A Networking Perspective on Self-Organizing Intersection Management

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***Abstract*—We explore the networking aspects of realizing self-organized intersection management. Inter-Vehicle Communication (IVC) based on DSRC/WAVE is expected to complement other communication technologies including Wi-Fi and 3G/4G. Applications range from road traffic efficiency to critical safety situations, intersection management being one of the most compelling applications. The Virtual Traffic Light (VTL) system is envisioned to replace or to complement physical traffic lights in order to reduce costs and to optimize the road traffic flow in urban environments. VTL, developed at Carnegie Mellon University, outlines the general capabilities of such a system. The VTL system heavily relies on coordinating clusters of cars and the communication among them. We developed a DSRC/WAVE based communication protocol for the management of these clusters, carefully investigating all the networking aspects related to this management and the communication between the cluster leaders. Comparing VTL to physical traffic lights, we are able to show a speedup of up to 35 % in realistic environments. Looking at the packet loss on the wireless link, we can show that even in high communication load scenarios, the speedup remains stable.**

I. Introduction

In the U.S., more than 240 000 traffic lights are regulating intersections [1]. Of these, more than 50 % are in need of repair [2]. Others are running at much less than the best level operation, leading to traffic delays of up to 40 % in excess of an optimal configuration [1]. Repairing and/or reconfiguring these traffic lights is cost intensive – and many intersections (up to 99.5 % in the U.S. [3]) are simply left unequipped with traffic lights.

A way towards safer and more efficient traffic is hinted at in the 2010 report *Towards a computational transportation science* [4], 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 [5]–[8].

One example of potential work in this new discipline are Virtual Traffic Lights (VTL) [3], [9], [10]. Vehicles that are approaching an intersection are exchanging messages wirelessly to create a dynamic traffic light program for the junction. This information is then presented to the driver on a display, thus replacing or complementing physical traffic lights by in-vehicle displays.

The VTL approach offers numerous benefits: First, it eliminates the cost of deploying traffic light infrastructure on the streets. At the same time, VTL can react better 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. It is currently being discussed, e.g., by the US DoT, to make this technology mandatory for new cars [12]. Similar discussions also take place in the European Union.[1]

In the scope of this paper, we 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. In particular we model leader election, which is a core component in the VTL concept, in detail to determine the impact of networking effects in different scenarios. Based on a set of simulation experiments, we can show the advantages of the VTL system and also highlight some of the open issues.

II. Related Work

VTL 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. However, using a custom built discrete-event simulation tool they are able to show that the average delay of vehicles decreases significantly.

Avin et al. [13] 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 SUMO they show that this scheme reduces the number of delayed vehicles by up to 20 %.

[1] http://www.car-to-car.org/

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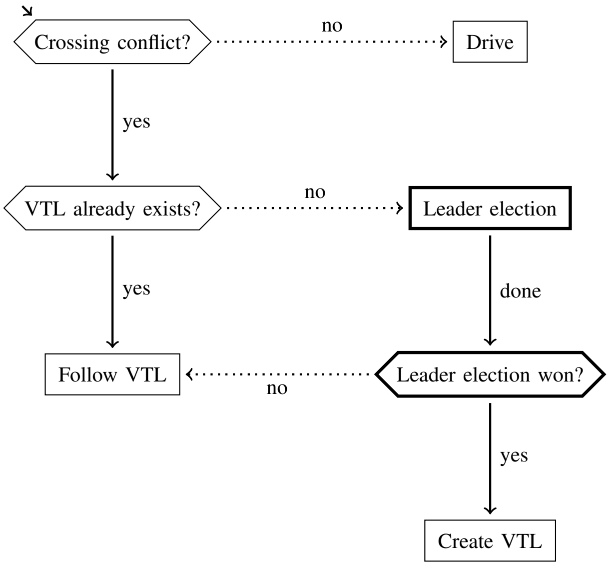

Figure 1. The basic Virtual Traffic Light (VTL) flow. It depicts what steps a single car has to perform when participating in the algorithm.

The most complete proposal of VTL to date, and the one that we are building on, is by Ferreira et al. [3]. By using simulations they have shown that VTL has the potential to reduce the amount of CO_2 by up to 18 % [14]. Simulations were conducted with the road traffic simulator DIVERT combined with NS-3. The impact of different human machine interfaces for VTL was investigated by Olaverri-Monreal et al. [15]. They showed that a VTL yields similar brake activity to regular physical traffic lights. Viriyasitavat and Tonguz [16] used simulations based on the road traffic simulator SUMO to show that emergency vehicles can reach their destination minutes earlier when using VTL. It is not stated if a network simulator was employed for the study.

Three shortcomings can thus be identified in earlier work:

- simulations have often been conducted using abstract representations of either road traffic or network traffic,
- leader election is a core component of VTL, but has only been modeled very abstractly and no specific algorithm has been proposed, and
- most algorithms' performance is closely tied to network performance, but this has received little attention.

This paper addresses these problems as follows:

- We use 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.
- We provide a leader election algorithm that works well for VTL.
- Due to the fact that we use a fine grained network simulator we are able to analyze the network performance of VTL.

III. Virtual Traffic Light Algorithm

The VTL algorithm [3], [14], an overview of which is given in Figure 1, is based on the election of a unique leader at each intersection which then computes and disseminates a traffic light program to other cars. The highlighted parts of the algorithm have been investigated in more detail by us as we present a complete leader election algorithm. This is made possible by three key assumptions:

1) Every car is equipped with a wireless network device for vehicular networking. This assumption is well supported by current plans to introduce (and potentially make mandatory) IEEE 802.11p in cars.
2) Every car has a means of obtaining accurate positioning information and is aware of whether VTL is needed (e.g., defined as being in a pre-defined *service region* around an intersection). The accuracy of GPS units, supplemented by distributed self-localization methods, could be shown to be adequate for this task.
3) Every car maintains a neighbor table containing vehicle IDs and positions. Both DSRC/WAVE and ITS G5 include proposals for Cooperative Awareness Messages (CAMs) and Basic Safety Messages (BSMs), respectively, that would enable cars to maintain such tables on the fly.

While the original publication [3] highlights the importance of leader election, no algorithm is proposed. The tasks of a leader in our implementation are as follows. It periodically broadcasts the current VTL program, i.e., who is allowed to drive. It also performs a second broadcast telling other cars that it is the current leader. In regular intervals and when the last car of a lane crosses the intersection, it recalculates the traffic light program.

If, at any time, the leader has green and therefore crosses the intersection it hands over leadership by assigning the leading role to the car with the shortest distance to the junction.

To calculate the traffic light program the original publication [3] uses a simple table based scheme with no dynamic component. To react better on microscopic traffic conditions we employ a simple dynamic scheme. At fixed intervals the leader counts how many neighbors are known for each incoming lane, then assigns *green* to the lane with the most cars. One exception is the first interval, in which the leader always gets assigned *red*. This ensures that a car which became leader during the last election does not cross the intersection immediately. Such a simple traffic light program can lead to starvation if a road with a huge amount of traffic (e.g., a highway exit) intersects with a low traffic road. We plan to address this issue in future work based on a weighted traffic light scheme.

The election of a single entity is a well researched problem because many distributed algorithms rely on a unique node controlling the process. In the case of VTL this unique entity is the leader. The more dynamic the network is, the more difficult the task of determining such a leader becomes. A large body of work exists for static hierarchical distributed

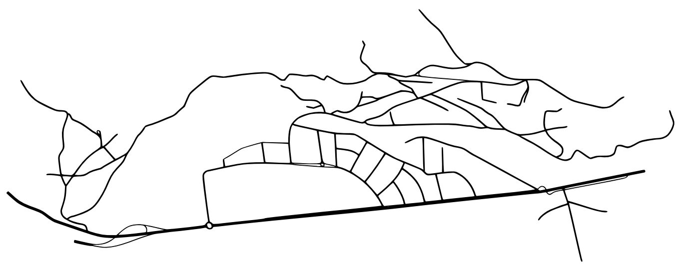

Figure 2. Road network used for the simulative performance evaluation: Campus *Technik* of the University of Innsbruck and surrounding roads.

systems and peer-to-peer networks [17]. The difficulty rises if nodes move and/or dynamically enter and leave the network, both of which is the case for VTL.

However, having a single leader even in such a dynamic network is essential to ward against two dangers:

1) If multiple nodes independently assume they are leader, they might start broadcasting conflicting traffic light programs.
2) If every node assumes that a unique leader exists (but no node actually has this role), a deadlock will occur.

We adapted the work by Vasudevan et al. [18], who proposed an algorithm for dynamic ad hoc networks based on the following assumptions:

1) Nodes can be ordered following a specific metric. We choose the distance to the intersection.
2) If there is a tie between two nodes, everyone has to have a unique and ordered ID, allowing the algorithm to break such ties. In the simplest case, this ID might be derived from the MAC address, but we acknowledge that privacy concerns might necessitate other schemes.
3) Every node i keeps track of a serial number identifying the current election it participates in (n_i).

We adapted the algorithm to the context of VTL to work as follows:

- If a car sees the need to make an election (as defined by being within the *service area* of the next intersection) it broadcasts an ANNOUNCEMENT message. This message contains its current distance and the election number n_i, incremented by 1. The car initially assumes that it is the one closest to the intersection, storing its own distance and ID. Additionally, a timeout defines how long the initiator waits for replies to the announcement.
- After a timeout, the initiator determines which node won the election (based on shortest distance to the intersection and, to break ties, node ID). It then sends out a LEADER broadcast to the other cars. This message contains the ID of the new leader and also informs the other cars that the election has been concluded.
- If a car receives an ANNOUNCEMENT and is currently not participating in any election, the car gets engaged in the new election, adapting its n_i and replying to the ANNOUNCEMENT with its own distance.
- If a car receives an ANNOUNCEMENT and an election is running that has higher precedence (based on n_i and, in the case of a tie, vehicle ID), the car participates in this election instead. Otherwise the node ignores the message.

Compared to the scheme proposed in [18], we adapted the algorithm in the following aspects:

- As the messages are only sent using broadcasts, no message chain has to be built. Therefore there is no notion of parents and children. The only distinctive node is the initiator of the election.
- Nodes leaving during the election are handled via neighbor table timeouts only. Cars also check if the leader is still inside the communication range. If a car finds out that no leader exists for an intersection, it starts a new election.

By using n_i and the node ID it is assured that many cars finding out no leader exists at the same time are no problem.

IV. Simulation Setup

To simulate the VTL, we used the well established simulation framework Veins [19]. It combines the network simulator OMNeT++ and the traffic simulation environment SUMO into an Open Source framework[2] for vehicular network simulation. Veins provides validated and very accurate models covering radio signal propagation (including shadowing caused by buildings and other vehicles) and current IVC protocols (including IEEE 802.11p). The framework was extended with the ability to access and configure intersection handling.

As the simulation scenario, we picked the surroundings of the University of Innsbruck, as depicted in Figure 2. We imported road geometry and lane properties from OpenStreetMap[3] and manually supplemented the data with traffic lights. Traffic demand is generated using a simple model proposed by Viriyasitavat and Tonguz [16]. This model splits simulation time into four parts of equal length $Q = 300\,\mathrm{s}$, yielding a total simulation time of 20 minutes.

Traffic density is governed by a value N, as follows. The first and the last period add $\frac{N}{3}$ cars following random routes to the simulation, uniform randomly distributed over the time. The middle parts, taken together, add $\frac{4 \cdot N}{3}$ cars. Figure 3 shows

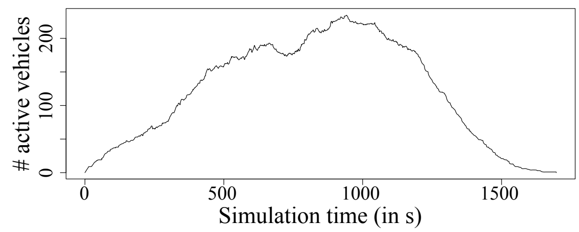

Figure 3. The total traffic demand for $N = 300$ and $Q = 300\,\mathrm{s}$.

[2] http://veins.car2x.org/
[3] http://www.openstreetmap.org/

Table I
THE PARAMETERS USED IN THE SIMULATION.

Parameter	Value
Maximum Transmit Power	10 mW
Carrier Frequency	5.890×10^9 Hz
Service Region around intersection	100 m
Position Update Frequency	1 s
Neighbor Table Timeout	5 s
Leader Election Timeout	3 s
Traffic Light Phase Duration	30 s
Yellow Light Duration	3 s

an example trace of the generated total traffic demand, which closely matches the shape of the traffic density trace discussed as very realistic in [16].

Table I shows the used parameters in for the simulation. The upper part of the table contains the general simulation parameters for the network layer and the lower region the ones used in the VTL application.

V. RESULTS AND DISCUSSION

Before we turn to network centric performance metrics, we first investigate the results of a basic performance study of statically configured traffic lights compared to the described VTL system. We record the total travel time of cars on the main route for traffic of different densities (corresponding to different values of the N parameter introduced earlier). This total travel time represents also the key metric being used in the original publication of VTL [3].

Figure 4 shows the value of this metric for both static traffic lights and VTL. It can be seen that VTL is successful in managing intersections, reducing travel times by up to 35 %. Even though the traffic light algorithm of VTL is very basic, cars equipped with VTL are faster for all configurations, independent of the traffic density.

We now investigate the impact of network effects on VTL by looking at the leader count, a metric of the leader election performance: We carefully observe each car's crossing of an intersection and track (for the complete duration of it crossing the intersection) if at any point in time more than one leader is active for this intersection anywhere in the network.

During preliminary studies of simple, unobstructed intersection topologies less than 1 % of intersection passes had more than one leader active. Conversely, for the complex intersection topologies of this study, numbers increased to as much as 23 %. Figure 5 shows the results of these simulations. In order to investigate what this means for the performance of the system, we replaced the VTL leader election with a perfect *Oracle* leader election. This perfect leader election resulted in a maximum of 5 % faster travel time.

The reasons for leader election problems having only limited impact on the system performance are twofold: Commonly, the duplicate leader is only elected for a very brief time before the algorithm rectifies the situation – thus three or more leaders are almost never active (as can be seen in the figure). In other cases, the duplicate leader is too far away

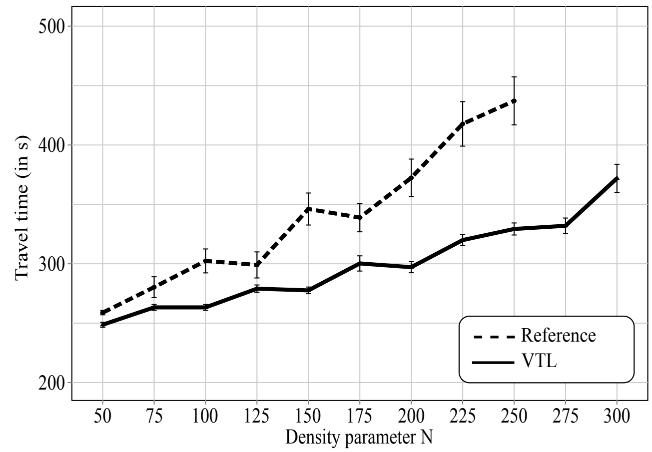

Figure 4. Travel time of cars for various traffic densities, drawn for Virtual Traffic Lights (VTL) and for physical traffic lights (reference). Also shown is the 95 % confidence interval. There are no data points for $N = 275$ and $N = 300$ in case of the reference traffic lights because for these density we experienced vehicles waiting for longer than 1000 s. Such a long inactive time does not make sense for a realistic simulation and shows that VTL is able to handle a higher density.

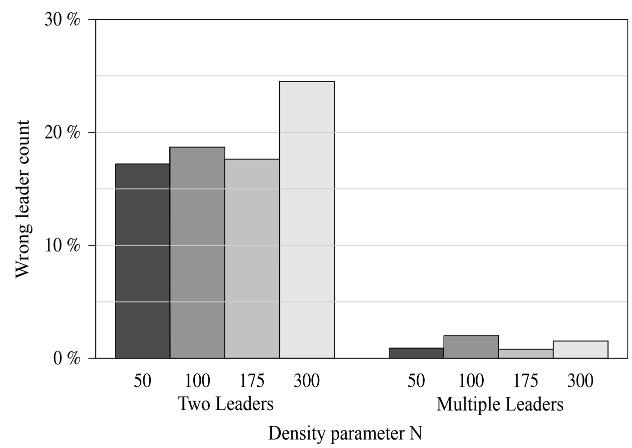

Figure 5. Fraction of intersection crossings during which two or more leaders were active in the simulation, plotted for different density parameters N.

from the intersection to recognize the existing leader, but also too far away to interfere with traffic at the intersection.

Still, these results point to the fact that complex intersection topologies are very challenging for the leader election algorithm of VTL – a point that warrants special consideration.

Turning towards network traffic performance metrics, we investigate the impact of VTL on the wireless channel. We examine two metrics in particular, the number of received packets and the number of lost packets. Taken together, they represent the total load put on the network.

Figure 6 shows that the total traffic behaves as expected. With larger vehicle densities the amount of network traffic increases, with more and more packets being exchanged – but also more and more packets being lost, mostly due to collisions.

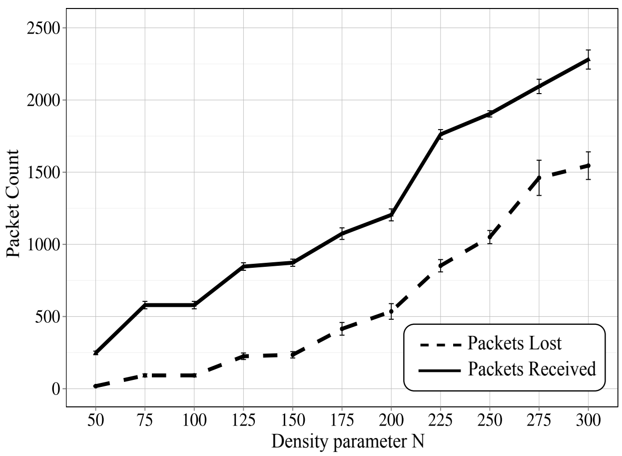

Figure 6. Received broadcasts and lost packets during the simulation, plotted for different density parameters N.

The number of received broadcasts follows a linear trend, which can be approximated as $N \cdot f$ where f is between 6 and 7.6. This holds for all values except for $N = 50$ where the number of cars is too low.

Interestingly, there is no direct correlation between the increasing number of lost packets at high densities and the overall performance of VTL in terms of travel time (cf. Figure 4), up to $N = 300$ where the travel time in the VTL scenario increases sharply. This leads us to conclude that the VTL algorithm is able to tolerate a high amount of packet loss.

VI. Conclusion

In this paper, we studied the networking related aspects for Virtual Traffic Lights (VTL). VTL are envisioned to replace classic physical traffic lights and regulate the intersections in a self-organized fashion via wireless communication. For this, we developed an implementation of Virtual Traffic Lights (VTL) for the Veins framework. Veins couples a network and a traffic simulator together and allows a fine grained simulation of these VTL. By comparing VTL to a physical traffic light, we discovered that the speedup by using VTL is up to 35 %. For low road traffic densities, the speedup was barely detectable but for increasing densities it got much bigger. This substantiates findings in the related literature that studied VTL on way more abstract levels. A very interesting result is that the number of lost packets does not follow a linear but an exponential increase. Still the travel time of cars is not critically affected by this behavior.

Future work includes in-depth studies of the fairness issues of the algorithm. Depending on the geometry of the road network, this is not inherently guaranteed. Also, it would be useful to extend the algorithm to be intersection aware. This means that VTL would be able to support green waves on major streets to prevent frequent stops at subsequent intersections. Such a behavior would most probably yield an even lower travel time.

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