Optimal Distributed Vertical Handoff Strategies in Vehicular Heterogeneous Networks

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***Abstract*—This paper addresses the problem of optimal vertical handoff (VHO) in a vehicular network setting. The VHO objective can be minimizing the data transfer time or alternatively minimizing the cost of transmitting traffic. As a framework for performance evaluations, we first analyze a heterogeneous network consisting of a wide-area cellular network interworking with wireless local area networks (WLAN) with fixed inter-distance between access points (APs) placed along roadsides. We further analyze a scenario with random inter-distance between WLAN APs. In both aforementioned cases, only Vehicle-to-Infrastructure (V2I) capability is assumed. We show that in order to minimize the cost of transmission or alternatively transmission time, performing VHOs is an appropriate choice at lower speeds, whereas it would be better to avoid VHO and stay in the cellular network at higher speeds. We further generalize our study, to investigate the VHO strategies in a random inter-distance scenario with both V2I and Vehicle-to-Vehicle (V2V) communication capabilities. We demonstrate that the combination of WLAN plus cellular plus ad hoc networking outperforms any other networking strategies considered in this work in terms of transmission times and transmission costs. The presented results provide insightful guidelines for optimal VHO decision making based on the characteristics of the network as well as the user mobility profile.**

***Index Terms*—Vehicular Network, Vertical Handoff, Heterogeneous Network, V2I, V2V.**

I. INTRODUCTION

THE EXTENSIVE development of wireless communication systems has resulted in the availability of several access technologies at any geographic area, such as cellular networks, wireless local area networks (WLANs) and wireless broadband networks. This heterogeneous wireless environment can help meet the diverse quality of service (QoS) demands of end users. Vehicular networks will particularly benefit from such a rich set of connectivity options as various types of vehicular infotainment applications are expected to be simultaneously accessed by vehicular users and the use of a single wireless access network may not suit the needs of all vehicular applications. Therefore, developing Vehicular Heterogeneous Networks (VHNs), comprised of different wireless access technologies which may be solely dedicated to vehicular communications or else are part of a wider public network, is a priority in the near future. Some further beneficial consequences of integrating different wireless access technologies include the more efficient usage of the resources of such heterogeneous networks, extending the coverage of service availability and offering a range of connectivity alternatives, in terms of QoS support, coverage areas and service costs. In this work we consider a VHN consisting of a wide-area cellular network for global access complemented by WLANs with fixed or random inter-distances between access points placed along roadsides as shown in Fig. 1. The cellular network provides coverage to areas not covered by the access points.

The possibility to switch from one access technology to another based on performance, availability or economical reasons, while maintaining active connections, is called inter-technology or vertical handoff (VHO). Besides supporting extensive mobility of nodes, VHO would enable novel types of applications to be developed, especially in a vehicular network. The VHO decision, i.e., selecting the most appropriate access technology among available alternatives for a particular application can depend on both user preferences, in terms of perceived QoS, cost and/or battery lifetime, among other parameters, and network preferences such as load balancing, interference avoidance and revenue maximization.

In this respect, many VHO decision-making algorithms have been proposed in the literature [1]–[10]. However, extension and adaption of such solutions in the contexts of VHNs has received relatively less attention. In [1] users select the wireless access technology with the highest bandwidth as the most appropriate option. The authors of [2] formulated a multi-objective optimization problem and proposed a heuristic with the aim of selecting a network connection for transferring each component of data. In [3], [4] each user provides the network with up to ten different inputs to assist the network in making a VHO decision based on its specific preferences. Half of the input values are weights describing the importance of VHO decision-making parameters including cost, security, power, network conditions and network performance to the user. The rest of the inputs are threshold values specifying allowable range of the VHO decision parameters. In [5], available access networks are first characterized as acceptable if they satisfy the minimum cut-off criteria, and unacceptable otherwise, by using a non-compensatory Multi-Attribute Decision Making (MADM) algorithm. Then a compensatory MADM algorithm is used to calculate the rankings of the acceptable networks based on their costs, available bandwidths, allowed bandwidths, utilizations, delays, jitters, and packet losses. The authors of [6] proposed a VHO decision algorithm which focuses on the joint optimization of total battery lifetime of the network, and fair distribution of traffic load at attachment points which improves the overall QoS by avoiding congestions.

When it comes to VHNs, which have highly dynamic network topologies and highly variable environment conditions due to the inherent characteristics of high mobility vehic-

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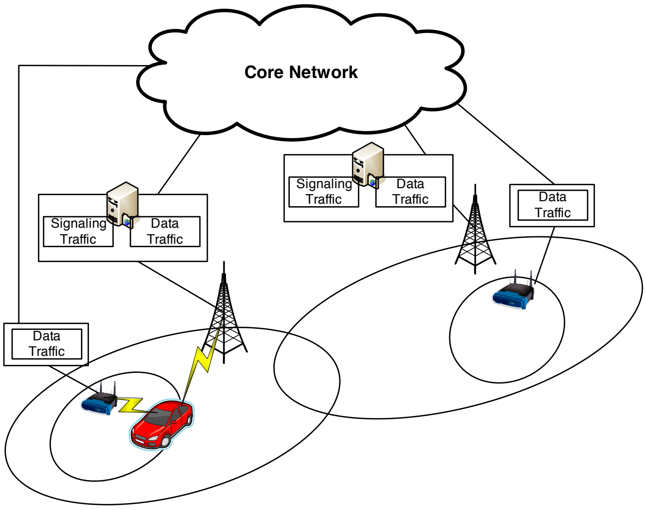

Fig. 1. The reference model

ular communications, the VHO decision-making algorithms mentioned above might be inefficient and ineffective. This inefficiency stems from the fact that in the design of the VHO decision making algorithms the mobility models of users including their movement trajectories and their velocities are often neglected. To emphasize the role of mobility pattern awareness, note that when traveling at high speeds, it is more likely that one user travels through several access technologies in a short span of time. Therefore, when legacy VHO decision-making algorithms are being used, it is highly probable that handing off from a wide-coverage network to a newly emerged local-coverage network may be followed by another VHO back to the original network immediately afterwards resulting in too many VHOs. Since the procedure of a VHO involves a set of signaling functions and consequently imposes both VHO processing loads and signaling overhead to the network, unnecessary VHOs should be discouraged. Overloading the network with signaling traffic in turn causes additional costs and longer transfer times incurred by delays of reconnecting the user to the new network. Another aspect of the mobility models that has been neglected in most previous studies is the fact that the movements of vehicles are confined by roadways, so that the directions of movements are highly constrained and only the network coverage along these directions of movements is of interest.

Very few studies have exploited the knowledge of mobility patterns of users in a VHO decision making mechanism for VHNs. In [7], the authors utilized a centralized location service server (LSS) to which vehicles report their current positions and consequently receive the information of available access networks in their vicinity. Further, a utility function is used to determine the satisfaction of users in accessing the available networks, which is fed back to LSS. Finally, the optimal hand-off decisions are periodically calculated in LSS at the beginning of discrete time intervals based on nodes movement predictions and are reported back to the users. To the best of our knowledge the decision-making mechanism we will present in this paper is the first work in which vehicles continuously select optimal access networks, based on their mobility patterns, in a distributed event-based manner.

A final issue of interest in analyzing VHO is the signaling traffic associated with this process. The VHO signaling traffic can be transmitted either on an existing access technology or via a dedicated wireless signaling system as in [11]. The authors of [11] suggested the use of a two-way paging system for signaling negotiations of VHO decisions. Since we assume that all areas of the network are covered by the cellular networks, in our study we use cellular systems for signaling transmissions so that its location and mobility management functionalities can be shared with other access networks without any extra deployment costs. For this purpose, a combination of tight and loose coupling can be used through which the cellular core network considers WLANs as part of its access network to enable signaling traffic transfer through the cellular network. Different architectures for tight and loose couplings and their pros and cons are studied in more detail in [12].

Main Contributions: In this paper we develop an optimal, event-activated, and thus continuous-time, VHO decision-making algorithm, which is based on the mobility profiles of users including their velocities, and further takes the preferences of users in terms of costs or transfer times into account. As opposed to most existing solutions, the proposed approach is deterministic and is fully distributed in the sense that vehicular users will make the VHO decisions rather than core network entities. We address handoff decision making in a comprehensive set of system models, pertinent to infrastructure-based access technologies (known as Vehicle-to-Infrastructure, or V2I, communications) as well as in scenarios where both V2I and ad hoc communications between vehicles (referred to as Vehicle-to-Vehicle, or V2V communications) are feasible. Furthermore, we obtain the optimal VHO decision making mechanism when planned WLANs for vehicular communications exist at certain areas, where the locations of access points are known a priori by the vehicular users, and extend the analysis to the case of open WLAN access points that are randomly located. To the best of our knowledge, our contribution is the first rigorous study of VHO decision making, addressing such a comprehensive set of scenarios.

The rest of this paper is organized as follow. Section II elaborates on the details of problem formulation. Optimal VHO decisions with fixed inter-distance access points are studied in Section III, followed by an analysis for random inter-distance access points in Section IV. Both V2I and V2V communications are considered in Section V. Numerical results are presented in Section VI. Section VII concludes the paper.

II. PROBLEM FORMULATION

We focus on a scenario where cellular networks and WLANs interwork to form a VHN. However, our proposed solution can be readily extended to any arbitrary set of access technologies. Although recently there have been a lot of studies on the integration of various wireless access technologies, our motivations for this choice include the widespread availability of dual-mode terminals, the relatively long history of coexistence of these technologies, and the complementary characteristics of cellular and WLANs, whereby the cellular system provides a larger coverage area with a relatively lower data rate at a higher cost whereas a WLAN can offer a relatively higher data rate in a shorter range with a lower cost. In the presence of both WLAN and cellular network, the vehicle has the option of picking either of them for communications, whereas upon leaving the WLAN coverage the cellular network will be the only alternative, if V2V communication is not feasible. We will extend our analysis to consider both V2I and V2V communications in Section V.

Every vehicle that wishes to access the VHN should establish a connection to an attachment point, i.e., a base station (BS) on the cellular network or an access point (AP) of the WLAN. Since we assume that the cellular network provides global coverage, the vehicle can always find a BS with a strong enough level of received signal strength (RSS). Fig. 1 depicts a reference model for the architecture described.

If the RSS of an AP starts decaying rapidly and falls below a threshold for a specific period of time, the vehicle will initiate the VHO to the cellular network. All BSs and APs periodically broadcast advertisement messages announcing their availability and their prices of data transfer, denoted by c_w and c_c ($) as the costs of sending one bit in WLAN and cellular network, respectively. In practice, service providers price their services based on business considerations, among which use of capacity is but one of the factors. However, we approach the problem at hand from a *system design* perspective to determine the minimal time or cost of communication for the vehicular users. Deriving such lower-bound access time or cost limits will facilitate profitable pricing strategies for service providers. As both WLAN and cellular technologies support periodic network identification signaling, addition of access cost and access rate information will have a negligible effect on the system overhead. Note that as we assume that cellular network is responsible for transferring the signaling traffic, the cost of sending a signaling bit will also be c_c. Clearly, both access networks have limited capacities and therefore their costs are dependent on the available resources at the time instant they broadcast their advertisement messages. Therefore, one objective of the pricing mechanism can be adaptive load balancing; however, determination of optimal pricing strategies is out of the scope of this paper. Note that BSs and APs could be under the ownership and control of different service providers and consequently follow different policies for the determination of their costs. A glossary of all variables and their definitions is given in TABLE I.

TABLE I
VARIABLES AND THEIR DEFINITIONS

Variable	Definition
c_w	Cost of sending a bit in WLAN
c_c	Cost of sending a bit in cellular network
c_1	Transmission cost of only cellular networks
c_2	Transmission cost of WLANs + cellular
c_3	Transmission cost of WLANs + ad hoc
c_4	Transmission cost of WLANs + cellular + ad hoc
r_w	Data rate in WLAN
r_c	Data rate in cellular network
W	Coverage area of each WLAN AP
A	Distance between two consecutive AP coverage areas
A'	Distance over which ad hoc delay is tolerable
b_t	Data bits required to be sent
b_{VHO}	Signaling bits required for a VHO
N_w	Number of WLANs needed for transmitting all b_t bits
T_w	Total transmission time when WLANs + cellular
T_c	Total transmission time when only cellular networks
T_u	Usage time
T_{w+AH}	Total transmission time when WLANs + ad hoc
T_{c+w+AH}	Total transmission time when WLANs + cellular + ad hoc
th	Pre-determined threshold adjusting the accuracy of VHO
λ	Arrival rate of WLAN coverage areas
t_i	Inter-arrival times with lengths smaller than W
D_i	Inter-arrival times with lengths greater than W
d_{AH}	Ad hoc communication delay
ρ	Average vehicle density
v_h	Average vehicle velocity
d_{hop}	Average delay per hop

III. VHO DECISION-MAKING ALGORITHM WITH FIXED AP INTER-DISTANCES

Since VHO decision-making requires a relatively high level of transmission power and processing power capabilities, in most studies the decision-making procedure is carried out in a fixed network processing centre, i.e., in a centralized manner. However, for vehicular networks such power constraints can be relaxed and consequently in this paper we propose a distributed VHO decision-making algorithm which removes the need for deploying a data-processing and decision-making centre in the core network and the packet traffic between the centre and nodes. In this distributed setting, every vehicle, based on the information initially loaded in its database and the inputs repeatedly updated by the network, will make VHO decisions. Provided that at the time instant in which the VHO decision is being made, b_t data bits are required to be transmitted and given that both the WLAN and the cellular network are available to the vehicle, the VHO decision-making algorithm should decide which one to access depending on the user's preferences. These preferences can include minimization of the transmission cost or alternatively the transmission time. Note that even when the WLAN is prioritized over the cellular network, using the cellular network in areas that are not covered by the WLAN is inevitable and this is why this case is referred to as *WLAN plus cellular* throughout the paper. In the case that the vehicle's first priority is to minimize the transmission cost, the decision making algorithm should calculate the cost of transmission for both accessing the cellular network, i.e. c_1 ($), or else the WLAN (WLAN plus cellular), i.e., c_2 ($), and hence selects the access network with the lowest cost. In the following subsection the case of cost minimization VHO strategy is discussed, which is followed by transmission-time minimization analysis in subsection *B*.

A. Cost-Minimization Approach

We begin with a set of simplifying assumptions to define the cost functions, but as we move forward, we will relax the assumptions and improve the functions accordingly to make our formulations more realistic. We assume that all vehicles are equipped with both WLAN and cellular interfaces and the

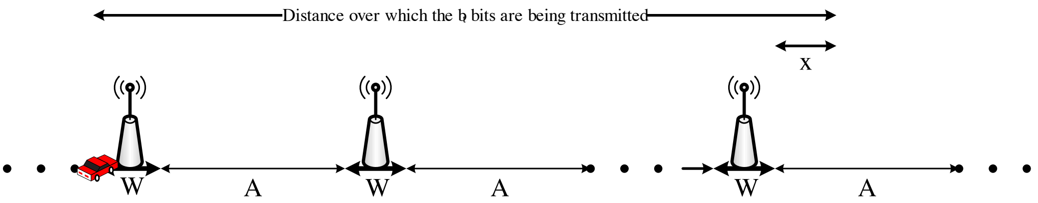

Fig. 2. A vehicular network with fixed inter-distance APs.

allowable data rates announced by the WLAN and cellular at the time of decision-making are r_w and r_c (bps), respectively. Further, we consider a highway vehicular communication scenario, where without loss of generality we can confine our analysis in spatial domain to the direction of moving vehicles, and therefore in the rest of paper we address the space in (m) rather than (m^2). The coverage area of each AP is assumed fixed and equal to W (m) implying a planned network. Furthermore, the APs are all equidistant and the distance between the coverage areas of two consecutive APs, which is covered by cellular network, is equal to $A > 0$ (m). The scenario of a vehicle driving along a highway including the defined parameters is depicted in Fig. 2. Although we derive all formulas based on the highway scenario, the extension to an urban area with a number of intersecting streets is straightforward.

Assuming that the velocity of the vehicle at the decision-making time is v (m/s), the access costs c_1 and c_2 are obtained as

$$c_1 = b_t c_c, \tag{1}$$

$$c_2 = N_w\left(\frac{W}{v}\right) r_w c_w + \left(T_w - N_w\left(\frac{W}{v}\right)\right) r_c c_c, \tag{2}$$

where N_w is the number of AP coverage areas the vehicle drives across before all the b_t bits are transmitted and T_w is the total time needed for transmission in the case where the WLAN is prioritized over the cellular network (WLAN plus cellular). Note that b_t does not include the VHO signaling bits. The first term on the right hand side of (2) is the cost of transmitting/receiving data-only bits over the WLAN. The second term in c_2 is the incurred cost of transmitting data, and signaling bits, over the cellular network. Therefore, given that b_{VHO} is the number of signaling bits needed for a VHO, N_w is the maximum integer value so that

$$N_w \frac{W}{v} r_w + (N_w - 1)\frac{A}{v} r_c - 2N_w b_{VHO} \leq b_t, \tag{3}$$

and T_w is given by

$$T_w = [x + N_w W + (N_w - 1)A]/v \tag{4}$$

where x is the distance depicted in Fig. 2 and can be obtained from the equation below:

$$b_t - \left[N_w \frac{W}{v} r_w + (N_w - 1)\frac{A}{v} r_c - 2N_w b_{VHO}\right] = \frac{x}{v} r_c. \tag{5}$$

Note that to derive (3), we assume that even if the user is initially within the range of an AP, before it starts to access any network, the access initialization signaling, which is taken care of by the cellular network, is comparable to VHO signaling overhead, and thus irrespective of the initial location of vehicular user $2N_w b_{VHO}$ signaling bits are required. When the velocity goes up, the number of required VHOs increases which in turn may cause an unreasonable amount of VHO signaling traffic compared to the data traffic and consequently a higher cost of data transmission. By computing the costs and selecting the access technology with the minimum cost the VHO decisions are adapted to the velocity of the vehicle accordingly.

B. Transmission-Time Minimization Approach

Under some circumstances, the vehicular user's preference could be accessing the technology with the highest QoS metrics. Among various QoS metrics, data rate can be considered of significant importance. Although the data rates offered by the WLAN and the cellular network are out of the user's control, by choosing appropriate access network at any point, the total transmission time of the data bits can be minimized. Therefore, using the same approach discussed in calculating the costs, the vehicle can calculate the transmission times T_c and T_w (s) which are the total times needed for the transmission when only the cellular network and WLAN plus cellular are used, respectively.

$$T_c = \frac{b_t}{r_c} \tag{6}$$

and T_w is given by (4). The vehicle selects the network with the minimum transmission time. It is worth mentioning that the provisioned decision-making process is event-based, whereby the aforementioned parameters will be recomputed upon observation of any significant change in the network such as advertisement of new costs or new allowable data rates, availability of new alternative access network, or following a considerable change in the velocity or direction of vehicle.

IV. VHO DECISION-MAKING ALGORITHM WITH STATISTICAL AP INTER-DISTANCES

IEEE 802.11-based WLANs have been extensively deployed in home and offices around the world. Since upstream access links of these networks are often idle, they could potentially be used for providing service to vehicles. The possibility of using such an unplanned set of open WLANs in terms of security, viability, and deployment to offer services to end users moving at vehicular speeds has already been studied in the literature [13], [14]. Since open APs are independently deployed along roadsides and no vehicles have prior information about their placements, we assume that the distances between consecutive APs follow negative exponential distribution. In other words, when a vehicle is moving with a fixed velocity,

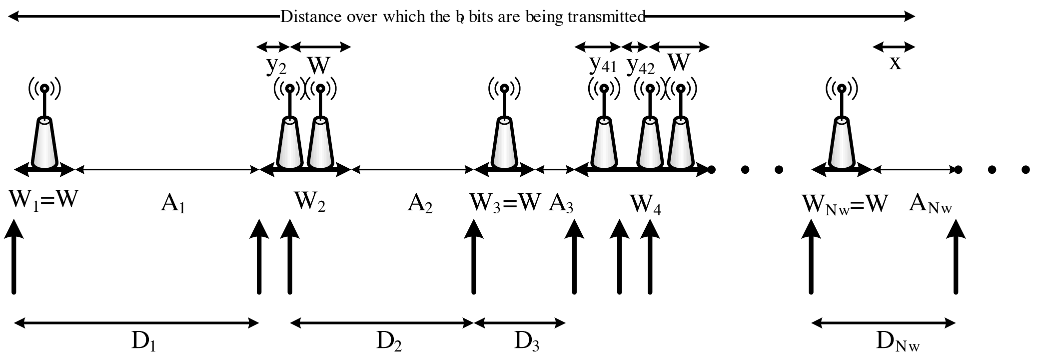

Fig. 3. Random inter-distance APs in a vehicular scenario.

APs will show up in its transmission range according to a Poisson arrival. This assumption is also aligned with real-life measurements of open WLAN coverage for vehicular networks such as [13]. So, in this section we extend our analysis in Section III to the scenario where the distances between various APs change randomly according to a Poisson process.

In case of an overlap where a new WLAN shows up before the vehicle exits the previous one, we assume that the vehicle continues its connection with the first AP and handoffs to the new AP when it is no longer covered by the first AP. Therefore, we can assume that the area covered by WLAN APs in this scenario is the sum of the areas covered by each AP, minus the overlapping area. Assuming that the coverage area of each AP is still fixed, and equals W as in previous section, the areas covered by the overlapping APs will be a random variable with a general distribution. A typical network topology in this new scenario is depicted in Fig. 3.

In this case, N_w is the maximum integer value satisfying (7). Note that both W_is and A_is are stochastic variables. Hence, N_w will be the maximum integer value such that

$$P(M \leq b_t) \geq th, \tag{8}$$

which is equivalent to

$$P(M \geq b_t) \leq 1 - th \tag{9}$$

where $P(x)$ denotes the probability of event x and th is a pre-determined threshold adjusting the accuracy of VHO decisions. Since M is a non-negative random variable and b_t is greater than zero, according to Markov's inequality [15] which provides a tight bound we have

$$P(M \geq b_t) \leq \frac{E(M)}{b_t}, \tag{10}$$

where $E(x)$ denotes the expected value of x. Therefore, if we obtain the maximum integer value for N_w such that $E(M)/b_t \leq 1 - th$ holds, (8) will hold as well. The idea is that for a given N_w, we compute $E(M)$ and compare it with $b_t(1 - th)$. Then, N_w is the maximum integer value for which the above inequality holds. Now, we explain how $E(M)$ is computed for a given N_w. For any given N_w we have,

$$E(M) = N_w \frac{E(W_i)}{v} r_w + (N_w - 1)\frac{E(A_i)}{v} r_c - 2N_w b_{VHO}, \tag{11}$$

where $E(W_i)$ is as in (12), where given a Poisson arrivals of APs with rate λ [16] the probability of k arrivals in time t equals

$$P(k,t) = \frac{(\lambda t)^k e^{-\lambda t}}{k!}. \tag{13}$$

Furthermore, y_is as shown in Fig. 3 are the inter-distances of APs in the areas covered by the WLANs, which have a negative exponential distribution with average $1/\lambda$. However, since y_is are all smaller than W, their expected value $E(y_i)$ will be:

$$\begin{aligned} E(y_i) &= E(y|y < W) = \frac{\int_0^W y f(y) dy}{P(y < W)} \\ &= \frac{(-We^{-\lambda W} + \frac{1}{\lambda} - \frac{1}{\lambda}e^{-\lambda W})}{(1 - e^{-\lambda W})}; \quad f(y) = \lambda e^{-\lambda y}. \end{aligned} \tag{14}$$

Therefore, $E(W_i)$ in (12) can be simplified as:

$$E(W_i) = \frac{We^{-\lambda W}(1 - \lambda We^{-\lambda W} - e^{-2\lambda W})}{(1 - e^{-\lambda W})(1 - \lambda We^{-\lambda W})^2}. \tag{15}$$

Also, $E(A_i)$ in (11) is given by

$$E(A_i) = E(D_i - W) = E(D_i) - W \tag{16}$$

where D_is as shown in Fig. 3 are the inter-distances of APs when no AP has showed up for at least W and consequently D_is are greater than W. Knowing that the arrivals of APs are Poisson, for $E(D_i)$ we have

$$\begin{aligned} E(A_i) &= E(y|y > W) = \frac{\int_W^\infty y f(y) dy}{P(y > W)} - W \\ &= W + \frac{1}{\lambda} - W = \frac{1}{\lambda}; \quad f(y) = \lambda e^{-\lambda y}. \end{aligned} \tag{17}$$

In the following subsections, we address the VHO decision making problem with cost minimization as well as transmission time minimization goals.

A. Cost-Minimization Approach

The computed N_w is used to obtain costs and transmission times required in the VHO decision-making algorithm. When the objective is selecting the access network with the minimum cost, and given the computed N_w, the expected value of c_2

$$\underbrace{\frac{W_1}{v}r_w + \frac{A_1}{v}r_c + \frac{W_2}{v}r_w + \frac{A_2}{v}r_c + \ldots + \frac{A_{N_w-1}}{v}r_c + \frac{W_{N_w}}{v}r_w - 2N_w b_{VHO}}_{M} \leq b_t. \tag{7}$$

$$\begin{aligned} E(W_i) &= E(W_i, 0 \text{ AP show up in } W) + E(W_i, \text{at least 1 AP show up in } W) \\ &= E(W_i, 0 \text{ AP show up in } W) \\ &+ E(W_i, 1 \text{ AP show up in } W \text{ and 0 AP Show up in } W \text{ after the first show up}) \\ &+ E(W_i, 1 \text{ AP show up in } W \text{ and at least 1 AP Show up in } W \text{ after the first show up}) \\ &= \ldots \\ &= WP(0,W) + [W + E(y_i)]P(0,W)P(1,W) + [W + 2E(y_i)]P(0,W)[P(1,W)]^2 + \ldots \end{aligned} \tag{12}$$

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which is used in decision-making can be obtained in a similar way to (2) as

$$E(c_2) = N_w \frac{E(W_i)}{v} r_w c_w + [T_w - N_w \frac{E(W_i)}{v}] r_c c_c \cdot \tag{18}$$

Similarly, from (4), we have

$$T_w = [x + N_w E(W_i) + (N_w - 1)E(A_i)]/v \tag{19}$$

where x is obtained in the same way as of (5), i.e.,

$$b_t - [N_w \frac{E(W_i)}{v} r_w + (N_w - 1)\frac{E(A_i)}{v} r_c - 2N_w b_{VHO}] = \frac{x}{v} r_c \cdot \tag{20}$$

B. Transmission-Time Minimization Approach

When the vehicle's preference is the access network resulting in the minimum transmission time, the decision making algorithm should compare T_c, which is calculated according to (6), with T_w as given by (19) to select the optimal access strategy. In Section VI we will benchmark the performance of the proposed VHO decision-making algorithm in case where AP inter-distances are statistically distributed with the fixed AP inter-distances case.

V. VHO DECISION-MAKING WITH ENABLED V2V MODE

We now generalize our proposed VHO decision-making algorithm to include the scenarios where multi-hop V2V communications are also allowed between vehicles, in addition to V2I communications, in the architecture of the VHN. Using intermediate vehicles to relay data to APs via ad hoc communications can alleviate the need for accessing the costlier cellular network when APs are out of range. There are few studies in the literature that include WLAN ad hoc mode in their architecture. One example is [6] where the authors have devised a route-selection algorithm to forward data to attachment points. However, contrary to our algorithm, which considers multi-hop ad hoc communication as a data transmission alternative in addition to cellular or WLAN plus cellular, the previous work employs ad hoc networking only as a means for forwarding data to the attachment points which have been pre-selected.

Since the delays of V2V communications consists of multi-hop relaying delays and the delays experienced when no next hop vehicle is found and the data is being carried, these delays are generally much longer than the communication delays in the core network, which has a high-speed wired backbone. Thus, the delays imposed by ad hoc networking should be well investigated for delay-sensitive applications in order to ensure meeting their maximum allowable delay requirements. To this end, we propose an ad hoc delay calculation scheme in the following. Note that our event-based VHO assumption means that the vehicular user initiates decision making process as soon as the level of received signal from its existing access network degrades for a certain period of time, or any significant changes in the network setting is detected. Therefore, it is logical to assume that VHO delay will not contribute towards the ad hoc delay calculated in this section.

A. Ad Hoc Networking Delay Analysis

We assume that vehicles are equipped with Global Positioning System (GPS) receivers and thereby they have accurate knowledge of their geographical positions. Also, they periodically broadcast beacon messages reporting their positions to their neighbors and based on these beacons they maintain an updated neighbor list in their look-up tables. Similar to the previous section, we start with the case where the APs' inter-distances are fixed and then extend the results to the scenario where APs show up randomly with an identical independent distribution.

A typical scenario when the distances between consecutive APs are fixed and equal to $d = A + W$ is depicted in Fig. 4. In this section we will take the worst case ad hoc communication delay into account. Alternatively, the expected (average) ad hoc delay could be calculated. However, since our approach in this paper is to develop a deterministic VHO decision making policy, if the expected delay is considered instead of the worst case delay in the decision making, it might result in outage in connectivity due to instances of excessive delay over the average delay in the network. The worst case delay profile in accessing the APs is when a specific vehicle is exactly equidistant from both APs. The ad hoc communication delay, d_{AH} (s), which is the time it takes the vehicle to forward the data to any of the APs, depends on the average vehicle population density, ρ (car/km), the average vehicle velocity, v_h (m/s), and the average delay per hop, d_{hop} (s), on different parts of the highway. If we assume that the arrival of vehicles on the highway is Poisson, which is a common assumption in the literature [17], then the inter-distances between vehicles

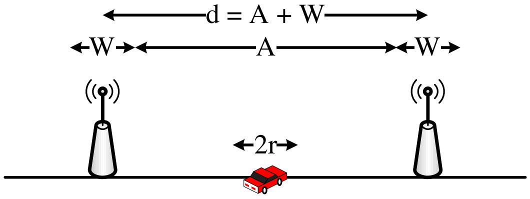

Fig. 4. Two consecutive APs with distance $d = A + W$.

on the highway with average density ρ have exponential distribution with an average $1/\rho$. Therefore, d_{AH} can be written as:

$$d_{AH} = (1 - e^{-\rho r})(\frac{A/2}{r})d_{hop} + e^{-\rho r}(\frac{A/2}{v_h}) \tag{21}$$

where $(1-e^{-\rho r})$ is the probability that the packet is forwarded via wireless communications while $e^{-\rho r}$ is the probability that the vehicle carries the packet itself, because it cannot find any next hop vehicle within its range. If the packet is being forwarded via V2V communications, then $(A/2/r)$ is the number of hops that are needed to cover a distance equal to $A/2$, which constitutes the forwarding delay when multiplied by d_{hop}. Note that the rationale to approximate the division of the distance by transmission range r to obtain the number of hops is the packet forwarding mechanism we consider in which the forwarding vehicle delegates the packet forwarding responsibility to the *farthest* vehicle in its look-up table. On the other hand, $(A/2/vh)$ is the delay the packet experiences when it is carried along a distance equal to $A/2$. We assume that vehicles are equipped with digital maps that contain the locations and street names as well as the average density and average velocity of vehicles in each street, which are the main factors for decision making in our proposed VHN with V2V communications. Such digital maps have been already commercialized [18].

One of the parameters, which needs to be determined in (21), is d_{hop}. In [19] the performance of the IEEE 802.11 DCF when the traffic is uniformly distributed is analytically characterized for the non-saturated case and d_{hop} is estimated with high accuracy between two very close upper bounds and a lower bound. We give more details on the computation of d_{hop} in Section VI. In the next subsections, the VHO decision-making problem when V2V communication is included as an alternative is studied with both cost minimization and transmission time minimization goals.

B. Calculation of Cost and Transmission Time

Assuming the computed ad hoc communication delay satisfies the application's delay requirement, the communication cost c_3 when using only WLANs and ad hoc communications, interchangeably called WLAN plus ad hoc in the rest of the paper can be written as:

$$c_3 = T_u r_w c_w \tag{22}$$

where T_u is the usage time which is the total amount of time the connection to APs remains established. This usage time is given by,

$$T_u = (N_w - 1)(\frac{W + A}{v} - d_{AH}) + \frac{W}{v} + (\frac{x}{v} - d_{AH}), \tag{23}$$

where N_w is the maximum integer value such that

$$[(N_w - 1)(\frac{W + A}{v} - d_{AH}) + \frac{W}{v}]r_w \leq b_t, \tag{24}$$

and x is obtained from:

$$b_t - [(N_w - 1)(\frac{W + A}{v} - d_{AH}) + \frac{W}{v}]r_w = (\frac{x}{v} - d_{AH})r_w, \tag{25}$$

Note that due to definition of d_{AH} as the worst case delay, (23) approaches the lower bound of usage time, T_u. Alternatively, by setting $d_{AH} = 0$, only in the second term at the right hand side of (23), we can compute the upper bound usage time too. Also, note that the transmission time (T_{w+AH}) when WLAN plus ad hoc is being used is different from T_u and equals:

$$T_{w+AH} = [N_w W + A(N_w - 1) + x]/v + d_{AH}, \tag{26}$$

So far we have discussed the cases where only cellular networks, WLAN plus cellular and WLAN plus ad hoc are used. Now, we turn to the case where the combination of all three access technologies is selected as the best way of data transmission. This type of transmission called WLAN plus cellular plus ad hoc is particularly beneficial when d_{AH} does not satisfy delay requirements but the vehicle is willing to have the most economical set of access networks.

C. WLAN Plus Cellular Plus Ad Hoc

The idea is that for the given maximum tolerable delay, the distance A' over which the ad hoc delay is smaller than the maximum tolerable delay is obtained according to (21) by setting the left hand side of (21) to the maximum tolerable delay. Then, ad hoc communications is used for distances $A'/2$ in the beginning and $A'/2$ in the end of A and cellular communications are used for transmission over the rest of A. Note that in this case the number of VHOs is smaller or equal to the case of WLAN plus cellular. Therefore, if $c_2 < c_1$, the cost incurred by using WLAN plus cellular plus ad hoc (c_4) will also be $c_4 < c_2 < c_1$. Similarly, if $T_w < T_c$, the transmission time in the case of WLANs plus cellular plus ad hoc will be $T_{c+w+AH} < T_w < T_c$.

When the inter-distances of APs are not fixed and they show up independently, the decision-making vehicle cannot count on upcoming APs. Based on its distance to the previous AP it uses ad hoc communications for distances smaller than $A'/2$ and cellular communications for any longer distance. The discussion in the previous paragraph on relative costs and relative transmission times of WLAN plus cellular plus ad hoc compared to WLAN plus ad hoc or only cellular communications still holds. Note that the case in which the delay experienced by a packet is approaching the maximum tolerable delay is one of the scenarios that trigger the recomputation of decision-making parameters which includes filtering unacceptable alternatives.

VI. PERFORMANCE EVALUATIONS

In this section we compare the performance of the proposed distributed system selection scheme with the case where global knowledge of the network is available. For this purpose, we simulated the network using MATLAB. IEEE 802.11p

TABLE II
MOBILITY-RELATED AND WIRELESS COMMUNICATION-RELATED PARAMETERS USED IN THE SIMULATION

W	100 m
A	200 m
Decision-making vehicle's velocity	5∼40 m/sec
Average velocity	10∼25 m/sec
ρ (Average vehicle density)	2∼10 veh/km
r_w	6 Mbps
r_c	0.6 Mbps
b_{VHO}	8.8 Mb
c_w	1 Unit
c_c	4 Unit
r (Transmission range)	100 m
MAC layer	IEEE 802.11 DCF
Max. contention window	32
Propagation model	Two Ray Ground
Simulation time for ad hoc delays	10000 sec.
Beaconing frequency	2 beacons/sec
Beacon size	512 bits

DSRC WLANs are not expected to be widely deployed in the near future. However, IEEE 802.11p MAC layer is derived from IEEE 802.11 MAC and its physical layer parameters are based on IEEE 802.11a standard with minor changes. IEEE 802.11a supports data rates range from 6 Mbps to 54 Mbps depending on the distance between the transmitter and the receiver [20]. We have selected the values of WLAN parameters in our evaluation based on [21]. As a result of these parameter choices, the coverage area of APs is set to 100 (m). Further, the signaling overhead required to perform a VHO is determined based on the assumptions made in [22]. Our choice of cellular system is CDMA20001x-EV [23] with an average data rate of 600 Kbps. The type of applications of concern in our study is non real-time non-safety applications, e.g., file transfer, non real-time multimedia services, data delivery, etc. In these applications a stream of b_t data bits is required to be transmitted. So, the preferences of users could be transmission cost minimization or total transmission time minimization. Both of these approaches will be investigated in our evaluations. A complete list of the parameters used in the evaluation, including those related to the mobility model and the wireless communications system, is given in TABLE II.

We first investigate the performance of the VHO decision-making algorithm, for the scenarios with fixed and random AP inter-distances. We analyze both the transmission times as well as transmission costs versus the velocity of the decision-making vehicle. There exist three networking possibilities, namely accessing and remaining only in the cellular network, using VHO between WLAN and cellular giving priority to WLAN over cellular when available (we call this WLAN plus cellular), and using WLAN connection as well as V2V communication (we refer to this as WLAN plus ad hoc). Note that in the more realistic case of random inter-distances, when WLAN plus cellular is being used, our proposed algorithm makes decisions based on prior knowledge of average distance between consecutive APs. Hence, the decisions may be different from those made based on global knowledge of the network.

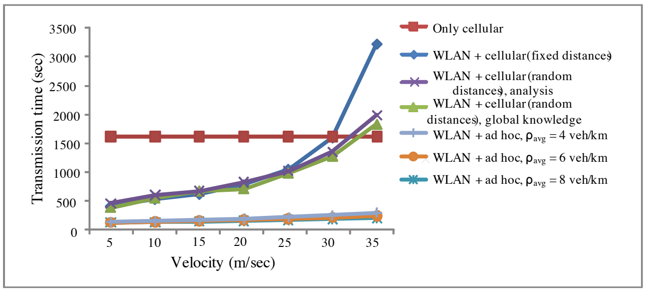

Fig. 5. Comparison of transmission time performance in the proposed algorithms, when $b_t = 1$ Gb.

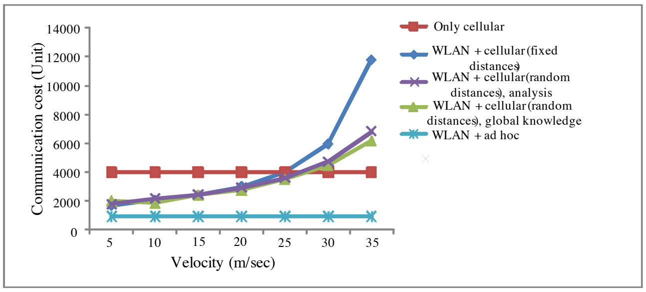

Fig. 6. The cost of communication using different VHO policies for the scenario similar to Fig. 5.

Figs. 5 and 6 demonstrate the VHO policies that should be used to achieve time minimization and cost minimization, respectively. We have presented the results for average AP inter-distances of 300 meters for all networking possibilities, and for the case in which global knowledge of the network is available. The graph for global knowledge stands for the case where decisions are made with the aid of the network in a centralized manner. For obtaining each of the values in the graph we used Monte-Carlo method. Based on this method, the placement of APs has been randomly generated using a Poisson distribution such that the AP inter-distances follow a negative exponential distribution with an average equal to 300 meters, and the transmission time or cost is computed with respect to this placement deterministically in a centralized manner. Each of the presented values in the graph is averaged over 30 individual computations. The analytic and global knowledge results for WLAN plus cellular scenario show a high degree of similarity, thereby verifying our approach.

The figures demonstrate the system selection policies that should be used to achieve time minimization and cost minimization. As observed in the figures, the choice of VHO to a WLAN when available (i.e., WLAN plus cellular) seems generally a viable strategy in low speed vehicular communications. However, as the speed of a communicating vehicle increases, the rate of VHOs increases, and the vehicle spends less time in each WLAN coverage area transmitting less traffic to that AP. In the case of WLAN plus cellular access scheme, the extra cost of performing VHO makes staying on the cellular network a more efficient choice. This no VHO strategy applies only to a limited scenario of very high speed vehicles (around 35 m/s).

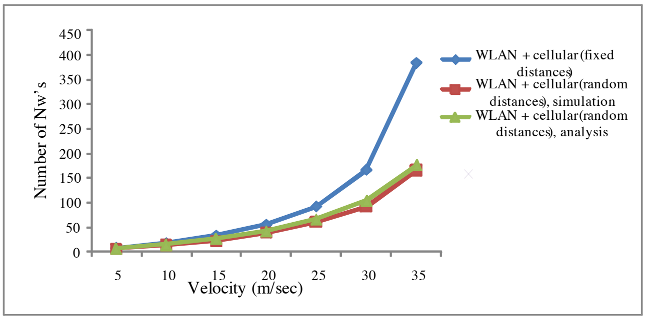

Fig. 7. The required number of VHO for the proposed vehicular communication strategies.

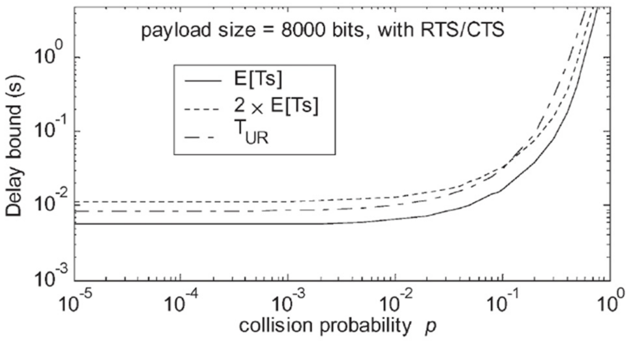

Fig. 8. Upper and lower delay bounds for d_{hop} [19].

In Fig. 7 the number of VHOs needed for sending $b_t = 1$ Gb is shown versus the velocity of the vehicle. This result further confirms our intuition of optimal VHO decision in the previous paragraphs. As can be observed from Fig. 7, the number of VHOs increases almost exponentially as the speed increases, thereby making VHO a less attractive choice in high speed vehicular networks.

The simulation results in Figs. 5-7 provide comparisons of accessing only cellular system, WLAN plus cellular network, and WLAN plus ad hoc. The data transmission time or communication cost performance of the latter case, depicted for different average vehicle densities, outperforms other networking possibilities. Although the case of WLAN plus ad hoc shows a relatively better performance, the introduced ad hoc delay may not be tolerable for many applications. Therefore, we will now introduce further simulation scenarios to investigate the performance of ad hoc communication mode in detail. More specifically, since the delay problem becomes more challenging when multi-hop communications are used over larger distances, we study the dependence of ad hoc delays (d_{AH}) incurred by multi-hop communications on the AP inter-distances. As stated before, to determine parameter d_{hop} in (21), we used the results of [19] in which the performance of the IEEE 802.11 DCF under traffic that is uniformly distributed among all nodes is analyzed for the non-saturated case. According to queuing theory [16], in a non-saturated network the average arrival rate of the input traffic is smaller than the average rate at which the traffic is being served, which is equivalent to successful transmission to the next-hop node.

In this study d_{hop} is characterized with a high accuracy between two very close upper bounds and a lower bound, as depicted in Fig. 8. The lower bound and the upper bounds are obtained by using queuing theory [16], [24] and considering that the arrival of packets is unknown and follows a general distribution, i.e., a $G/G/1$ system [19], as follows.

$$E[Ts] \leq d_{hop} \leq 2E[Ts] \tag{27}$$

$$d_{hop} \approx E[Ts] + E[R] \leq E[Ts] + \frac{E[Ts^2]}{2E[Ts]} \equiv T_{UR} \tag{28}$$

where Ts is the service time and d_{hop} is comprised of both the waiting time in the queue and the service time. Parameter p in Fig. 8 is the probability that one node encounters collisions when it transmits, which is equal to

$$p = 1 - (1 - p_t)^{n-1} \tag{29}$$

where n is the number of the nodes that are contending for the wireless media and can potentially cause collision with each other, and p_t is the transmission probability of each node in any time slot which depends highly on the packet traffic of the network.

As it is observed in Fig. 8, the lower bound and the upper bounds are very close, and as a result, d_{hop} can be estimated with high accuracy. Since the collision probability, p, is small for non-saturated case, among two higher bounds, T_{UR}, which is tighter for smaller p's is taken into account. According to Fig. 8, if p is kept smaller than or equal to 0.1, d_{hop} will remain below 30ms. Based on this observation and the assumptions in [19], for any given average vehicle density on the highway, the average value of n, the number of contending vehicles, can be determined. By taking the calculated n into account and using (29), the maximum background packet traffic in the network that yields $p = 0.1$ is obtained which is necessary to make sure d_{hop} remains below 30ms. The background packet traffic in the network is constantly kept below the calculated values. For different AP inter-distances, A, ranging from 0 meter to 600 meters with the vehicle located at equal distances from the APs, the average d_{AH} versus A is obtained via both simulations and analyses by employing (21), which is shown in Fig. 9. As it is observed in this figure, the simulation results agree well with the results of analyses. The parameters utilized in the simulations are given in TABLE II. Based on the graphs in Fig. 9, for any required delay and given average density, A', which is the distance over which ad hoc networking is allowed, is obtained. Clearly, for distances greater than A' the use of cellular communications is inevitable.

Finally, in order to study the case of WLAN plus cellular plus ad hoc, the maximum tolerable delay, which specifies the distance over which ad hoc data forwarding is allowed, should be determined. Different end-user multimedia categories for a variety of multimedia services were investigated in [25] and it turned out that the maximum allowable one-way transmission delays for a relatively large number of multimedia services is either 1 or 5 seconds. Thus, we set the allowable maximum tolerable delay, i.e., the allowable two-way transmission delay in our simulations to 2 or 10 seconds, respectively. For

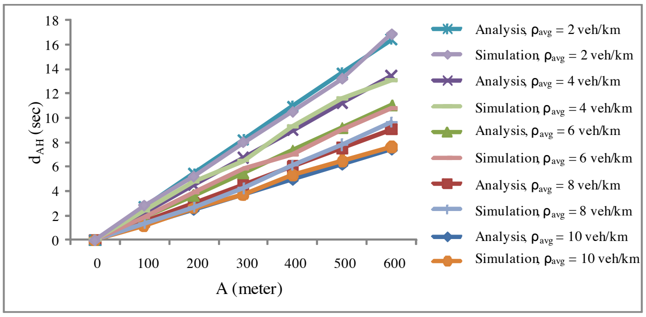

Fig. 9. Ad hoc delay as a function of inter-distance of APs.

these maximum tolerable delays and for different average vehicle densities, which is the other parameter affecting ad hoc communications, we compared the transmission times and costs with only cellular and WLAN plus cellular cases. Other parameters remain the same as before. The results for different velocities of the vehicle are shown in Figs. 10 and 11. It is observed that as long as the speed is not too high, the case of WLAN plus cellular plus ad hoc communications yields remarkable performance improvements over the other cases. As seen clearly in Fig. 9, for average vehicle densities equal to or larger than 10 veh/km and the average AP inter-distances of 300 meters, the maximum ad hoc delay stays lower than the pre-determined maximum tolerable delays which yields the same results as the case of WLAN plus ad hoc. That is why in our simulations we have obtained the results for more challenging situations in which average densities are smaller than or equal to 10 veh/km.

VII. CONCLUSIONS

A crucial aspect of vehicular networking in a heterogeneous wireless environment is the optimal choice of access technology. This optimal VHO decision will in general depend on several factors such as the available capacity of each access technology, the cost of transmitting traffic in that network and the speed of the vehicle, among others. In this paper we have considered a vehicular heterogeneous network comprised of WLAN and cellular systems. We have shown that in order to minimize the cost of communications or alternatively minimize the communication time, use of VHO is an appropriate choice in lower speeds, whereas it would be better to avoid VHO and stay in the cellular network at higher speeds. Furthermore, we demonstrated that if V2V communication is also possible, the combination of WLAN plus cellular plus ad hoc networking outperforms any other networking strategies we have considered in terms of transmission times and transmission costs.

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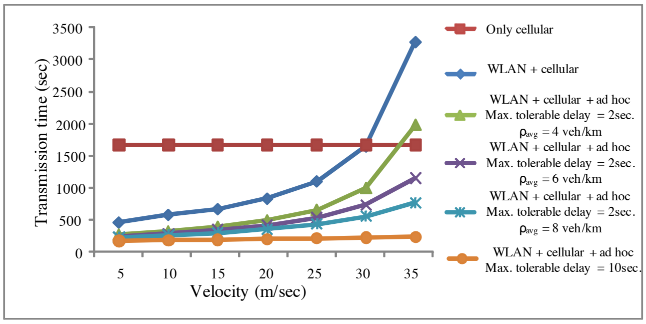

Fig. 10. Comparison of transmission time performance in the proposed algorithms.

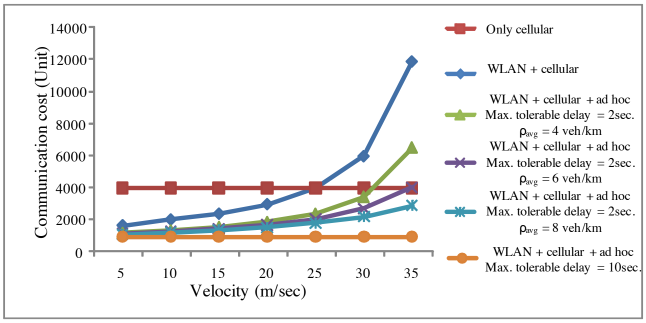

Fig. 11. The cost of communication using different VHO policies for the scenario similar to Fig. 10.

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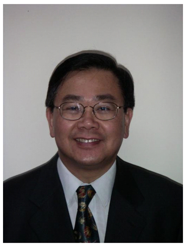

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