Self-Organized Traffic Control

Michel Ferreira
Instituto de Telecomunicações
DCC/FC - University of Porto
4169-007 Porto, Portugal
michel@dcc.fc.up.pt

Ricardo Fernandes
Instituto de Telecomunicações
DCC/FC - University of Porto
4169-007 Porto, Portugal
rjf@dcc.fc.up.pt

Hugo Conceição
Instituto de Telecomunicações
DCC/FC - University of Porto
4169-007 Porto, Portugal
hc@dcc.fc.up.pt

Wantanee Viriyasitavat
Dept. of Electrical and Computer Engineering
Carnegie Mellon University
Pittsburgh, PA 15213-3890, USA
wviriyas@ece.cmu.edu

Ozan K. Tonguz
Dept. of Electrical and Computer Engineering
Carnegie Mellon University
Pittsburgh, PA 15213-3890, USA
tonguz@ece.cmu.edu

ABSTRACT

In this paper we propose and present preliminary results on the migration of traffic lights as roadside-based infrastructures to in-vehicle virtual signs supported only by vehicle-to-vehicle communications. We design a virtual traffic light protocol that can dynamically optimize the flow of traffic in road intersections without requiring any roadside infrastructure. Elected vehicles act as temporary road junction infrastructures and broadcast traffic light messages that are shown to drivers through in-vehicle displays. This approach renders signalized control of intersections truly ubiquitous, which significantly increases the overall traffic flow. We provide compelling evidence that our proposal is a scalable and cost-effective solution to urban traffic control.

Categories and Subject Descriptors

C.2.4 [**Computer-Communication Networks**]: Distributed Systems—*Distributed Applications*; J.2 [**Computer Applications**]: Physical Sciences and Engineering—*Engineering*

General Terms

Design, Management, Performance

Keywords

Traffic lights, V2V communication, self-organized traffic

1. INTRODUCTION

One of the main application areas for Vehicular Ad Hoc Networks (VANET) is the mitigation of traffic congestion. This is a very significant problem, as its cost has been estimated to reach 1% of the European Union's (E.U.) GDP in 2010 [3]. In theory, the solution to this problem could follow three different approaches: a) reducing the total number of vehicles on the roads; b) increasing the existing road infrastructure; c) increasing traffic flow on the existing road infrastructure. In economic terms, the most sustainable approach to reduce congestion would be based on increasing the throughput of the already existing road infrastructure, which is also the relevant approach for VANET-based research. To this end, several papers have described VANET-based traffic information systems (TIS) that allow vehicles to avoid congested roads and select alternative routes that provide a higher flow of traffic [8, 9]. Such TIS enable a wider usage of the road network, diverting drivers from congested roads. Whether a massive usage of the informed, but yet selfish, routing engines that are fed by TIS will actually provide a solution to traffic congestion, remains to be seen [11].

It is clear that a wider exploration of the road network will result in higher conflicts at road intersections. Considering these road junctions as a crucial *resource* that is responsible for the continuity of traffic flows, we focus in this paper in the role of VANET for the efficient management of these fundamental components of the road network. Currently, a small percentage of the intersections of the road network are equipped with adaptive traffic lights, providing the state-of-the-art in terms of intersection management to maximize traffic flow [14]. What we propose in this paper is the migration of these roadside-based traffic lights to in-vehicle virtual signs supported only by the advent of vehicle-to-vehicle (V2V) communications[1]. In our proposal, elected vehicles act as temporary road junction infrastructures and broadcast traffic light messages that are conveyed to drivers through in-vehicle displays. The improvement in traffic flow would result not only from the optimized management of individual intersections, which is enabled by the

[1]There are other examples where technology has enabled similar migrations from roadside-based infrastructures to in-vehicle alternatives. The invention of plastic money, for instance, has enabled the replacement of roadside-based parking meters by in-vehicle portable meters (see for example: `http://www.smartpark.co.nz`).

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neighborhood awareness of VANET protocols, but also from the *scalability* of our solution that renders signalized control of intersections truly ubiquitous. This ubiquity would allow maximizing the throughput of the *complete* road network, rather than the reduced number of road junctions that are currently managed by traffic lights. This is particular important in the context of traffic, as a single bottleneck can rapidly propagate congestion through the road network.

The remainder of this paper is organized as follows. In the next section, we provide relevant data about traffic lights, their deployment rates, installation and operation costs, as well as related research in their optimization. Section 3 describes the design of our virtual traffic lights system and its implementation in the context of a VANET simulator. Section 4 provides preliminary results on the impact on traffic flow, evaluated in the context of a large european city. Finally, Section 5 concludes the paper.

2. BACKGROUND

To provide some background data on the issue of road intersection management, we have computed the number of road junctions in the United States (U.S.) using the road maps of the country available from the U.S. Census Bureau 2009 TIGER/Line data [16]. We resorted to pgRouting, a project that provides routing functionality to the well-known PostGIS module of PostreSQL. We imported the map of each county and created a table of the intersections. 3138 out of 3234 counties in the U.S. were successfully processed, resulting in a total of $48,685,733$ intersections[2].

Out of these ≈ 50 million junctions, only around $260,000$ are governed by traffic lights which corresponds to a 0.5% ratio [13]. Most of these traffic lights are deployed in urban areas where traffic density is high. In New York City (NYC), for example, out of $45,000$ intersections in the five boroughs, only $10,800$ are directed by traffic signals [7] which corresponds to a ratio of 24%. Similarly, in the Irish city of Dublin, [12] reports a 25% ratio of signalized intersections in the downtown area. Porto, the second largest city of Portugal, has a total of 2000 intersections, out of which only 328 are governed by traffic lights, corresponding to a 16% ratio. Whether one considers the downtown, the city, or the country level, the deployment of traffic lights is very scarce with respect to the total number of intersections. This phenomenon is certainly quite counter-intuitive and warrants a deeper look and better explanation.

According to [18], the cost of equipping an intersection with traffic lights ranges from $\$50,000$ to more than $\$200,000$, depending on the complexity of the intersection and the characteristics of the traffic using the intersection. If one uses the average of this range, then the deployment cost of current traffic lights in the U.S. was about $33 billion. In addition, according to the same source, the annual operating cost of each intersection with traffic lights ranges from $\$1,000$ to $\$5,000$. Again taking the average value of $\$3,000$, one gets that the annual operating cost of current traffic lights in the U.S. is $780 million. Based on these deployment and operational costs, it is clearly unrealistic to envision a scenario where physical traffic lights will govern 100% of the road junctions of a country.

[2] 96 out of 3234 counties (less than 3%) could not be processed through pgRouting due to errors in the conversion of the maps.

The highly partial deployment of physical traffic lights is also due to the fact that the conventional traffic lights can result in increased delay rather than increased flow. [14] has reported that $70-90\%$ of the deployed traffic lights work under fixed parametrization of cycle duration and green splits. Hence, the large majority of traffic lights cannot adapt to changing traffic conditions and can result in unnecessary stops of vehicles under red lights.Under this non-adaptive scenario, only the more congested intersections become candidates for the installation of traffic lights [18]. One possibility for mitigating the increased delay introduced by traffic lights under low traffic scenarios is to make them work just as part-time (see Fig. 1) signals. This type of management of traffic lights provides evidence that the adaptation to traffic conditions is not trivial in terms of installation and maintenance costs, as it requires the coupling of magnetic loop-detector sensors or cameras to each traffic light. In addition, the adaptive functioning is more relevant under low-traffic scenarios, which raises the cost per vehicle of installing such adaptive traffic signals in non-congested intersections.

Figure 1: Part time traffic lights are used in many parts of the world to avoid the increased delay that sensor-less signals can introduce during low-traffic hours. The part time warning message is used to avoid people reporting the intentionally turned-off signals as broken (picture reproduced with permission from United Kingdom Roads website: `http://www.ukroadsltd.com`.

2.1 Optimization of Traffic Lights

Traffic lights functioning at each intersection is defined by the following parameters: cycle duration (the total green time given to all roads connected to the intersection), green splits (the green duration of each approach), and phase sequence (the order for the transition of green between different approaches). For inter-connected adjacent traffic lights, another variable is the offset, defining the time between signaling such adjacent intersections. The optimization of all these parameters in traffic-light-based urban traffic control (UTC) has been the subject of a large amount of research over the past forty years. Most existing UTC systems are based on complex mathematical models that determine the above variables in order to optimize traffic flow in specific settings.Two well-known systems, SCATS (Sydney Coordinated Adaptive Traffic System) [1] and SCOOT (Split, Cycle and Offset Optimization Technique) [10], follow this methodology. These systems have detectors placed on every approach to an intersection, usually at a single point of the road or at two points for calculating the size of the queue. Thus, they cannot get accurate data when this queue grows beyond the length between detectors, or the link is oversaturated. Since they use a model based especially on occupancy, they also have difficulties in differentiating between high flows or intersection stoppage.

A further optimization of adaptive traffic lights was proposed in [6], where an adaptive traffic light system based on wireless communication between vehicles and a wireless controller node placed at the intersection. As compared to the approaches mentioned previously, the adaptive traffic light system includes more information (e.g., vehicles' positions and speeds) in the signal decision process. As a result, this approach overcomes the shortcomings of traditional systems that can result from the fixed location of the detectors.

Our approach uses a new self-organizing traffic paradigm whereby the cars themselves act as mobile sensors of the traffic state, and resolve the conflicts at intersections *without* the need for external traffic lights. This approach is enabled just by the vehicle-to-vehicle communication capability of cars based on the DSRC standards at 5.9 GHz band. It is important to note that none of these previous studies employ the approach proposed in our paper; namely, use of in-vehicle traffic lights based on V2V communications for resolving the conflicts at intersections for determining the "right of way" in a seamless manner.

3. SYSTEM DESIGN

The implementation of the in-vehicle virtual traffic lights (VTL) system is based on the following assumptions:

- All vehicles are equipped with DSRC devices;
- All vehicles share the same digital road map;
- All vehicles have a global positioning system (GPS) device that guarantees global time and position synchronization with lane-level accuracy.
- The security, reliability, and latency of the wireless communication protocol are assumed to be adequate for the requirements of the VTL protocol.

The principle of operation of the proposed scheme is relatively simple and is illustrated in Fig. 2. Each vehicle has a dedicated Application Unit (AU) which maintains an internal database with information about intersections where a virtual traffic light can be created. When approaching such intersections, the AUs check whether there is a virtual traffic light running that must be obeyed, or if there is a need to create one as a result of perceiving crossing conflicts between approaching vehicles (see Fig. 2(a)).

The detection of the need to create a VTL uses the beaconing and location tables features of VANET geographical routing protocols.It is assumed that each node maintains a location table containing information about every node in its vicinity, that is constantly updated through the reception of new beacons. With the assumed lane-level accuracy of the GPS devices, this table can be queried to infer crossing conflicts. If it is necessary to create a VTL, then all the

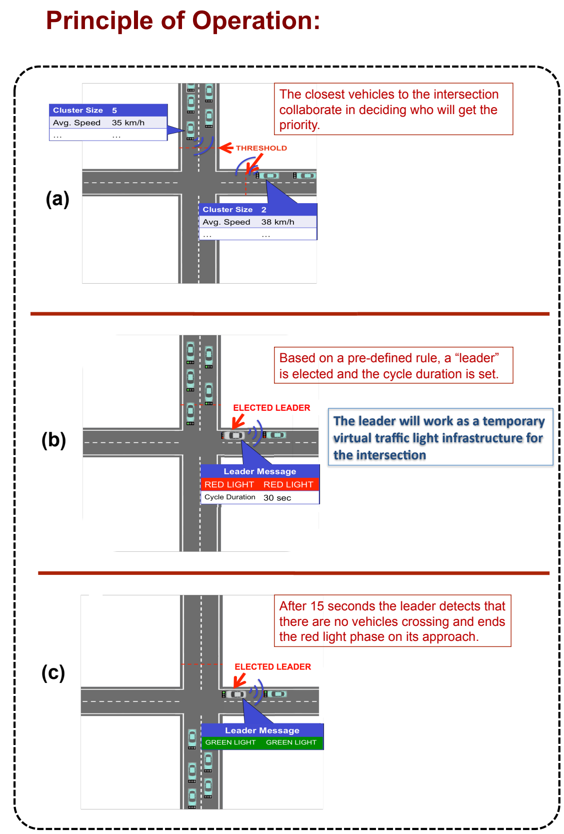

Figure 2: The principle of operation of the proposed in-vehicle traffic light scheme at an intersection of a Manhattan Street topology.

vehicles approaching the intersection must agree on electing one of them to become the *leader*, which will be the responsible for creating the VTL and broadcast the traffic light messages (see Fig. 2(b)). This vehicle will work as a *temporary virtual infrastructure* for the intersection and assume the responsibility of controlling the VTL.

The *leader* vehicle should have two important characteristics: i) be presented with a red light, and thus be stopped at an intersection while leading it; and ii) be the closest vehicle to the intersection center in its own cluster, in order to improve the omni-directional broadcast of the VTL messages to all approaches. We should note that the stopping place of leader vehicles in the VTL protocol is much closer to the center of the intersection than the usual stopping place of cluster leading vehicles in existing physical traffic light systems. As the visual perspective of the traffic light is always perfect through in-vehicle display, we can optimize the omni-directional emission of the radio signal by assigning the stopping place of the *leader* to be as close as possible to the center of the intersection. During the existence of this *leader*, the other vehicles act as passive nodes in the protocol, listening to the traffic light messages and just presenting them to the driver through the in-vehicle displays.

During the VTL lifetime, the leader only commutes its current phase, but the virtual traffic light message remains the same. Once the current phase is finished, the leader changes the virtual traffic light message to apply the next phase. When the green light is in the leader's lane, a new leader must be elected to maintain the VTL. If there are vehicles stopped before a red light at the intersection, the current leader just selects one of these vehicles to become the new leader, which will maintain the current state list and use the same rule for phase transitions. If there are no stopped vehicles under red lights, then a new leader will be elected by the same process whenever necessary.

Note that once the VTL leader detects that the road with the green light has no additional vehicles attempting to cross the intersection, the current phase is interrupted and the green light is given to the next approach. Moreover, if the VTL is no longer required, the cycle can be interrupted and vehicles proceed without stopping(see Fig. 2(c)).

3.1 VTL Simulation

We implemented the VTL protocol in the DIVERT simulator [2]. DIVERT is a large-scale simulator that allows for micro-simulation of thousands of vehicles with a high degree of realism. It includes a complex editor of traffic entities, allowing use of road segments at the lane-level, describing detailed connectivity at intersections, traffic lights interplay, and several individual parameters that affect the behavior of drivers (e.g., aggressiveness, braking and accelerations patterns, patience threshold). It takes advantage of the object-oriented paradigm of C++, and implements a version of the widely used Intelligent Driver Model [15], a time-continuous car-following model of the simulation of freeway and urban traffic. DIVERT mobility model has been validated against empirical data collected through a comprehensive stereoscopic aerial survey [5].

In a VTL scenario, the information received from the network has to affect the mobility simulation at a microscopic level and vice versa. Currently, very few VANET simulators support this feature. The most common way to achieve such coupling has been through the use of TraCI [19]. In DIVERT, since the network simulator uses very simple models, abstracting the MAC and physical layers, we embedded the VTL protocol in the *car* module where the microscopic mobility model is implemented. This embedding facilitates the interaction between network and mobility simulators, which is crucial for simulation efficiency, enabling the large-scale simulation of VTL scenarios. In addition, to implement the VTL protocol, a "Location Table" (LT), storing information about all the neighbors of a node, and a "Traffic Signs Table" (TST), storing information about the traffic light configuration at an intersection, were added to the *car* module of the simulator. In DIVERT, each vehicle uses a time frame or portion of the simulation execution time to execute the code associated with its own behavior. During this time frame, the vehicle is able to send/receive packets to/from the network layer. To enable periodic beaconing, new methods were added to create beacon packets and broadcast them to vehicles within the communication range. In addition, new methods were also created to update the location table (LT) upon reception of a beacon packet. Each vehicle has a variety of micro-simulated features, such as speed, acceleration, heading, and position. Vehicles that are approaching an intersection query their internal TST for a traffic light, and if such a light exists, they move exactly as if in the presence of a physical traffic light. The visualization component of the simulator was also modified to display each vehicle in the color associated with its in-vehicle traffic light (green, yellow, or red) providing graphical feedback to understand the distributed behavior of the protocol. This can be observed in the online video clip of a simulation over Porto available at `http://drive-in.cmuportugal.org/vtl/vtl_porto.avi`.

4. PRELIMINARY RESULTS

We evaluated the impact on traffic flow of our VTL system in the scenario of an entire European city, Porto, with a total of 965 km of roads and 2000 intersections, 328 of which are governed by physical traffic lights. The map of the city of Porto is shown in Fig. 3, where we also display the location of the 328 intersections that are governed by traffic lights. We use DIVERT to run two types of simulations: one using the real physical traffic lights that govern the 328 signalized intersections of the city (with fixed cycle duration and green splits); and one using the VTL protocol.

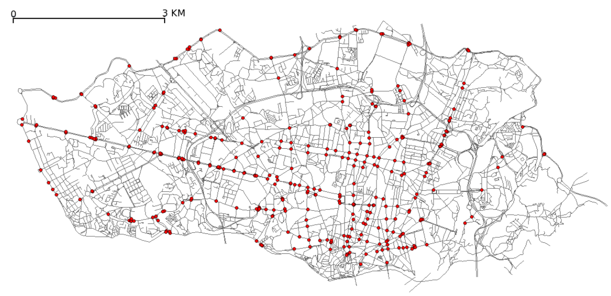

Figure 3: Traffic light deployment in the city of Porto. The red dots show the location of the intersections that are managed by traffic lights in Porto. The city has a total of 965 kms of roads and 2000 intersections, of which 328 are governed by physical traffic lights. The annual electricity bill of these traffic lights amounts to 0.6 million euros.

The routing model of vehicles was defined based on the aerial survey described in [5], forcing each vehicle to choose a route that passes through the road segment where the vehicle was pinpointed. The simulations also use four different densities: 24 veh/km^2 (low), 120 veh/km^2 (medium-low), 251 veh/km^2 (medium-high), and 333 veh/km^2 (high). Statistics were collected (after a 15 minutes warm-up period) from simulations which lasted for additional 15 minutes for each data point. The results are averaged over 14 runs for each density. The 95% confidence intervals are computed by randomly dividing the 14 data points obtained from simulations into 2 batches of 7 data points.

Figure 4 shows the percentage benefit in terms of the increase in average flow rate of the VTL protocol versus the real physical traffic lights that govern 16% of the intersections of Porto, as a function of vehicle density. The percentage benefit starts at nearly 20% for low traffic density. Under such low-dense scenario, the gain is due to the elimination of unnecessary red lights enabled by the VTL protocol. This value is not higher because such unnecessary red lights happen at most in 16% of the intersections in the simulations with the real traffic lights of the city. As density increases, these unnecessary red lights become irrelevant, as intersection conflicts are permanent. Interestingly, and despite the irrelevance of the unnecessary red light elimination, the percentage benefit of VTL increases substantially as traffic density becomes higher. The gains at these higher densities result from the ubiquitous traffic control that is enabled by

VTL, highlighting the significance of a subtle phenomenon associated with partial deployment of traffic lights in several U.S. and European cities: the absence of traffic lights at the majority of intersections clearly exacerbates the contention (and the congestion) at those intersections for high densities. The proposed in-vehicle traffic lights can alleviate the congestion due to absence of traffic lights dramatically (by more than 60%) at high traffic densities. Considering cities such as NYC, Dublin, and Porto, this translates to a 60% increase in average flow rates which is quite significant.

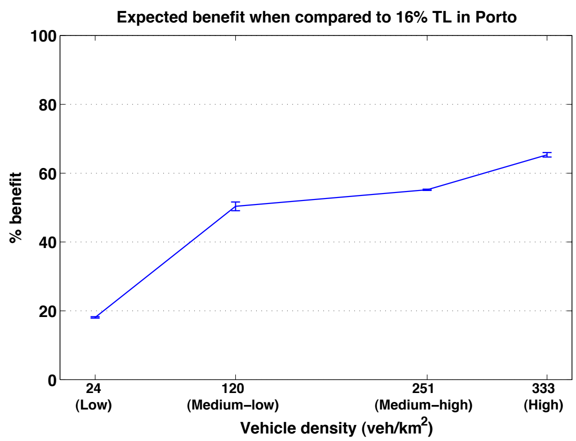

Figure 4: Percentage benefit of using in-vehicle traffic lights in the city of Porto, Portugal. Benefit is quantified in terms of the increase in average flow rate (with 95% confidence intervals) as a function of vehicle density

5. CONCLUSION

In this paper, we propose a new self-organizing traffic control paradigm whereby the existing physical traffic lights are replaced by in-vehicle traffic lights. We envision that through V2V communications such in-vehicle traffic lights not only can resolve the conflicts at intersections in an autonomous and efficient manner but can also render traffic management truly ubiquitous. The large-scale simulations conducted for Porto, the second largest city of Portugal, provide compelling evidence on the viability and significant benefits of the proposed scheme in terms of the increase in flow rates (more than 60% increase at high densities). This new self-organizing traffic paradigm thus holds the potential to revolutionize traffic control, especially in urban areas.

6. ACKNOWLEDGMENTS

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