VCAST: An infrastructure-less vehicular traffic information service with distance-sensitive precision

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***Abstract*—In this paper, we describe *VCAST*, an algorithm for obtaining individual vehicle location as well as aggregate traffic information over an infrastructure-less multi-hop wireless vehicular network. *VCAST* can be used to improve safety against collisions, inform about approaching emergency vehicles and lane merging vehicles (that may even be beyond a single hop communication range) and to enable dynamic routing and navigation techniques by providing aggregate traffic information in an extended neighborhood. To ensure scalability in forwarding information over multiple hops, we exploit a notion of *distance sensitivity in information propagation*, by which traffic information is propagated at a rate that decreases linearly with distance from the source. By doing so, traffic information can be obtained with a staleness, which is a measure of error in the traffic information, that is bounded by $O(d_h^2)$ where d_h is the communication *hop* distance from the source of the information. At the same time, the required communication rate per unit time at each node only depends on the radius of the region in terms of communication hops, and not on the vehicular density or the number of vehicles in the region. *VCAST* does not require any special hardware or modification to vehicular transmission standards; instead it can simply piggyback on basic *Here I am* communication for vehicular networks.**

I. INTRODUCTION

Infrastructure-less, V2V wireless communication is expected to be the basis for both safety and navigation applications in future intelligent transportation systems [1], [2]. Examples of safety applications in transportation scenarios include collision warnings and stopped vehicle alert, while examples of intelligent navigation applications include dynamic travel-time computations and re-routing based on congestion information. A building block for all these applications is a real-time vehicular traffic mapping system on board every vehicle, which portrays information about current position of other vehicles in its vicinity and provides guidance about accidents, approaching emergency vehicles and traffic congestion over an extended neighborhood. In this paper, we design *VCAST*, a scalable, infrastructure-less peer-to-peer wireless network service for computing such a real-time traffic map over a given region surrounding each vehicle.

We assume that vehicles are equipped with a differential GPS that can estimate its location to an accuracy of about 1m. As a result, by advertising this information, vehicles can learn about traffic in their near vicinity, i.e., a one hop communication range. However, estimating traffic maps over a large area using multi-hop wireless communication is a much more challenging task. Firstly, we note that forwarding each vehicle's information over multiple hops at a constant rate is unlikely to be scalable as it will cause the amount of communication required at each vehicle to grow with the number of vehicles in the region over which traffic information is required. As a result, both the allowable broadcast rate and the accuracy of the traffic map obtained at each vehicle will decrease as vehicular density and size of the region increase. Hence effective forwarding algorithms need to be designed that ensure that the system remains scalable with vehicular density and region size. Secondly, there exist tradeoffs in choosing the rate and communication range of each broadcast. While higher broadcast rates and range promise greater tracking accuracy, in reality wireless channel contention can cause an adverse effect in tracking accuracy as these levels exceed a certain limit. While these tradeoffs have been studied in the context of single hop networks, the impact of these tradeoffs in multi-hop traffic estimation need to be investigated.

Contributions: To address these challenges and to ensure scalability when providing traffic maps over large regions in real-time, we exploit a notion of *distance-sensitivity* in propagating individual vehicle information: information about each vehicle is propagated at a rate that decreases linearly with the distance from the vehicle [3], [4]. By doing so, we show that traffic information can be obtained with a worst-case staleness that is bounded by $O(d_h^2)$ where d_h is the communication hop distance from the source of the information. We use staleness as a measure of error in vehicle position as it reflects how old the current information about a particular vehicle is. Thus, using *VCAST* we are able to obtain traffic information with *distance-sensitive precision* in which the error does not grow with the number of vehicles in the region. At the same time, the average communication cost (the required transmission rate at each node) also does not grow with the number of vehicles in the region, but is rather only bounded by $O(R_h p)$, where R_h is the maximum number of communication hops in the region over which traffic information is to be propagated and p is the broadcast rate at the source. Thus, in comparison with periodic one hop vehicular safety messages, the increase in communication overhead is only by a factor R_h. *VCAST* can be used to propagate actual vehicle location as well as to propagate aggregate traffic information such as average speed and density of vehicles over individual traffic *cells* inside a region. One possible scenario is to propagate actual vehicle location up to a distance of $500 - 1000m$ and aggregate traffic information up to several miles. When propagating only aggregate cell information, we note that the required communication rate per node decreases further by a factor r_c, where r_c is the radius of each aggregation cell.

By forwarding traffic information over multiple communication hops, we expect several advantages: (1) vehicle location over a vicinity will be available even if the communication range is extremely low because of high density, thus improving vehicular safety (2) information about approaching emergency vehicles will be available (3) information about lane merging vehicles will be available even if they are outside a single communication range, and (4) information about road blocks, accidents and impending congestion will be available from several miles ahead, thus permitting higher level applications that dynamically re-route based on this information. To achieve scalability, *VCAST* provides traffic information with an accuracy that degrades with distance, but we expect this to be a reasonable condition that is still sufficient for both vehicular safety and intelligent navigation. For example, at larger distances there is more reaction time for taking safety actions or for computing new routes towards the destination based on traffic information. Finally, we note that *VCAST* does not require any special hardware or modification to vehicular transmission standards; instead it can simply piggyback on the proposed *Here I am* communication [1], [2] for vehicular networks.

Related work: The design of wireless communication protocols for vehicular safety has received a lot of research attention lately [1], [5]–[9]. There have been several recent papers that have focused on the problem of balancing broadcast range and reliability so as to maximize the number of successful receptions in close proximity of the sender [5]–[8]. A common foundation in these papers to handle the tradeoff is to reduce the communication range in regions of high density so as to improve the reliability of reception. However, these papers mainly focus on a one-hop message reception and not on multi-hop propagation. As a result information about vehicles outside the communication range are not available even when the range has to be very low because of high density. On the other hand, the algorithm developed in this paper can be used to propagate both individual vehicle information and aggregate traffic information over several communications hops and yet keep the required communication rate low. As a result, nearby vehicles can be tracked even when they are outside the communication range. Additionally, aggregate traffic information such as vehicular traffic density, congestion information can be propagated to several miles in a scalable manner, which can enable intelligent navigation applications. We note that rate and power control algorithms [1], [5]–[8] developed for a single hop vehicular broadcast are complementary and can be used in conjunction with the distance-sensitive multi-hop forwarding algorithm designed in this paper.

Multi-hop broadcast algorithms for vehicular networks have mainly focused on the choice of optimal forwarding vehicles and on the reduction of redundant forwarding vehicles using one of several heuristics proposed in [10]. The idea of distance-sensitive broadcasting rates developed in this paper for ensuring scalable information broadcast has thus far not been explored in the context of mobile ad-hoc and vehicular networks.

Outline of the paper In Section 2, we describe our system model, the VCAST algorithm and provide an analysis for the expected accuracy and communication cost. In Section 3, we evaluate the performance of our system in simulations. In Section 4, we present conclusions and state future work.

II. SYSTEM DESCRIPTION

In this section, we first state the system model and objective. We then describe *VCAST* and analytically characterize its accuracy and required communication rate.

A. System model and problem statement

We model the vehicular network as a large geographic area with multiple traffic flows, each with potentially different traffic densities at different places. Let ρ denote the maximum density, i.e., the maximum number of vehicles per unit area at any time in the whole region. Note that the geographic area will consist of regions with no traffic flows (i.e., no roads), as well as regions with high density traffic flows. We assume that the region is partitioned into geographic *cells* which allow representation of aggregated traffic information for that cell. The cells need not be of the same size, but for ease of explanation we assume that the area of each cell is constant and equal to A_C with a radius of r_c. Let r_h denote the single hop communication range for a vehicle ($r_h << R$). The objective of our system is to provide each vehicle with information about all vehicles and all cells within a radius R around itself [1]. We call this area of radius R around each vehicle as the *tracking zone*.

Let N denote the maximum number of nodes in the tracking zone of a vehicle. Thus $N = \rho\pi R^2$. Let L denote the maximum number of cells in a radius of R around each node. Thus $L = \frac{\pi R^2}{A_c}$. Let p denote the frequency at which each vehicle broadcasts its own information. Let $d(i,j)$ denote the geographic distance between vehicles i and j. Let $d_h(i,j)$ denote the distance between vehicles i and j in terms of communication hops. Thus, we have $d_h(i,j) = \frac{d(i,j)}{r_h}$. Let $d_c(i,j)$ denote the distance between vehicle i and cell j in terms of smallest number of cells traversed to reach cell j from i. In the following subsections, we first describe *VCAST* assuming that only vehicle location is propagated up to a distance R. Then we describe the required changes when aggregate *cell* information is propagated. The communication cost and accuracy for both these cases are characterized in Section II-C.

B. Distance-sensitive broadcast algorithm

A naive technique would be to require each vehicle to obtain information about all vehicles in its tracking zone at a constant interval of $1/p$ seconds. However, in such a scenario each vehicle would have to broadcast information about at most N vehicles at p Hz, making the required communication rate at each node per unit time to be $O(Np)$. Note that the required communication rate grows with the number of vehicles in the region and is therefore directly proportional to the vehicle density and the size of the region. Also if C denotes the allowable wireless channel transmission capacity at a node in bits per second, we observe that the allowable broadcast rate p is limited by $p < \frac{C}{N}$, i.e., inversely proportional to the number of vehicles. This in turn has an adverse effect on the latency with which traffic information is obtained and as a result the accuracy of the obtained traffic map information decreases with increasing vehicular density, which is not desirable.

To address these drawbacks, we propose to forward information about a vehicle at a rate that is proportional to the distance from that vehicle. Also, in *VCAST*, a vehicle suppresses forwarding of information about a vehicle in an interval, if some other vehicle has already forwarded information about the respective vehicle in that interval. By doing so, we show that the update rate, system accuracy and communication cost do not depend on N. A more formal description of *VCAST* is presented below. A pseudo-code in guarded command notation [11] is provided in Fig. 1, which shows the program at each vehicle in the form of $<$*event* $\rightarrow$ *action* $>$ pairs.

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[1] We note that our system can also be specialized to propagate individual vehicle information within a smaller radius than aggregate cell information.

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Protocol: VCAST
Vehicle: j
Var:
    $j.V$ : List of vehicles within radius $R$
    $j.X_i \forall i \in V$ : Location of $i$
    $j.T_i \forall i \in V$ : Timestamp of $i$'s record
    $j.\nu_i \forall i \in V$ : Counter for $i$'s information
    $j.\lambda$ : Sequence number of current interval
    $j.V_\lambda$ : Forwarding list for $j.\lambda$
Actions:
  $\langle A_1 \rangle$ :: Initialization: $\longrightarrow$
      $j.V = j; j.\nu_i = 0; j.\lambda = 0;$
      Timer.start ($\frac{1}{p}$)
  $\langle A_2 \rangle$ :: Timer fired: $\longrightarrow$
      $j.\lambda = j.\lambda + 1;$
      $j.V_\lambda = j;$
      $\forall i \in j.V$
        if ($\lambda \ mod \ d_h(i,j) == 0$)
          if $j.\nu_i < 2$
            Add $i$ to $j.V_\lambda$
          fi
          $j.\nu_i = 0;$
        fi
      $\forall i \in j.V_\lambda$
        Send $j.X_i$, $j.T_i$
  $\langle A_3 \rangle$ :: $recv_i(V) \longrightarrow$
      $\forall k \in i.V$
        if $j.T_k < i.T_k \vee k \notin j.V$
          $j.X_k = i.X_k; j.T_k = i.T_k; j.\nu_k = j.\nu_k + 1;$
        fi
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Fig. 1. VCAST: Protocol Actions at vehicle j

In *VCAST*, each vehicle j maintains a list $j.V$ of vehicles that are within a distance R from itself. Associated with each vehicle $i \in j.V$ is the location $j.X_i$ of i as most recently heard by j, a timestamp $j.T_i$ associated with the location and $j.\nu_i$ which is the number of times information about i has been heard since the last broadcast interval. A timer is fired at each vehicle every $\frac{1}{p}$ seconds for broadcasting information and a randomness is introduced in this interval because of CSMA based transmission. Let $\lambda = 1, 2, ...$ denote the timer sequence at vehicle j. Let $j.V_\lambda$ denote the set of vehicles whose information is forwarded in the interval number λ at vehicle j. $j.V_\lambda$ is initially set to be equal to $\{j\}$. Thus information about itself is broadcast by a vehicle in every interval along with the current time which serves as the timestamp for this record. Node i is added into the set $j.V_\lambda$ only if $\lambda \ mod \ d_h(i,j) = 0$ and if information about i has not been broadcast by any other vehicle within j's range in the last $d_h(i,j)$ intervals. This ensures that information about nodes at a distance of k communication hops is broadcast at most once every k intervals in each communication neighborhood. In the presence of channel interference, we note that nodes may occasionally duplicate the transmission of information of a vehicle within a neighborhood. But we expect this to cause a much smaller overhead when compared with all nodes transmitting. Finally, whenever information about a vehicle i is heard by a node j, it is added into the list $j.V$ if the timestamp of the incoming record is more recent than $j.T_i$.

For the case where aggregate traffic information is to be propagated, each vehicle computes summary information such as density and average speed for the cell in which it resides based on information it possesses about vehicles within its communication range. This summary is then propagated in a distance-sensitive manner: information about a cell at distance d_c is forwarded at a rate of $\frac{p}{d_c}$ Hz.

C. Analysis

Theorem II.1. *The average amount of data communicated per unit time by each node in* VCAST *to obtain information about all vehicles within a distance of* R *from itself is bounded by* $O(\frac{Rp}{r_h})$.

Proof: Let B denote the average amount of data communicated per unit time, by each node in *VCAST*. The number of vehicles at a distance of at most h communication hops from a vehicle is bounded by $O(\rho h^2 r_h^2)$. As a result the number of vehicles at exactly h hops away from a vehicle is bounded by $O(\rho h r_h^2)$. Information about vehicles at distance h hops is broadcast at $\frac{p}{h}$ Hz. Thus the total amount of data to be communicated about vehicles h hops away is $O(\rho p r_h^2)$. Note that this information is broadcast by at most one vehicle in every area πr_h^2. Hence, on average each node is responsible for communicating only $O(\frac{\rho p r_h^2}{\rho r_h^2})$ bits about vehicles at distance h hops away from itself. Summing up over all distances and by noting that each vehicle broadcasts its own state at p Hz, we get:

$$B = O(p + \Sigma_{i=1}^{\frac{R}{r_h}} \frac{\rho p r_h^2}{\rho r_h^2})) = O(\frac{Rp}{r_h})$$

■

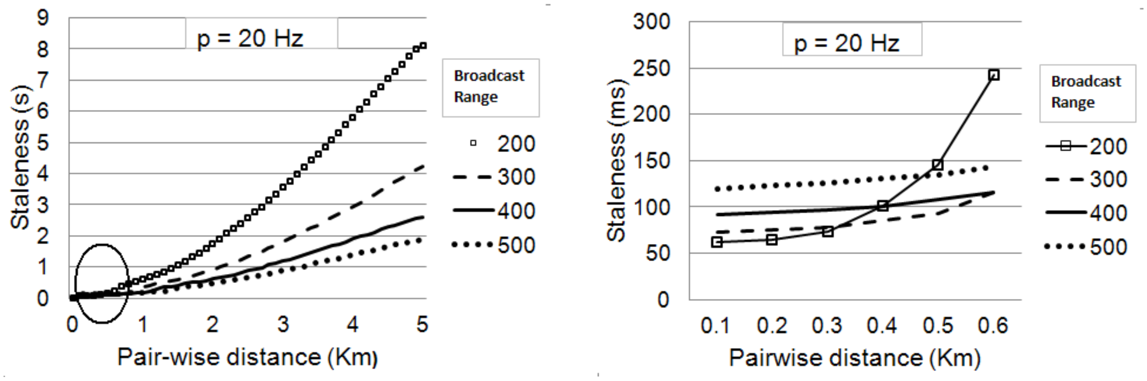
Thus, we see that the amount of data communicated per node does not depend on the number of vehicles. As a result, if C denotes the allowable wireless transmission capacity at a node then $p < \frac{C r_h}{R}$. Thus the maximum broadcast frequency at the source also is not limited by the number of vehicles but rather only by the radius of the tracking zone in terms of communication hops. We now obtain a bound on the maximum delay after which information about a vehicle is received since it was transmitted at the source. We refer to this as *staleness* in the information posessed by a vehicle.

Definition II.1 (Staleness(j,i))**.** *The staleness in the state of vehicle* i *at vehicle* j *is the time elapsed since the timestamp of the state of* i *(*$j.T_i$*).*

Theorem II.2. *The staleness in the state of vehicle* i *at vehicle* j *in* VCAST *is bounded by* $O(\frac{d_h(i,j)^2}{p^2})$*, i.e.* $O(\frac{d(i,j)^2}{p^2 r_h^2})$.

Proof: Consider a vehicle j at a distance of h communication hops away from a vehicle i, i.e., $d_h(i,j) = h$. Note that at a distance of $h - 1$ communication hops from a vehicle i, information about i is updated only once every $h - 1$ intervals. As a result the maximum time before which j hears fresher information about i from some vehicle at distance $h - 1$ hops away from i is bounded by $\frac{h-1}{p}$ seconds. Likewise, the maximum time elapsed between a vehicle at $h - 2$ hops receiving information about i and a vehicle at distance $h - 1$ hops obtaining that information is bounded by $\frac{h-2}{p}$ seconds. Summing from a distance of 1 hop to h hops, we get the result. ■

From Theorem II.2, we note that the staleness at a distance d from a vehicle does not depend upon the vehicular density or the region size, but only on the communication hop distance and the initial broadcast rate at the source. Hence, we expect that as the communication range increases the staleness should decrease. However, as the communication range increases, the interference within the vehicular transmission also increases and this can adversely affect the network reliability and system accuracy. In Section III-C, we analyze the performance of our



(a)

(b)

Fig. 2. (a) Maximum staleness vs pair-wise vehicular distance: $p = 20$Hz, one hop communication range of $200m$, $300m$, $400m$ and $500m$. (b) Zoomed in version of the previous plot at smaller distances (shown by the ellipse in Fig. (a))

algorithm in large scale simulation and point out the impact of p and r_h on the staleness at different distances.

We now state the average communication rate and staleness when aggregate cell information is propagated instead of actual vehicle location information. The proofs have been omitted for reasons of space.

Theorem II.3. *The amount of data communicated by each node in* VCAST *per unit time, when aggregate cell information is propagated, to obtain information about each cell at distance up to* R *from itself is bounded by* $O(\frac{Rp}{\rho r_c r_h})$.

In comparison with the result from Theorem II.1, we note that the average communication rate reduces by a factor equal to the number of vehicles in each cell (ρr_c) because only aggregate information about the cell is propagated with distance-sensitive rate as opposed to propagating information about each vehicle in the cell.

Theorem II.4. *The staleness in the state of cell* z *at vehicle* j *in* VCAST, *when aggregate cell information is propagated, is bounded by* $O(\frac{d_c(j,z)d_h(j,z)}{p^2})$, *where* $d_h(j,z)$ *denotes the communication hop distance between* j *and the closest vehicle to* j *in cell* z.

III. PERFORMANCE

A. Experimental setup

We evaluate the performance of *VCAST* at different broadcast ranges and source broadcast rates, using simulations in Jprowler [12], a discrete event simulator for wireless networks. JProwler models wireless channel interference, incorporates the Rayleigh fading model, and supports CSMA based wireless transmission with adjustable backoff times, transmit power and transmission times. To systematically study the impact of broadcast range on system performance, we disable the channel fading in the simulation and instead use a fixed radius communication. We simulate 800 vehicles moving with uniform speed in the same direction in a 5Km long 4 lane highway with an average inter-vehicle separation of 20m. By simulating vehicles with uniform velocity, we are able to remove the effect of mobility on system performance - for instance, if vehicles move in opposite directions, the information staleness may reduce because of faster propagation of information. Instead, by simulating uniform velocity, the relative distance between vehicles is maintained during the course of the simulation allowing the clear characterization of distance versus information staleness. We consider communication ranges of 200m, 300m, 400m and 500m and initial broadcast rates of 20 Hz, 10 Hz and 5Hz, which are within the range of expected transmission rate and range values of *Here I am* messages for intelligent transportation systems [1], [2].

B. Experimental procedure

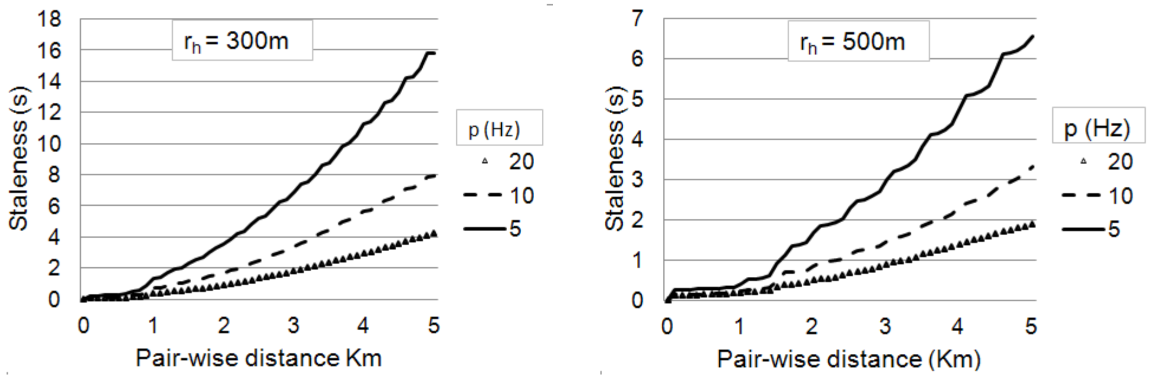
At each vehicle, we measure the maximum staleness with respect to every other vehicle by measuring the time elapsed since the information originated at the source, just before fresh information about a vehicle is received. For information aggregation, we consider the cell size equal to the communication range of each vehicle and propagate only aggregate cell information instead of individual vehicle information, and measure the maximum staleness with respect to every cell in the region. We then group the maximum staleness based on pairwise distances between vehicle-vehicle and vehicle-cell respectively. The average of these measurements over multiple experiments are used in our evaluations.

C. Key observations

In Fig. 2(a), we plot the maximum staleness in vehicle information against the inter-vehicular distance for $p = 20$Hz and different communication ranges. We note that as the communication range increases, the staleness at larger distances reduces because of fewer number of hops to traverse. Moreover, the staleness decreases quadratically with the increase in communication range, corroborating our result from Theorem II.2. However, increasing the communication range also has an adverse effect on the information accuracy at smaller distances. In Fig. 2(b), we highlight the staleness with $p = 20Hz$ at closer distances under different values for the communication range. We observe that with $r_h = 200m$ can achieve a staleness of as low as $55 - 60$ms within $200m$, but with $r_h = 500m$, the staleness increases to $120 - 130$ ms. Thus, for larger distances higher communication range is preferable while for closer distances smaller range is preferable.

We now investigate the impact of initial broadcast rate on system performance. In Fig. 3(a) and Fig. 3(b), we compare the staleness at different values of p for $r_h = 300m$ and $r_h = 500m$ respectively. We note that at both these communication range values, a higher initial broadcast rate is able to decrease the staleness significantly at higher distances. At $p = 20$Hz, the staleness values at a distance of 5Km are approximately 4s and 2s for $r_h = 300m$ and $r_h = 500$m respectively.

Finally, in Fig. 4, we plot the maximum staleness in aggregate



(a)

(b)

Fig. 3. (a) Maximum staleness vs pair-wise vehicular distance: $r_h = 300m$ (b) Maximum staleness vs pair-wise vehicular distance: $r_h = 500m$

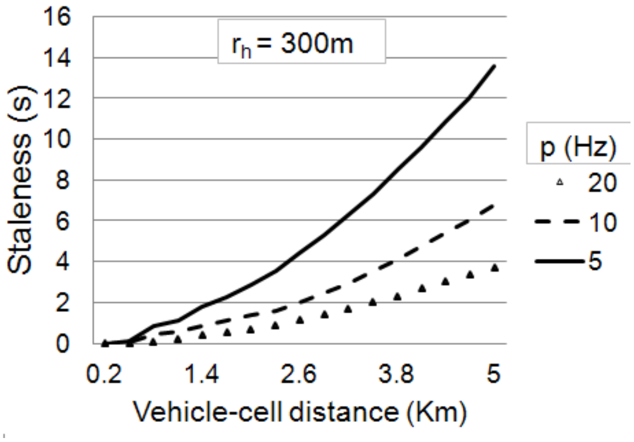


Fig. 4. Maximum staleness vs vehicle-cell distance: $r_h = r_c = 300m$

cell information against pairwise vehicle-cell distance for $r_h = 300m$ at different values of p. In comparison with individual vehicle information from Fig. 3(a), we observe that the error is lower at the corresponding distances because a single message from a cell is enough to convey information about the entire cell as opposed to potentially requiring multiple messages to learn about individual vehicles. We note that at $r_h = 300m$ and $p = 20$Hz, aggregate traffic information from 5Km away can be communicated in under 4 seconds without too much extra overhead when compared to basic *Here I am* messages.

IV. CONCLUSIONS

In this paper, we have described an algorithm for obtaining individual vehicle location and aggregate traffic information over a multi-hop wireless vehicular network without the need for expensive road-side infrastructure, any special hardware or modification to vehicular transmission standards. To ensure scalability in forwarding information over multiple hops, traffic information is propagated at a rate that decreases linearly with distance from the source. By doing so, traffic information can be obtained with a latency, which is a measure of error in the traffic information, that is bounded by $O(d^2)$ where d is the communication hop distance from the source of the information. We showed that both the accuracy and the average communication rate do not depend on vehicular density and number of vehicles in the region. Our algorithm can be used to improve safety against collisions, inform about approaching emergency vehicles and lane merging vehicles (that may even be beyond a single hop communication range) and to enable dynamic routing and navigation techniques by providing aggregate traffic information in an extended neighborhood. We showed using simulations that our algorithm could provide traffic information up to 5 km away in under 4 seconds without a drastic increase in communication overhead when compared with basic one hop safety messages.

In future work, we would like to augment our basic four lane vehicular network simulation with a more comprehensive traffic simulator and evaluate the performance under different mobility patterns, vehicular densities and traffic flows. We would like to use these extensive simulations to more throughly investigate the relation between communication range, initial broadcast rate and achievable accuracy at different vehicular densities. Finally, we would like to integrate our vehicular traffic mapping service with a navigation front-end for dynamic computation of alternate routes and evaluate the impact of distance sensitivity on the quality of navigation performance.

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