Evaluation of Multihop Relaying for Robust Vehicular Internet Access

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Abstract— **In this paper, we study connectivity benefits of using a multihop relaying strategy for improved Internet access in a WiFi-based vehicular environment relative to the common strategy that allows only direct communication between vehicles and access points (APs). We use real AP location data and realistic and detailed vehicular mobility traces for our study. Our results show that multihop relaying strategy leads to substantial gains in connectivity relative to direct access as much as 400%, and that multihop relaying combined with increased communication range provides even greater gains (up to 467%). Further, relay paths with few hops are sufficient to realize most of the gain with multihop relaying.**

I. INTRODUCTION

As people continue to spend substantial amount of time in their daily lives traveling using either private vehicles or public transport, their need to stay connected to the Internet and have access to information on the move is becoming increasingly important. Until recently, cellular networks served as the primary means for vehicular Internet access. Though the current generation of cellular networks provides wider coverage, they are plagued by low and variable data rates (especially at vehicular speeds), high and variable latencies, and occasional communication blackouts (depending on the mobile node's spatial location) [12]. Besides, users are also required to subscribe to their data services. With the widespread deployment of WiFi (802.11) [6] access points (APs) everywhere and the introduction of DSRC standards to enable intelligent transport systems (ITS), WiFi-like technologies are becoming a promising alternative for vehicle to infrastructure/roadside communication (necessary for Internet access) as well as for inter-vehicular communication. This shift is mainly driven by performance and cost considerations.

When using WiFi for Internet access in highly dynamic vehicular environments, ensuring continuous and seamless connectivity becomes the primary issue because of the relatively smaller communication range of WiFi devices (compared to cellular-based access). While recent measurement studies [3], [5], [10] demonstrate the viability of WiFi for vehicular Internet access, they also suggest that such access will be suitable mainly for applications tolerating intermittent connectivity because of the short duration of connections observed (in the order of few tens of seconds) [3]. These studies, however, only focus on direct communication between vehicles and roadside APs, and do not consider inter-vehicular communication.

Internet connectivity in vehicular environments using WiFi devices depends on several factors, including: AP density and distribution, vehicle density, distribution and speed, and communication range of nodes (APs and vehicles). Some of these factors may not be easy to influence (e.g., the number of APs and their locations), whereas others like communication range allow some degree of control. Though increasing the communication range by using higher transmission power can extend the coverage, the extent to which this can be done is limited due to regulatory restrictions and hardware limitations. Moreover, higher transmission power can reduce overall network throughput due to increase in interference and reduction in spatial reuse opportunities. Increasing the communication range using other physical layer modalities also involve similar tradeoffs, such as lowering transmission bit-rates for longer ranges.

Having vehicles not directly connected to APs depend on other vehicles to relay packets, possibly over multiple hops using inter-vehicular communication, offers a seemingly better alternative to improve connectivity as it does not require high power transmissions nor force the use of lower bit-rates. Such a *multihop relaying* strategy can exploit greater connectivity opportunities resulting from high density of vehicles. Multihop relaying as a design strategy has been found to be beneficial in other contexts (e.g., improving the coverage and data transfer performance of home wireless networks [11] and wireless LANs [7], improving aggregate and end-user data rates while preserving fairness by using heterogeneous wireless technologies [8]). Internet connectivity for mobile ad hoc networks (MANETs) also involves multihop relaying [13]. But none of these past efforts give insight into the connectivity properties of multihop relaying expected in real-world vehicular environments. On the other hand, there has been considerable amount of work in vehicular networks involving inter-vehicular communication, focusing on routing, measurements and such (see [14], for example). But, as far as we know, this body of work does not consider connectivity issues arising from communication with fixed infrastructure as is the case with vehicular Internet access. There has also been some work on analyzing connectivity properties of (hybrid)

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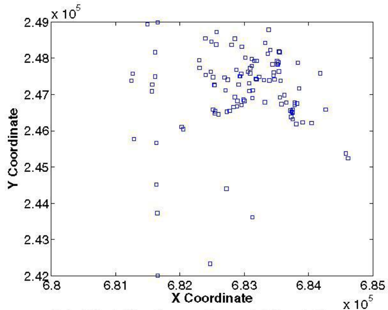
ad hoc networks [4], [2], where the focus is on connectivity between nodes in an ad hoc (multihop wireless) network with or without the use of wired infrastructure. In contrast, our focus is on connectivity between mobile nodes (vehicles) and the fixed Internet, possibly via multiple wireless hops.

In this paper, our goal is to study the potential connectivity improvement from using multihop relaying via inter-vehicular communication as opposed to relying only on direct communication between APs and vehicles (referred henceforth as *direct access*). We also study the effect of communication range for both strategies; this is in contrast to prior measurement studies [3], which focus only on one extreme setting of radio parameters, i.e., lowest bit-rate and maximum transmission power. To meet the above goals, we study spatio-temporal aspects of connectivity for direct access and multihop relaying strategies by analyzing real AP location data in conjunction with realistic vehicular mobility trace for a city scenario (in our case, we consider the city of Zurich, Switzerland). We conduct this study independent of any specific vehicular network protocols and applications, but focusing on connectivity metrics like connection duration and percentage of vehicles connected, which are relevant for supporting any application. Our evaluation approach allows us to efficiently study connectivity characteristics of large scale vehicular network scenarios with several thousands of vehicles and hundreds of APs. For instance, we were able to process mobility traces spanning a four hour period and containing as many as 4000 vehicles in few tens of minutes.

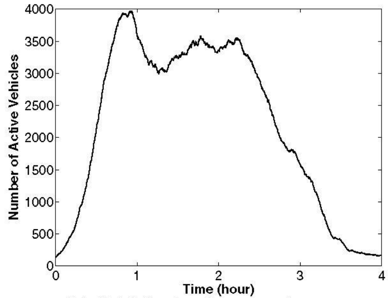
Our study leads to the following key observations:

- Multihop relaying provides substantial gains in connectivity relative to direct access, with small number of relays sufficient to achieve most of this gain. The additional gain in connectivity from allowing additional hops tends to diminish after a few hops, and this gain is dependent on the communication range. For the scenarios we considered, going from direct access to two hop relaying provides the highest improvement in most cases (up to 152%).
- In terms of spatial connectivity (measured as percentage of vehicles connected), multihop relaying and direct access with increased communication range yield similar improvements. Combination of multihop relaying and increased communication range provides the most gain (up to 150%).
- With regard to temporal connectivity metrics (connection and disconnection durations), multihop relaying provides greater improvement compared to direct access with increased communication range. As with spatial connectivity, multihop relaying with increased communication range is the most effective strategy, which achieves gain as much as 467%.
- Spatial connectivity is unaffected by vehicle density, whereas connection duration improves with higher vehicle density.

The following section describes our evaluation methodology and results in detail.



(a) Distribution of roadside APs



(b) Vehicle density over time

Fig. 1. Spatial distribution of APs and vehicle density variation over time in a selected region in the city of Zurich, Switzerland.

II. EVALUATION

A. Methodology

We consider two communication strategies: direct access and multihop relaying. Recall that direct access refers to a common communication strategy where a vehicle is connected to the Internet only when it is in the coverage area of an AP. This is similar to the WLAN architecture that is commonly used in WiFi networks. On the other hand, multihop relaying strategy allows vehicles not directly connected to any AP to depend on other vehicles for relaying their packets, possibly over multiple hops using inter-vehicular communication. For both communication strategies, we assume a commonly used strongest signal strength based AP selection policy to determine the AP a vehicle associates with when faced with multiple choices. Once a vehicle is associated with an AP, it stays associated to the same AP until they move out of each other's communication range. We further assume that a vehicle remains directly connected as long as it is in the coverage area of some AP. With multihop relaying, a vehicle not directly connected to any roadside AP uses a relay path (involving other vehicles) with least hop count and below a specified hop count threshold, if available. A path once selected is used as long as it is valid. A vehicle remains connected as long as it has a path to an AP satisfying the hop count threshold. When studying connectivity with multihop relaying, we consider the effect of using different hop count thresholds.

We use the city of Zurich, Switzerland as a representative scenario for our connectivity characterizations. This choice was influenced by the ready availability of detailed vehicular movement traces for the Zurich region. The mobility trace

Rate	Receiver Sensitivity
1Mbps	-93dBm
2Mbps	-89dBm
5.5Mbps	-87dBm
11Mbps	-83dBm

TABLE I

RECEIVER SENSITIVITY VALUES ASSUMED AT DIFFERENT 802.11B TRANSMISSION RATES.

Rate (⇓), Power (⇒)	15dBm	19dBm
1Mbps	483m	609m
2Mbps	370m	467m
5.5Mbps	353m	445m
11Mbps	283m	357m

TABLE II

COMMUNICATION RANGE VALUES FOR DIFFERENT 802.11B TRANSMISSION RATE AND POWER LEVEL COMBINATIONS.

is obtained from a detailed vehicular movement simulation over real road maps using MMTS [9]. It contains a 24-hour movement pattern (coordinates, moving directions and speeds) of a total number of $259,978$ vehicles in Switzerland (area of $41,559km^2$). The traces are further parsed to obtain movement data for selected regions and scenarios (e.g., city, highway) and with desired vehicle density and speed. The results presented in this paper correspond to a small region ($28Km^2$ in area) in Zurich city. We obtained AP location data for this region from www.jiwire.com. There are a total of 132 APs, whose spatial distribution is shown in Fig. 1(a) with x, y coordinates in Swiss projection coordinate format. We use a subset of the vehicular mobility trace corresponding to this selected region and a 4-hour rush hour period. Variation of number of vehicles (and vehicle density) during the 4-hour period is shown in Fig. 1(b). The minimum, mean and maximum vehicle speeds in this trace were 1m/s, 16m/s and 33m/s respectively.

For determining the radio communication range, we make the following assumptions. We assume the 802.11b physical layer and omnidirectional antennas (placed at 1.5m height). Receiver sensitivity values used for various transmission rates are shown in Table I. For the channel, we assume two-ray ground reflection based radio propagation path loss model and constant shadowing with mean 4.0dB. We do not consider the effect of small-scale fading, which does not affect our observations about the relative merits of multihop relaying and direct access communication strategies with regard to connectivity. Different communication range values in our study are obtained from varying transmission power and rate values. Table II summarizes the different power and rate combinations used and associated communication range values. Two power values used were obtained by looking up typical and maximum power values used in commodity 802.11b wireless network interface cards (specifically, the Proxim ORiNOCO Gold 802.11b/g card).

B. Results

This section presents our results studying the impact of communication strategy (i.e., direct access versus multihop relaying) and communication range on vehicular Internet connectivity. Broadly speaking, we study connectivity across the spatial and time dimensions. Spatial connectivity at a given time is measured as the fraction of vehicles connected at that time, whereas connection and disconnection durations are used as metrics for temporal connectivity.

Fig. 2 shows the benefit of multihop relaying and increased communication range with respect to spatial connectivity over time, corresponding to the 4-hour period shown in Fig. 1(b). Fig. 2(b) and 2(c) correspond to multihop relaying with hop count threshold set to 2 hops and 3 hops, respectively. Individual curves in each plot represent specific communication range values obtained from various power and rate combinations shown (see Table II). Comparing Fig. 2(a), 2(b) and 2(c), we observe that multihop relaying gives substantial improvement in coverage over direct access for the same communication range. Direct access with increased communication range and multihop relaying seem to provide similar gains. For instance, compare (19dBm, 1Mbps) curve in Fig. 2(a) to (15dBm, 11Mbps) curve in Fig. 2(c). Combination of multihop relaying and increased communication range provides the best coverage overall (up to 150%). It is also interesting to note that there is no correlation between vehicle density and spatial connectivity (compare Fig. 1(b) and Fig. 2). Spatial distribution of vehicles at different vehicle densities shown in Fig. 3 helps explain this behavior and suggests that increased vehicle density leads to more uniform increase in vehicles across all road segments. Essentially, given that AP locations are fixed, the number of connected vehicles proportionately increases with the number of vehicles, thereby keeping spatial connectivity unaffected by vehicle density variation.

Moving onto temporal connectivity, Fig. 4 shows average connection duration[1] over time, obtained by averaging across all vehicles in each 250 second interval. Like in the case of spatial connectivity, multihop relaying fairs better than direct access, and the combination of multihop relaying and increased communication range gives the most improvement (up to 467%). But, relatively speaking, the use of multihop relaying is more effective than direct access with increased communication range, especially at higher vehicle densities. This can be explained by the clustered distribution of APs (see Fig. 1(a)) and the ability of multihop relaying strategy to exploit higher vehicle densities for improving connectivity. This is because AP clustering increases the likelihood of vehicles moving in and out of their range, which hurts temporary connectivity of direct access with increased communication range. Multihop relaying, on the other hand, allows using other vehicles as relays to stay connected. We note that there is noticeable though smaller gain in connection duration with increased vehicle density even for direct access as vehicles move slowly at higher densities.

Connection duration statistics (CDF, average and median), taken over all connections across all vehicles over the whole

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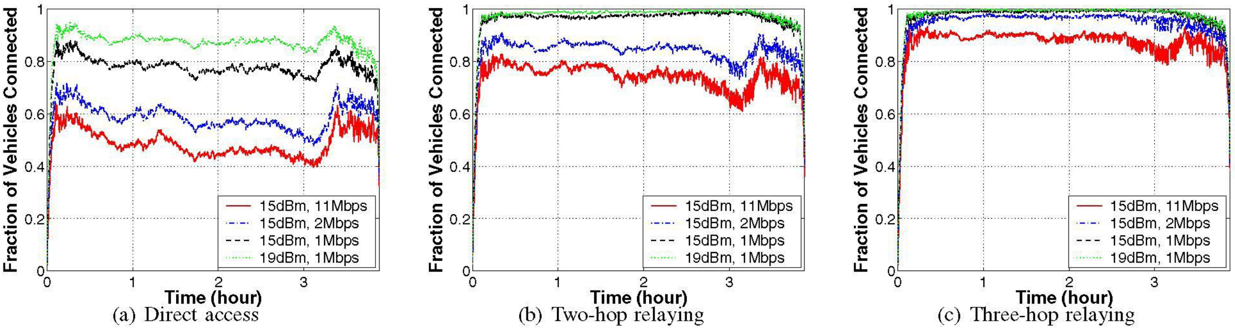
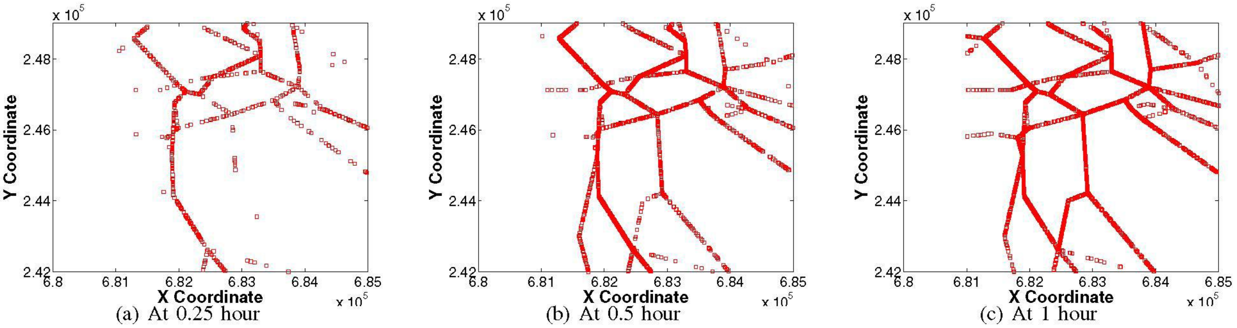
[1] Note that our estimate of connection duration is at a coarse level in that it includes overheads like AP association and IP address acquisition latencies.



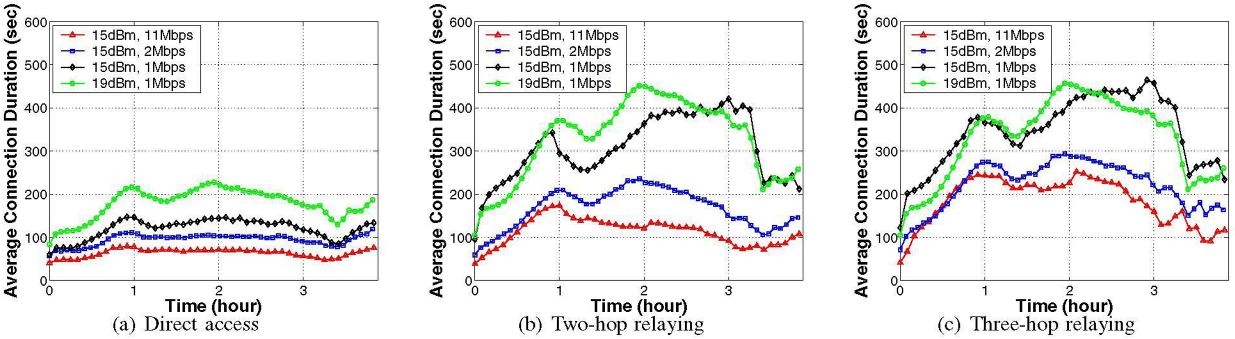
(a) Direct access (b) Two-hop relaying (c) Three-hop relaying

Fig. 2. Spatial connectivity (fraction of vehicles connected) over time with direct access and multihop relaying strategies at different power and rate combinations (reflecting different communication range values).



(a) At 0.25 hour (b) At 0.5 hour (c) At 1 hour

Fig. 3. Spatial distribution of vehicles in the selected region of Fig. 1(a) after first 15 minutes, 30 minutes and 1 hour in the 4-hour period shown in Fig. 1(b).



(a) Direct access (b) Two-hop relaying (c) Three-hop relaying

Fig. 4. Connection duration, averaged across all vehicles over 250 second time intervals, with direct access and multihop relaying strategies at different power and rate combinations (reflecting different communication range values).

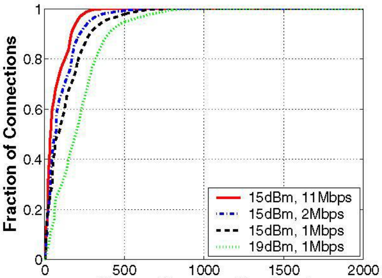
four-hour period, are shown in Fig. 5 and Table III. Corresponding data for disconnection duration (contiguous period without connectivity) are given in Fig. 6 and Table IV. These results clearly highlight the value of multihop relaying as an effective and flexible mechanism for achieving long connectivity periods (close to a factor of two improvement over direct access strategy with increased communication range — from 212.36 seconds to 376.59 seconds). When seen together with negligible disconnection periods, multihop relaying with increased communication range makes it feasible to stay connected most of the time.

Average (median) connection duration (s)	1hop	2hop	3hop
(15dBm, 11Mbps)	66.65 (37)	124.45 (70)	206.24 (166)
(15dBm, 2Mbps)	98.04 (66)	188.37 (152)	252.49 (210)
(15dBm, 1Mbps)	126.73 (84)	320.26 (250)	367.20 (268)
(19dBm, 1Mbps)	212.36 (195)	372.51 (272)	376.59 (273)

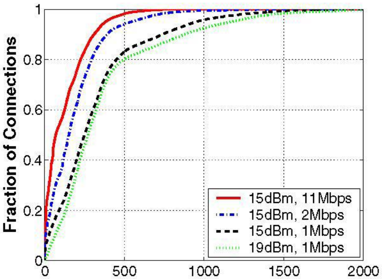
TABLE III

AVERAGE AND MEDIAN CONNECTION DURATION WITH DIRECT ACCESS AND MULTIHOP RELAYING STRATEGIES AT VARIOUS COMMUNICATION RANGE VALUES.

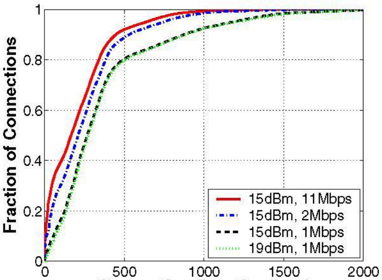
We have also investigated the impact of path length on gains with multihop relaying. First, we studied the path length (hop count) distribution when hop count threshold is set to infinity (i.e., no limit). Path length CDF (Fig. 7) shows that most paths



(a) Direct access



(b) Two-hop relaying



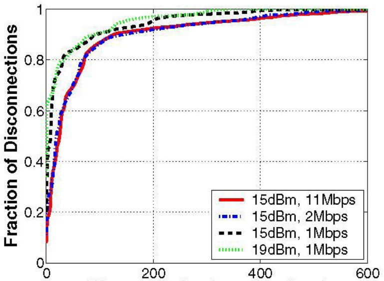
(c) Three-hop relaying

Fig. 5. Connection duration CDF with direct access and multihop relaying strategies at various communication range values.

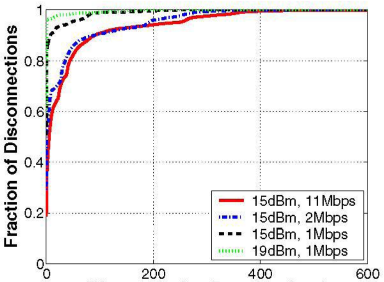
are only few hops long (at most 3-4 hops), regardless of the communication range. Table V studies the percentage of gain in connection duration with multihop relaying relative to direct access for increasing hop count thresholds. We observe that going from direct access (threshold = 1) to two-hop relaying yields the highest improvement (up to 152%), with further increase in the threshold giving diminishing returns, which suggests that few hops are sufficient to get most of the gain with multihop relaying. We also observe that communication range influences the gain from increased hop count threshold.

C. Discussion

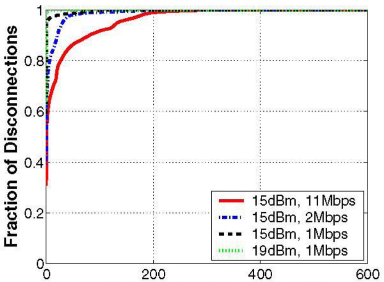
The foregoing results suggest that multihop relaying is a promising strategy for vehicular environments from the connectivity viewpoint. Even though our evaluations are based on AP location data and vehicular mobility trace for one city (Zurich, Switzerland), we expect our results to hold generally for two reasons. First, AP density and distributional characteristics (e.g., clustering) observed in our study seem to match that of data reported for other cities [3], [1]. Second,



(a) Direct access



(b) Two-hop relaying



(c) Three-hop relaying

Fig. 6. Disconnection duration CDF with direct access and multihop relaying strategies at various communication range values.

Average (median) disconnection duration (s)	1hop	2hop	3hop
(15dBm, 11Mbps)	61.23 (25)	36.86 (6)	22.42 (1)
(15dBm, 2Mbps)	59.40 (19.34)	29.36 (1)	6.74 (0.69)
(15dBm, 1Mbps)	33.14 (8)	6.33 (0.49)	1.87 (0.38)
(19dBm, 1Mbps)	26.56 (0.91)	2.56 (0.37)	0.49 (0.35)

TABLE IV

AVERAGE AND MEDIAN DISCONNECTION DURATION WITH DIRECT ACCESS AND MULTIHOP RELAYING STRATEGIES AT VARIOUS COMMUNICATION RANGE VALUES.

% gain over direct access	2hop	3hop	4hop	5hop
(15dBm, 11Mbps)	86.72	209.44	285.51	400.53
(15dBm, 2Mbps)	92.14	157.54	248.34	251.51
(15dBm, 1Mbps)	152.71	189.75	195.94	196.49
(19dBm, 1Mbps)	75.41	77.34	77.95	77.97

TABLE V

PERCENTAGE OF GAIN IN CONNECTION DURATION WITH MULTIHOP RELAYING RELATIVE TO DIRECT ACCESS FOR INCREASING HOP COUNT THRESHOLDS AT VARIOUS COMMUNICATION RANGE VALUES.

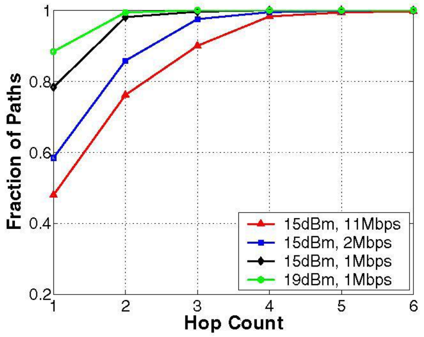


Fig. 7. Path length CDF at various communication range values for multihop relaying with hop count threshold set to infinity.

vehicular mobility traces we used are not based on real data for a specific city, but instead obtained via realistic microscopic vehicular movement simulation that is likely to be applicable more generally.

A crucial next step to assess if multihop relaying strategy improves Internet access in vehicular environments is understanding its data transfer performance. Multiple access interference and channel dynamics (fading) are key factors in this regard. While the capacity scaling issues of multihop wireless networks are well known, it is unclear whether relay assisted vehicular Internet access networks with small diameter are also interference limited. Besides, conducting realistic data transfer performance evaluation in this setting is closely tied to the protocols and techniques used (e.g., routing, channel allocation, link adaptation and mobility management), whereas the latter task of designing vehicular Internet access protocols is challenging in itself (e.g., performing route maintenance seamlessly and efficiently). Also cross-layer approach may be needed for best performance. For instance, a key observation from our study is that multihop relaying combined with increased communication range is the most effective strategy to achieve seamless and continuous connectivity, which suggests the need for a cross-layer approach involving at least network and link layers for achieving robust vehicular Internet access. In our on-going and future work, we plan to address the above issues.

Let us turn our attention to the implications of clustered AP distribution (as observed in our study, see Fig. 1(a)) on vehicular Internet access protocol design. During our analysis of connectivity characteristics, we have noticed that only 40% of the APs are used by the vehicles for association because of clustered AP distribution. With large number of vehicles, each AP then may have to serve up to as many as 80 vehicles, resulting in overloading of a small fraction of the APs. The above observation points to the need for intelligent AP selection and association schemes that take AP load into consideration. Another consequence of clustered AP distribution is that AP coverage areas tend to overlap considerably. This in turn makes seamless connectivity provisioning easier through the use of smooth handoff techniques (e.g., concurrent association of vehicles with multiple APs).

III. CONCLUSIONS

We have studied the connectivity benefits of enabling a multihop relaying strategy via inter-vehicular communication for WiFi-based vehicular Internet access. A unique aspect of our study is the use of real AP location data and detailed vehicular movement traces. Overall, our results show that multihop relaying strategy leads to substantial gains in connectivity, and that multihop relaying combined with increased communication range provides even greater gains. We have also found that relay paths with few hops are sufficient to realize most of the gain with multihop relaying. The focus of our on-going and future work is on understanding the data transfer performance with multihop relaying and on developing suite of effective protocols for enabling robust vehicular Internet access.

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