-based model. However, these works do not consider the vehicular passenger movement pattern for resource management.

III. System Model

As shown in Figure 2, vehicles are classified into handoff vehicles, new vehicles, and adjustment vehicles. A handoff vehicle is defined as one coming into a tagged cell from another cell. On the other hand, a vehicle newly starting a call in the tagged cell is referred to as a new vehicle. The number of passengers in a vehicle can be changed when the vehicle stops at a station because several passengers get on or off the vehicle. Such a vehicle can request the adjustment of bandwidth units and thus it is named as an adjustment vehicle.

In vehicular environments, handoff vehicles should be assigned bandwidth units as much as ones in the previous cell in order to provide a consistent level of QoS to passengers even after handoff. Moreover, it is worse to disrupt ongoing calls than to block new calls with the respect to the user's perceived QoS. Therefore, handoff vehicles and adjustment vehicles should have higher priority than new vehicles when they compete bandwidth units of a BS. In this paper, the total capacity of a BS is assumed as C bandwidth units. Also, to implement the prioritization, $C-K$ bandwidth units are reserved for handoff vehicles and adjustment vehicles, and thus new vehicles can use up to K bandwidth units.

Due to the vehicular passenger movement pattern, the number of passengers is fluctuated and thus the fixed bandwidth

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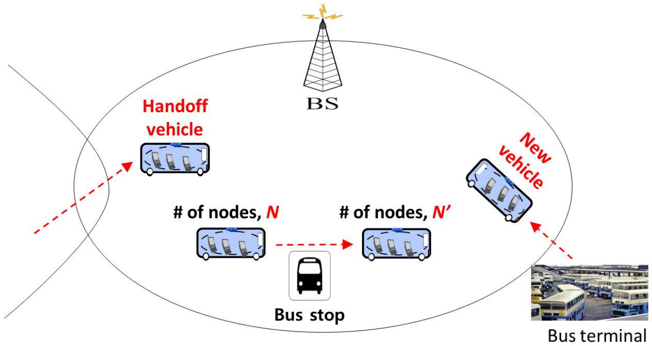

Fig. 2. System model.

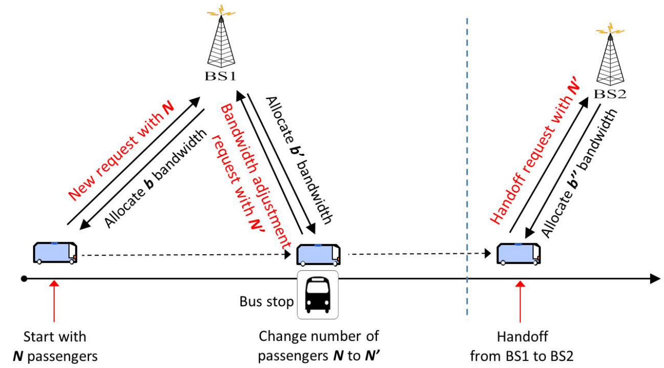

Fig. 3. Message flows in V-MBA.

allocation scheme can cause inefficient resource utilization since the required bandwidth units of the vehicle are dependent on the number of passengers. For example, suppose there are two vehicles whose riderships are 5 and 30, respectively, and the same bandwidth units of 2 are assigned to the vehicles. Then, the passengers in the latter vehicle experience worse QoS than the former one due to insufficient bandwidth units. Therefore, it needs to allocate bandwidth units proportionally to the number of passengers in the vehicle [24]. In this paper, it is assumed that each vehicle requires $\lceil \alpha \cdot N \rceil$ bandwidth units, where N is the number of passengers with active calls in the vehicle and α is the coefficient value for the appropriate bandwidth allocation[2]. $\lceil x \rceil$ is a function to return the minimum integer equal to or larger than x. Although N can be changed when the vehicle stops at a station or it is moving, N is significantly affected by the vehicular passenger movement (i.e., getting on or off the vehicle) at the station. In addition, the vehicular passenger mobility-aware bandwidth allocation during the vehicle's movement leads to significant signaling overhead and complexity. Therefore, it is assumed that N is regarded as the number of passengers, and thus N is constant when the vehicle is moving in this paper.

We also assume that the maximum number of passengers of a vehicle is L. Then, the number of bandwidth units which can be allocated to a vehicle is between 1 and $\lceil \alpha \cdot L \rceil$, and the state of a BS can be described by

$$\mathbb{V} = (v_1, v_2, \cdots, v_{\lceil \alpha \cdot L \rceil}), \tag{1}$$

where v_k represents the number of vehicles to be assigned k bandwidth units ($1 \leq k \leq \lceil \alpha \cdot L \rceil$).

IV. Vehicular Passenger Mobility-Aware Bandwidth Allocation Scheme

In this section, we first describe the proposed V-MBA scheme with an example. After that, implementation and deployment issues of the V-MBA scheme are discussed.

A. Description of V-MBA

Figure 3 shows the message flow for the V-MBA scheme, in which three request messages are defined: 1) new request, 2) handoff request, and 3) bandwidth adjustment request. When a vehicle is newly initiated within a cell, the vehicle sends a new request message with the current number of passengers, N, to request bandwidth allocation from the BS. On the other hand, when the vehicle performs a handoff from one cell to another, it should send a handoff request message that includes the information on the number of passengers in the vehicle. In vehicular environments, the vehicle stops at a station, and some passengers can get on/off the vehicle. Therefore, if the number of passengers is changed at the station, the vehicle sends a bandwidth adjustment request message. Intuitively, when the ridership is increased, more bandwidth units should be allocated whereas the previously allocated bandwidth units should be returned to the BS if the ridership is decremented.

In the V-MBA scheme, the CAC function determines whether to accept new or handoff vehicles and how many bandwidth units are assigned. On the contrary, the BA function determines whether to add or return bandwidth units when the bandwidth adjustment request message is received.

The V-MBA scheme is described in Algorithm 1. When a new request message with the ridership of N arrives at the BS, the CAC function is first run (lines 3-13 in Algorithm 1). As mentioned earlier, for fair bandwidth allocation, the number of bandwidth units for the new vehicle is determined based on the number of passengers N. That is, $b_r = \lceil \alpha \cdot N \rceil$ bandwidth units are requested by the new vehicle. When b_r bandwidth units are requested, the BS should check the remaining number of bandwidth units for new vehicles. In the CAC function, up to K bandwidth units can be used by new vehicles because $C - K$ bandwidth units are exclusively reserved for handoff vehicles. Therefore, the remaining bandwidth units for new vehicles are computed as

$$r_n = K - \sum_{k=1}^{\lceil \alpha \cdot L \rceil} k \cdot v_k. \tag{2}$$

When the required number of bandwidth units is equal to or less than the available bandwidth units (i.e., $b_r \leq r_n$), the new vehicle is accepted and b_r bandwidth units are allocated. After allocating b_r bandwidth units, v_{b_r} is incremented by one. On the contrary, if there are no sufficient bandwidth units (i.e., $0 < r_n < b_r$), the remaining bandwidth units of r_n are assigned to the new vehicle and v_{r_n} is incremented by one. If r_n is 0, the BS cannot assign any more bandwidth units to the new vehicle.

[2]The parameter α determines the maximum number of bandwidth units to be allocated to a vehicle. Therefore, α can be selected by considering the network operators' policy and the available network bandwidth in target wireless systems. For example, the maximum bandwidth for video streaming services in WiMAX networks is set to 8 Mbps in [25].

The operation of the CAC function for the handoff request message is similar to that for the new request message (lines 14-24 in Algorithm 1). When the handoff request message is received, the BS computes the available bandwidth units for the handoff vehicle. Since handoff vehicles can use all C bandwidth units, the available bandwidth units for handoff vehicles can be computed as

$$r_h = C - \sum_{k=1}^{\lceil \alpha \cdot L \rceil} k \cdot v_k. \tag{3}$$

Then, the requested bandwidth units of b_r are allocated if r_h is equal to or larger than b_r. In sequel, v_{b_r} is incremented by one. Otherwise, the available bandwidth units r_h are assigned to the handoff vehicle and v_{r_h} is incremented by one. Note that insufficient bandwidth units can be allocated to handoff or new vehicles when no sufficient bandwidth units are remained; however, there is a chance to receive more bandwidth units by means of the BA function.

The BA function is called when the BS receives a bandwidth adjustment request message (lines 25-45 in Algorithm 1). Note that the total BS capacity, C bandwidth units, can be used for the BA function. Differently from the CAC function, the currently allocated bandwidth unit b_c to the vehicle is notified to the BS for bandwidth reallocation. As illustrated earlier, the required number of bandwidth units b_r is computed as $\lceil \alpha \cdot N \rceil$ where N is the number of passengers when the bandwidth adjustment request is sent.

When the number of passengers in the vehicle is reduced (e.g., more passengers take off the vehicle), b_r is less than b_c. In such a case, excessive bandwidth units (i.e., $b_c - b_r$) should be returned to the BS. That is, the BS newly computes b_r and the corresponding bandwidth units are assigned to the vehicle (lines 28-31 in Algorithm 1). Accordingly, the BS state $\mathbb{V}$ is updated. In this manner, it is possible to improve the resource utilization in the V-MBA scheme.

On the other hand, if b_r is larger than b_c, more bandwidth units should be allocated and the remaining bandwidth units at the BS should be checked (lines 32-42 in Algorithm 1). When the available bandwidth units r_h is equal to or larger than $b_r - b_c$, $b_r - b_c$ bandwidth units are additionally allocated, i.e., the vehicle is assigned the requested $b_r (= b_c + (b_r - b_c))$ bandwidth units. On the contrary, if the available bandwidth units r_h is less than $b_r - b_c$, only r_h bandwidth units can be augmented. That is, $b_c + r_h$ bandwidth units are assigned to the vehicle. For both cases, the BS state is updated after allocating bandwidth. Of course, when there is no available bandwidth unit at the BS, no further action is done. If the required number of bandwidth units b_r is the same as b_c, no further operations are conducted and b_c bandwidth units are still used.

For example, assume that C and K are 5 and 1, respectively. When a new request message arrives at the BS and its b_r is 2, one bandwidth unit is assigned to the vehicle because only one bandwidth unit is available for the new vehicle (i.e., $r_n = 1$). After allocating the bandwidth unit, the state of the BS, $\mathbb{V}$, is updated from $(v_1, v_2, \cdots, v_{\lceil \alpha \cdot L \rceil})$ to $(v_1 + 1, v_2, \cdots, v_{\lceil \alpha \cdot L \rceil})$. Also, r_n and r_h become 0 and 4, respectively. This represents that new vehicles cannot be admitted by the BS until other

Algorithm 1: Vehicular passenger mobility-aware bandwidth allocation scheme.

1 Receive a request message with N;
2 **switch** *message* **do**
3   **case** *New request*
4   Calculate b_r and r_n;
5   **if** $b_r \leq r_n$ **then**
6   Assign b_r bandwidth units;
7       $v_{b_r} \leftarrow v_{b_r} + 1$;
8   **else if** $0 < r_n$ **then**
9   Assign r_n bandwidth units;
10       $v_{r_n} \leftarrow v_{r_n} + 1$;
11   **else**
12   Block a new request;
13
14   **endsw**
15   **case** *Handoff request*
16   Calculate b_r and r_h;
17   **if** $b_r \leq r_h$ **then**
18   Assign b_r bandwidth units;
19       $v_{b_r} \leftarrow v_{b_r} + 1$;
20   **else if** $0 < r_h$ **then**
21   Assign r_h bandwidth units;
22       $v_{r_h} \leftarrow v_{r_h} + 1$;
23   **else**
24   Block a handoff request;
25
26   **endsw**
27   **case** *Bandwidth adjustment request*
28   Calculate b_r and r_h;
29   Bring b_c currently allocated bandwidth units;
30   **if** $b_r < b_c$ **then**
31   Assign b_r bandwidth units;
32       $v_{b_c} \leftarrow v_{b_c} - 1$;
33       $v_{b_r} \leftarrow v_{b_r} + 1$;
34   **else if** $b_r > b_c$ **then**
35   **if** $b_r - b_c \leq r_h$ **then**
36   Assign b_r bandwidth units;
37         $v_{b_c} \leftarrow v_{b_c} - 1$;
38         $v_{b_r} \leftarrow v_{b_r} + 1$;
39   **else if** $0 < r_h$ **then**
40   Assign $r_h + b_c$ bandwidth units;
41         $v_{b_c} \leftarrow v_{b_c} - 1$;
42         $v_{r_h + b_c} \leftarrow v_{r_h + b_c} + 1$;
43   **else**
44   Keep b_c bandwidth units;
45
46   **else**
47   Keep b_c bandwidth units;
48
49   **endsw**
50 **endsw**

vehicles return their allocated bandwidth units. On the contrary, handoff vehicles can obtain bandwidth units since r_h is 4. Suppose that the vehicle's ridership changes at a station and two bandwidth units are needed. Then, the vehicle sends a bandwidth adjustment request message to adjust the amount of bandwidth units and the request can be accepted because there are available bandwidth units for the BA function. After that, $\mathbb{V}$ is changed to $(v_1, v_2+1, \cdots, v_{\lceil \alpha \cdot L \rceil})$; then r_n and r_h become 0 and 3, respectively. To conclude, the V-MBA scheme can give additional chance of allocating bandwidth units to a vehicle that did not receive sufficient bandwidth units in the previous trail.

B. Deployment and Implementation Issues

To deploy the V-MBA scheme in real environments, some V-MBA functions should be implemented at the AP. In particular, the AP requires the information on the number of mobile nodes (MNs) in a vehicle. Since each MN has a unique identification (e.g., MAC address) and conducts a WiFi association procedure when it is connected to the AP, the number of MNs in a vehicle can be easily measured by counting the number of WiFi association messages. Depending on the measured information, the AP sends a bandwidth allocation request message and therefore the function for sending the request message should be also implemented at the AP. Recently, several prototypes on the AP in mobile hotspots have been reported in [23], [26]. We believe above-mentioned key functions of the V-MBA scheme can be easily implemented at those prototypes.

In the V-MBA scheme, the BS should support proportional bandwidth allocation to the number of MNs, and the function can be tactically supported in most of recent wireless communication systems. For example, discrete bandwidth units in OFDMA-based wireless communications systems (e.g., WiMAX and LTE) can be defined by adjusting time/frequency block sizes of the frame structure as in [27], [28]. In sequel, the total capacity of the BS can be assumed as a fixed number of bandwidth units. In addition, the BS can dynamically adjust the amount of bandwidth units to be allocated to each vehicle by considering its remaining capacity as in [29].

Note that the V-MBA scheme does not require any modifications to MNs; conventional MNs with WiFi interfaces can utilize the V-MBA scheme by connecting to the AP with the V-MBA functions. Therefore, the V-MBA scheme can be widely deployed in mobile hotspot environments.

V. Performance Analysis

In this section, we analyze the V-MBA scheme by considering both the vehicular passenger movement pattern and the vehicular mobility (movement between two adjacent stations). First, in order to investigate the effects of the vehicular passenger movement pattern, we induce the limiting distribution on the number of passengers by getting on/off events. After that, a CTMC model on the BS state $\mathbb{V}$ is developed. Important notations for the analytical model are summarized in Table I.

For the CTMC model of the V-MBA scheme, we have the following assumptions.

- The arrival processes of new vehicle and handoff vehicle follow Poisson distributions with rates λ_n and λ_h, respectively [30].
- The cell residence time of each vehicle follows an exponential distribution with mean $\frac{1}{\mu_c}$.
- The moving time of each vehicle between two adjacent stations follows an exponential distribution with mean $\frac{1}{\mu_m}$.

Let X_t be the number of passengers in a vehicle when it leaves the tth station. Also, Y_t and Z_t represent the numbers of passengers who board and take off at the tth station, respectively. Then, we have $\{X_t = X_{t-1} + Y_t - Z_t,\, t > 0\}$, and it is an embedded discrete-time Markov chain since X_t only depends on X_{t-1}. Assume that Y_t is an independent and identically distributed random variable and follows a general distribution $p_k = \Pr(Y_t = k)$, where $0 \le k \le L$. Every passenger has a probability p of taking off a vehicle at each station. Then, the one-step transition probability $\mathbf{P_{ab}} = \Pr\{X_t = b | X_{t-1} = a\}$, where $0 \le a, b \le L$, can be obtained as Eq. (4)[3].

Based on Eq. (4), we can obtain the limiting distribution on the number of passengers $\phi_b = \lim_{t\to\infty} \Pr\{X_t = b\}$ by Chapman-Kolmogorov equation [31].

After that, we can develop the CTMC model with the finite state space $\mathbb{V}$. For tactical analysis, we assume that $\alpha = \frac{2}{L}$ since the dimension of $\mathbb{V}$ is in proportion to $\lceil \alpha \cdot L \rceil$, as shown in Eq. (1). However, the CTMC model can be extended to consider other values of α. When α is $\frac{2}{L}$, $\mathbb{V}$ becomes (v_1, v_2) and the BS allocates one and two bandwidth units to the vehicles with $0 \sim \frac{L}{2}$ and $\left(\frac{L}{2}+1\right) \sim L$ passengers, respectively. Let s_1 and s_2 be the steady probabilities that the number of passengers in each vehicle is 0 to $\frac{L}{2}$ and $\frac{L}{2}+1$ to L, respectively, and they can be computed as

$$s_1 = \sum_{b=0}^{\frac{L}{2}} \phi_b \qquad (5)$$

$$s_2 = \sum_{b=\frac{L}{2}+1}^{L} \phi_b. \qquad (6)$$

That is, s_1 and s_2 are the probabilities that an arrived vehicle is assigned one and two bandwidth units, respectively. Then, the developed CTMC model on $\mathbb{V}$ can be illustrated as Figure 4, where it is assumed that C and K are even numbers, and C_f and K_f represent $C/2$ and $K/2$, respectively. As mentioned earlier, i and j respectively represent the number of vehicles assigned 1 and 2 bandwidth units in state (i, j), where $0 \le i + 2j \le C$. By the superposition property of Poisson process, the total vehicle arrival rate into a cell is $\lambda_n + \lambda_h$.

In states (i, j) where $K \le i+2j$, only handoff vehicles can acquire bandwidth units from the BS since $C - K$ bandwidth units are reserved for handoff vehicles; thus, the arrival rates from (i, j) to $(i+1, j)$ and $(i, j+1)$ are given by $s_1\lambda_h$ and $s_2\lambda_h$, respectively. On the other hand, in states $(1, C_f - 1)$ and $(3, C_f - 2)$, handoff vehicles can acquire only one bandwidth unit regardless of vehicular status because there is only one

[3]See Appendix A for detailed derivations of the one-step transition probability.

TABLE I
SUMMARY OF NOTATIONS.

Notation	Description
C	Total capacity of a base station
K	Threshold value for the handoff prioritization
L	Maximum number of passengers in a vehicle
α	Coefficient value for bandwidth allocation
λ_n	Arrival rate for new vehicles
λ_h	Arrival rate for handoff vehicles
$1/\mu_c$	Average cell residence time for vehicles
$1/\mu_m$	Average moving time of vehicle between adjacent stations
ϕ_b	Steady state probability that there are b passengers in a vehicle
$\pi_{i,j}$	Steady state probability that there are i and j vehicles assigned one and two bandwidth units
P_{NV}	New vehicle service blocking probability
P_{HV}	Handoff vehicle service dropping probability
P_{AV}	Adjustment vehicle service blocking probability

$$\mathbf{P_{ab}} = \begin{pmatrix} p_0 & p_1 & p_2 & \cdots & p_L \\ pp_0 & \sum_{k=0}^{1}\binom{1}{k}p^k(1-p)^{1-k}p_k & \sum_{k=0}^{1}\binom{1}{k}p^k(1-p)^{1-k}p_{k+1} & \cdots & 1-\sum_{b=0}^{L-1}\mathbf{P}_{1b} \\ p^2p_0 & \sum_{k=1}^{2}\binom{2}{k}p^k(1-p)^{2-k}p_{k-1} & \sum_{k=0}^{2}\binom{2}{k}p^k(1-p)^{2-k}p_k & \cdots & 1-\sum_{b=0}^{L-1}\mathbf{P}_{2b} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p^Lp_0 & \sum_{k=L-1}^{L}\binom{L}{k}p^k(1-p)^{L-k}p_{k+1-L} & \sum_{k=L-2}^{L}\binom{L}{k}p^k(1-p)^{L-k}p_{k+2-L} & \cdots & 1-\sum_{b=0}^{L-1}\mathbf{P}_{Lb} \end{pmatrix} \quad (4)$$

available bandwidth unit. Hence, the arrival rates in such states are λ_h. Diagonal lines in Figure 4 represent bandwidth adjustment events. State transitions from (i,j) to $(i+1,j-1)$ for $0 \le i < C$, $0 < 2j \le C$, and $i+2j \le C$ are always possible since they indicate that vehicles return their excessive bandwidth units and the corresponding transition rate from (i,j) to $(i+1,j-1)$ is $s_1 j\mu_m$ due to the memoryless property of an exponential distribution. Similarly, the state transition rate from (i,j) to $(i-1,j+1)$ is $s_2 i\mu_m$. On the contrary, when $i+2j=C$, the transition rate is zero because no bandwidth unit is available at the BS. In short, the state transition rates $p(i,j;i',j')$ from state (i,j) to (i',j') can be summarized as

$$\begin{aligned} p(i,j;i,j+1) &= s_2(\lambda_n+\lambda_h),\ \text{for } i+2j<K \\ p(i,j;i,j+1) &= s_2\lambda_h,\ \text{for } K \le i+2j<C \\ p(i,j;i+1,j) &= s_1(\lambda_n+\lambda_h),\ \text{for } i+2j<K \\ p(i,j;i+1,j) &= s_1\lambda_h,\ \text{for } K\le i+2j<C-1 \\ p(i,j;i+1,j) &= \lambda_h,\ \text{for } i+2j==C-1 \\ p(i,j+1;i,j) &= (j+1)\mu_c,\ \text{for } i+2(j+1)<C \\ p(i+1,j;i,j) &= (i+1)\mu_c,\ \text{for } (i+1)+2j<C \\ p(i,j+1;i+1,j) &= s_1(j+1)\mu_m,\ \text{for } i+2(j+1)\le C \\ p(i+1,j;i,j+1) &= s_2(i+1)\mu_m,\ \text{for } (i+1)+2j<C. \end{aligned}$$

Let $\pi_{i,j}$ denote the steady state probability that there are i and j vehicles assigned one and two bandwidth units, respectively. Then, the balance equations can be obtained as Eq. (7) where $max(a,b)$ returns the maximum of a and b, and $u(x)$ returns 0 and 1 when $x \le 0$ and $x > 0$, respectively. Finally, the steady state probabilities $\pi_{i,j}$ can be obtained numerically by means of an iterative algorithm [32].

As for performance evaluation, the new vehicle service blocking probability, the handoff vehicle service dropping probability, and the adjustment vehicle service blocking probability are studied. The new vehicle service blocking probability is defined as the ratio of the number of blocked new vehicles to the total number of initiated new vehicles in the cell. Since the service of a new vehicle is blocked when the number of occupied bandwidth units is equal to or larger than K, the new vehicle service blocking probability P_{NV} can be obtained as

$$P_{NV} = \sum_{K\le i+2j\le C}\pi_{i,j}. \quad (8)$$

On the other hand, the handoff vehicle service dropping probability is defined as the ratio of the number of dropped handoff vehicles to the total number of incoming handoff vehicles. The service of a handoff vehicle is dropped when there is no more bandwidth unit. Hence, the handoff vehicle service dropping probability P_{HV} is given by

$$P_{HV} = 1 - \sum_{i+2j<C}\pi_{i,j}. \quad (9)$$

In addition, the adjustment vehicle service blocking probability P_{AV} is defined as the probability that a vehicle cannot acquire additional bandwidth units due to insufficient resources at the BS although the ridership of the vehicle has been increased. Since the blocking events of adjustment requests occur both when there is no more bandwidth unit for adjustment requests at the BS and when the number of vehicles possessing one bandwidth unit is at least one, P_{AV} can be obtained by

$$P_{AV} = P_{HV} - \pi_{0,C_f}. \quad (10)$$

VI. Simulation Results

In this section, we evaluate the performance of the V-MBA scheme and compare it with the fixed bandwidth allocation

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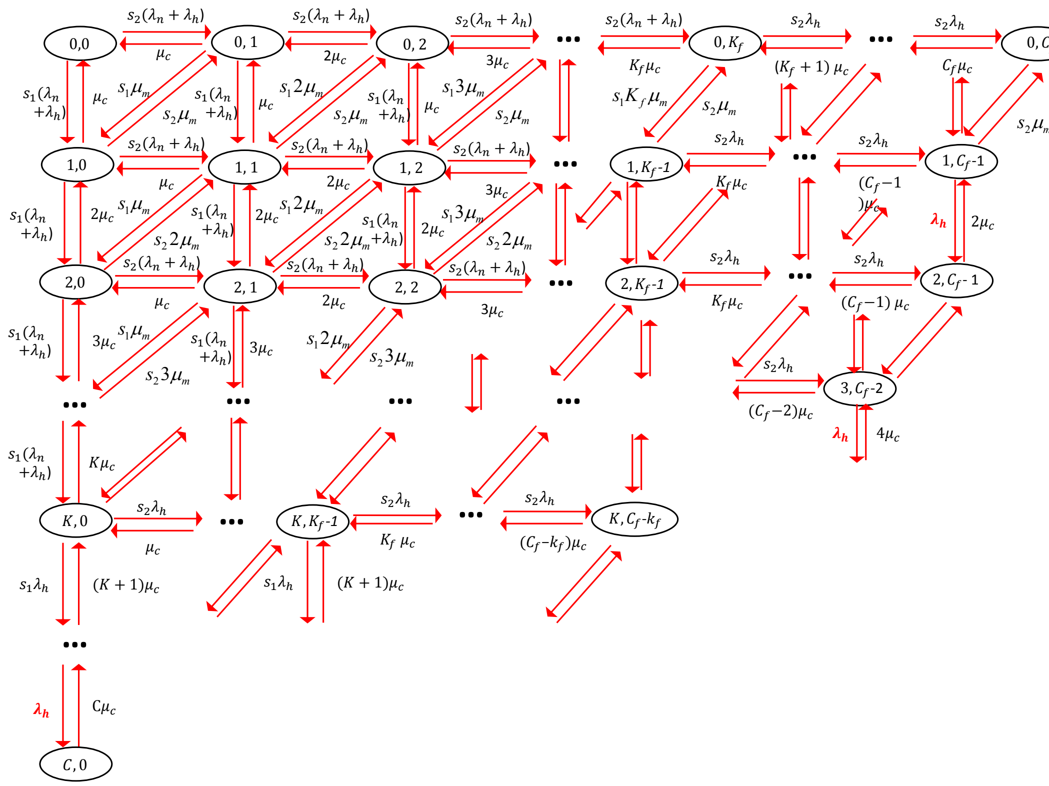

Fig. 4. Two-dimensional CTMC for the V-MBA scheme.

1) $0 \le i$, $0 \le j$, and $i + 2j < C - 1$

$$\Bigg[s_1\Big\{\lambda_h + u\Big(K - (i+2j)\Big)\cdot\lambda_n\Big\} + s_2\Big\{\lambda_h + u\Big(K - (i+2j)\Big)\cdot\lambda_n\Big\} + (i+j)\,\mu_c + (s_1 j + s_2 i)\,\mu_m\Bigg]\pi_{i,j}$$
$$= u(i)\cdot s_1\cdot\Big\{\lambda_h + u\Big(K-(i-1+2j)\Big)\cdot\lambda_n\Big\}\pi_{max(0,i-1),j}$$
$$+ u(j)\cdot s_2\cdot\Big\{\lambda_h + u\Big(K-(i+2(j-1))\Big)\cdot\lambda_n\Big\}\pi_{i,max(0,j-1)}$$
$$+ \mu_c\,(i+1)\,\pi_{i+1,j} + \mu_c\,(j+1)\,\pi_{i,j+1} + u(i)\cdot s_1\,(j+1)\,\mu_m\cdot\pi_{max(0,i-1),j+1}$$
$$+ u(j)\cdot s_2\,(i+1)\,\mu_m\cdot\pi_{i+1,max(0,j-1)},$$

2) $0 \le i$, $0 \le j$, and $i + 2j = C - 1$

$$\Big(\lambda_h + (i+j)\,\mu_c + (s_1 j + s_2 i)\,\mu_m\Big)\pi_{i,j}$$
$$= u(i)\cdot s_1\cdot\lambda_h\cdot\pi_{max(0,i-1),j} + u(j)\cdot s_2\cdot\lambda_h\cdot\pi_{i,max(0,j-1)}$$
$$+ \mu_c\,(i+1)\,\pi_{i+1,j} + u(i)\cdot s_1\,(j+1)\,\mu_m\cdot\pi_{max(0,i-1),j+1}$$
$$+ u(j)\cdot s_2\,(i+1)\,\mu_m\cdot\pi_{i+1,max(0,j-1)},$$

3) $0 \le i$, $0 \le j$, and $i + 2j = C$

$$\Big((i+j)\,\mu_c + s_1\cdot j\cdot\mu_m\Big)\pi_{i,j} = u(i)\cdot\lambda_h\cdot\pi_{max(0,i-1),j} + u(j)\cdot s_2\cdot\lambda_h\cdot\pi_{i,max(0,j-1)}$$
$$+ u(j)\cdot s_2\,(i+1)\,\mu_m\cdot\pi_{i+1,max(0,j-1)}. \tag{7}$$

(FBA) schemes with/without guard bandwidth. In the FBA scheme, the same amount of bandwidth units is assigned to each vehicle regardless of the number of passengers. In addition, $C - K$ bandwidth units are reserved for handoff vehicles in the FBA scheme with guard bandwidth. For the FBA scheme without guard bandwidth, the new vehicle service blocking probability ($P_{NV}^{without}$) is the same as the handoff vehicle service dropping probability ($P_{HV}^{without}$), and they are

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TABLE III
ANALYTICAL RESULTS (A) VS. SIMULATION RESULTS (S).

λ_h	P_{HV} (A)	P_{HV} (S)	P_{NV} (A)	P_{NV} (S)
2	0.0	0.0	0.071	0.043
3	0.0	0.0	0.212	0.173
4	0.0	0.0	0.395	0.35
5	0.002	0.001	0.587	0.481
6	0.013	0.007	0.761	0.652
7	0.041	0.048	0.888	0.8
8	0.093	0.089	0.957	0.874
9	0.156	0.148	0.986	0.905
10	0.22	0.199	0.995	0.937
11	0.279	0.26	0.998	0.938

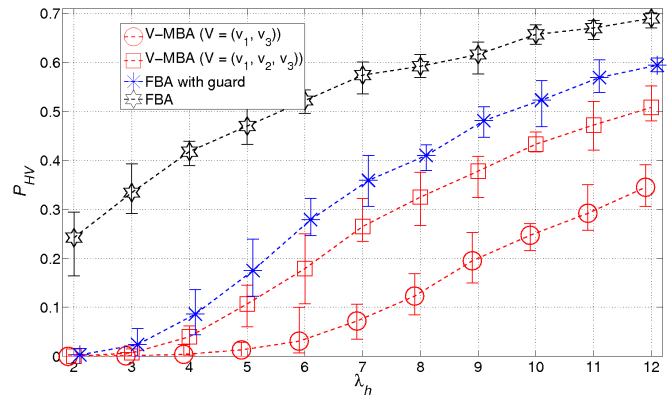

Fig. 5. P_{HV} as a function of λ_h.

given by

$$P_{NV}^{without} = P_{HV}^{without} = \frac{\frac{(\rho_n+\rho_h)^C}{C!}}{\sum_{n=0}^{C} \frac{(\rho_n+\rho_h)^n}{n!}} \quad (11)$$

where ρ_n and ρ_h represent λ_n/μ_c and λ_h/μ_c, respectively [33]. On the other hand, the new vehicle service blocking probability and the handoff vehicle service dropping probability of the FBA schemes with guard bandwidth, denoted by P_{NV}^{with} and P_{HV}^{with}, are respectively obtained as

$$P_{NV}^{with} = \frac{\sum_{j=K}^{C} \frac{(\rho_n+\rho_h)^K \rho_h^{j-K}}{j!}}{\sum_{j=0}^{K} \frac{(\rho_n+\rho_h)^j}{j!} + \sum_{j=K+1}^{C} \frac{(\rho_n+\rho_h)^K \rho_h^{j-K}}{j!}} \quad (12)$$

and

$$P_{HV}^{with} = \frac{\frac{(\rho_n+\rho_h)^K \rho_h^{C-K}}{C!}}{\sum_{j=0}^{K} \frac{(\rho_n+\rho_h)^j}{j!} + \sum_{j=K+1}^{C} \frac{(\rho_n+\rho_h)^K \rho_h^{j-K}}{j!}}. \quad (13)$$

For numerical analysis, we do not consider any specific target wireless systems. Instead, we evaluate the performance of the V-MBA scheme over a wide range of parameters. Specifically, we set $C = 90$ and $K = 75$. The mean cell residence time $1/\mu_c$ and traveling time between two adjacent stations $1/\mu_m$ of a vehicle are assumed as 10 (minutes) and 2 (minutes), respectively. Also, we assume that vehicular passenger arrival process Y_t at a station follows a Poisson distribution with rate λ_u. Finally, the maximum number of passengers of a vehicle L and the new vehicle arrival rate λ_n are set to 60 and 4, respectively. The probability of alighting from a vehicle p follows a uniform distribution between 0 and p_{max} where the default value of p_{max} is 0.8. The effects of the handoff vehicle arrival rate λ_h, the vehicular passenger arrival rate λ_u, and p are examined in the following subsections. Simulation parameter settings are summarized in Table II.

To verify the analytical model, we have developed an event-driven simulator and conducted ten simulation runs for 20 hours with different seed values independently. Table III shows the analytical and simulation results. From Table III, it can be found that the analytical results are consistent with the simulation results.

A. Effect of λ_h

To compare the performance of the V-MBA and FBA schemes, it is assumed that two bandwidth units are assigned to vehicles in the FBA scheme. We also consider two cases of the BS state $\mathbb{V}$, (v_1, v_3) and (v_1, v_2, v_3), to show the effect of fine-grained bandwidth allocation in V-MBA. When $\mathbb{V} = (v_1, v_3)$, the BS assigns one and three bandwidth units if $N \leq \frac{L}{2}$ and $N > \frac{L}{2}$, respectively, where N is the number of passengers in the vehicle. On the other hand, if $\mathbb{V} = (v_1, v_2, v_3)$, fine-grained bandwidth units can be allocated, i.e., one, two, and three bandwidth units are allocated to a vehicle if $N \leq \frac{L}{3}$, $\frac{L}{3} < N \leq \frac{2L}{3}$, and $N > \frac{2L}{3}$, respectively. In Figures 5, 6, and 7, λ_u and p_{max} are set to 10 and 0.8, respectively.

Figure 5 shows the effect of the handoff vehicle arrival rate λ_h on the handoff vehicle service dropping probability P_{HV}. Compared with the FBA scheme without guard bandwidth, P_{HV} in the V-MBA scheme can be drastically reduced by preserving guard bandwidth units for handoff vehicles. From Figure 5, it can be also seen that the V-MBA scheme can reduce P_{HV} even compared with the FBA scheme with guard bandwidth. This is because the V-MBA scheme fairly allocates bandwidth units depending on the number of passengers in the vehicle and bandwidth units can be flexibly reallocated by means of the bandwidth adjustment function when the vehicle's ridership is changed. In addition, the V-MBA scheme with $\mathbb{V} = (v_1, v_3)$ has lower P_{HV} than the V-MBA scheme with $\mathbb{V} = (v_1, v_2, v_3)$ since the former allocates one bandwidth unit to more vehicles whereas the latter assigns two bandwidth units more frequently. Interestingly, the V-MBA scheme with $\mathbb{V} = (v_1, v_2, v_3)$ has lower P_{HV} than the FBA scheme with guard bandwidth. This indicates that the V-MBA scheme can provide better QoS to vehicular passengers than the FBA scheme in handoff scenarios.

Even though the guard bandwidth is effective to reduce the handoff vehicle service dropping probability, it can increase the new vehicle service blocking probability P_{NV}. As shown in Figure 6, the FBA scheme with guard bandwidth has higher P_{NV} than the FBA scheme without guard bandwidth. Due to the same reason, the V-MBA scheme with $\mathbb{V} = (v_1, v_2, v_3)$ has higher P_{NV} than the FBA scheme without guard bandwidth. On the contrary, it can be seen that P_{NV} of the V-MBA scheme with $\mathbb{V} = (v_1, v_3)$ is lower than that of the FBA scheme without guard bandwidth when $\lambda_h < 4$. If $\lambda_h < 4$, there are few handoff vehicles in the cell area and thus less bandwidth units are used by handoff vehicles. Therefore, more bandwidth units can be used by new vehicles and P_{NV} of

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TABLE II
SIMULATION PARAMETER SETTINGS.

C	K	$1/\mu_c$	$1/\mu_m$	λ_u	p_{max}	L	λ_n	λ_h
90	75	10 (minutes)	2 (minutes)	$6 \sim 14$	$0.2 \sim 1.0$	60	4	$2 \sim 12$

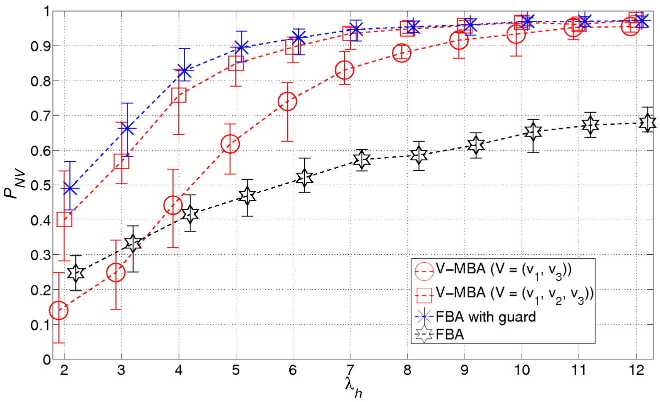

Fig. 6. P_{NV} as a function of λ_h.

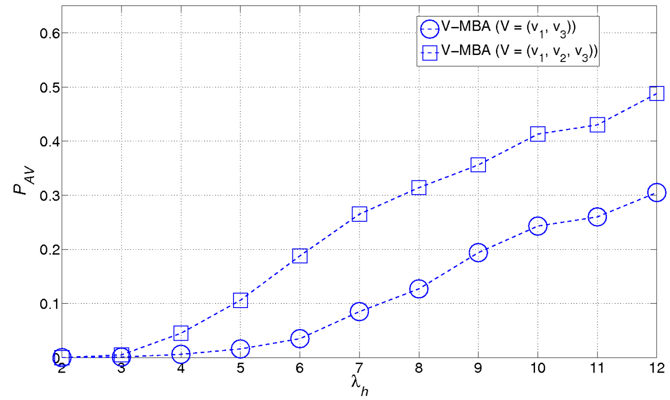

Fig. 7. P_{AV} as a function of λ_h.

the V-MBA scheme with $\mathbb{V} = (v_1, v_3)$ is lower than the FBA scheme without guard bandwidth when λ_h is very low although guard bandwidth units are set for handoff vehicles. In addition, it can be also seen that two V-MBA schemes have lower P_{NV} than the FBA scheme with guard bandwidth since the V-MBA schemes manage bandwidth units in a flexible manner.

Figure 7 shows the adjustment vehicle service blocking probabilities P_{AV} as a function of λ_h. P_{AV} is defined as the probability that a vehicle cannot acquire additional bandwidth units due to insufficient resources at the BS although the ridership of the vehicle increases. Intuitively, P_{AV} increases with the increase of λ_h since the total bandwidth units are consumed more aggressively by handoff vehicles. P_{AV} of the V-MBA scheme with $\mathbb{V} = (v_1, v_3)$ is lower than that of the V-MBA scheme with $\mathbb{V} = (v_1, v_2, v_3)$ because the BS allocates more than two bandwidth units to a large number of vehicles if the state of the BS is (v_1, v_2, v_3). Note that, in the V-MBA scheme, even though a vehicle cannot acquire additional bandwidth units, the vehicle can maintain the existing connection using the previously assigned bandwidth units. Moreover, the V-MBA scheme allows another chance to get more bandwidth units at the next station by means of the bandwidth adjustment function.

In order to consider more realistic environments, we conduct more simulations by assuming that the traveling time between two adjacent stations $1/\mu_m$ follows a Gamma distribution. Gamma distribution is widely accepted for comprehensive simulations because it is versatile and can emulate any general distribution by selecting appropriate mean and variance [34]. Figure 8 shows P_{HV} and P_{NV} when the variance of the traveling time between two adjacent stations is high, i.e., the variance is 10 times larger than those of Figures 5 and 6. From Figure 8, it can be observed that the average value of each scheme follows a similar tendency with Figures 5 and 6. Also, compared with Figures 5 and 6, the variances of P_{HV} and P_{NV} are not high in spite of high variance of the traveling time. Consequently, it can be concluded that the V-MBA scheme can work well under such dynamic environments.

B. Effect of λ_u

In this subsection, we investigate the effect of the vehicular passenger arrival rate into a vehicle λ_u. To this end, the handoff vehicle arrival rate λ_h and the new vehicle arrival rate λ_n are set to 6 and 4, respectively. Other parameter values are the same as those in the previous subsection.

Figure 9 shows P_{HV} when λ_u varies from 6 to 14. From Figure 9, it can be observed that P_{HV} of the FBA schemes with/without guard bandwidth are almost consistent since they do not consider the vehicular passenger movement pattern. On the contrary, as shown in Figure 9, P_{HV} of the V-MBA schemes increases as λ_u increases since more passengers require more bandwidth units. In particular, when λ_u exceeds 12 (or 13), P_{HV} of the V-MBA scheme with $\mathbb{V} = (v_1, v_2, v_3)$ (or $\mathbb{V} = (v_1, v_3)$) exceeds that of the FBA scheme with guard bandwidth. This is because a larger λ_u leads to an increase of the number of passengers, and thus most vehicles carry a large number of passengers. In other words, these vehicles require more bandwidth units (e.g., three bandwidth units). Hence, the V-MBA scheme has higher P_{HV} than the FBA scheme with guard bandwidth when λ_u is so high, but the V-MBA scheme can guarantee lower P_{HV} than the FBA scheme with guard bandwidth except such extreme cases.

Due to the same reason, P_{NV} of the V-MBA schemes increases as λ_u increases, and P_{NV} of the V-MBA schemes is larger than that of the FBA scheme with guard bandwidth when λ_u exceeds 12 as shown in Figure 10. However, it can be seen that P_{NV} of the V-MBA scheme is lower than or similar to that of the FBA scheme with guard bandwidth in most cases. If the value of λ_u is very low or high, the number of passengers in the vehicle is very small or large. Thus, one or three bandwidth units are assigned for most vehicles when λ_u is too low or high both in the V-MBA schemes with

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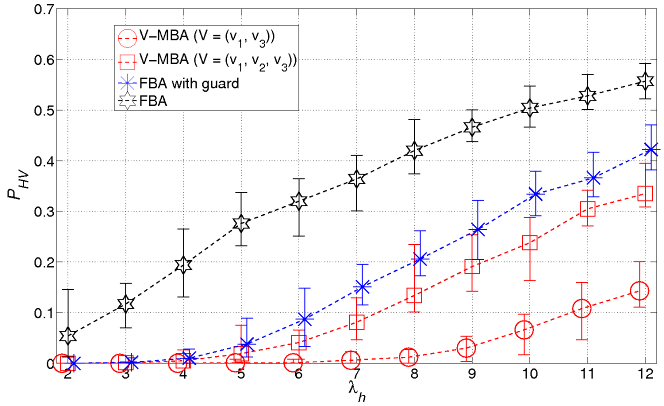
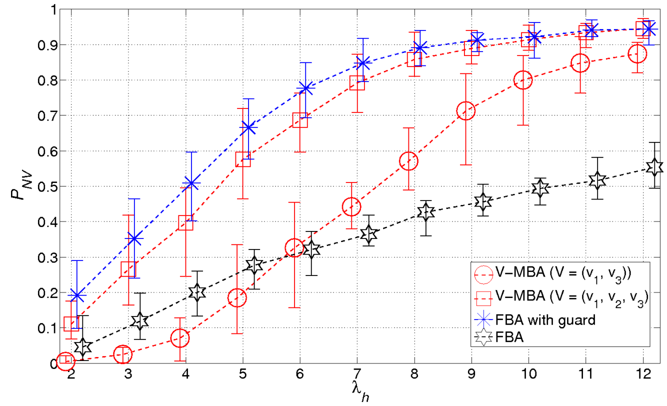


(a) Handoff vehicle service dropping probability



(b) New vehicle service blocking probability

Fig. 8. Effect of variance in traveling time (Gamma distribution with variance of $10/\mu_m^2$).

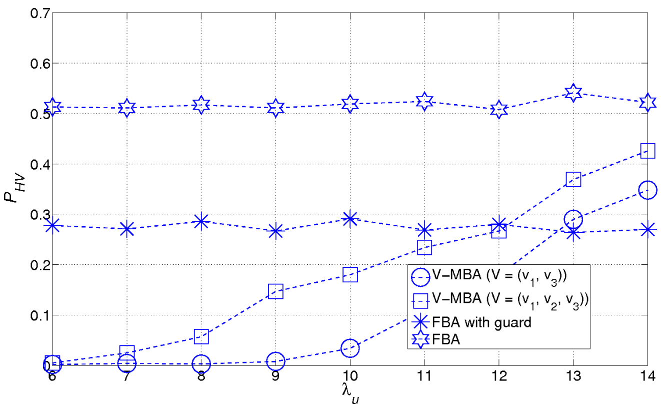


Fig. 9. P_{HV} as a function of λ_u.

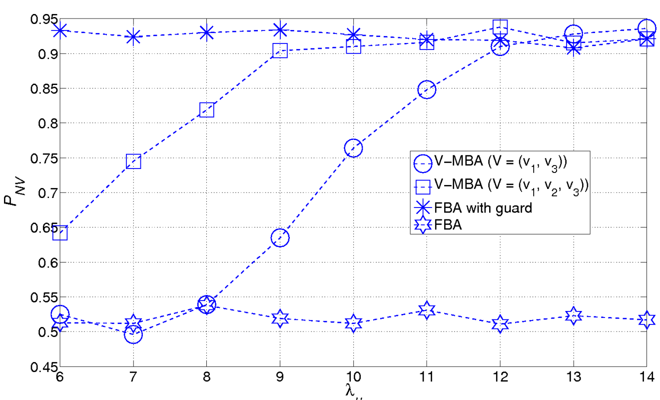


Fig. 10. P_{NV} as a function of λ_u.

$\mathbb{V} = (v_1, v_3)$ and $\mathbb{V} = (v_1, v_2, v_3)$. Therefore, from Figures 9 and 10, it can be observed that the difference of P_{NV} (and P_{HV}) between two V-MBA schemes with $\mathbb{V} = (v_1, v_3)$ and $\mathbb{V} = (v_1, v_2, v_3)$ becomes insignificant as λ_u decreases or increases.

Figure 11 shows P_{AV} with respect to λ_u. Similar to Figure 7, it can be seen that P_{AV} increases with the increase of λ_u. However, it can be observed that the difference of P_{AV} between the V-MBA schemes with $\mathbb{V} = (v_1, v_2, v_3)$ and $\mathbb{V} = (v_1, v_3)$ becomes smaller as λ_u increases or decreases. This is because both V-MBA schemes with $\mathbb{V} = (v_1, v_2, v_3)$

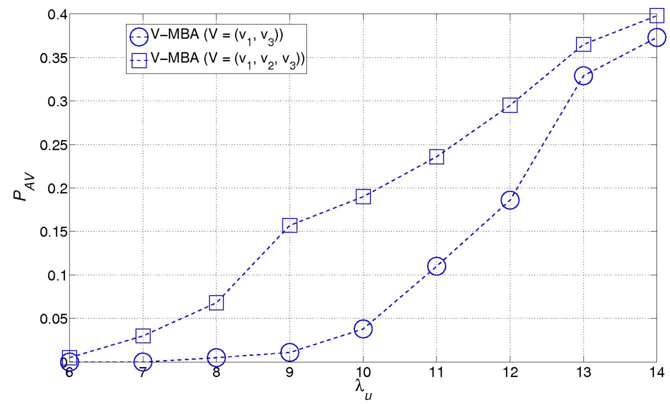
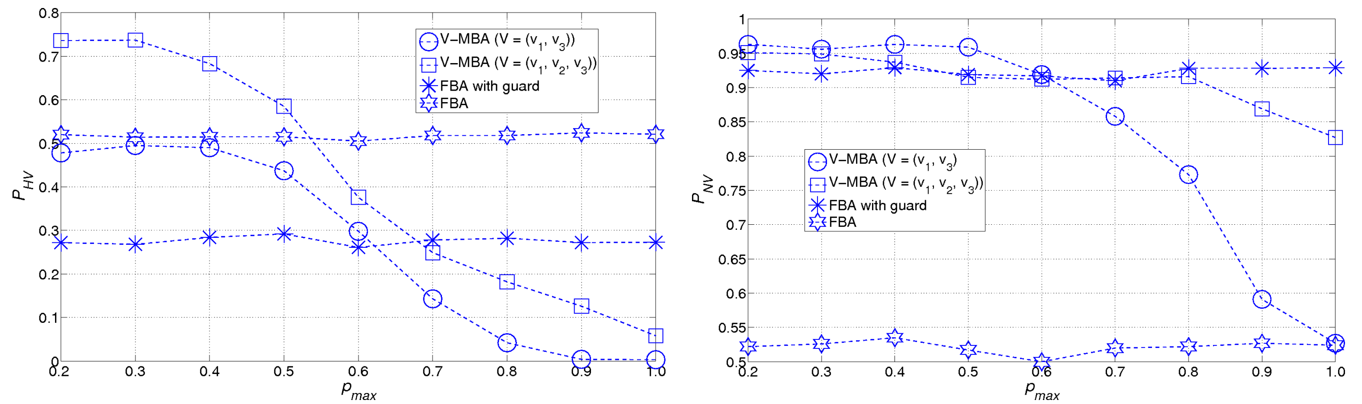


Fig. 11. P_{AV} as a function of λ_u.

and $\mathbb{V} = (v_1, v_3)$ assign the same amount of bandwidth units (i.e., 1 or 3) if λ_u is very low or high.

C. Effect of p_{max}

The effect of the probability of getting off a vehicle is investigated in this subsection. To this end, λ_h and λ_u are set to 6 and 10, respectively. If p_{max} is low, the average number of passengers on board is large. On the other hand, higher p_{max} leads to a smaller number of passengers in a vehicle. Therefore, as shown in Figure 12(a), P_{HV} of the V-MBA schemes significantly decreases with the increase of p_{max} since most vehicles require less bandwidth units when p_{max} is high. From Figure 12(b), a similar trend on P_{NV} as a function of p_{max} can be observed. From Figure 12, it can be concluded that the V-MBA scheme becomes better than the FBA scheme with guard bandwidth in terms of the new vehicle service blocking and handoff vehicle service dropping probabilities especially when p_{max} is sufficiently high. In the case of low p_{max}, the V-MBA schemes have higher P_{HV} and P_{NV} than the FBA schemes since more bandwidth units, i.e., three bandwidth units, are allocated to each vehicle. However, the blocked vehicles can have another chance to get bandwidth units at the next station by means of the bandwidth adjustment function.



(a) Handoff vehicle service dropping probability (b) New vehicle service blocking probability

Fig. 12. Effect of p_{max}.

VII. Conclusions

In this paper, we proposed a vehicular passenger mobility-aware bandwidth allocation (V-MBA) scheme in mobile hotspots, which consists of the call admission control (CAC) function and the bandwidth adjust (BA) function considering the vehicular passenger movement pattern and the vehicular mobility. In the V-MBA scheme, the BS dynamically assigns appropriate bandwidth units to the vehicle depending on the vehicle's ridership. As a result, the V-MBA scheme can guarantee both low new vehicle service blocking probability and low handoff vehicle service dropping probability compared with the fixed bandwidth allocation (FBA) scheme with guard bandwidth. In our future work, we will consider more diverse vehicular features (e.g., traveling time and passenger capacity) and application features (e.g., non-real time and real-time applications) to design resource management schemes in mobile hotspots.

Appendix A
Derivation of (4)

In Sections V, it is assumed that Y_t follows a general distribution $p_k = \Pr(Y_t = k)$, and every passenger has the probability p of taking off a vehicle at each station. Then, $\mathbf{P_{ab}}$ where $a \geq 0$ and $b \geq 0$ can be obtained as

$$\begin{aligned}
\mathbf{P_{ab}} &= \Pr\{X_{t+1} = b | X_t = a\} \\
&= \Pr\{a - Z_t + Y_t = b | X_t = a\} \\
&= \Pr\{-Z_t + Y_t = b - a | X_t = a\} \\
&= \sum_{k=max(a-b,0)}^{a} \Pr\{Z_t = k, Y_t = b - a + k | X_t = a\} \\
&= \sum_{k=max(a-b,0)}^{a} \Pr\{Y_t = b - a + k | X_t = a, Z_t = k\} \\
&\qquad \cdot \Pr\{Z_t = k | X_t = a\} \\
&= \sum_{k=max(a-b,0)}^{a} \Pr\{Y_t = b - a + k\} \Pr\{Z_t = k | X_t = a\} \\
&= \sum_{k=max(a-b,0)}^{a} p_{b-a+k} \binom{a}{k} p^k (1-p)^{a-k}. \qquad \text{(A.1)}
\end{aligned}$$

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Younghyun Kim received the B.S. and M.S. degrees both in Computer Engineering from Soongsil University, Seoul, Korea, in 2005 and 2007, respectively. He also received the Ph.D. degree in the Department of Electrical Engineering, Korea University, Seoul, Korea, in 2013. From 2007 to 2008, he was a software engineer at Celrun Inc., Seoul, Korea. His research interests include mobility management, Future Internet and quality-of-service provision issues in next-generation wireless/mobile networks.

Haneul Ko received the B.S. degree from Korea University, Seoul, Korea, in 2011. He is currently an M.S. and Ph.D. integrated course student in School of Electrical Engineering, Korea University. His research interests include mobility management and Future Internet.

Sangheon Pack received the B.S. and Ph.D. degrees from Seoul National University, Seoul, Korea, in 2000 and 2005, respectively, both in computer engineering. In 2007, he joined the faculty of Korea University, Seoul, Korea, where he is currently an Associate Professor in the School of Electrical Engineering. From 2005 to 2006, he was a Postdoctoral Fellow with the Broadband Communications Research Group, University of Waterloo, Waterloo, ON, Canada. He was the recipient of KICS (Korean Institute of Communications and Information Sciences) Haedong Young Scholar Award 2013, IEEE ComSoc APB Outstanding Young Researcher Award in 2009, LG Yonam Foundation Overseas Research Professor Program in 2012, and Student Travel Grant Award at the IFIP Personal Wireless Conference (PWC) 2003. From 2002 to 2005, he was a recipient of the Korea Foundation for Advanced Studies Computer Science and Information Technology Scholarship. He was a publication co-chair of IEEE INFOCOM 2014, a co-chair of IEEE VTC 2010-Fall transportation track, a co-chair of IEEE WCSP 2013 wireless networking symposium, a TPC vice-chair of ICOIN 2013, and a publicity co-chair of IEEE SECON 2012. He is an editor of the *Journal of Communications Networks* (JCN) and a senior member of the IEEE. His research interests include Future Internet, SDN/ICN/DTN, mobility management, mobile cloud networking, multimedia networking, and vehicular networks.

Xuemin (Sherman) Shen received the B.Sc.(1982) degree from Dalian Maritime University (China) and the M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey (USA), all in electrical engineering. He is a Professor and University Research Chair, Department of Electrical and Computer Engineering, University of Waterloo, Canada. Dr. Shens research focuses on resource management in interconnected wireless/wired networks, wireless network security, wireless body area networks, vehicular ad hoc and sensor networks. Dr. Shen serves/served as the Editor-in-Chief for *IEEE Network*, *Peer-to-Peer Networking and Application*, and *IET Communications*; a Founding Area Editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS; an Associate Editor for IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, *Computer Networks*, and *ACM/Wireless Networks*, etc.; and the Guest Editor for IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, *IEEE Wireless Communications*, *IEEE Communications Magazine*, and *ACM Mobile Networks and Applications*, etc. Dr. Shen is a registered Professional Engineer of Ontario, Canada, an IEEE Fellow, an Engineering Institute of Canada Fellow, a Canadian Academy of Engineering Fellow, and a Distinguished Lecturer of IEEE Vehicular Technology Society and Communications Society.