Adaptive Traffic Lights Using Car-to-Car Communication

Victor Gradinescu, Cristian Gorgorin,
Raluca Diaconescu, Valentin Cristea
"Politehnica" University Bucharest
Computer Science Department
313 Splaiul Independentei Bucharest Romania
valentin@cs.pub.ro, {victor, cristig,ralucad}@egov.pub.ro

Liviu Iftode
Rutgers University
Computer Science Department
110 Frelinghuysen Road,
Piscataway, New Jersey, USA
iftode@cs.rutgers.edu

Abstract **– Traffic coordination in intersections is a very studied and challenging topic. This paper presents an adaptive traffic light system based on wireless communication between vehicles and fixed controller nodes deployed in intersections. We present the integrated simulation environment we have developed in order to study the system. We argue that our system can significantly improve traffic fluency in intersections, and has clear advantages over other architectures regarding both cost and performance.**

I. Introduction

Advances in mobile computing and wireless communication have offered new possibilities for Intelligent Transportation Systems (ITS), aiming at improving driving safety and traffic efficiency. By adding short-range wireless communication capabilities to vehicles, the devices form a mobile ad-hoc network, allowing cars to exchange information about road conditions. This is referred to in the literature as Vehicular Ad-hoc Networks (VANETs).

Traffic safety is the focus of current research on VANETs and the main motivation of deploying this technology and to make it ubiquitous. However, there are a number of other applications that could improve the way we drive today.

This paper examines the possibility of deploying an adaptive signal control system in intersections, a system that can base its control decision on information coming from cars. We assume each vehicle is equipped with a short-range wireless communication device, as is a controller node placed in the intersection with traffic lights (**Figure 1**).

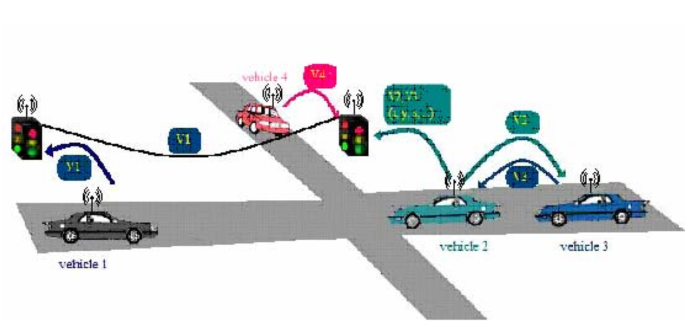

Figure 1. Traffic lights communicate with cars to adapt timings

The remainder of this paper is organized as follows. In section 2, we present related work in the field of traffic signals, relevant to our work. Section 3 describes our adaptive traffic light system. In section 4, we present the simulation framework we have developed, in order to study the system. We show our results in section 5, and we conclude in section 6.

II. Background and Related Work

For over thirty years now, efforts have been made to create traffic light systems that can respond to the ever increasing traffic. Most of the signal control systems in United States, for example, rely on timing plans generated offline by traffic engineers using optimization models. These systems are hard to maintain and do not respond well to special traffic events. More sophisticated adaptive traffic lights use data coming from sensors, cameras and loop detectors to generate online timing plans.

There are several goals that can be taken into consideration when designing a signal control mechanism [1], like minimizing the average delay of vehicles approaching an intersection, increasing progression by coordinating vehicle platoons between intersections, reducing the queue length of all approaches to an intersection and even reducing overall fuel consumption and pollutant emissions.

We will consider the main measure of effectiveness (MOE) for an intersection is the control delay, which is the component of vehicles' delay caused by the presence of the signal control [2]. It is measured in comparison with the travel time calculated in the absence of a control mechanism. Another relevant parameter is *v/c* or volume per capacity ratio, which reflects the degree of saturation of an approach to the intersection. For saturated intersections, the degree of saturation is calculated through the demand per capacity ratio which is greater than 1.

Minimizing the delay at intersections suggests the selection of a cycle length as short as possible in order to produce less red time and shorter queues. The intuition here is that the cycle length should be shortened until a critical value is reached, a value under which the overhead of phase changing starts to significantly influence the delay.

In theory, the optimum cycle length can be approximated with the well-known Webster's equation [1], as a function of lost times and critical flow ratios:

$$C_O = \frac{1.5 \cdot L + 5}{1 - \frac{1}{X_C} \cdot \sum_{1}^{n} \frac{v_i}{s_i}} \tag{1}$$

C_O is the optimum cycle length. L is the sum of lost times for all the phases (yellow and all-red times). n is the number of critical lane groups. A critical lane group is a group of movements that can access the intersection concurrently. v_i / s_i is the maximum flow ratio for the critical lane group i. 1 / X_c is the desired degree of intersection utilization (1.0 for operation at full capacity, usually 0.95).

Several adaptive traffic control systems have been implemented for intersections all over the world. Some of the most important ones include Split, Cycle and Offset Optimization Technique (SCOOT) [3] and Sydney Coordinated Adaptive Traffic System (SCATS) [4]. SCOOT [3] is based on loop detectors placed on every link to an intersection, usually at the upstream end of the approach. Other systems, including SCATS, have detectors placed immediately before the stop line at an intersection. Thus, they cannot get accurate data when the queue grows beyond the length of the detector, or the link is over saturated. Since they use a model based especially on occupancy, they also have difficulties in differentiating between high flows or intersection stoppage. Reported research shows poor performance when incidents occur [5].

Adaptive traffic lights based on wireless communications with the vehicles can employ greater flexibility than the ones mentioned above as they are provided with more information for the signal decision process (e.g. vehicles positions and speeds). The cost is also significantly lower considering loop detectors are usually installed in the asphalt under each lane approaching the intersections and cameras require high processing power (not to mention visibility issues). If we assume that vehicles will be equipped with wireless communication devices (as current research suggests), then all that is needed is wireless devices with some processing power in intersections.

III. System Design

TrafficView [6], a research project we have contributed to, is a VANET platform for data dissemination between vehicles. By making use of wireless communication and GPS, it enables vehicles to collect and disseminate traffic information and, finally, to provide meaningful data to the driver. As input for the digital maps, we use freely available TIGER files [7]. Vehicles periodically transmit information about themselves and other cars they know about. They use one-hop broadcasts to avoid a broadcast storm. Each record consists of a position, identification number, speed, direction, state and a timestamp of the moment when the information was created.

Next, we describe our adaptive traffic light system in the context of the TrafficView platform. It relies especially on wireless communication with the approaching vehicles. The traffic light controller listens to all the information the cars are exchanging, thus finding out how crowded the intersection approaches are. In a city environment, controllers in adjacent intersections may communicate through a wired network, in order to provide each other with additional information. The upstream signal controller forwards to the downstream signal controller packets about the cars that enter the link between the two. Thus, the downstream intersection can decide its timing based on information known in advance. This model is depicted in **Figure 1**.

For every vehicle record received, the controller checks it against its local database. If the vehicle wants to pass through the controlled intersection and there is no newer record about this vehicle in the database, the record will be stored and taken into account when calculating link parameters (demand, queue length etc.).

Existing models estimate these metrics using complex mathematical models based on driver behavior assumptions and statistical facts. The Highway Capacity Manual [2] is a complete guide that explains these well accepted models and gives directions on how to apply them in traffic analysis software tools and in real traffic control devices. However, the real situations are very complex and traffic conditions depend on a large number of variables, so estimation models can sometimes have significant errors.

Our control method benefits from the wireless communication system with vehicles and can accurately determine traffic metrics. The most important metrics we use are control delay and queue length. The control delay is calculated for each car that passes through an intersection. It is the difference between the estimated travel time in the absence of the intersection control and the travel time reported by a vehicle, in the presence of the intersection control. The queue length is computed by the traffic controller, which knows the traffic configuration at every moment.

The controller keeps track of the vehicles throughout the entire period when they are in a few miles range around the intersection (through the information propagation scheme of TrafficView), so it is able to measure accurately both volume and demand. The timing plan generation process takes place once during each cycle and establishes a plan for the following cycle based on the measured parameters. During a cycle further optimizations may occur, such as phase skipping, extension or interruption. The first step is to calculate the cycle length using Webster's formula. For this, the system calculates the critical flow per capacity ratio (v/c ratio) for each group of concurrent movements. v/c for a link is considered as the link demand per link saturation flow. The critical ratio is the maximum v/c ratio of the concurrent movements. The demand volume of each approach is calculated once per cycle just before computing the cycle length and it is considered for an analysis period. Having determined the cycle length, the green splits for each phase are allocated to produce equal degrees of saturation on each link.

$$G_i = (C - L) \cdot \frac{\frac{v_i}{s_i}}{\sum \frac{v_j}{s_j}} \qquad (2)$$

G_i is the green time for phase i, C is the cycle length, L the total lost time, and v_i/s_i the critical "volume per saturation flow" ratio for the movements in phase i.

This preliminary signal plan is adjusted to meet various limitations, such as a maximum cycle length or pedestrian minimum green time. The green time for pedestrians is usually calculated considering the average pedestrian speed of 4 ft/s, the road width and a minimum WALK light time before the last pedestrian starts crossing the road. After the minimum green time for an approach has passed, which allowed pedestrians to cross the conflicting approach(es), the phase is interrupted if no incoming vehicles are detected. On the other hand, if the green phase for an approach has finished, but cars keep coming while there is no demand on the conflicting approach(es), the green phase is extended until an acceptable maximum pedestrians waiting time. Another special event that can occur at the end of a green phase is when the controller detects left turning vehicles with unusual waiting times, comparing to the through movement. This may be because of high volumes on the opposing movement, which cause the formation of a queue on the left lane. That may influence and cause delays on the right-through movements as well. In this situation, the green phase for the approach with the left lane queue will be extended to allow protected left turns and discharge the queue.

As a future enhancement, we study the possibility that the traffic lights broadcast feedback messages for the incoming cars giving information such as when the phase will switch or how large the queue is on each lane of every approach. Feedback messages have several benefits. First, they increase safety as drivers will not be surprised by the end of the green phase. Furthermore, they can adapt their speed accordingly (avoid useless accelerations or react faster on green). Fuel consumption and pollutant emissions are thus reduced. Moreover, in-vehicle software could recommend appropriate speeds based on when the current phase will end, and how many cars are already queued.

IV. SIMULATION ENVIRONMENT

For the evaluation of a complex VANET protocol, a simulation tool is required. Simulating a vehicular network involves two different aspects. First, there are issues related to the network, such as medium access control, signal strength, propagation delays. Network simulators, like ns-2 [8] and Jist/SWANS [9], cope with these issues. The second very important aspect of a vehicular network simulator is using an accurate vehicular mobility model. There are a lot of commercial vehicular traffic simulators, which have not been designed especially for vehicular computing, but for traffic engineering. The adaptive traffic light system we have designed implies that nodes react to messages. The controller decides the traffic light phases according to the traffic flows, and all vehicles react according to the indication of the traffic light. In order to study such reactive events, combining an existing vehicular traffic simulator with an existing wireless network simulator is not possible. An integrated simulator is needed. Based on these aspects, we have chosen to develop a VANET discrete-event simulation tool integrating vehicular mobility and simulation of wireless transmission.

The traffic simulator is microscopic. It is based on the driver behavior model developed by Wiedemann [10][11]. The same model is used in the widely-used commercial traffic simulator “VISSIM” [12]. Wiedemann [13] is supposing that a driver can be in one of four modes: free driving, approaching, following or braking. Free driving means there is no influence from preceding vehicles on the same lane, and the driver will seek to obtain and maintain a desired speed. In the “approaching” mode there is a slower, preceding vehicle that influences the driver, who will apply a deceleration in order to obtain the same speed as the preceding vehicle. The “following” mode means there is a preceding vehicle, but the speeds of the two vehicles are practically equal and the driver will seek to keep the speed constant. The “braking” mode means there is a slower preceding vehicle, very close in front and, due to the immediate danger, the driver will apply high deceleration rates. We have also implemented a lane-changing model for multi-lane roads, based on the hierarchy between the four driving modes.

The network simulator module copes with the delivery of messages from one node to another. It offers a set of network primitives that can be called by the node applications emulated on top of our simulation framework. At the physical layer, we use a model with cumulative noise calculation and signal reception based on SNR (Signal-To-Noise) threshold. This means that, when a radio receives a signal of a given strength, the noise is calculated as the sum of all the other signals on the channel, and the ratio of the two values is the SNR. The signal can be successfully received if the value of SNR is higher than a given threshold SNRT. The radio wave propagation can be affected by three independent phenomena: path loss, fading and shadowing [14]. The path loss effect is considered to be the most important factor and it reflects the signal power attenuation due to the propagation distance. Our simulator has two signal propagation models: free-space and plane earth two-ray path loss. While the first is an idealized model, the two-ray path loss model considers the effect of earth surface reflection and is more accurate. At the Link Layer, we have implemented the CSMA/CA channel access mechanism which is the base of IEEE 802.11 standard. The basic principles of CSMA/CA are *listen before talk* and *contention*. When a node has to send a packet, it starts by listening the environment and, if idle, begins the transmission. If the medium is busy, the node waits for a random amount of time before checking again.

Because we wanted to prove that the adaptive traffic light system helps reduce fuel consumption and pollutant emissions, we have integrated a module for computing them in our simulator. The model is based on the work of Akcelik and Besley [15]. We have focused on the relation between fuel consumption and emissions and the speed and acceleration of the vehicle. We have simplified the model and taken only light vehicles into account. Based on the vehicles’ motion, our simulator’s engine computes the fuel consumption and pollutant emissions of each vehicle. Statistics and global measures can easily be obtained.

V. SIMULATION RESULTS

The first test scenario we evaluate is the intersection Iuliu Maniu / Vasile Milea streets in downtown Bucharest. A screenshot of our simulation of this intersection can be seen in **Figure 2**. We study the traffic at this intersection without considering the effect of adjacent intersections. We focus on comparing two types of signal control strategies: the real, existing pre-timed signal control and our adaptive strategy based on communication between the controller and approaching vehicles.

We have chosen to test this intersection under stressed conditions in the after-noon peak hour period. The input flow on each approach is shown in **Figure 3**. The flow values are approximations of real traffic, which we have measured in the studied intersection. Usually, on the northbound and eastbound approaches, endless queues can be seen at this hour.

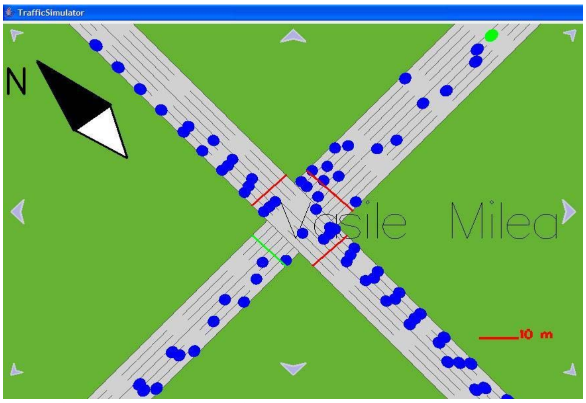

Figure 2. First scenario: a simple intersection in Bucharest during morning rush-hour (simulator screenshot).

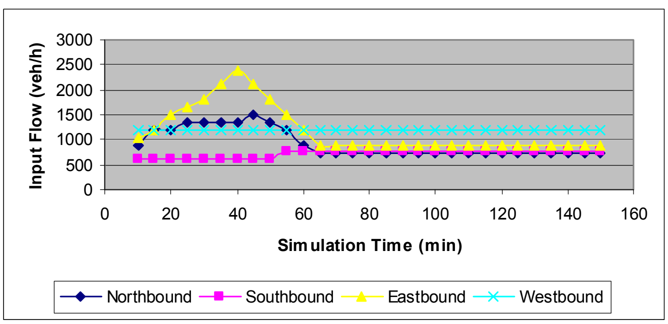

Figure 3. Input flows for the first scenario.

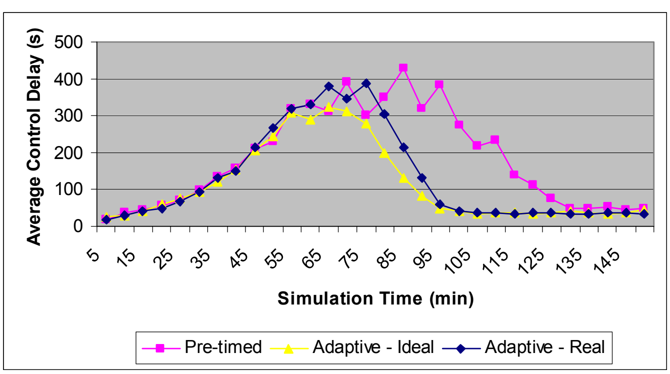

Figure 4. Average control delay for the simulated period during the first scenario.

The simulation starts at 17:00. We have studied the behavior of the traffic for a period of time long enough to catch all the influences of the peak period (150 min).

The adaptive strategy was evaluated under two communication environments: an ideal one, without packet loss, and a more realistic one using the model described in section 3.2 for signal propagation and interference. The main MOE evaluated was the average control delay as defined in section 4. The adaptive method out-performs the pre-timed one, with both communication models. The intersection recovers faster from the congestion (**Figure 4**). This is due to the fact that the controller tries to obtain equal saturation degrees in each approach, by reducing the green phase for the less demanded approaches. Thus, queues on conflicting approaches tend to equalize, resulting in better overall efficiency. The total fuel consumption and pollutant emissions are also reduced when using the adaptive system, as shown in **Figure 5**.

	Total Delay [vehicle hours]	Fuel Consumed [L]	CO_2 [Kg]	CO [Kg]	HC [Kg]	NO_X [Kg]
Pre-timed	539.5	1597.7	4209.3	334.4	6.9	11.1
Adaptive (Real)	386.3	1572.6	3931.7	321.9	6.3	10.7
Adaptive Benefits	28.3%	6.5%	6.5%	3.7%	8.9%	3.2%

Figure 5. The adaptive strategy benefits over the existing solution.

The next intersection we have studied is “Ciurel”, a T-shaped intersection, in western Bucharest (**Figure 6**). There are residential areas to the south, and usually in the morning peak hour traffic, endless queues form as people drive towards north and east to get to work. The opposing traffic coming from the north is also considerable, and one lane is reserved for vehicles that turn left here. The real signal plan works in green phases of 30 s for the north-south movement, 15 s for the protected left turn on the southbound approach, and 20 s of green for the eastbound approach.

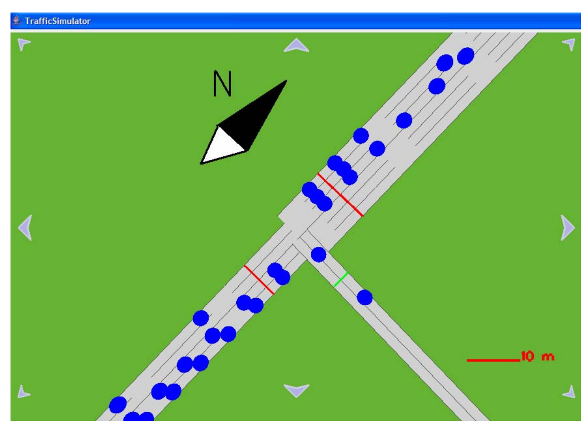

Figure 6. Second scenario: a T-shaped intersection with high traffic (simulator screenshot).

We try to demonstrate the efficiency of pro-active detection of the need for protected left movement. For that, we assume that vehicles broadcast their turning intentions together with the other information. As the number of left turning vehicles varies from cycle to cycle, our system allocates enough green time for the protected left on the northbound approach, which ensures acceptable delays for both the southbound and the northbound approaches. If the queue on the left lane grows too large, it may influence the through movement on the northbound, while too much green for protected left would increase delays on the southbound approach.

The scenario we have simulated is a three hour period of morning traffic with input flows on the three approaches as shown in **Figure 7**. The percent of left-turning vehicles on the northbound approach varies around 15%.

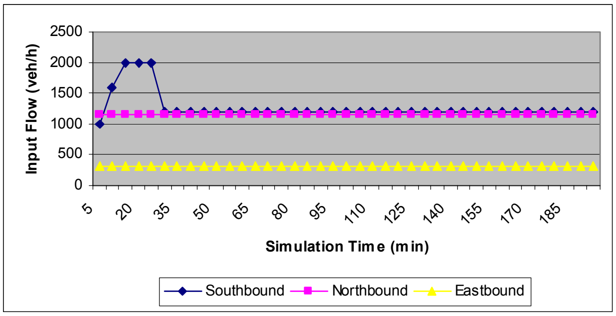

Figure 7. Input flows for the second scenario.

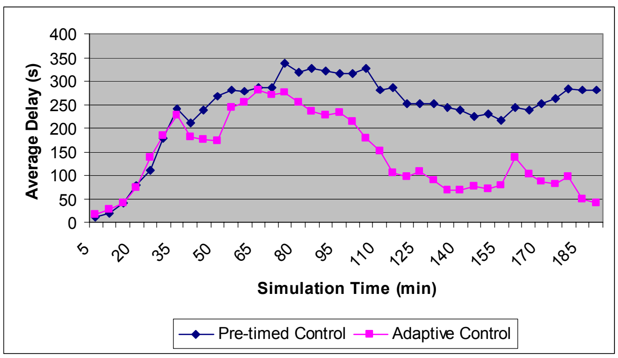

Figure 8. Average control delay during the simulation of the second scenario.

Simulations once again show positive results when comparing the average delay. **Figure 8** shows the average delay along the simulation time, computed on five minutes intervals. Under the adaptive control method, the intersection recovers sooner from congestion.

Unlike the smooth curve from the previous test-case, here the irregularities of the curve are caused by the existence of the left movement on the northbound approach. Discharging the left lane queue implies a separate phase of varying length under adaptive control, which prevents abnormal delays on this lane but deviates from the ideal timing plan established in previous cycle.

VI. Conclusions

We have designed an adaptive traffic light system based on short-range wireless communication between vehicles. The system is based on a controller wireless node placed in the intersection, which determines the optimum values for the traffic lights phases. We have argued that this architecture has clear benefits compared to adaptive systems based on sensors or cameras. We have developed an integrated simulator in order to validate the system. The simulation framework comprises a realistic mobility model for vehicles and a wireless network simulator. We have studied two major intersections in Bucharest and found that the system significantly improves traffic fluency, compared to the existing, pre-timed traffic lights. We focused our analysis on how the system reacts to rush hour traffic and obtained promising results. The total average delay, as well as fuel consumption and pollutant emissions, were significantly reduced.

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