Virtual Traffic Lights in Partial Deployment Scenarios

Hugo Conceição¹,², Michel Ferreira¹ and Peter Steenkiste²

Abstract—Vehicular ad hoc networks (VANETs) are seen as an important enabling technology for improving both traffic safety and efficiency. Virtual Traffic Lights (VTLs) are a promising proposal for reducing travel time by efficiently controlling road intersections. VTLs use vehicle-to-vehicle communication to dynamically optimize traffic flow and they display traffic light information on the windshield. However, research so far has assumed that all vehicles are equipped with VTL support and it has ignored the incremental deployment phase, which could last decades. In this paper we present a solution for a VTL partial deployment scenario that is based on the idea of having VTL equipped cars display traffic light information on the outside of the vehicle. This allows drivers in non-equipped vehicles, or even pedestrians, to see the light color and respond accordingly. We show that the benefits of VTLs in terms of intersection throughput and average delay reduction grow as a function of the penetration rate of equipped vehicles.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) are foreseen to have important applications in both road safety and traffic efficiency. Road intersections play a critical role in both of these areas. Intersections are where the majority of road crashes happen, and they are also the major factor affecting the continuity of traffic flows. Much research in VANETs is thus devoted to the safe and efficient management of road junctions [10].

Recently, Virtual Traffic Lights (VTLs) have been proposed as an intersection control mechanism that leverages vehicle-to-vehicle (V2V) communication [8]. The main idea of this proposal is to have a virtual traffic signal created on the windshield, inside of cars, as they approach intersections. The creation and operation of such VTLs are solely based in vehicular inter-networking, which is used to efficiently coordinate access to the intersection. In the original proposal, the operational cycle of VTL is executed by a stopped vehicle at the intersection; this vehicle acts as a temporary infrastructure for creating and managing a traffic light wherever necessary. This ubiquity of virtually signalized intersections, emerging as a result of traffic conditions, can potentially result in metropolitan-scale benefits of more than 60% in traffic flow reported in [8], at no expense of additional infrastructure and energy costs.

Research so far has assumed a 100% penetration rate scenario [8], in which all vehicles were required to be equipped with Digital Short Range Communications (DSRC) radios [10] and VTL. However, VTL deployment is likely to be incremental. While it possible to introduce legislation that mandates that new cars be equipped with V2V communication and VTLs, retrofitting the existing car fleet with VTL technology in a short time window is likely to be unattractive. In this paper we show how VTLs can be used in a partial deployment scenario. We also use accurate traffic simulation to show that VTLs offer performance benefits even for low penetration rates, and that the benefit increases approximately linearly with the VTL penetration rate.

To handle the interaction between equipped and non-equipped vehicles we propose that VTL equipped vehicles have an exterior representation in the form of a clearly visible light that guides the behavior of drivers of non-equipped vehicles. Our solution for VTL use in partial deployment does not modify the VTL protocol used by equipped vehicles and so in this paper we focus on the protocol that drivers of non-equipped vehicles need to follow to cross the intersection based on what other vehicles are at the intersection. Such exterior lights in a stopped vehicle at the entrance of an intersection may also help deal with other road users such as bicyclists and pedestrians, but we do not consider this further in this paper.

This paper is organized as follows. We first review related work and we then present our proposal for how to support partial VTL deployment. Next we describe our simulation setup to evaluate VTL under partial deployment and we present the results. We conclude with a summary of the paper.

II. RELATED WORK

A common problem in the deployment of novel cooperative systems is reaching a critical penetration rate threshold that materializes the theoretical benefits claimed by such novel systems under ideal scenarios. This problem is particularly acute in the context of VANETs, given the significant financial effort entailed by the renewal of the car fleet. If no benefit is observed in the early stages of VANET deployment, such technology will not be appealing to people and will slow down market penetration.

In [4], it is estimated that in the first years after the deployment, the probability that a driver in an equipped vehicle will benefit from a safety related application such as crash avoidance at intersections, is only of 1%. This is due to the expected initial low market penetration of DSRC, and the fact that all vehicles involved in the event need to be equipped. The same study predicts that, in a scenario where it is mandated that new vehicles are equipped with DSRC radios, and considering a phase-in period, the percentage of

¹H. Conceição and M. Ferreira are with Instituto de Telecomunicações, FCUP DCC, University of Porto, Portugal.hc,michel at dcc.fc.up.pt
²H. Conceição and P. Steenkiste are with the Department of Electrical and Computer Engineering, Carnegie Mellon University, USA prs at ece.cmu.edu
new vehicles equipped will escalate very fast, starting with 30% in the two years after the supposed final regulatory rule is issued (expected to 2015), to 60%, and 90% in the following years, and reaching 100% five years after the baseline year.

Considering the car fleet of the United States to be close to 260 million vehicles [14], the recent numbers of 7.9 million vehicles sold per year [1], and the average increment of 3.69 million per year [15] in the total number of vehicles in the United States, one can expect, according to the estimate in [4], that it will take 5 years to reach the symbolic number of 10% of market penetration of DSRC-equipped vehicles, and less than 18 years to reach 40%. These estimates do not consider the possibility of retrofitting due to lack of data. However, it is clear that this would accelerate this process significantly. It is thus clear that there will be a long period of interaction between DSRC equipped and non-equipped vehicles. It is thus important to design applications and interaction mechanisms between these two classes of vehicles that can function effectively and yield partial benefits.

Vision, either computer or driver-based, is likely to play an important role here, as it is able to detect equally equipped and non-equipped vehicles. For instance, the VANET-based overtaking assistant in [9] brings important benefit in partial deployment scenarios because it relies on the drivers vision to detect oncoming vehicles. Similarly, in [2], the authors proposed to use simple modifications of frequency or intensity of the hazard warning lights or the stop lights of radio-equipped vehicles to convey different messages to drivers of non-equipped vehicles. Note that the activation by drivers of the hazard lights, or its automated activation based on a deceleration threshold, is already well established as a collaborative action to disseminate warning messages in a non-vehicular-networking context. In the same work, the authors report that a radio penetration rate of 30% is sufficient to inform more than 95% of drivers in the region of interest in a timely manner.

III. PARTIAL DEPLOYMENT AND VTL

We now describe how we use VTL in partial deployment scenarios.

A. Protocol Overview

Let us first briefly summarize the VTL concept introduced in [8]. VTLs use V2V communication to coordinate access to the intersection by the vehicles. The system relies on periodic beacons to identify and learn the position of all other vehicles that are in or near the intersection. The vehicles then use the VTL protocol to reach consensus on the order in which vehicles can cross the intersection and corresponding traffic light information is displayed on the windshield of all the drivers. The ordering of the vehicles can be optimized based on traffic conditions. For example, vehicles can cross in groups, similar to the effect of regular traffic lights.

The above solution clearly requires 100% penetration rate: it assumes that all vehicles know the position of all other vehicles and drivers who do not have VTL displayed on their windshield will not know when they can safely cross since there are no physical traffic lights. To address this problem we rely on the vision of drivers of non-equipped cars to coordinate the crossing of equipped and non-equipped vehicles. This is done by means of an outside representation on equipped vehicles that conveys a regulatory message regarding the right-of-way at an intersection.

The basic idea is easily understood if we imagine that equipped vehicles transport a traditional traffic light, as illustrated in Fig. 1a). A stopped equipped vehicle at the entrance of the intersection is used as a temporary infrastructure to create a traffic light. It uses V2V communication to execute the VTL protocol, as described earlier in this section, jointly with other equipped vehicles and to create VTLs on the windshield of all equipped cars. It also uses its exterior lights to guide non-equipped vehicles in determining the right-of-way at the intersection.

The focus of this paper is on the protocol used by drivers of non-equipped cars to cross the intersection. We need to consider three cases, depending on the number of equipped vehicles:

- No equipped vehicles: in this case the standard rules for the intersection apply;
- One equipped vehicle: the equipped vehicle will give itself a green light, effectively claiming priority. This policy has the advantage that it creates an incentive for drivers to install and use VTLs;
- More than one equipped vehicle: the equipped vehicles execute the VTL protocol and display coordinated traffic signs to non-equipped cars.

We now discuss some key features of the proposed solution in more detail.

B. Key Features

In this subsection we describe the most important aspects we consider for this version of the protocol:

Scenarios Considered: we assume that not all intersections are suitable to be governed by VTLs. In particular, the existing intersections governed currently by physical traffic lights would continue to be governed by such existing infrastructure. Note that for these intersections there is no visibility requirement for the orthogonal roads, which would be a problem for our solution. Note that in some cases, however, physical traffic lights could be replaced by VTLs on some intersections. Hence, in this paper we focus on a simple configuration of an intersection that is governed by all-way stop signs or the yield-to-the-right rule, and where visibility is required. We also assume that there is a single lane in each direction.

External Lights: Clearly, the metaphoric representation of these exterior lights shown in Fig. 1a) must be replaced by a drivable version. We show a possible design in Fig. 1b). While the focus of this work is not so much on defining the best representation for the exterior lights, we do need a viable proposal so we elaborate on the design and impact of the exterior lights in terms of right-of-way in a setting.
Fig. 1: Frame a) is a metaphoric representation of how an equipped vehicle could be used to convey regulatory messages about intersection crossing to non-equipped vehicles. Frame b) show a drivable representation of such exterior lights, in a scenario where all vehicles are equipped. The vehicle on the right is acting as the temporary infrastructure for the traffic light governing the intersection. It shows a red light yielding priority to vehicles approaching from its left and right. Equipped vehicles also display a windshield representation of VTLs (shown in the figure as an arrow) indicating its priority to the driver. Non-equipped vehicles would not have the windshield representation, being guided solely by the exterior light of the white vehicle.

where equipped and non-equipped cars co-exist and conflict at intersections.

Our proposal is that the exterior lights indicate the current or future action of the vehicle (or vehicles in the same lane) that is displaying the light. Note that this meaning is different from the standard lights (as suggested in Fig. 1a)). Traffic lights indicate what the drivers seeing the light should do, e.g. red light means stop, while in our case a red light means that the car displaying the light is stopping. Drivers of non-equipped cars that see the red light will decide whether they should stop or go depending on what lane they are in. One reason for picking this definition of the lights is that it is consistent with the lights already existent in a car, e.g. blinkers indicate that the vehicle will turn; or the brake light that indicate the vehicle will stop. Note that states such as Washington, Oregon and Idaho, permit vehicles to be equipped with auxiliary rear signal systems displaying green light when the accelerator is depressed, yellow light when the vehicle is coasting, and red light when the brake is depressed [16]. It is clear that there will be a period where there are cars on the road with VTL exterior lights, but intersections are still governed by traditional rules. This period will allow drivers to get familiar with such lights and create the minimum percentage of equipped vehicles that bring traffic flow benefit to both equipped and non-equipped vehicles when the governing of intersections by the new rules is mandated. An alternative definition would be to try to mimic a standard traffic light. However, this is likely to lead to a more complex representation, since different lights would have to be shown to vehicles in different lanes. This could lead to situations where drivers would see multiple colors, making their understanding/decision more difficult.

For the situation when there is only one equipped vehicle, and the VTL is not created, the equipped vehicle should display a flashing green light, indicating it has the right of way. The choice of a different signal was needed to inform vehicles in lanes parallel to the lane of the equipped vehicle, that they do not have the same priority. Table I summarize the meaning of each color.

<table>
<thead>
<tr>
<th>Light</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>Lane is yielding</td>
</tr>
<tr>
<td>Yellow/Green</td>
<td>Lane has right of way</td>
</tr>
<tr>
<td>Flashing Green</td>
<td>Vehicle has right of way</td>
</tr>
</tbody>
</table>

**VTL Timing:** Let us consider how VTLs can affect the efficiency of the traffic flow. We can consider two distinct scenarios depending on the traffic volumes crossing the intersection. At high traffic volume, even under low penetration rate of equipped vehicles, it is expected that it will be fairly common to have two or more equipped cars at the intersection, so the traffic flow will be governed by VTLs. The model is that one of the equipped cars will be stopped at the intersection with a red light while traffic (including both equipped and non-equipped vehicles) traveling on the cross-direction can proceed. At the end of this phase the VTL lights switch. The equipped vehicle that was controlling traffic will handover such execution to another equipped vehicle and will get a green light so it can cross. The result is that during a typical phase duration (e.g. 30 or 45 seconds) both equipped and non-equipped vehicles can benefit from the existence of a traffic light, i.e. a group of cars cross without stopping. This is true even with low deployment rate of VTLs.

At low traffic volumes, the governing of the intersection by a traffic light will be rare. VTL will primarily benefit equipped vehicles in such scenarios, since they will have the right-of-way if no other VTL equipped vehicle emerges to create a VTL. Non-equipped vehicles will have to obey
The Last Equipped Vehicle Leaves Phase Switch

Fig. 2: Possible sequence of states at an intersection, temporarily govern by a VTL. Equipped vehicles are marked with ‘G’, ‘R’ or ‘F’, according to if they are displaying a green, red, or flashing green light. Non-equipped vehicles are marked with ‘N’.

to the yield-to-the-right or all-way-stop rules, while always yielding to equipped vehicles, so they are unlikely to see any benefit.

Fig. 2 depict a sequence of three different states of VTL: a) the light phase ends, and the equipped vehicle with red at the intersection switches phase with the equipped vehicle with green; in b) the vertical lane has now the priority; in c), after all other equipped vehicles crossed the intersection, the one left immediately obtains the right of way; finally, the non-equipped vehicles, will obey to the standard rules.

C. Operational Sequence

We here represent the interactions of a driver in a non-equipped vehicle through means of an Operational Sequence Diagram [3].

Fig. 3: Operational Sequence Diagram representing the interactions of a driver in a non-equipped vehicle, when approaching an unsignalized intersection.

Considering Fig. 3, when a driver in a non-equipped vehicle is approaching the intersection, he will first see a stop/yield sign. Whether or not he will obey to it, is not considered by VTL, e.g. brakes won’t be actioned. The distinction from an autonomous vehicle setting is then clear. When the driver reaches the intersection, if he sees no equipped vehicle, the standard all-way stop/yield rules apply. If otherwise at least one equipped vehicle is there, the driver should obey to the light being displayed as already explained, the VTL mode. The driver must continuously check for the presence of equipped vehicles at the intersection. If, for example, the last one leaves the intersection, the priority scheme changes. Note that this need to scan for (equipped) vehicles is already present given that we are considering all-way stop intersections.

The VTL mode is depicted in Fig. 4. If there is only one equipped vehicle at the intersection, it will display the flashing green light, indicating to drivers on non-equipped vehicles that it has priority. If there are multiple equipped vehicles, the driver will decide he has the right of way if a vehicle in an orthogonal road displays a red light and/or a vehicle in a parallel road display the green light. Note again that the light being displayed in orthogonal roads, have a converse meaning, relative to standard traffic lights.

IV. Evaluation

In this section we evaluate the benefit, in terms of traffic efficiency, introduced by VTL in partial deployment scenarios, enabling the extrapolation of the time it will take for significant gain to be achieved. The metrics considered are average trip duration, and throughput.

A. Simulation Setup

To evaluate the proposed metrics, we resorted to VNS1 [7], a highly scalable simulator, that integrates a microscopic traffic simulator DIVERT 2.0 [5], and the well-known network simulator NS3 [12]. We consider a four-way stop controlled intersection (or unsignalized intersection), with the adequate volumes and arrival distribution, as described next. The volumes at such intersections are typically low compared to intersections controlled by traffic lights. However, we also consider higher values for volume, contemplating that the better traffic control provided by VTL at previously unsignalized intersections may lead to an increase in demand.

Being our objective to evaluate the efficiency of VTL, the most important aspect of this setup is the traffic simulation. We use a standard setup in transportation engineering studies [11] to simulate traffic in non-signalized intersections. We consider a single lane per approach, with infinite length, and the four approaches are symmetric in terms of demand.

1Vehicular Network Simulator
TABLE II: Simulation Parameters

<table>
<thead>
<tr>
<th>Scenario Setup</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Topology</td>
<td>Single Unsignalized Intersection</td>
</tr>
<tr>
<td>Lanes</td>
<td>Single Lane / Approach</td>
</tr>
<tr>
<td>Road Length</td>
<td>125 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Traffic Simulation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility Model</td>
<td>IDM w/ AWSC support</td>
</tr>
<tr>
<td>Traffic Demand split %</td>
<td>25/25/25/25</td>
</tr>
<tr>
<td>Vehicle Movement</td>
<td>20% turn left, 20% turn right</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vehicle Arrival Headway Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>t&lt;sub&gt;ref&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network Simulation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication Range</td>
<td>100 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiments</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>4 hours</td>
</tr>
<tr>
<td>Traffic Volumes (veh/h)</td>
<td>100,200,400,...,2200</td>
</tr>
<tr>
<td>% Equipped Vehicles</td>
<td>0,10,...,100</td>
</tr>
<tr>
<td>Runs</td>
<td>30 per point</td>
</tr>
</tbody>
</table>

The mobility model used in DIVERT 2.0 is a version of the Intelligent Driver Model [13], enhanced to consider all-way stop controlled (AWSC) intersections where vehicles always have to stop, and gain priority according to the time of arrival at the intersection. Regarding routing, vehicles move straight with a probability of 60%, and turn to either left or right with the same probability. An important factor when simulating the traffic in this scenario is the vehicle arrival headway distribution, which defines the spacing/time between two consecutive vehicles entering the simulation. Cowan’s M3 headway distribution [6] is commonly used.

We implemented the Cowan’s M3 headway distribution in DIVERT 2.0, as well as the validation of the extension of the IDM model to consider AWSC intersections, not shown here due to space constrains. Regarding communication, for this preliminary study we use a simple unit-disk model. The simulation parameters are listed in Table II. A video of a running simulation is available at: http://www.dcc.fc.up.pt/~hc/pdvtl.avi

B. Results

In this section we present results showing that VTL, even under partial penetration, increases the capacity of the intersection, and reduces the average trip duration. It is also shown that equipped vehicles have a significant edge over the non-equipped vehicles, in low density scenarios, which represents an incentive for the adoption of VTL.

Fig. 5 depicts the throughput of the intersection. Here, throughput is measured as the number of vehicles per hour that finish their trips. As expected, the throughput increases linearly with the traffic until the intersection is saturated. We see that the saturation point depends on the VTL deployment rate, reflecting different capacities for the intersection. When there are no equipped vehicles, all vehicles obey the standard all-way stop rules and the saturation point is reached around 1400 veh/h. As the percentage of equipped vehicles increases, the saturation point is shifted to 1600 veh/h, and then peaking at 1800 veh/h in the scenario of full penetration of DSRC and VTL, which represents an increase in the capacity of 28.6%. Note that half of the maximum improvement is already reached when only 40% of the vehicles are equipped. Capacity gains at low penetration rates are important because they may accelerate the acceptance of this technology. As a result of improvements in capacity, a wider usage of the road network could take place as new routes are taken by drivers.

In Fig. 6, it is shown how the delay increases with the volume for different penetration rates. We observe that the average trip duration is reduced when VTL is used, and improvement increases as more vehicles are equipped. For 1400 veh/h, the saturation point of the intersection when VTL is not used, the benefit of using VTL starts to be significant. The improvement is 17% with 50-60% of equipped vehicles; 39% with 90% of equipped vehicles; and reaching the 53% with full penetration. The results are, as expected, even better after this point (1600 veh/h), with benefits of 40.30% with just 40% of equipped vehicles, peaking at 87.58% with full penetration. While the delays for volumes that are higher than the saturation point are not stable since they do not correspond to a steady state condition. However the comparison is still useful since it can give insights in
what could happen, for example, the morning rush hour.

The results so far show that VTLs can offer benefits in both throughput and delay. Better traffic control both reduces dead periods for equipped vehicles (they only stop at the intersection if necessary), and gives priority to roads with more (equipped) vehicles. In Fig. 7, this incentive is noticeable, showing the benefit, in terms of average trip duration, of equipped vehicles over the non-equipped ones. Note that the gain is higher for low volumes, and tends to zero as the volume increases. The reason is that for low volumes, equipped vehicles can avoid dead periods. For higher volumes, the number of dead periods decreases, and so do the benefits for equipped vehicles. The initial edge of equipped vehicles over non-equipped vehicles is of critical importance, acting as a catalyst to the adoption of VTL.

V. FUTURE WORK

In this paper we suggest an external representation for the VTL. Yet aspects such as visibility, and legislation, were not addressed. Clearly, these issues will play a major role in deciding what is the most appropriate representation.

One aspect that should be developed further is the integration of pedestrians in the protocol. With the proposed solution, pedestrians are able to see the light color, but a mechanism is necessary to consider pedestrians in the generation of the traffic light, e.g. allowing enough time for them to cross the road, or even detect their presence.

The verification of the safety and correctness of the VTL protocol is mandatory. An important question is whether, by giving priority to equipped vehicles, starvation can occur. Intuitively, the problem here is the same as for the stop or yield sign. A more detailed communication model might have impact on the execution time of the VTL protocol, which could lead to higher delays at the intersection.

VI. CONCLUSIONS

Although examples such as H-day (“The right-hand traffic diversion”) have been witnessed in the past at country-level scales, it is clear that a major paradigm shift regarding traffic control at intersections will not happen over night. The success of VTL in mitigating the problem of traffic congestion would be just theoretical if it is based on the unrealistic assumption of 100% deployment rate on the car fleet. In this paper we have shown that a re-design of the VTL protocol to include exterior lights on equipped vehicles can solve the problem of the co-existence with non-equipped vehicles, making the technology deployable. Moreover, we have shown that the benefit that is enabled by VTL increases linearly as a function of the percentage of equipped vehicles, which is a key result to sustain the gradual deployment of the technology.

ACKNOWLEDGMENT

This work was funded in part by the Portuguese Foundation for Science and Technology under the Carnegie Mellon/Portugal program (grant SFRH/BD/33766/2009) and the Virtual Traffic Lights project (PTDC/EIA-CCO/11814/2010).

REFERENCES