An Efficient Association Control Method for Vehicular Networks with Mobile Hotspots

Jaeryong Hwang[1], Jaehyuk Choi[2], Joon Yoo[3], Hwaryong Lee[1] and Chong-kwon Kim[1]
[1]School of Computer Science and Engineering, Seoul National University,
Seoul, Korea 151-744
[e-mail: {jrhwang, hrlee}@popeye.snu.ac.kr, ckim@snu.ac.kr]
[2]Dept. of Software Design & Management, Kyungwon University,
Seongnam City, Korea
[e-mail: jchoi@kyungwon.ac.kr]
[3]Bell Labs, Alcatel-Lucent
Seoul, Korea 120-170
[e-mail: joon.yoo@alcatel-lucent.com]
*Corresponding author: Jaehyuk Choi

Received November 30, 2010; revised January 20, 2011; revised March 30, 2011; accepted April 29, 2011; published May 31, 2011

Abstract

The increasing demand from passengers in vehicles to improve safety, traffic efficiency, and comfort has lead to the growing interest of Wi-Fi based vehicle-to-infrastructure (V2I) communications. Although the V2I system provides fast and cost-effective Internet connectivity to vehicles via roadside Wi-Fi access points (APs), it suffers from frequent handoffs due to the high mobility of vehicles and the limited coverage of Wi-Fi APs. Recently, the Mobile AP (MAP) platform has emerged as a promising solution that overcomes the problem in the V2I systems. The main advantage is that MAPs may yield longer service duration to the nearby vehicles that have similar mobility patterns, yet they provide smaller link capacities than the roadside APs. In this paper, we present a new association control technique that harnesses available connection duration as well as achievable link bandwidth in high-speed vehicular network environments. We also analyze the tradeoff between two association metrics, namely, available connection duration and achievable link bandwidth. Extensive simulation studies based on real traces demonstrate that our scheme significantly outperforms the previous methods**.**

Keywords: V2I communication, mobile AP, duration and bandwidth estimation, and association control.

This work was supported in part by the ministry of knowledge economy (MKE), Korea, under the information technology research renter (ITRC) support program supervised by the national IT industry promotion agency (NIPA) (NIPA-2010-(C1090-1011-0004)) and the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government(MEST) (No. 20100027410) and by the National Research Foundation of Korea Grant funded by the Korean Government (NRF-2009-352-D00261) and by the Seoul R&BD Program (WR080951).

DOI: 10.3837/tiis.2011.05.002

1. Introduction

With the increasing demand from passengers in vehicles for improved car safety, traffic efficiency, and passenger comfort, vehicle-to-infrastructure (V2I) communication technology is drawing considerable attention [1][2][3][4][5][6][7]. The primary role of V2I systems is to support various vehicular network applications, such as road safety, passenger convenience and commercial applications. The key requirements for the development of V2I communication systems are to provide ubiquitous network connectivity and to ensure timely and reliable communication between moving vehicles and infrastructure elements.

Wi-Fi network technology has been considered as a promising solution to meet these requirements, since it is a cost effective and high performance communication means of providing Internet connectivity. Moreover, a plethora of Wi-Fi hotspots have already been widely deployed, sometimes covering over an entire metropolitan area [3], thus offering seamless Internet connectivity to moving vehicles.

Despite the numerous potential benefits, several challenges still exist in the vehicular Wi-Fi access. Different from the traditional data access systems for stationary users, the connection time in Wi-Fi based vehicular networks is typically short, because vehicles move fast and the coverage of roadside APs is limited within 150 – 250m. Furthermore, the condition of the wireless channel varies dynamically due to high mobility. To sustain the connectivity and maintain high link quality, the moving vehicles have to continuously associate with different APs and conduct frequent handoffs. The frequent handoffs, however, can incur high overheads and significant delay such as association and DHCP latency [3][6]. Therefore, it is an important yet challenging problem to determine how to manage the association with available APs and when to execute handoff appropriately.

Several solutions have been proposed to address the association and handoff problem. For example, Giannoulis et al. [4] have suggested a handoff protocol which supports a vehicle's mobility in urban mesh topology. Kim et al. [5] presented an association control solution that minimizes the frequency of handoffs to mobile devices. Existing mechanisms consider the association problem only in the stationary infrastructure environments in which vehicles associate with fixed roadside APs. However, the vehicles still have an inherent weakness of a short connection time due to the limited coverage of 802.11 APs, thus inevitably resulting in frequent handoffs.

To address this issue, this paper considers mobile Wi-Fi hotspot systems as a new V2I component providing on-the-move wireless Internet access to moving vehicles. Through mobile APs (MAP), mobile hotspots can provide mobile Internet connectivity and thus extend the service time of V2I communications. A MAP is equipped with multiple wireless network interfaces and is able to utilize different access technologies; including both Wi-Fi and cellular/3G interfaces such as UMTS, 1xEV-DO, LTE and WiMAX. It uses a wide-area broadband data connection to access the Internet and acts as an access router to provide wireless connectivity to multiple vehicles in its service coverage through the Wi-Fi interface.

The main benefit of using MAPs is that vehicles can obtain longer service duration by connecting to the MAPs with similar mobility patterns. In result, the vehicles can avoid frequent handoffs and reduce the high delay required in the handoffs, thus resulting in higher throughput. Actually, empirical results in [3] have shown that there is a strong correlation between the movement of vehicles and the distribution of connection time. Motivated by its potential benefits, many major vendors around the world have recently launched commercial portable MAP products. For example, in the United States, *Verizon Wireless* started the intelligent mobile hotspot service with the Novatel MIFI-2200 MAP modem [8]. It uses 3G mobile broadband network with typical download speeds ranges from 600Kbps to 1.4 Mbps [8]. Korea Telecom's KWI-B2200 uses Wibro complying with mobile WiMAX/IEEE 802.16e [9] for its South Korean Wi-Fi network. These technologies mentioned above can enable not only mobile users to use lab-top computers or Wi-Fi-enabled devices, such as smartphones, but also mobile vehicles to access infrastructure via Wi-Fi. MAPs are envisioned to be used by being installed on buses or taxis for a mobile vehicular network.

The use of MAPs, however, involves a tradeoff between long connectivity and low end-to-end throughput. Since MAPs bridge via 3G link (or WiMAX) which has narrower link capacity than 802.11 based WiFi links, the end-to-end throughput of the client vehicle is usually lower than that of road-side APs. Therefore, there is a strong need to develop an efficient association control mechanism that balances between the throughput and handoff overheads.

In this paper, we present a new association control technique that takes available connection duration as well as achievable link bandwidth into consideration as MAP selection criteria in mobile vehicular network environments. We first study and analyze the effect of two MAP association metrics, namely achievable bandwidth and connection duration. Our analytic result shows that the optimal association strategy based on these two association metrics has a threshold-based structure depending on the density of nearby APs and their available service time. In addition, we develop a run-time estimation technique for predicting the available connection duration and achievable bandwidth with nearby roadside APs/MAPs. Finally, based on the measured metrics, we present an AP association control scheme that considers both available durations and bandwidth from nearby APs in a distributed manner. We evaluate the proposed scheme through extensive simulations, which use a real bus trace database [7], and the performance evaluation results show that our scheme improves overall throughput by effectively regulating frequent handovers.

The rest of the paper is organized as follows. We present the related work in Section 2. Section 3 describes the system model and defines the problem by the analysis. Section 4 introduces the estimation method for connection time and achievable bandwidth from MAPs. Section 5 proposes an association control technique to consider both connection time and achievable bandwidth together. Section 6 evaluates the proposed strategy via extensive simulation studies based on the real bus trace. We discuss with future research plan in Section 7 and conclude in Section 8.

2. Related Work

Several recent studies have explored the vehicular access networks via roadside access points from moving vehicles. In [1], Ott and Kutscher have identified the characteristics of the drive-thru access network. They have shown that vehicles experience three different connectivity phases while passing the access point: the entry phase, the production phase, and the exit phase. During the entry phase and exit phase, the client vehicles mostly suffer from weak connectivity while the production phase is the only phase providing a good connection quality. In [2], Hadaller et al. have studied the impact of the above three different phases on the TCP goodput performance through a detailed experiment in several drive-thru network access scenarios. In [3], Bychkovsky et al. have performed an experimental performance studies by using numerous open Wi-Fi access points for vehicular Internet access in urban environments. The experiments observe that the distribution of the duration of link layer per AP is short

(12-13s), and it requires a high latency to complete acquiring an IP address. The application performance suffers due to this high connection setup delay. Our goal is to improve the application performance through association control techniques.

There have been various approaches to improve the mobile user performance by association control. Association control is a decision of how to select APs and when to conduct handoff to the other APs. Generally, mobile users using stock implementations use the channel quality as the handoff initiation and association metric. In [4], Giannoulis et al. have proposed a handoff technique that supports vehicular users in the urban mesh network deployed in southeast Houston. Similar to our method, they consider AP-quality scores as well as channel quality to associate with deployed APs. The AP-quality scores are determined by average loads and backhaul connectivity. However, they have not considered connection duration to control the handoff frequency. In [5], Kim et al. have presented an association control solution that minimizes the frequency of handoffs to the mobile devices. The mobile devices always select APs with the longest connection time due to severe handoff overheads, such as association and DHCP latency. Unlike [5], the focus of our scheme is on balancing the connection time with instantaneous bandwidth. Note that, under the system model with MAPs, such a solution that aims to minimize the handoff frequency cannot guarantee the maximal throughput performance since less frequent handover may be achieved only at the sacrifice of link bandwidth. In [6], Deshpande et al. developed a new handoff and data transfer strategies for moving vehicles in urban areas. They reduce the connection setup latency by using RF fingerprints of APs. The moving vehicles know useful APs in the current location beforehand by the RF fingerprint, and thus the moving vehicle can select the optimal APs and conduct handoffs. We consider both roadside fixed APs and MAPs moving along the roads as available APs set. In this paper, however, due to the unpredictability by the mobility of MAPs, it is not easy for the client vehicle to acquire the information of APs in advance. Unlike these approaches, the focus in this paper is a local optimal association control with APs discovered by scanning.

3. System Model and Analysis

In this section, we describe the system model and assumptions that are used throughout the paper. Next, we discuss the association problem in MAPs.

3.1. System Model

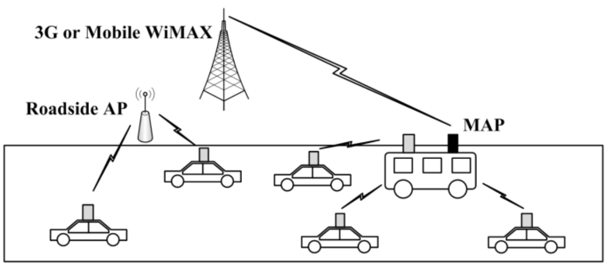


Fig. 1. System model.

We consider a V2I communication system consisting of MAPs and stationary roadside APs, as shown in **Fig. 1**. The MAP is a base station that can provide mobile Internet connectivity through its mobile hotspot service. The MAPs may be managed by several service providers, such as public transportation operators. In this paper, we focus on the scenario in which citywide public buses act as MAPs where each bus is equipped with Wi-Fi and 3G/WiMAX modems and moves along its regular route. We assume that every vehicle including MAPs has a GPS device, so that they know its location, speed, and direction information. We also assume that the route information of each bus is available to the vehicular users, and they use this information to predict the connection duration with the bus. Actually, UMass Transit [10] and Seoul TOPIS [11] offer not only the bus route but also real-time location information of buses.

Client vehicles move along the roads and opportunistically access the Internet by using nearby roadside APs and MAPs. The transmission range of client vehicles, roadside APs, and MAPs are limited, so that the client vehicle can only utilize the APs that reside within its coverage range. At a given time, each vehicle is associated with one AP among the several available APs that are within its transmission range according to the AP selection method. If the vehicle satisfies the handoff criteria such as disconnection with its current AP or decreased signal strength below a predefined threshold, it conducts handoff from the current AP to a new one.

3.2. Analysis: Achievable Bandwidth and Connection Duration based Association

For the below analysis, we first present a V2I network model that consists of MAPs and vehicles. Then, we characterize and study the effect of two MAP association metrics, namely achievable bandwidth and connection duration. We denote every set of APs in the system as every set $A = \{ AP_1, AP_2, \dots, AP_i, \dots, AP_k \}$ and denote the set of available APs at an arbitrary time t, from a vehicle's perspective, as set $A(t) \in A$. We assume that the achievable bandwidth b_i and connection duration d_i of AP_i are known beforehand [6]. We derive the expected throughput that can be achieved at a vehicle, when each of the AP association metric is employed.

A vehicle moving along the road may encounter several APs, such that the set of available APs dynamically vary over time. **Fig. 2** shows an example of the set of available APs over time, i.e., $A(t)=\{ AP_1, AP_2, AP_3 \}$, $\{ AP_1, AP_3 \}$, or $\{ AP_3, AP_4 \}$. For simplicity, we assume that only a single AP may appear or disappear from a vehicle's perspective at a discrete time t. Therefore, this procedure can be regarded as a birth-death process where each state represents the number of available APs. We also assume that an AP arrives with a Poisson arrival process and leaves with an exponential distribution for its service time [12]. We denote $1/\lambda$ and $1/\mu$ as the average inter-arrival time and service time of APs, respectively. Note that, each arriving AP is granted its own server on the birth-death system, thus we define the system as an $M/M/\infty$ queuing model [13]. **Fig. 3** shows the state transition diagram for the $M/M/\infty$ queuing model.

We compute the probability of k APs available within the vehicle's transmission range. Let $P_k(t)$ denote the probability that the number of available APs is k at some time t by:

$$P_k(t) = \Pr(|A(t)| = k) \tag{1}$$

where $|A(t)|$ denotes the number of available APs.

In steady-state, the probability, P_k, that the number of available APs, k, within a vehicle's transmission range at some arbitrary time is given by:

$$P_k = \lim_{t \to \infty} P_k(t) \tag{2}$$

$$P_k = P_0 \prod_{i=0}^{k-1} \frac{\lambda}{(i+1)\mu} \quad \text{and} \quad P_0 = \frac{1}{1+\sum_{k=1}^{\infty}\left(\frac{\lambda}{\mu}\right)^k \cdot \frac{1}{k!}} \tag{3}$$

Therefore, we rewrite equation (2) as

$$P_k = \left(\frac{\lambda}{\mu}\right)^k \cdot \frac{e^{-\lambda/\mu}}{k!} \tag{4}$$

In the following two subsections, we compare the performance of the two association metrics based on the queuing model presented above.

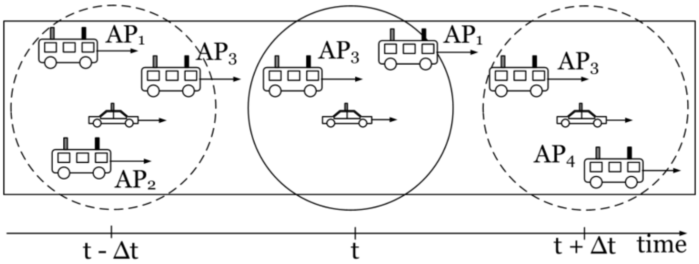


Fig. 2. Available APs over the time.

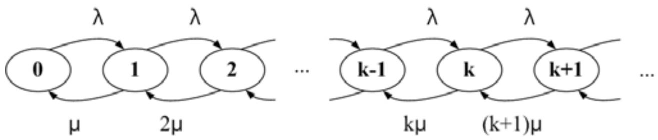


Fig. 3. State transition diagram for birth-death process of APs.

Achievable bandwidth based AP association (BBA)

In this approach, the vehicle selects the AP with the largest achievable bandwidth among set *A(t)*. If the achievable bandwidth of the currently associated AP is smaller than that of some other AP, the vehicle re-associates with the AP that has the highest available bandwidth at that time. However, this policy may cause frequent handoffs by frequent re-associations between APs [14]. For the handoff decision, we use the setting of a *hysteresis* [4] which controls the frequency of handoffs by using a threshold. We denote this threshold as α, which considers the overhead of handoff delay: $\alpha = (1/\mu+\omega)/(1/\mu)$, where ω is the handoff delay. If a newly arrived AP's bandwidth is larger than the current associated AP's bandwidth multiplied by α, the vehicle initiates handoff. In order to compute the expected throughput of BBA, we first define the expected maximum achievable bandwidth as $B_{max} = \max\{b_1, b_2, \ldots, b_k\}$. We denote the *probability density function* (PDF) of a random variable b_i as $f_{b_i}(x)$ and its *cumulative density function* (CDF) as $F_{b_i}(x)$. When k APs are available, the PDF of B_{max} is:

$$\begin{aligned}\Pr(B_{\max} \le z) &= \Pr(b_1 \le z, b_2 \le z, \cdots, and\ b_k \le z) \\ &= (\Pr(b_i \le z))^k = (F_{b_i}(z))^k\end{aligned} \tag{5}$$

$$f_{B_{\max}}(z) = \frac{d}{dz}(F_{b_i}(z))^k = k(F_{b_i}(z))^{k-1} \cdot f_{b_i}(z) \tag{6}$$

Therefore, we obtain the expected B_{max} of the $M/M/\infty$ queuing system as follows:

$$E[B_{\max}] = \sum_{k=0}^{\infty} p_k \cdot \int_0^{\infty} z \cdot f_{B_{\max}}(z)dz \tag{7}$$

Next, we obtain the expected duration, $E[D_i]$ when a vehicle uses the BBA. The vehicle performs the handoff if a newly arrived AP's bandwidth, B_{new}, is larger than $E[B_{max}]\cdot\alpha$, and we define its probability as p_h. Thus, the arrival of these APs follows the exponential distribution with parameter $p_h\cdot\lambda$. Equation (8) explains the expected duration with the BBA. We define P_{h_0} as the probability that there are no arrivals of APs whose bandwidths are larger than $E[B_{max}]\cdot\alpha$ for the duration of $1/\mu$. Also, let p' denote the probability that the new arrival satisfies the handoff condition within the duration of $1/\mu$.

$$\mathrm{E}[D_i] = (p_{h\_0} \cdot \frac{1}{\mu} + (1 - p_{h\_0}) \cdot (p' \cdot \frac{1}{p_h \cdot \lambda} + (1 - p') \cdot \frac{1}{\mu})) \cdot (1 - p_0) \tag{8}$$

where

$$\begin{aligned} p_h &= \Pr(B_{new} > E[B_{\max}] \cdot \frac{1/\mu + \omega}{1/\mu}) \\ p' &= \Pr(X \le 1/\mu) = 1 - e^{-p_h \cdot \lambda \frac{1}{\mu}} \\ p_{h\_0} &= \Pr((N(t + 1/\mu) - N(t)) = 0) \\ &= \frac{e^{-p_h \cdot \lambda \frac{1}{\mu}} \cdot (p_h \cdot \lambda \cdot \frac{1}{\mu})^0}{0!} \end{aligned} \tag{9}$$

Therefore, when the vehicle associates with the new AP with the largest achievable bandwidth after it terminates the connection with the current AP, the expected throughput is computed as follows:

$$\frac{E[B_{\max}] * E[D_i]}{E[D_i] + \omega}. \tag{10}$$

Connection duration based AP association (DBA)

This strategy associates with the AP that provides the longest connection duration among the available APs. Even if a new AP is expected to give a longer duration, the vehicle re-associates with the new AP after the current connection is terminated. This exploits the fact that the duration-based association can improve the performance by minimizing the handoff overhead [5].

Similar to $E[B_{max}]$, we obtain the expected value of maximum connection duration, D_{max}, where $D_{max} = \max\{d_1, d_2, \ldots, d_k\}$. We denote the PDF of AP$_i$'s connection duration d_i as $w_{d_i}(x)$ and its CDF as $W_{d_i}(x)$.

$$\begin{aligned}\Pr(D_{\max} \le \tau) &= \Pr(d_1 \le \tau,\ d_2 \le \tau,\ \cdots, and\ d_k \le \tau) \\ &= (\Pr(d_i \le \tau))^k = (W_{d_i}(\tau))^k\end{aligned} \tag{11}$$

$$w_{D_{\max}}(\tau) = \frac{d}{d\tau}(W_{d_i}(\tau))^k = k\,(W_{d_i}(\tau))^{k-1} \cdot w_{d_i}(\tau) \tag{12}$$

$$E[D_{\max}] = \sum_{k=0}^{\infty} p_k \cdot \int_0^{\infty} t \cdot w_{D_{\max}}(\tau)\,d\tau \tag{13}$$

Therefore, when the vehicle associates with a new AP that gives the longest connection duration, the expected throughput is:

$$\frac{E[B_i] * E[D_{\max}]}{E[D_{\max}] + \ \omega}, \tag{14}$$

where $E[B_i]$ is the average achievable bandwidth.

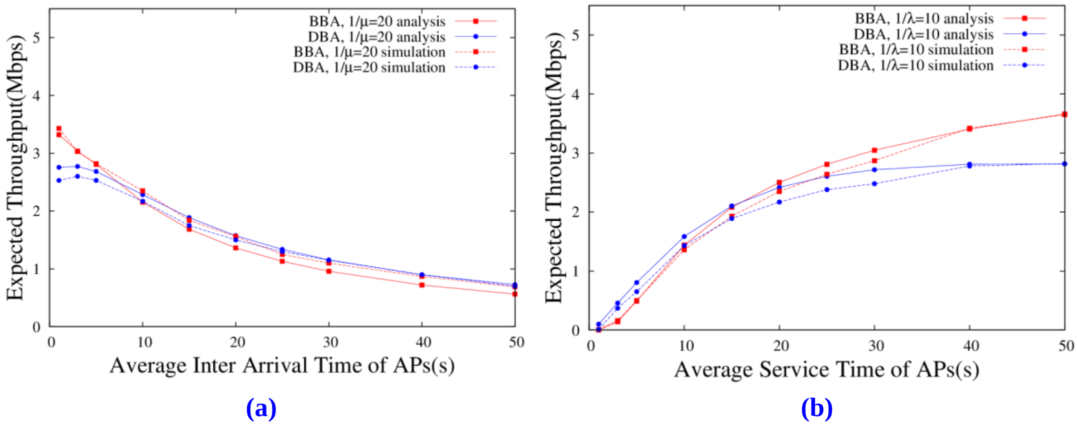


Fig. 4. Expected throughput during an association as a function of **(a)** average inter arrival time and **(b)** average service time of APs. The bandwidth of the APs is uniformly distributed in the range from 1 to 5Mbps.

Fig. 4 plots the throughput performance of the two association strategies as a function of APs' inter arrival time and service time, respectively. As the inter-arrival time of APs decreases, then the density of APs within vehicle's coverage increases, and in turn, the throughput of BBA outperforms that of DBA. In the mean time, the throughput decreases with shorter service times. In result, DBA performs better at a shorter service time, while the BBA is better at a longer service time. This is because the BBA typically offers better instantaneous throughput, but its gain is limited by the severe overhead due to frequent handoffs, so that the overhead eliminates the gain with shorter AP service times. It is worthwhile noting that, DBA should show better performance than BBA if the vehicle moves at a high speed (representing small service time).

To evaluate the accuracy of our analytical results, we have performed extensive simulations. For the simulations, we consider a number of APs with various inter-arrival time and service time whose average values are equal to those of the parameter used in the analysis evaluation. The comparison results are shown in **Fig. 4** and we can observe a close match between the results of analysis and simulation.

4. Run-time Estimation of Association Metrics

The analytic results in the previous section show that the optimal association method depends on factors such as AP arrival rate or service time. Our proposed association control scheme takes these factors into account and utilize the service duration and available bandwidth as association metrics. However, these association metrics should be measured by the vehicles on real-time. Therefore, we propose a run-time estimation technique to measure the available connection duration and achievable bandwidth with nearby roadside APs or MAPs

4.1. Duration Estimation between the Vehicle and APs

First, we present a method to estimate the roadside-AP/MAP connection duration at the vehicle via its own mobility information obtained from GPS devices. Mobility of vehicles is different from the random waypoints model of Mobile Ad-hoc Networks [15] in which the mobile nodes move randomly and freely without restrictions. In other words, all vehicles including MAPs move along the roads and are expected to have similar mobility with front and rear vehicles, namely group mobility. Note that the vehicles do not have completely random mobility even though the drivers have different driving habits [16]. Since the geographical information of vehicle, such as its location, moving direction, and speed, is available via GPS device, the vehicle can predict its future movement from the current location with high accuracy [17]. Thus, we can easily predict the connection duration with roadside APs based on the client vehicle's mobility information since the roadside APs have no mobility. However, it is a challenging task to estimate the connection duration with MAPs because the MAPs also move along the roads and have their own mobility pattern.

Next, we present a traffic-lane model [16] in order to estimate the duration from a vehicle to other moving vehicles, such as MAPs. The traffic-lane model reflects realistic traffic characteristics, such as different speed at each lane and driving habits. As shown in **Fig. 5**, vehicles move along n traffic lanes and update its own mobility information, $H(t)$:

$$H(t) = \{r_m, v_m \mid 1 \le m \le n, T\} \tag{15}$$

where r_m is the ratio of time a vehicle remains in the m^{th} lane, and v_m is the average velocity of the vehicle in the m^{th} lane during time T. The r_m and v_m are defined as

$$r_m = \frac{t_m}{T}, \quad v_m = \frac{\int_{t-T}^{t} v_m(t')\,dt'}{t_m} \tag{16}$$

Here t_m is a duration that the vehicle stays in m^{th} traffic lane during T, and $v_m(t')$ is a velocity in the m^{th} lane at time t'.

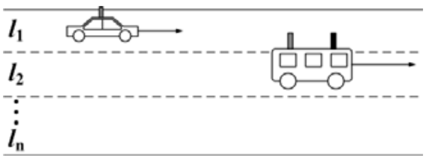


Fig. 5. Traffic-lane model.

The distance that each vehicle moves from the current location after a certain time τ is:

$$\sum_{m=1}^{n} v_m r_m \cdot \tau = (v_1 r_1 + v_2 r_2 + ... v_n r_n) \cdot \tau. \tag{17}$$

Then, we obtain the relative distance between client vehicle and MAPs depending on time is:

$$D(\tau) = \delta + \left| \sum_{m=1}^{n} (v_m^{cv} r_m^{cv} - v_m^{mAP} r_m^{mAP}) \right| \cdot \tau. \tag{18}$$

Here, δ is the current distance between the client vehicle and MAPs. By solving the condition of $D(\tau) = R$, we can easily obtain the time τ when $D(\tau)$ becomes larger than transmission range R.

The client vehicle requires location and mobility information of the APs in order to estimate the connection time between the APs and itself. To this end, we utilize the beacon message of IEEE 802.11 [18]. The message has some reserved fields and can include one or more vendor specific information. Thus, the APs can deliver their mobility information, such as the current location, and direction, through the reserved fields in the beacon message. The client vehicle that receives the beacon message estimates the duration through the above equations. On the other hand, the vehicle also may receive the beacon message not having the location and mobility information from fixed roadside APs, which do not have the location information or GPS devices. In this case, we assume that we can use commonly available location information services, which provide location information of APs on Internet. For example, actually, several public or commercial service providers have already provided a list of APs, their geographical coordinates and other deployment attributes like usage channel number [6].

4.2. Achievable Bandwidth Estimation

We present a simple yet effective method to estimate the achievable bandwidth between the vehicles and APs by exploiting the BSS loads information received from APs while not violating the 802.11 standard.

Achievable bandwidth estimation of roadside APs: In 802.11 WLANs, client-side solutions to estimate the achievable bandwidth have been widely adopted in order to behave intelligent AP associations [19][20]. Without any support from APs, clients can locally gather AP's load information, such as channel idle intensity and collision probability, by monitoring the channel or relying on successful transmitted and/or received packet information to/from the APs [19]. Such client-side approaches have many benefits, such as feasibility and no requirement of network-side module. However, in V2I environments, it is an inappropriate method that the client vehicle locally measures the channel state, such as channel busy ratio and AP's loads, since it is a time-consuming task [20]. Moreover, the client vehicle should stay on a certain channel for a long time to gather enough network information for high accuracy, which causes high overhead. Therefore, in a mobile vehicular environment, it is reasonable that the APs should provide the information related to its effective bandwidth.

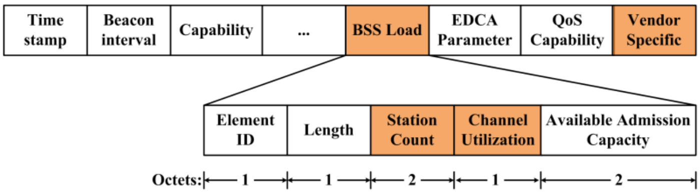


Fig. 6. Beacon and BSS load element format.

Usually, an AP can sufficiently measure its load as well as channel state information. For instance, the AP maintains the information about the number of currently associated clients, traffic levels, and so on. This information is transmitted periodically through AP's beacon message, so that the client can use it for AP selection. **Fig. 6** presents the BSS Load element format in the 802.11 beacon frame [18]. The *Station Count* field indicates the number of stations currently associated with this AP. The *Channel Utilization* field defines the percentage of time the AP sensed the medium was busy. By exploiting above information, we present an achievable bandwidth estimation method while following 802.11 standards without any modification.

To estimate achievable bandwidth of nearby APs, we employ a bandwidth estimation method introduced in [20], which is derived from the channel busy ratio, φ, collision probability, p_c, and channel error rate, p_e, where the channel busy ratio, collision probability, and channel error rate are announced by APs or readily measurable by using many existing estimation mechanisms [20][21]. The channel error probability p_e can be estimated by using the RSSI values of periodic beacon frames from nearby APs [24].

From the given and received above information, the achievable bandwidth that the vehicle can obtain from AP i is finally given as

$$b_i = \frac{F \cdot p_s}{\frac{1}{1-\varphi}\left(\sum_{l=1}^{L}(1-p_s)^{l-1} \cdot p_s \cdot \frac{CW_l}{2} \cdot t_{slot}\right) + T_o}, \tag{19}$$

where

$$p_s = (1-p_e)\cdot(1-p_c),$$

$$CW_l = \min[\ 2^{l-1}(CW_{\min}+1)-1,\ CW_{\max}\ ],$$

$$T_o = t_{Data} + t_{SIFS} + t_{ACK}.$$

The first term of the denominator in (19) means the expected time overhead for the channel contention, and the other term T_0 is an overhead for data transmission, SIFS, and ACK reception. F is frame size and p_s is the probability that a data is successfully transmitted in a unit frame exchange. CW_l represents the contention window (CW) size at the l^{th} transmission attempt. The backoff procedure updates the CW size up to long-retry limit, L, when a transmission fails.

Achievable bandwidth estimation of MAPs: To estimate the achievable bandwidth between the vehicle and an MAP, we should consider the unique feature of MAP determining its achievable bandwidth. The MAP has another wireless link as a backhaul contrary to the roadside fixed AP that is connected by a wired line. Usually, the link capacity of 3G (or WiMAX) is smaller than that of Wi-Fi WLAN. Consequently, even if the Wi-Fi link bandwidth between the client and MAP is very high, the vehicle's achievable bandwidth is dominated by the slowest (or bottleneck) link, i.e., the 3G link. For example, as shown in [22], the performance measurement of a kind of WiMAX access network shows that the downlink goodput on public vehicles nearly ranges from 1Mbps to 3Mbps. When the client uses MAPs with the performance to access Internet, even though the vehicle has a high-speed WiFi data link, such as 54Mbps, its achievable throughput is bounded by the maximum capacity of the WiMAX link, i.e., 3Mbps.

If a MAP i associated with n client vehicles has a 3G or WiMAX link of the bandwidth w_i, and each client is fairly scheduled, then the bandwidth assigned to each client is w_i / n. Therefore, the link bandwidth can take from MAP i is actually a smaller value as follows:

$$\min\,[\,b_i\;, w_i\,/\,n\,], \tag{20}$$

where b_i is the link bandwidth between the client vehicle and the MAP given in (19).

Based on (20), MAPs can easily know actual achievable bandwidth for associated nodes. We utilize the *Channel Utilization field* in the beacon frame to provide the actual link bandwidth to client vehicles.

5. Association Control with Fixed and Mobile APs

In this section, we propose an efficient association control algorithm to maximize the association/handoff gain by considering the link duration as well as the achievable bandwidth between a vehicle and nearby APs/MAPs (roadside APs or MAPs).

We first formulate the association control problem. We are given a set of available AP/MAPs, denoted by A, obtained by AP scanning, where the set $A = \{ AP_1, AP_2, \dots , AP_i, \dots, AP_k \}$. The simplest way to find the optimal association sequence is to enumerate all finitely many possibilities. However, due to the *combinatorial explosion* resulting from the parameter size, only the smallest instances could be solved by such an approach. Therefore, we first obtain a set of actually effective APs by reducing the candidate APs that have no benefit to associate, and then we find the best association sequence by using a newly proposed tree-based search algorithm.

Let us consider an association sequence, $\Phi = (\rho_1, \rho_2, \dots, \rho_k \mid \rho_i \in A \text{ and } d_1 \le d_2 \le \dots \le d_k)$, composing of the elements of set A, whose elements are sorted in a decreasing order of the duration, where the duration of AP/MAP ρ_i is shorter than that of ρ_{i+1}, i.e., $d_1 \le d_2 \le \dots \le d_k$. Here, d_i represents the estimated available connection time of AP/MAP ρ_i, so that the client vehicle cannot associate with AP ρ_i after the time of d_i. In order to find the best profitable sequence, we need a way to evaluate the profit of a sequence Φ. We thus develop a new decision metric that quantifies both the link bandwidth and the available link duration as follows:

$$f(\Phi) = \sum_{i=1}^{k} b_i \cdot (d_i - d_{i-1}) - b_i \cdot \omega \cdot g(i) \quad , \tag{21}$$

$$\text{where} \quad g(i) = \begin{cases} 0 & \rho_c = \rho_{1,} \\ 1 & \text{otherwise.} \end{cases}$$

Here b_i is the bandwidth of AP ρ_i,, d_i is the available duration with ρ_i, and ρ_c is the current associated AP/MAP. If the current associated AP is different from the first AP ρ_1 of the sequence Φ, the handoff overhead is considered by the function *g(i)* in (21).

Algorithm 1 Extracting effective APs

Input: A = { AP_i | $1 \le i \le N$ }
Initialize effective APs set S
Sort APs with its duration
// $\hat{A}$ = {AP_i | $1 \le i \le N$ and $d_1 \le d_2 \le \ldots \le d_N$ }
repeat
    Setp1. Extract the AP_i which has the max duration in the set
      $\hat{A}$. If the AP_i is not same with current associated AP and d_i
      is shorter than handoff latency ω, then stop the process.
    Step2. For each $AP_{i \in \hat{A}}$, delete APs having lower bandwidth
      than the b_i in the $\hat{A}$
    Step3. Include the AP_i in effective AP set S
until $\hat{A}$ = { }
return S = { a_i | $1 \le i \le n$ and $d_1 \le d_2 \le \ldots \le d_n$ }

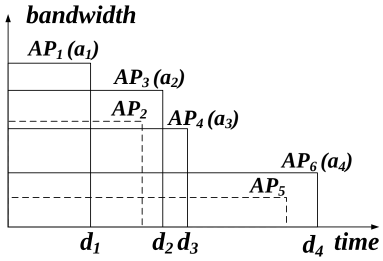
Now, we cast the problem of finding the best association control sequence to the problem of finding the best sequence that maximizes $f(\Phi)$. In Algorithm 1, we illustrate a method to remove the undesirable APs among all available candidate APs/MAPs in the sequence Φ. Here, the undesirable APs is defined as the APs with lower bandwidth and shorter duration than the currently associated AP *i*, so that the client vehicle does not obtain any gain from associating with such the APs. For the given set, *A*, of nearby APs/MAPs, we sort the elements (APs) in a increasing order of the duration, and next proceed to construct the effective AP set S until the iteration set of $\hat{A} = \{AP_i \mid 1 \le i \le N$ and $d_1 \le d_2 \le \ldots \le d_N \}$ becomes empty. Then, we obtain a set of effective APs, $S = \{a_i \mid 1 \le i \le n$ and $d_1 \le d_2 \le \ldots \le d_n \}$, which is a subset of original set *A*.

We next present Algorithm 2, that searches the best association sequence from the given set, S, of effective APs. The basic idea is that we iteratively generate a set *U* of all possible association sequences Φ by evaluating the handoff latency (ω) between consecutive elements, i.e., a_i and a_{i+1}, and find the sequence having the maximum value of $f(\Phi)$ given in (21). In the Algorithm 2, U_i denotes the subset of the sequences and Φ_{ij} is the j^{th} sequence in the subset U_i where index *i* denotes the AP under the iterative operation. We can get the sequence set U_i by exploiting sequences which has already been made from U_1 to U_{i-1}, because the elements of sequence is sorted by duration and Φ_{ij} is a combination of APs from a_1 to a_i. To this end, we insert AP a_i into the tail of the sequences ending with a_k ($1 \le k \le i$-1). We denote this process as a function $U_k * \{a_i\}$. Next, each sequence of U_i, which has one or more elements, is evaluated by (21), and we choose the sequence having maximum transmitted bits. The above process is repeated until U_n is evaluated. In the case of d_i - $d_{i-1} < \omega$, adding the a_i into the sequences of U_{i-1} causes negative effects on the handoff from a_{i-1} to a_i, due to its latency higher than its gain. Thus, we do not insert the sequence into the set in such cases. Since the proposed algorithm is a tree-based enumeration method, the complexity of finding the maximum association sequence is dependent on the number of scanned APs. However, we reduce many possibilities by excluding the non-effective association sequences. Actually, even the case of finding 17 APs by scanning on simulation for performance evaluation, we merely compare 370 sequences from 2^{17} possibilities.

Algorithm 2 Maximum association sequence algorithm

Input: S = {a_1, a_2, … , a_n} // $d_1 \le d_2 \le \ldots \le d_n$
Initialize Φ^*, Max
// make association sequences of which the last element is a_i
for i = 1 to n do

```
4:      Ui ← { }
5:      for k=1 to i do
6:          if k ≠ i then
7:            if (di – dk ) < ω then
8:               Ui ← Ui ∪ { (ai) }
9:               Continue
10:           Else
11:              Ui ← Ui ∪ { Uk * {ai}}
12:           end if
13:         Else
14:           Ui ← Ui ∪ { (ai) }
15:         end if
16:     end for
17:  // Ui ={ Φi1, Φi2, … , Φij }
18:  // find maximum association sequence Φ*
19:     for each Φij ∈ Ui do
20:        calculate f( Φij) by (21)
21:        if f(Φij) > Max then
22:           Max ← f(Φij)
23:           Φ* ← Φij
24:        end if
25:     end for
26:  end for
```



U_1={ (a_1) }
U_2={ (a_1, a_2), (a_2) }
U_3={ (a_1, a_3), (a_3) }
U_4={ (a_1, a_4), (a_1,a_2, a_4), (a_2, a_4), (a_1, a_3, a_4), (a_3, a_4), (a_4) }

Fig. 7. An example scenario with an available AP association sequence.

Fig. 7 illustrates an example scenario with mixed roadside APs and MAPs where there are four roadside APs and two MAPs near the client vehicle. We suppose that the MAPs (AP_5 *and* AP_6) provide longer service durations while the roadside APs (AP_1, AP_2, AP_3, *and* AP_4) give higher bandwidth. Then, the offset of available APs, A, is given by $A = \{AP_1, AP_2, AP_3, AP_4, AP_5, AP_6\}$, where the available connection time of all the APs is larger than the handoff overhead, ω, and the difference of the available time between a_2 and a_3, i.e., $d_3 – d_2$, is smaller than ω. Initially, the vehicle can obtain the effective APs based on Algorithm 1. When the AP_6 and AP_3 are extracted, the AP_5 and AP_2 are dropped, respectively. As a result, the vehicle achieves effective APs set $S=\{a_1, a_2, a_3, a_4\}$. Next, by using Algorithm 2, all the possible effective sequences are generated, and then the vehicle compares the profit of each sequence by (21). In **Fig. 7**, we also show the sequences made by set S. The U_3 has just two sequences. This is because the handoff from a_2 to a_3 causes negative effects due to d_3 - $d_2 < \omega$. Therefore, the sequences including both a_2 and a_3 do not made by line 6-13 of Algorithm2.

6. Performance Evaluation

We evaluate the performance of proposed association control algorithm in vehicular environments with MAPs. To do this, we perform real bus trace-driven-based simulations. We first describe the simulation method, and then present the simulation results that show the benefits obtained from using MAPs by comparing the proposed algorithm with conventional association metrics.

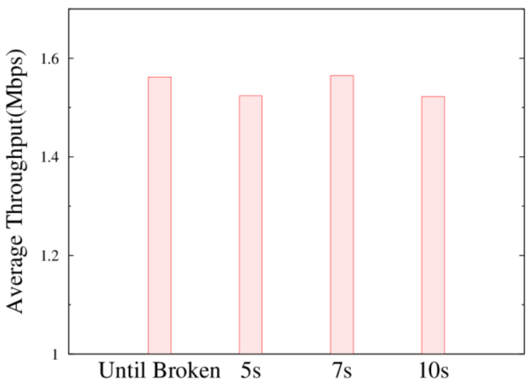
6.1. Simulation Methodology

In order to evaluate the performance under a realistic vehicular mobility scenario, we have utilized the *DieselNet* traces [10] compiled from 40 buses of *UmassTransit*. The buses of *UmassTransit* equipped with DieselNet equipments recorded their GPS information and all connection events in log files. We use the GPS-logs of 40 buses in the *DieselNet* traces to generate the movement of MAPs in the simulations. Thus, the MAPs move along one of the 40 bus routes in the simulations. The client vehicle moves along the given routes around the UMass at the average speed of the buses on the route. Thus, the speed of the client vehicle is determined depending on the road type, such as freeways and local roads.

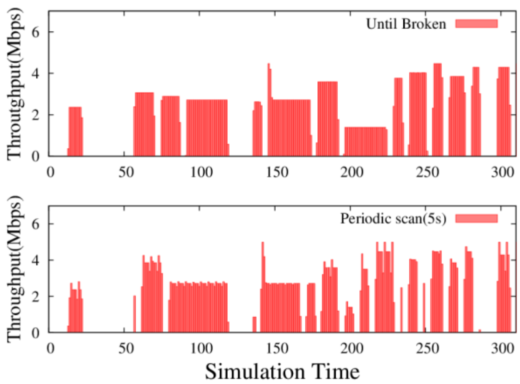
For the locations of fixed roadside APs, we obtained the locations from another open real Wi-Fi database, namely the Wigle [23], which provides the GPS locations of APs. We have sampled 200 APs location around the UMass from the Wigle database and used them for the locations of roadside APs.

In order to make simulation scenarios more realistic, we utilize the experiment results of previous works [6][22] for simulation setting. We consider that the MAPs have a mobile WiMAX/IEEE 802.16e modem for its backhaul link. Based on the results of measurement in [22], we set the link bandwidth of MAPs to range from 1Mbps to 3Mbps. For the bandwidth differentiation, the bandwidth of fixed APs is set from 3Mbps to 5Mbps. Thus, each MAP has a lower capacity than that of fixed APs due to the low capacity of the WiMAX link. We set the handoff overhead to 3.88s and the scan overhead to 0.32s by following the recent experiment results of [6].

6.2. Effects of Scan Policy



(a)



(b)

Fig. 8. Average throughput vs. scan policy.

In this paper, we make an association sequence based on available AP sequences that are obtained by scanning. The vehicle associates with the APs following the sequence, and it starts to find new APs when the current connection is broken. Note that the AP sequence information, i.e., achievable bandwidth and connection duration, may change over the time depending on the vehicle's mobility and AP's loads transition. Therefore, it is necessary to update the information through periodic scanning for accuracy. In this paper, we consider vehicles equipped with a single wireless interface where the data transmission is not feasible during the scanning. Therefore, we also need to consider scan overheads and we examine the effect of periodic scanning on the performance.

We compare a passive scanning policy, so-called Until Broken, with periodic scanning policies with three different scanning periods, where Until Broken scheme triggers a new scan only when the association connectivity is broken while periodic scan polices scan a new AP periodically. **Fig. 8-(a)** shows the average throughput with both until broken and three periodic scan policies with 5s, 7s, and 10s scanning periods. From the figure, we can observe that there is no prominent scan policy from the viewpoint of throughput performance under the simulation environment. This is because the vehicle adopting with shorter periodic scan may have more chances that can give to find new arrival APs or update each available APs' information, but this policy suffers from higher scan overheads. **Fig. 8-(b)** shows the operation results of scan policies in detail, which the graph shows throughput every second over time. The vehicle takes periodic scanning with 5s interval has higher instantaneous throughput by new association, but experiences more service interruption due to scanning and handoffs. Therefore, we adopt Until Broken policy for the rest of performance evaluation.

6.3. Performance Comparison with Mobile APs

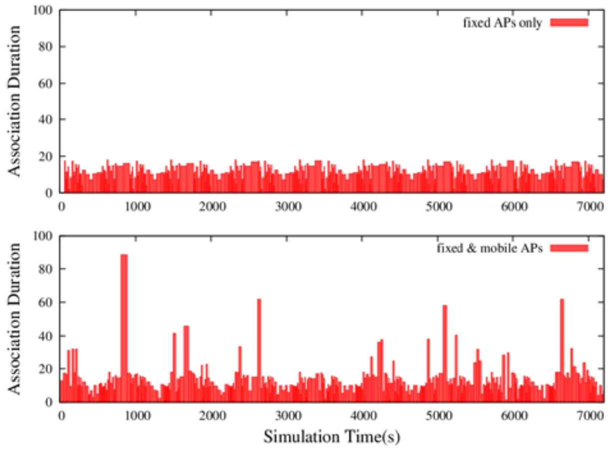


Fig. 9. Association durations of the client.

In order to evaluate the effects of using MAPs, we first compare the performance results with two different AP deployment scenarios consisting of: (1) 200 fixed APs only, and (2) 160 fixed APs and 40 MAPs.

Fig. 9 shows the association duration over time, under these two deployment scenarios. As shown in the results, the client vehicle has longer (about 10%) association durations with MAPs. The results imply that the client opportunistically associates to the MAPs having similar mobility.

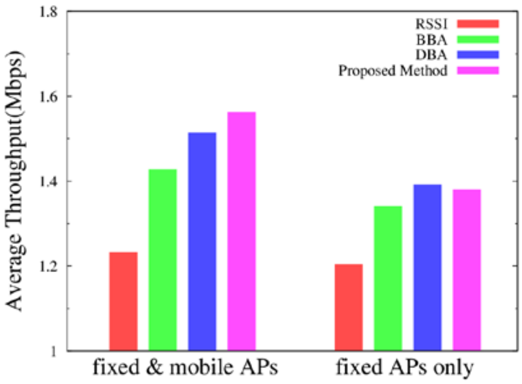


Fig. 10. Average throughput with two different APs deployments.

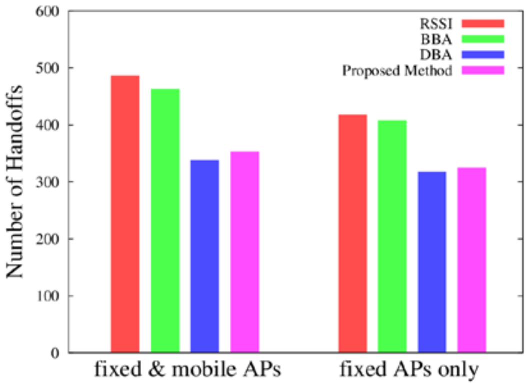


Fig. 11. Number of handoffs with two different APs deployments.

Fig. 10 depicts the average throughput with four association metrics, i.e., (i) RSSI, (ii) BBA, (iii) DBA, and (iv) proposed method, for the two different APs deployment scenarios. With the RSSI-based method, a vehicle uses the RSSIs of beacon messages received from nearby APs for the association metric and selects the AP with the highest RSSI among the APs. From **Fig. 10**, the average throughput in the scenario with the MAPs is 15% higher than that of the fixed APs-only environment regardless of the association metrics. We can also see that proposed association control algorithm is more effective and suitable for the association than other metrics. Specially, our scheme is shown to achieve a higher throughput gain in the mixed scenario with the MAPs and fixed APs. This is because our scheme effectively harnesses the longer connectivity to the MAPs as shown in **Fig. 11**. This result demonstrates that our solution effectively leverages the trade-off between instantaneous achievable bandwidth and handoff overheads. Meanwhile, if the client vehicle selects the AP with the highest bandwidth (BBA in **Fig. 10**), the performance of the client is shown to decrease due to the frequent handoff costs as shown in **Fig. 11**. In contrast, if the client vehicle associates with the AP using DBA, the vehicle shows lower throughput performance since the vehicle cannot utilize an opportunity to connect the APs with higher bandwidth, even though the client may conduct a small number of handoffs. With the RSSI-based scheme, the vehicle shows the lowest throughput. This is because, as shown in the literature [20], the RSSI-based association does not account for the actual achievable throughput but only for physical-layer link quality. Moreover, the RSSI measured at a moving vehicle tends to change fast depending on the vehicle's movement. As a result, the vehicle frequently conducts the handoff to associate with the new AP with a higher RSSI value, resulting in high handoff overhead as shown in **Fig. 11**. We can also observe that, in the scenario with fixed-APs only deployment, there is no standout method that gives absolute advantages among the three association metrics. This is because the average available link connection duration between the vehicle and fixed APs is relatively small. On the other hand, in the environment with the mixed APs, the longer connection duration with MAPs may be opportunistically exploited to compensate for the gain obtained by re-associating with the APs with higher achievable bandwidth. Consequently, by considering both duration and bandwidth enables our proposed algorithm to outperform the other schemes based on bandwidth or association duration alone.

6.4. Impact of Vehicle's Velocity

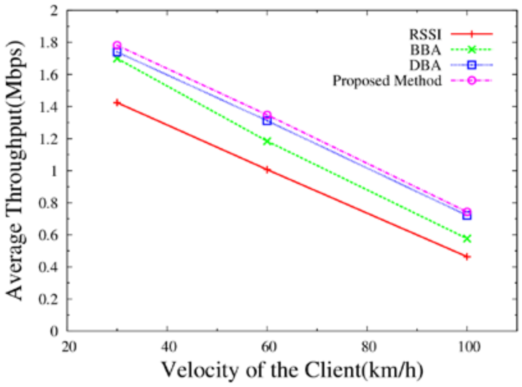


Fig. 12. Impact of vehicle's velocity on average throughput.

We evaluate the impact of the vehicle's velocity on the association control schemes. We have tested with three different velocities: 30km/h, 60km/h, and 100km/h. **Fig. 12** shows the average throughput of the three association control schemes with varying velocity with both fixed APs and MAPs. We can observe in **Fig. 12** that, as the velocity of the vehicle increases, the average throughput decreases. When the client vechiel move at 30km/h, the BBA, DBA, and proposed scheme, except RSSI achieve similar performance results. In the mean time, when the client vehicle moves at 100 km/h, the throughput differences between duration considering schemes (DBA and proposed scheme) and no-duration considering schemes (BBA and RSSI) become larger. This implies that the proposed scheme controls the handoff strategy of a moving vehicle by balancing the benefit from re-associating to the new AP with its cost, depending on the mobility status of the vehicle. Meanwhile, BBA and RSSI schemes do not consider vehicle's mobility, but just consider AP's quality like achievable bandwidth and distance from APs. Although BBA has smaller performance differences with DBA and proposed scheme at 30 km/h according to compensate frequent association overheads with instantaneous higher bandwidth and average longer duration of APs, increasing vehicle speed makes the performance differences with DBA and proposed scheme as the vehicle experiences shorter duration and more frequent handoffs.

Consequently, the proposed scheme outperforms the RSSI- and BBA-based schemes with 30% performance improvement. When the client moves at the velocity of 100 km/hour, the performances of the RSSI- and BBA- based schemes significantly decrease due mainly to short duration and frequent handoff.

7. Discussion

In this section, we will discuss some issues in the design and implementation for acquiring AP information.

We have described the design issue of scanning policy in section 6.2 and have drawn the tradeoff between the benefit and the overhead of periodic scanning policies. The main observation is that periodic scanning can provide accurate available APs' information at the expense of the scan overheads of hundreds of milliseconds. An alternative way to improve association performance is to use adaptive scan intervals. To do this, we should consider the following parameters: AP density, vehicle mobility, and handoff and scan overheads. For instance, as shown in **Fig. 4-(a)** and **(b)**, it is more profitable for vehicles to choose the BBA metric rather than the DBA when the AP density is higher. As future work, we plan to develop a scanning interval adaptation method to improve user performance.

We can also consider computational overheads of the proposed scheme. The proposed scheme gathers the APs' information passively from scanning and generates an association sequence through algorithms 1 and 2. However, this process may involve an implementation issue. In particular, it may cause latency depending on the vehicle's computing capability. To address this issue, we can consider a centralized architecture. A centralized association scheduling server can provide AP information and association sequences based on periodically gathered roadside APs information. Then, the vehicle can use the best AP with lower power consumption and computational overheads.

8. Conclusion

In this paper, we have considered a new vehicular environment with emerging mobile hotspot, i.e., mobile APs (MAPs). We develop a new technique for estimating the achievable bandwidth and connection duration with fixed roadside APs and MAPs. Based on the estimated information of nearby APs/MAPs, we present an efficient method that obtains the association sequence to maximize the throughput. The extensive performance evaluations, which use real bus traces to reflect the actual mobility of vehicles, have shown that our proposed association scheme controls the handoff frequency toward improving the overall throughput. As a result, client vehicles can take advantage of the environment with MAPs and can achieve higher throughput than other schemes based on the duration or bandwidth alone. We expect that our approach can improve further by considering when to scan to find better APs and can readily be applied to many practical VANET systems, such as drive-thru access networks.

References

[1] J. Ott and D. Kutscher, "Drive-thru Internet: IEEE 802.11b for 'automobile' user," in *Proc. of IEEE INFOCOM'04*, pp. 362-373, 2004. Article (CrossRef Link).

[2] D. Hadaller, S. Keshav, T. Brecht and S. Agarwal, "Vehicular opportunistic communication under the microscope," in *Proc. ACM MobiSys'07*, pp. 206-219, 2007. Article (CrossRef Link).

[3] V. Bychkovsky, B. Hull, A. K. Miu, H. Balakrishnan and S. Madden, "A measurement study of vehicular Internet access using *in situ* Wi-Fi networks," in *Proc.ACM MobiCom'06*, pp. 50-61, 2006. Article (CrossRef Link).

[4] A. Giannoulis, M. Fiore and E. W. Knightly, "Supporting vehicular mobility in urban multi-hop wireless networks," in *Proc. ACM MobiSys'08*, pp. 54-66, 2008. Article (CrossRef Link).

[5] M. Kim, Z. Liu, S. Parthasarathy, D Pendarakis and H. Yang, "Association control in mobile wireless networks," in *Proc. IEEE INFOCOM'08*, pp. 1256–1264, 2008. Article (CrossRef Link).

[6] P. Deshpande, A. Kashyap, C. Sung and S. R. Das, "Predictive methods for improved vehicular Wi-Fi access," in *Proc. ACM MobiSys'09*, pp. 263-279, 2009. Article (CrossRef Link).

[7] N. Banerjee, M.D. Corner, D. Towsley and B.N.Levine, "Relays, base stations, and meshes: enhancing mobile networks with infrastructure," in *Proc. ACM MobiCom'08*, pp. 81-91, 2008. Article (CrossRef Link).

[8] http://www.novatelwireless.com/.

[9] http://www.show.co.kr/index.asp?code=WAD0000.

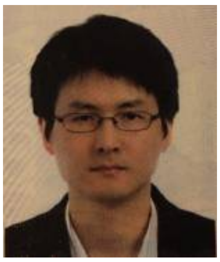
[10] UMass Transit. http://www.umass.edu/transit/buses.html.

[11] TOPIS. http://topis.seoul.go.kr/.

[12] X. Zhang, G. Neglia, J. Kurose and D. Towsley, "Performance modeling of epidemic routing," *Elsevier Computer Networks journal*, 2007, vol. 51/10, pp. 2859-2891. Article (CrossRef Link).

[13] L. Kleinrock, “Queueing Systems, Volume I: Theory,” *Wiley Interscience*, New York, pp99-101, 1975.
[14] B. G. Lee and Sunghyun Choi, “Broadband Wireless Access & Local Networks: Mobile WiMAX and Wi-Fi,” *Artech House*, Norwood, MA, USA, May 31, 2008, pp935-982.
[15] W. Navidi and T. Camp, “Stationary distributions for the random waypoint mobility model,” *IEEE Transactions on Mobile Computing*, vol. 3, no. 1, pp. 99-108, 2004. Article (CrossRef Link).
[16] G.H. Mohimani, F. Ashtiani, A. Javanmard and M. Hamdi, “Mobility modeling, spatial traffic distribution, and probability of connectivity for sparse and dense vehicular ad hoc networks,” *IEEE Trans. Vehicular Techno.*, vol. 58, no. 4, pp. 1998–2007, 2009. Article (CrossRef Link).
[17] A. J. Nicholson and B. D. Noble, “BreadCrumbs: forecasting mobile connectivity,” in *Proc. MobiCom'08*, pp. 46-57, 2008. Article (CrossRef Link).
[18] Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE Std. 802.11-2007.
[19] S. Vasudevan, K. Papagiannaki, C. Diot, J. Kurose and D. Towsley, “Facilitating access point selection in IEEE 802.11 wireless networks,” in *Proc. ACM IMC’05*, pp. 293-298, 2005. Article (CrossRef Link).
[20] H. Lee, S. Kim, O. Lee, S. Choi and S. Lee, “Available bandwidth-based association in IEEE 802.11 wireless LANs,” in *Proc. ACM MSWiM’08*, pp. 132-139, 2008. Article (CrossRef Link).
[21] J. Choi, 1. Na, Y. Lim, K. Park, and C. Kim, "Collision-aware design of rate adaptation for multi-rate 802.11 WLANs," *IEEE J. Select. Areas Commun*, vol. 26, no. 8, pp. 1366-1375, 2008. Article (CrossRef Link).
[22] D. Kim, H. C., M. Na and S. Choi, “Performance measurement over mobile WiMAX/IEEE 802.16e network,” in *Proc. IEEE WoWMoM’08*, pp. 1-8, 2008. Article (CrossRef Link).
[23] Wigle. http://wigle.net.
[24] B. Sadeghi, V. Kanodia, A. Sabharwal and E. Knightly, “Opportunistic Media Access for Multirate Ad Hoc Networks,” in *Proc. ACM MobiCom’02*, pp. 24–35, 2002. Article (CrossRef Link).

Jaeryong Hwang received the BS degree from Naval Academy, Korea in 2002 and the M.S. degree in computer science and engineering from Seoul National University, Korea in 2006. He is currently a PhD degree candidate in the School of Computer Science and Engineering at Seoul National University, Seoul, Korea. His current research interests include vehicular network, delay tolerant network, and wireless and mobile computing.



Jaehyuk Choi is currently an assistant professor at the Dept. of Software Design & Management in Kyungwon university, Seongnam, Korea. He received the Ph.D. degree in electrical engineering and computer science from Seoul National University, Korea, in 2008. He was with the Real-Time Computing Laboratory (RTCL) at The University of Michigan, Ann Arbor, U.S.A. as a postdoctoral researcher from Dec. 2009 to Feb. 2011. His current research interests are in the area of wireless/mobile networks with emphasis on wireless LAN/MAN/PAN, network management, next-generation mobile networks, cognitive radios, data link layer protocols, and cross-layer approaches.

Joon Yoo received his B.S. in Mechanical Engineering from KAIST, and Ph.D in Computer Science and Engineering from Seoul National University in 1997 and 2009, respectively. He has worked as a research assistant professor at University of Seoul in 2009. From 2009 to 2010, he worked as a postdoctoral researcher at the University of California, Los Angeles. Since December 2010, he has been with Alcatel-Lucent Bell Labs Seoul as a Member of Technical Staff. His research interests include vehicular ad hoc networks, mesh networks, cognitive radio and IEEE 802.11 and 802.16.

Hwaryong Lee received the B.S. degree in Computer Science and Engineering from Seoul National University in 2008. He is currently pursuing the MS degree in the department of computer science and engineering at Seoul National University, Korea. His current research interests include wireless networks and mobile computing.

Chong-kwon Kim received the B.S. degree in industrial engineering from Seoul National University, the M.S. degree in operations research from Georgia Institute of Technology, and the Ph.D. degree in Computer Science from University of Illinois at Urbana-Champaign in 1981, 1982, and 1987, respectively. In 1987, he joined Bellcore as a Member of Technical Staff and worked on Broadband ISDN and ATM. Since 1991, he has been with Seoul National University as a Professor in the School of Computer Science and Engineering. His research interests include wireless and mobile networking, high speed network control, distributed processing, and performance evaluation.