Advanced Leader Election for Virtual Traffic Lights

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***Abstract*—We examine the network performance of algorithms for self-organized traffic management with a strong focus on the wireless networking between the cars. One of many technologies to make road traffic more safe and efficient is the Virtual Traffic Light (VTL) system which is able to coordinate traffic flow at intersections without the need for physical lights. VTL uses a leading vehicle at the intersection for controlling the traffic light. We developed algorithms for leader election and traffic light computation in realistic vehicular networking scenarios. Our key contribution is the extension of this algorithm to support arbitrary intersection layouts. We investigated the proposal in synthetic and realistic scenarios. Our results show that, overall, VTL uses network resources efficiently and has a positive influence on the driving experience and outperforms stationary traffic lights at low to medium network load. We further identified optimization potentials in dealing with high network load and fairness.**

***Index Terms*—Virtual Traffic Lights, Self Organization, Vehicular Networks**

I. Introduction

A way towards safer and more efficient traffic is hinted at in the 2010 report *Towards a computational transportation science* [1], which introduces a new science discipline. This area focuses on the combined work of computer scientists and transportation experts to produce more useful models and technologies for the future of transportation.

Safety at intersections has become a key research challenge within the Inter Vehicle Communication (IVC) community. Solutions range from intersection warning to more intelligent assistant systems [2], [3], [4], [5].

In the U.S., more than 240 000 traffic lights are regulating intersections [6]. Of these, more than 50 % are in need of repair [7]. Others are running at suboptimal levels of operation, leading to traffic delays of up to 40 % in excess of an optimal configuration [6]. Repairing and/or reconfiguring these traffic lights is cost intensive – and many intersections (up to 99.5 % in the U.S. [8]) are simply left unequipped with traffic lights.

A completely new approach has been investigated to complement (or even replace) physical traffic lights: Virtual Traffic Lights (VTLs) [8], [9], [10]. Vehicles that are approaching an intersection are exchanging messages wirelessly to cooperatively create a dynamic traffic light program for the junction. This information is then presented to the driver on a display, thus replacing physical traffic lights by in-vehicle displays.

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The VTL approach offers numerous benefits: First, it eliminates the cost of deploying traffic light infrastructure on every street. At the same time, VTLs may react quicker to microscopic traffic conditions than normal traffic lights can.

One of many different wireless technologies that VTL can be built on is the IEEE 802.11p standard [11]. Based on this technology, IEEE DSRC/WAVE and ETSI ITS G5 are being standardized for vehicular networking. We are now in an era that completely changes the game in car manufacturing and road traffic management. This is supported by the U.S. federal government that just announced in February 2014 that it plans to require all new cars to be equipped with wireless technology to broadcast their location, speed, direction, and other data to warn drivers of impending collisions [12]. This National Highway Traffic Safety Administration (NHTSA) announcement coincides with the final standardization of higher layer networking protocols in Europe by the European Telecommunications Standards Institute (ETSI).

In this paper, we extend the model we developed in [13], which allows us to investigate the feasibility of current vehicular networking proposals for realizing VTL on a larger scale. We focus on the networking perspective and evaluate both the capabilities to establish the VTL as well as the clusters of cars in a reliable way. Our new leader selection and traffic light computation algorithm is now able to support arbitrary intersection layouts. We investigated this extended algorithm in a realistic scenario. Our main focus was to study the networking aspects. According to our findings VTL uses network resources efficiently and has a positive influence on the driving experience. It outperforms stationary traffic lights at low to medium network load. We further identified optimization potentials in dealing with high network load and fairness.

II. Related Work

VTLs have been repeatedly worked towards in the literature. One of the first examples is by Dresner et al. [10], who describe a system that allows vehicles to wirelessly coordinate passing at intersections, replacing physical traffic lights. Using a custom built road traffic simulator, they show a large increase in efficiency.

Gradinescu et al. [9] describe *Adaptive Traffic Lights* which gather data from approaching cars and adapt green times – albeit this research is primarily concerned with physical traffic lights. Using a custom built discrete-event simulation tool they are able to show that the average delay of vehicles decreases significantly if traffic lights can make use of wirelessly exchanged information.

Avin et al. [14] introduce a scheme to place another traffic light in front of intersections. These traffic lights should be dynamically placed and allow a much faster travel time over the intersection because of a synchronized program. To place these traffic lights at various positions they use virtual ones. Based on microscopic road traffic simulation with the road traffic simulator SUMO they show that this scheme reduces the number of delayed vehicles by up to 20 %.

The most complete proposal of VTLs to date, and the one that we are building on, is by Ferreira et al. [8]. By using simulations they have shown that VTL has the potential to reduce the amount of CO_2 by up to 18 % [15]. Simulations were conducted with the road traffic simulator DIVERT combined with NS-3. The impact of different human machine interfaces for VTLs was investigated by Olaverri-Monreal et al. [16]. They showed that a VTL yields similar brake activity compared to regular physical traffic lights. Viriyasitavat and Tonguz [17] used simulations based on SUMO to show that emergency vehicles can reach their destination minutes earlier when using VTLs.

We complement these studies using a complete state-of-the-art combined network and traffic simulation environment. The framework Veins connects the well-established network simulator OMNeT++ with the detailed vehicular simulation SUMO [18]. In our earlier work, we already developed algorithms for leader election and traffic light computation in realistic vehicular networking scenarios [13]. Our key contribution in this paper is the extension of this algorithm to support arbitrary intersection layouts and to investigate its performance in more realistic simulations.

III. Architecture

A. General Architecture

The basic idea for the algorithm of VTLs is proposed by Ferreira et al. in [8]. To be able to support such a system vehicles have to be equipped with a wireless networking device and the means to determine their current position. With IEEE 802.11p and GPS two technologies to support these needs are already existing and can be used to make VTL work. GPS is already used a lot in vehicles nowadays and it can be safely assumed that cars are equipped with it. Dedicated Short-Range Communications (DSRC) technologies are not widely deployed yet, but a decision has been made to make them mandatory in the U.S. soon [12].

The following steps are performed when VTL is active at an intersection:

1) Vehicles broadcast data about their current position to others in close proximity. In the future this may not only consist of the position but also information like speed and acceleration can be useful. The data is stored in a neighbor table and periodically updated if newer information is received. Such information is envisioned to be automatically provided by basic services of vehicular networks, e.g., the concept of Local Dynamic Maps (LDMs) maintained by Cooperative Awareness Messages (CAMs) in ETSI ITS G5.
2) If a *crossing conflict* for an intersection is detected a virtual traffic light has to be calculated. Such a conflict is a situation when two vehicles approach an intersection and a collision is imminent. In such a case there is the need to elect a leader which determines the traffic light program.
3) The vehicles choose a single car to be the leader of this intersection. This vehicle generates a traffic light program and sends the information to the other vehicles.
4) Vehicles receive traffic light data and present it via a display inside the vehicle to the driver.
5) If the traffic light program changes the leader sends out an updated version.
6) When the leader crosses the intersection a new one has to be elected. This can be either done by the old leader by automatically selecting a new one or by starting a new election. In such a case the algorithm continues at step 3.

Initial work describing VTL approaches [8] gives a very good introduction on the general concept, but lacks a detailed explanation in which way a leader is elected. Additionally it uses a simple table based scheme for the calculation of the traffic light program. In [13] we addressed these issues and proposed a detailed leader election scheme and a more dynamic traffic light program. Basically a single vehicle announces an election and others reply with their current distance to the intersection. After a timeout the vehicle closest to the intersection is elected as the new leader and determines the new traffic light program. If multiple elections are started by different vehicles every vehicle has a single, comparable ID to break ties. This can be for example the network address. For a more detailed description of the algorithm we refer to [13]. Still the used model had two deficits which are addressed in the improved version we describe in this paper:

- A simulated physical traffic light was used by the road traffic simulation and was controlled by the VTL leader. This meant that the traffic light program was directly obeyed in the road traffic simulation, without the need to send it to each vehicle approaching the intersection. Therefore it was not possible to simulate effects introduced by multiple leader entities.
- The algorithm was not aware of *non-conflicting* lanes. Such lanes can be given green without the possibility of crashes happening. With our first model only a single lane got green while the others had to wait. Such a scenario produces unnecessary delay for the drivers.

B. Improved Features

After analyzing the problems with our first proposal we started to develop an updated version that addresses these issues. The first thing we did was to remove the dependency from SUMO traffic lights. For this, we configured SUMO to always keep all traffic lights red, forcing vehicles to stop. We selectively allowed any vehicles with a VTL state of *green* to ignore the traffic light. With this in place cars now only follow a local *traffic light state* table which stores the information about the next intersection. Until a traffic light broadcast is

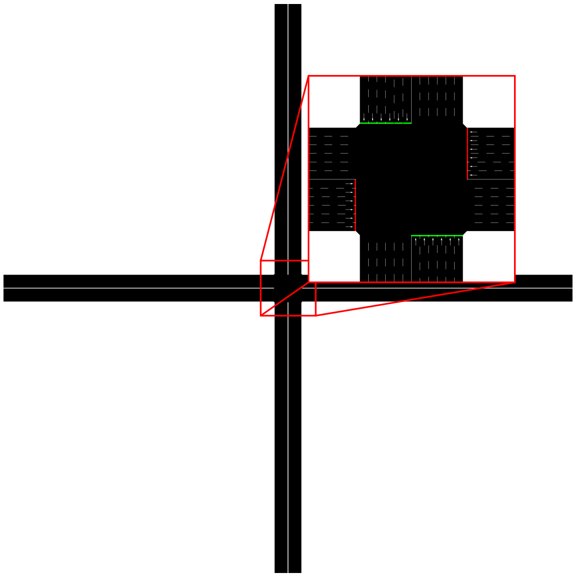

Fig. 1. Synthetic simulation scenario: multi-lane four-way intersection.

received vehicles assume the state *unknown* for a VTL. If this happens the vehicles will stop in front of the intersection. In such a case a timeout is started and afterwards the current state is requested at the intersection's leader. This is done to prevent vehicles waiting unnecessarily in front of the intersection.

Second, it is now possible to give green to multiple *non-conflicting* lanes. Our proposed protocol for VTL is able to detect such lanes and give green to multiple ones at the same time. This is done by selecting one lane as before and iterating over all other lanes, adding them to the set of lanes to give green to if there is no conflict.

Third, an update lets vehicles store a simplified topology of the road network. In this view on the street network lanes, which share the same endpoint and do not branch, are grouped together. This additional topology helps them to quickly identify which (if any) is the next traffic light that VTL needs to be performed for.

Finally, we further improved the election algorithm presented in [13], by adding fast leader hand-off: when a VTL leader crosses an intersection, it preferably hands-off the task of leader to a vehicle that is stopped to reduce rapid leader switching.

IV. Evaluation

We evaluated the performance of our proposed VTL protocol in two scenarios, a synthetic and a realistic one.

Our synthetic scenario is a simple four-way intersection of four roads, each 400 m long. In order to be able to force the intersection to experience very high network load without substantially hindering traffic flow, we set each road to be six lanes wide in each direction (see Figure 1) and forced vehicles to only go straight over the intersection, driving at the speed limit of $50\,\mathrm{km\,h^{-1}}$. For the same reason, we configured no buildings that would obstruct communication between vehicles. This scenario enables us to study the performance of

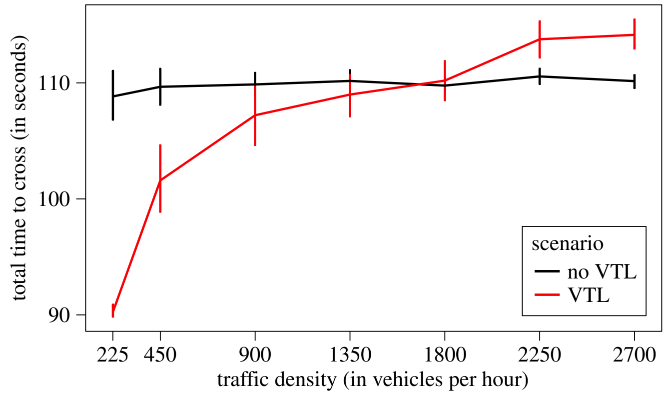

Fig. 2. Synthetic Scenario: Traffic Density vs. Travel Time

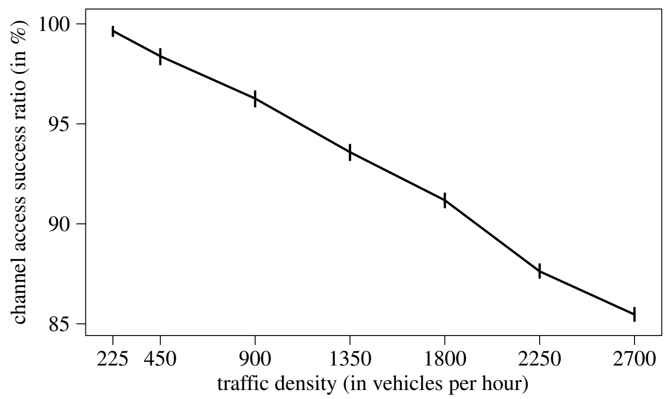

Fig. 3. Synthetic Scenario: Traffic Density vs. Ratio of Successful Channel Accesses (out of all packets sent)

VTL under arbitrary, uniform traffic flows – we picked a range of 225 to 2700 vehicles per hour crossing the intersection – and thus investigate the impact of network load on VTL performance.

The first metric we investigate is the mean total travel time, that is, how long vehicles took, on average, to cross through our scenario. This includes the time it took for them to travel the 400 m to the intersection and the 400 m after it. We compare travel times for two cases: an intersection that is managed by a conventional traffic light or by our proposed protocol for VTL. For the conventional traffic light, we configured standard fixed durations of 31 s green, 6 s yellow, and 37 s red.

Figure 2 plots the results of this comparison for seven different traffic densities. It shows the mean value across all repetitions, along with a 95 % confidence interval of the mean. As can be seen, at low traffic densities the average travel time is vastly improved if the intersection is governed by VTL: With a conventional traffic light regulating traffic, cars take up to 20 % longer to reach their destination. With higher traffic densities, however, this benefit becomes less pronounced. In fact, the performance of VTL and the conventional traffic light can be seen to break even for a traffic density of 1800 vehicles per hour crossing the intersection – and slightly worse for higher densities. It is important to note that this does not

Fig. 4. Realistic simulation scenario: $1.5\,\mathrm{km}^2$ Region of Interest (ROI) in the city of Ingolstadt.

appear to be due to the intersection not being able to handle the amount of traffic: For the simulated densities the mean travel time is invariant wrt. traffic density if the intersection is governed by a conventional traffic light. Instead, the reduction of the benefit of VTL must be attributable to some other effect.

We therefore investigate a second metric, which is indicative of the system's network performance: the channel access success ratio, that is, how often the channel was found to be idle when trying to send a packet (as opposed to finding the channel busy and needing to trigger a backoff).

Figure 3 plots the mean value of this metric as the traffic density increases. As can be seen, the probability of finding the channel empty decreases linearly with increasing traffic density, from almost $100\,\%$ at 225 vehicles per hour, to just above $90\,\%$ at 1800 vehicles per hour, and to approximately $85\,\%$ at 2700 vehicles per hour. Taken together with previous results this means that leader election and traffic light program dissemination work very efficiently – after all, the decrease is only linear. Still, even with as few as $10\,\%$ of channel access attempts failing, the proposed protocol already operates no more efficient than a conventional traffic light.

Naturally, this points toward multiple avenues for future work. While it can be argued that VTLs are unlikely to be needed in regions with such high traffic densities, the results point to a strong dependency between available network capacity and VTL performance.

For now, we restrict our analysis to good network conditions with low road traffic density where the full capacity is available to the VTL system, instead turning to the potential impact of VTL on traffic in a city. Rather than one simple intersection, we employ a different, more realistic traffic scenario for this investigation.

The realistic scenario is based on real geodata from OpenStreetMap for the city of Ingolstadt, Germany. It accurately captures road and building topology and geometry, such as speed limits, right of way, and one way streets. Most importantly, we took great care to accurately model intersection topologies, that is, we added correct turning lanes, configured traffic signal timing, and added buildings that attenuate radio

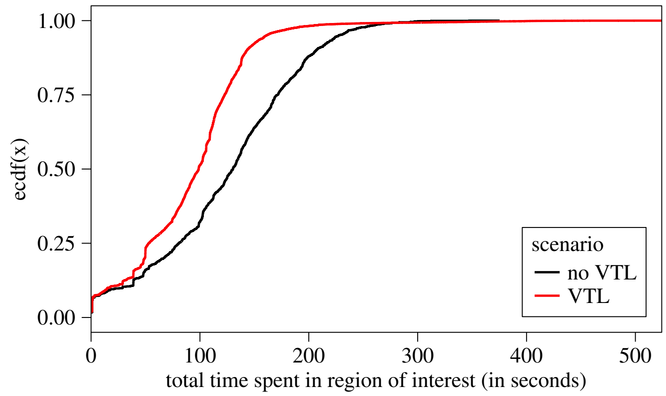

Fig. 5. Ingolstadt: Distribution of Travel Times

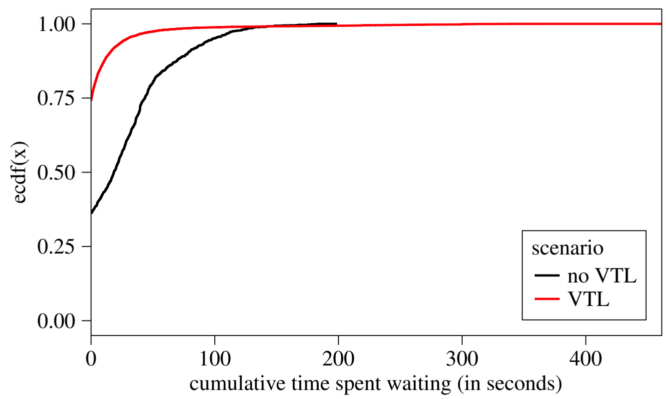

Fig. 6. Ingolstadt: Distribution of Waiting Times

propagation. Similar to earlier work [19], we simulated traffic in in the whole city of Ingolstadt, but only investigate nodes driving within a $1.5\,\mathrm{km}^2$ ROI (depicted in Figure 4). This ROI contains a typical mixture of high- and low-capacity roads, traffic lights, and unregulated intersections, as well as high and low node density areas. In this scenario, we generated traffic flows according to low demand, an average of 25 vehicles per square kilometer. This scenario enables us to get an indication of the impact of the designed VTL system on urban traffic flow. We compare the performance of a city governed by conventional traffic lights to the same city, but governed entirely using VTL. In the interest of fairness, we only operate VTL on those seven intersections that used to be covered by a conventional traffic light. All other intersections remain unregulated, with vehicles following the city's right of way rules (yield to priority road or yield to right).

Figure 5 depicts the results for the first metric we investigate, the total time that vehicles took to reach their destination (or to leave the ROI). The results are plotted as an empirical cumulative density function (eCDF) over all simulation runs to illustrate the actual distribution. As can be seen, both distributions share the same properties: Travel times are either extremely short (resembling vehicles that only briefly crossed through a small part of the ROI) or are approximately normal distributed around approximately $110\,\mathrm{s}$ and $130\,\mathrm{s}$ (mirroring the $20\,\%$ difference observed in our simulations of a single intersection). There is also a pronounced right tail that is visible, that is, some vehicles are substantially slower – particularly in the scenario where vehicles relied on VTL to coordinate crossing. To explore the reason, we will investigate a new metric.

Figure 6 plots this new metric, the cumulative time that each vehicle spent waiting, that is, moving less than $0.1\,\mathrm{m\,s^{-1}}$. As can be seen, the fraction of vehicles that did not have to wait at all increased from $36\,\%$ to $74\,\%$ when some intersections were managed by VTL – and overall waiting times decreased substantially as well. Yet, this metric also illustrates the reason for the pronounced right tail visible in the distribution of travel times: A very small number ($0.7\,\%$) of vehicles had to wait over twice as long as even the longest waiting time incurred when relying on conventional traffic lights. Closer investigation revealed these vehicles to be (unfortunate) VTL leaders on little-frequented streets. As it took a long time for enough vehicles to queue behind the leader on the little-frequented street to outweigh the amount of traffic on the major road, our naïve VTL traffic light program caused major delays for these vehicles. Thus, while overall traffic was still substantially smoother, these vehicles might feel unfairly treated by VTL.

V. Conclusions

In this paper, we presented evaluation results for an improved Virtual Traffic Light (VTL) system that can manage arbitrary intersection geometries. Using two scenarios, a realistic urban road network and an synthetic single intersection, we investigated the impact of VTL on traffic flows in a city and its overall network performance.

We could show that, overall, VTL has a positive influence on the driving experience of our simulated vehicles, cutting down both total travel time (typically $20\,\%$) and wait times ($74\,\%$ of vehicles do not have to wait at all). However, we also identified optimization potential: Few vehicles suffered from increased waiting times, pointing to missing considerations of fairness in the proposed algorithm. We further showed that our proposed protocol for VTL uses network resources efficiently: Channel load scales linearly with traffic density. Still, a deterioration of its performance in scenarios with than $10\,\%$ of channel load points to optimization potential in this area as well.

Future work might also include improved optimizations of which lanes to give green to, exploiting the full potential of combining multiple non-conflicting lanes into one green phase.

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