Harnessing Vehicular Broadcast Communications: DSRC-Actuated Traffic Control

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***Abstract*— Traffic congestion in major cities around the globe is a daunting problem that is getting worse as the speed of urbanization keeps increasing. The role of traffic lights (TLs) at intersections in regulating flows cannot be underestimated. Even though there are a variety of actuated traffic signals based on cameras or loop detectors, the vast majority of existing TLs in the world employ a timer-based decision logic which is clearly not very effective. In this paper, we present a new scheme for controlling traffic at intersections, which is known as dedicated short-range communications (DSRCs)-actuated traffic control. The proposed approach leverages the presence of DSRC radios in vehicles and gives priority (by displaying green light) to approaches (roads) that include DSRC-equipped vehicles (such as 10% or 20% of vehicles having DSRC radios). Using this priority mechanism, it is shown that the average waiting time at each TL can be significantly reduced. This, in turn, can reduce the average commute time of urban workers during rush hours substantially. One of the great advantages of the presented approach is that it can function well with even a low percentage of DSRC-equipped vehicles. Given that many industry forecasts predict a gradual penetration rate for the DSRC technology, this is a very attractive feature. It is also shown that the proposed new approach leads to a cost-effective solution for urban traffic control since the hardware and software platforms needed for its implementation are low cost.**

***Index Terms*— Reducing average commute time, improving traffic flows, communications-based traffic control, DSRC-actuated traffic control, distributed traffic control systems, transition scheme to Virtual Traffic Lights.**

I. Introduction

The applications envisioned with vehicular networking encompass both traffic safety and traffic efficiency [1]. While the original motivation for WAVE standards was safety, the interest in applying the Dedicated Short-Range Communications (DSRC) radio technology to traffic efficiency as well has been growing in the last 5 years [2]–[6]. In this paper, we explore such a traffic efficiency application. More specifically, we propose to leverage the presence of DSRC radios (which have been mandated in the USA on Februay 3, 2014), in particular, utilizing the Basic Safety Message (BSM) specified in SAE J2735 standard, for controlling traffic flows at intersections in urban areas [7], [8].

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The rapid urbanization in almost every country in the world has exacerbated the traffic congestion problem in urban areas. Especially during rush hours, the delay experienced by commuters keeps increasing. In certain cities (such as Mexico City, Sao Paulo, Rio de Janeiro, Moscow, St. Petersburg, Istanbul, Beijing, Bangkok, New Delhi, Jakarta, etc.) one-way commute times of more than 2 hours is not unusual.

While there are several factors behind traffic congestion, the role of traffic lights in regulating traffic flow at intersections cannot be underestimated. Indeed, infrastructure based traffic lights manage the traffic flow at intersections by deciding the right-of-way between competing flows. Essentially, traffic lights give the right-of-way to one direction, e.g., North-South (NS), by displaying green light to vehicles in the NS direction while displaying red light to the vehicles in the orthogonal direction, i.e., East-West (EW) direction. By displaying red light to EW direction while displaying green light to NS direction simultaneously, the system's safety is ensured. Indeed, it is this perfect synchronization which prevents collisions or accidents between the vehicles of competing flows at intersections. In addition, by splitting the cycle duration equally between the NS and EW directions (e.g., 30 s green light to NS and 30 s green light to EW), the "fairness" of the system is also guaranteed.

Unfortunately, this static way of giving the right-of-way to NS and EW directions has been the default mode of operation for the vast majority of traffic lights that have been installed in the last century. While this mode of operation seems fair, it is extremely inefficient for the most part of a day as the traffic flows are *not* symmetric during most of the day. Hence, it is clear that the decision mechanism of traffic lights should be aware of the mobility pattern of traffic flows to increase their efficiency. To achieve this "dynamic" or *adaptive approach* to giving the right-of-way is the key problem awaiting solutions. The significance of this problem cannot be underestimated. Recent work on such approaches has already shown that, using such adaptive traffic control, commute time of urban workers can be reduced by more than 30% which is pretty significant [2].

Using loop detectors, magnetic detectors and cameras for improving the performance of existing traffic lights has been known for a very long time [9]. These options can provide real-time information about the occupancy and number of vehicles in each approach of a signalized intersection, thus making the right-of-way decision more adaptive. These detectors serve as sensing devices for actuating existing traffic lights as opposed to a pre-timed mode of operation. Several existing adaptive systems are designed based on this strategy, such as SCOOT [10], SCATS [11], OPAC [12] and many others [13]. Unfortunately, these sensing and actuation mechanisms and the corresponding technologies are expensive options and due to this reason as well as other reasons (such as invasive nature of installing loop detectors, accuracy of cameras, etc.) they only exist at a very small percentage of intersections in few cities arround the world [14], mostly, a small subset of first tier cities. Hence, a more cost-effective solution is needed, especially for second-tier cities.

Thanks to the development in vehicular networking that employs vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communications, more economical adaptive traffic control methods have been reported recently. One of these approaches is known as Virtual Traffic Lights (VTL). The VTL technology is based on using Dedicated Short Range Communications (DSRC) radios within vehicles operating at 5.9 GHz to establish a leader for managing traffic flows at intersections [2], [6]. DSRC technology is based on the well-known 802.11p standard and it is allocated 75 MHz bandwidth in the USA by the FCC [15]. There are 7 channels in this frequency band, one of which serves as a control channel while the remaining 6 channels are service channels. DSRC standards and 802.11p were designed initially for safety applications that use broadcast as the main mode of communications (as opposed to unicast or multicast).

VTL is a very attractive *self-organizing traffic control scheme* as it can eliminate the need for infrastructure-based traffic lights which are expensive to install and maintain. Indeed, this self-organizing traffic control paradigm has led to several patented inventions and publications that shed new light on a totally new approach that involves distributed traffic control inspired by self-organizing biological systems that are common place in nature (e.g., colonies of ants, bees, and termites; school of fish, and flocks of birds) [6], [16]–[23]. Using VTL technology can reduce the commute time of urban workers by more than 30% during rush hours, thus increase productivity of nations, reduce carbon footprint of vehicles, reduce energy consumption in transportation, enhance safety at intersections, lead to a greener environment in addition to several other benefits [2], [6], [24].

Unfortunately, VTL might need 100% penetration of DSRC technology into vehicles which might not happen instantaneously. In addition, V2V communications in VTL might experience non-line-of-sight (non-LoS) conditions that might render timely decision making quite difficult. Hence, a cost-effective transition scheme between current traffic control systems and VTL is needed. Meanwhile, in most of the developed world (USA, Europe, as well as some Asian countries), traffic lights are already installed on some of the most densely used routes in cities and, as such, represent a huge capital investment in infrastructure used for ground transportation. Many governments might therefore be quite reluctant to abandon such a large capital investment and the infrastructure used for traffic control. Hence, many governments might be much more receptive to the idea of keeping this large infrastructure and upgrading it with certain new technologies to make those traffic lights adaptive and aware of the presence or absence of vehicles in competing flows of an intersection.

In this paper, we present such a new approach which shows that by installing DSRC radios at an intersection, traffic lights can be made "intelligent" in decision making, giving priority to approaches (roads) which include vehicles equipped with DSRC radios. Given that the US Department of Transportation (DoT) has decided to mandate the use of DSRC radios in February 2014 (see [7] and [8]), this paper shows that, one can leverage the existence of such radios in vehicles for increasing flow rates of urban traffic.

The remainder of this paper is organized as follows. Related work is presented in Section II. In section III, we give a problem statement. Details of the proposed solution are described in Section IV, while Section V gives the results of extensive simulations conducted for rush hours as well as non- rush hours to quantify the performance benefits of the proposed scheme. Other important aspects of the proposed DSRC-actuated Traffic Control scheme are highlighted in Section VI. Finally, Section VII concludes the paper.

II. Related Work

It has been long known that traffic-responsive control strategies will tremendously reduce delay at intersections. In the past few decades, various adaptive traffic systems were developed and implemented in some cities [14]. Some of these traffic systems such as SCOOT [10], [25], SCATS [11], are based on dynamic traffic coordination [26], and can be viewed as a traffic-responsive version of TRANSYT [27]. These systems optimize the offsets of traffic signals in the network, based on current traffic demand, and generate 'green-wave' for major car flow. Meanwhile, some other model-based systems has been proposed, including OPAC [12], RHODES [28], PRODYN [29]. These systems use both the current traffic arrivals and the prediction of future arrivals, and choose a signal phase planning which optimize the objective functions. While these systems work efficiently, they do have significant shortcomings. The cost of these systems are generally quite high [30]. Considering SCATS, for example, the initial cost of the system is \$20,000 to \$30,000 per intersection, and \$28,800 per mile per year, not to mention that the installation will cost an extra \$20,000 per intersection [31]. The cost is due to the fact that these systems use loop detectors and video cameras to detect vehicles, they are generally expensive and hard to install and maintain. Meanwhile, they are centralized control systems, which implies that a large communication systems is needed that can support centralized control with high data rates. All these factors add up to a very costly solution which explains why very few cities in the world so far have ended up installing these high cost systems.

Another promising approach to adaptive decision making is to use the recently proposed scheme, known as Virtual Traffic Lights [2]. VTL is an exciting vehicle-to-vehicle traffic control scheme which has huge potential as it can obviate the use of expensive traffic lights and improve traffic flows by more than 30%. Since its inception, the interest in VTL has grown considerably and different aspects of it has been studied by several different research groups [2], [32]–[41]. Unfortunately, VTL might need 100% penetration of DSRC technology into vehicles which might not happen instantaneously. In addition, V2V communications in VTL might experience non-line-of-sight (non-LoS) conditions which might make timely decision making quite difficult. Due to those reasons, a cost-effective transition scheme between current traffic control systems and VTL is needed.

Meanwhile, Virginia Department of Transportation has recently initiated (VDOT) connected and automated vehicle program (CV) [42], [43]. The program focuses on multiple V2V and V2I applications based on DSRC technology. Very similar to VTL, CV tries to eliminate/reduce high-cost infrastructures, including traffic signals and guide signs on the roadside based on DSRC technologies. As part of the program, Virginia Connected Corridors (VCC) are set up, facilitating the real-world development and deployment of connected-vehicle technology using more than 60 roadside equipment units. While this system is clearly a major step forward in eliminating traffic signal infrastructures at intersections, it will also require 100% penetration rate, hence a transition scheme will also be needed.

The solution proposed in this paper provides such *a transition scheme from pre-timed traffic signals to VTL*. Given that the US DoT has decided to mandate DSRC radios in future vehicles, our solution leverages the existence of DSRC radios in vehicles by harnessing the vehicular broadcast energy that vehicles will transmit in the form of Basic Safety Message (BSM) messages [44] every 100 ms for intelligent traffic control. The proposed solution is cost-effective as it only needs DSRC radios to be installed on existing traffic lights. This is a very low-cost solution (about an order of magnitude cheaper) when one compares it to traditional adaptive traffic control systems such as loop detectors and cameras.

III. Problem Statement

While VTL is a very promising new technology leveraging the presence of DSRC radios, one of the issues is the gradual penetration ratio of DSRC technology into vehicles. For ideal operation of VTL technology, all the vehicles at an intersection should be equipped with DSRC radios. This, however, is a strong assumption as the adoption of DSRC radios might take several years in the USA, Europe, and Asia. How to implement VTL technology with only a certain percentage of vehicles equipped with DSRC technology (e.g., 20% of all vehicles in a specific city) is certainly a challenge. This challenge was addressed in a recent study which showed how VTL can be implemented with a small percentage of vehicles equipped with DSRC radios [38]. The study is based on game-theoretic arguments and requires a Department of Transportation (DoT) or local traffic authorities in a given city, to allocate certain routes at designated times (e.g., during rush hours) to the exclusive use of DSRC-equipped vehicles [38]. In principle, this is very similar to the current negotiations between Google or Uber and certain states in the USA for permission or legislation to have dedicated routes for autonomous vehicles.

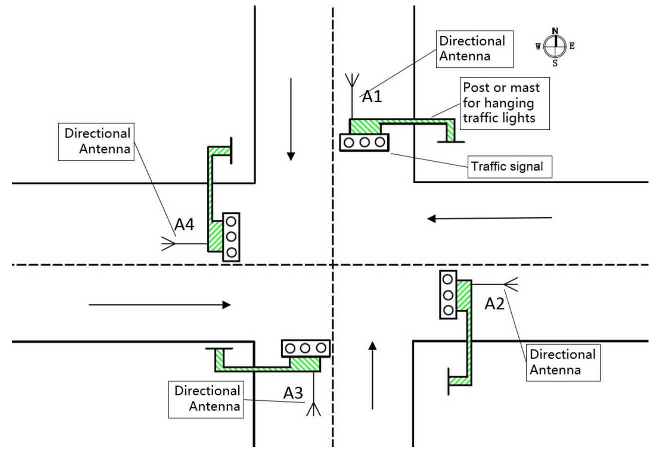


Fig. 1. System implementation of the proposed approach at given intersection. Observe that the DSRC-equipped vehicles in each approach will be detected by directional antennas placed on the mast arms supporting the traffic light for that approach. In other words, as an example, DSRC-equipped vehicles on the South-North approach moving Northbound can be detected by directional antenna A3 whereas the DSRC-eqipped vehicles of the North-South flow moving Southbound can be detected by the directional antenna A1. We note that other RF configurations for the directional antennas are also plausible; for instance, one could use A1 (instead of A3) to detect vehicles moving Northbound and A3 (instead of A1) to detect vehicles moving Southbound.

In this paper, we present a new adaptive approach that addresses the partial penetration problem (i.e., a small percentage of all vehicles are equipped with DSRC radios) and provides a way of asymptotically approaching the benefits reported for the VTL scheme as the percentage of vehicles equipped with DSRC radios increases.

In contrast, the DSRC-actuated traffic control scheme presented in this paper is a *communications-based* traffic control scheme whereby the current state of the traffic light is changed depending on the presence or absence of DSRC-equipped vehicles in the orthogonal direction. For example, if the NS direction has the green light, next state will be switched to green light for EW immediately when DSRC-equipped vehicles are detected in the EW approach, as opposed to a pre-timed traffic light, which switches phase based on a timer.

IV. Proposed Solution

In this section we outline the system, algorithms, and other implementation details of the proposed approach.

A. System

Figure 1 shows a possible system implementation of the proposed DSRC-actuated traffic control scheme. Observe that this implementation includes installing antennas on each mast arm supporting the current traffic lights. The function of these antennas is to detect the presence of DSRC-equipped vehicles in each approach of the intersection. For example, antenna A3 can be used to detect the DSRC-equipped vehicles approaching the intersection from the South direction, while A1 will be used to detect the presence (or absence) of DSRC-equipped vehicles approaching the intersection from the North. Similarly, A4 and A2 will be used to detect the presence/absence of vehicles approaching the intersection from the West and East, respectively.

On a major busy intersection, the 'broadcast storm' problem and/or the 'hidden terminal' problem might occur [45], [46]. While this is not the major concern in this paper, we evaluated this issue using results from previous research [47]. The work in [47] evaluates channel congestion problems both theoretically and using simulations. From their results, under very dense conditions (i.e., 0.2 veh/m), the delay of the message is found to be within 500 ms, which is far smaller than the requirements of our system, which can operate normally even with 1 second delay. Our paper has already considered the hidden terminal problem: under very dense traffic conditions, the Packet Reception Rate (PRR) is around 50%, meaning 50% of all messages are received. The system will work nicely under these conditions, since we do not necessarily need to receive every packet, but a sufficient number of packets to detect the presence of DSRC-equipped vehicles. The hidden terminal problem will occur when vehicles in a given approach are NOT aware of the existence of vehicles from another approach. To address this problem, we propose to use directional antennas. By using directional antennas, vehicles from different approaches will not share the same communication media; hence, they can completely avoid the 'hidden terminal' problem. Of course, one can choose either directional antennas or omidirectional antennas based on the actual channel conditions at the intersection. In general, for a major intersection with more than 3 lanes in each approach and heavy traffic arrival rate, directional antennas are recommended.

Each of these 4 directional antennas, which are used for receiving signals transmitted by vehicles in each of the four approaches of an intersection, are connected to a separate DSRC radio receiver for detecting DSRC-equipped vehicles through the BSM sent by DSRC-equipped vehicles (typically, BSM are sent every 100 ms). Since DSRC radios typically include a GPS system, it might appear that directional antennas are not really needed since GPS devices can also determine the approach a vehicle is coming from. However, it turns out that this is not true and directional antennas will still be needed to compensate for the measurement error of GPS system, and to provide an alternative solution when GPS data is not available (e.g., an intersection with tall buildings around that block GPS signal); it will also be helpful for alleviating the aforementioned 'broadcast storm' problem during rush-hour by separating the intersection into 4 sectors [45].

Figure 2 shows how the information obtained from A1, A2, A3, and A4 can be utilized by a traffic light for decision making. More specifically, we show how one can use this information for deciding what the next state of the traffic light will be. Assuming that the decision logic of current traffic lights is in the memory of the Control Unit, the output of these DSRC receivers are combined using Boolean logic which can be implemented in hardware by flip-flops. In the actual implementation, this Boolean logic can be implemented in software as well.

The principle of operation of the DSRC-actuated traffic light is therefore simple and it depends on the following (note that the principle here assumes that the current timing already surpassed minimum phase requirement but has not reached the maximum phase duration):

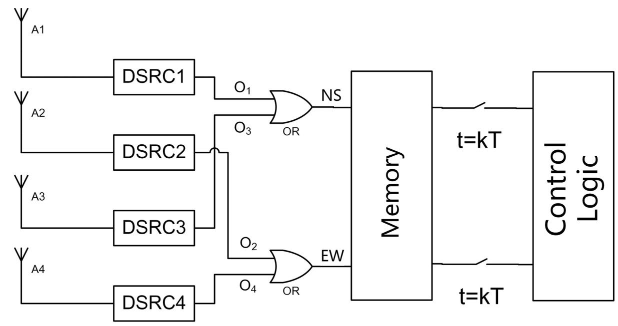


Fig. 2. The detected BSM messages of DSRC-equipped vehicles are combined in a specific manner to inform the traffic light whether there are DSRC-equipped vehicles in the orthogonal direction when the traffic light is in a given state. For example, when the current state displays the green light for the East-West approach, then the important information is to detect whether there are any DSRC-equipped vehicles in the orthogonal direction which is North-South and South-North. This information is coming from antennas A3 and A1, respectively. By performing a logical OR operation, it is detected whether there are any DSRC-equipped vehicles either in the NS or SN approaches. If so, the next state of light will be green for the NS and SN approaches. If not, then the green light for EW and WE will continue.

i) Current state of the traffic light
ii) Output of the DSRC receivers, denoted as O1, O2, O3, and O4 in Figure 2.

As a specific example, let's assume that the East-West (EW) approaches currently have the green light. If the system detect any BSM messages indicating the presence of DSRC-equipped vehicles in the orthogonal NS approaches, then the next state of the traffic light will be switched to display green light to NS direction. Otherwise, green light for EW will continue irrespective of the fact that it was already green in the last several seconds.

Figure 3 shows the overall principle of operation of the new DSRC-actuated Traffic Control Scheme as a flow chart: Observe that this new DSRC-actuated Traffic Light is continuously checking if DSRC radios exist. If no DSRC-equipped vehicles exist, then the proposed new scheme returns to the original pre-timed traffic signal mode of operation. If, on the other hand, the system detects the presence of DSRC-radios, then it checks whether the detected DSRC-equipped vehicles are on the approach that currently has the green light. If so, then the algorithm moves to the pre-timed operation mode where the green split is 50-50 between the orthogonal directions. If not, then this implies that the DSRC-equipped vehicles are in the orthogonal direction that currently has the red phase. In this case, the system checks whether the current time that has lapsed is larger than the minimum time (t_{min}) allowed for the green phase. If so, then switching occurs and the orthogonal approach that includes the DSRC-equipped vehicles gets the green light. If not, the green phase of the current state is maintained till the minimum time required for switching is satisfied at which point the switching occurs and the green light is given to the orthogonal direction.

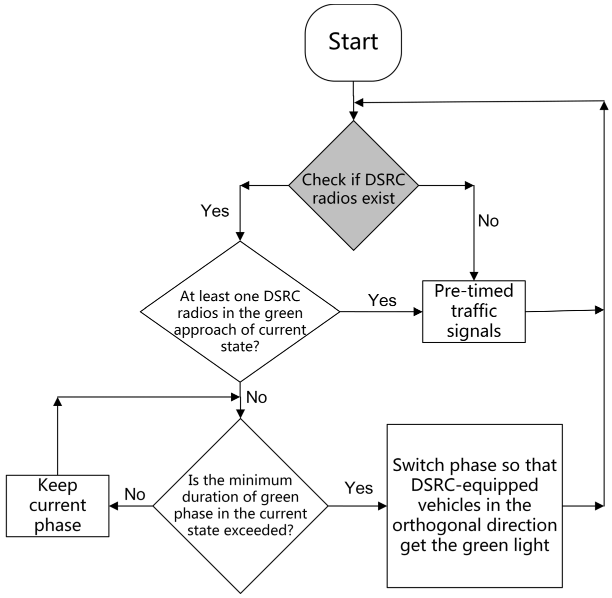


Fig. 3. The flow chart showing the overall algorithm used by the DSRC-Actuated Traffic Lights.

The maximum phase time can be calculated by Webster's equation [48].

$$t_c = \frac{1.5L + 5}{1 - \sum Y_i}$$
$$t_{max,i} = (t_c - L) \times r_i$$

where t_c is the optimum cycle length, L is the lost time per cycle, and Y_i is the critical lane volume divided by saturation flow of the i'th phase. Since L and saturation flow is static, to determine optimum cycle time dynamically, the system needs to infer the current traffic volume based on the detected arrival rate. For a known DSRC penetration rate p, Y_i can be estimated by $\frac{d_i}{p}$ where d_i is the detected lane volume. If p is unknown, we use a common cycle length by default (e.g., $t_c = 50\ s$). r_i is the proportion of the i'th lane volume to the total traffic volume. We estimate this value by using detected traffic volume rate, i.e., $r_i \approx \frac{d_i}{\sum d_i}$. In this way, we obtain a dynamic maximum phase time by applying Webster's formula on current detected flow rate. Therefore, when no vehicles are detected in the current cycle, (which is the worst-case situation), the traffic signal will still perform as an optimized pre-timed traffic signal based on current detected car flow; hence, will still perform reasonably well.

Overall, it is important to emphasize that when there are no DSRC-equipped vehicles detected, the system operation reduces to the current principle of operation of existing traffic lights which is a timer-based operation. However, the system behaves in a completely different manner when it detects the presence of DSRC-equipped vehicles, essentially giving priority to the approaches that include DSRC-equipped vehicles. As we will show in the next sections, this reduces the commute time of not only DSRC-equipped vehicles but also unequipped vehicles which is quite interesting and somewhat counter-intuitive. Hence, the average commute time of all vehicles is reduced with the proposed DSRC-Actuated Traffic Control scheme.

V. Performance

In this section, we provide simulation results for the performance of the proposed new approach. In the simulation, we consider the channel conditions to be ideal with no packets lost, since for most of the intersections, the communication capability of DSRC is radios will be adequate, as discussed in subsection IV-A. In some intersections where the channel conditions are harsh, the simulation results we report here might not apply, but such rare situations are not our main concern in this paper. We first quantify the performance at a single intersection and then extend our analysis to multiple intersections to quantify the improvement in commute time assuming a scenario characterized with bulk arrivals. Finally, we also quantify the performance of the proposed system for rush-hour traffic. Subsequently, we provide the overall performance of the DSRC-actuated traffic control system during the whole day. The main purpose of the simulation is to evaluate the performance of the proposed scheme during the transition period from the current traffic system, where most vehicles aren't equipped with DSRC-radios, to a traffic system where most of the vehicles are equipped with DSRC-radios. In addition, the performance of the proposed system with low penetration rates (such as 10% or 20% of vehicles having DSRC radios) is also quantified as this is of interest in and of itself. Finally, we checked the accuracy of our approach using some realistic traffic data as well. We apply the proposed scheme to two intersections using the TAPAS data [49], which is a 24-hour traffic scenario based on real demand and real map of the city of Cologne, Germany, to get a performance evaluation in a scenario with a high level of realism. We also check our approach using empirical data collected at the intersections at Shady Avenue and Northumberland Street, in Pittsburgh, at 1 PM on November 28, 2017, over a time window of 25 minutes, to see the performance at these intersections when one applies our scheme with the real traffic data measured on Shady Side and Northumberland Road in Pittsburgh.

A. Single Intersection

Figure 4 shows such a single intersection with 2-lane traffic in each approach. Assuming an arrival rate of 1500 cars/hr, which is the average arrival rate of a one-lane road [50], the arrival pattern of the cars is assumed to be a Poisson arrival, which is typical in traffic engineering simulations, the average waiting time of the DSRC-actuated traffic control scheme at an intersection is quantified. To provide a detailed analysis, the average waiting time for DSRC-quipped and unequipped vehicles are given in addition to the overall system performance of DSRC-actuated traffic control system. To put things in perspective, the performance of current traffic lights (TL) and VTL system are also provided which allows a more meaningful comparison which, in turn, leads to a better understanding of the benefits of the proposed new system

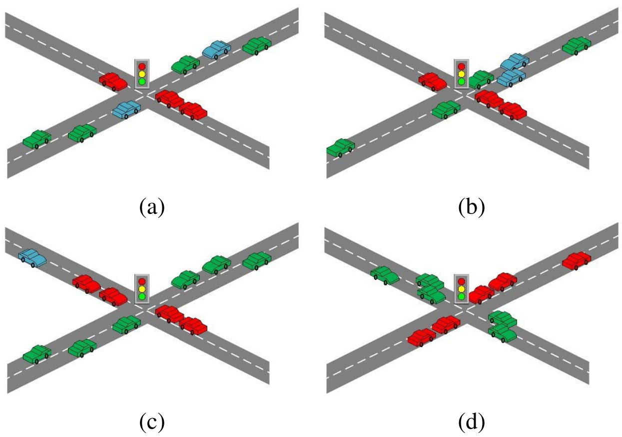


Fig. 4. Principle of Operation: From (4a) to (4b) no switching occurs as the orthogonal direction has no DSRC-equipped vehicles (depicted in the figure as blue vehicles). From (4c) to (4d), however, switching of green light occurs as the orthogonal direction has one DSRC equipped vehicle.

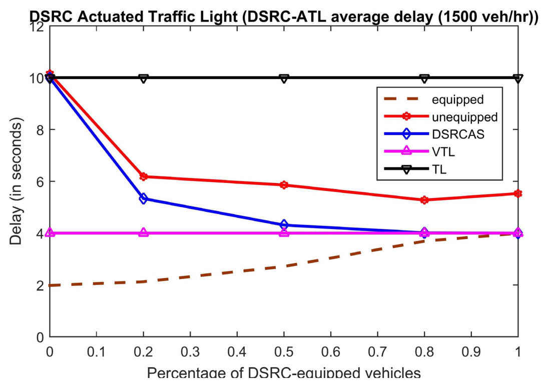


Fig. 5. Performance of the DSRC-Actuated Traffic Control Scheme at a single intersection in terms of Average Waiting Time as a function of the percentage of DSRC-equipped vehicles. For comparison, the average waiting time of regular traffic lights (TL) and Virtual Traffic Lights (VTL) is also shown.

as a function of the percentage of DSRC-equipped vehicles (penetration rate).

Figure 5 shows the results of the simulations obtained with the simulator known as Simulation of Urban Mobility (SUMO) [51], an open-source large-scale simulator developed by German Aerospace Center (DLR). For the single intersection considered, observe that the VTL system reduces the average waiting time at the intersection from 10 s to 4 s, which corresponds to a 60% benefit. This is in line with several previous results reported about the benefit of VTL [2]. As expected, the overall system performance of the DSRC-actuated Traffic Control System asymptotically approaches the performance of VTL system. What is quite interesting is that, even the performance of the unequipped vehicles (the legend in red) improves which might seem counter-intuitive at a first glance. This is based on the probabilistic argument and the fact that, even at low penetration rates (such as 20%), in each approach there might be a few DSRC-equipped vehicles. Hence, after their presence is detected, that approach gets the green light. Observe that when that approach gets the green light, even the unequipped vehicles benefit from this even though they are not equipped with DSRC radios. This is the main reason behind the better performance of unequipped vehicles compared to the current traffic light system which is denoted as TL in Figure 5. Clearly, when one considers only the performance of DSRC-equipped vehicles, because at an intersection they always get priority, it is not surprising that their performance is even better than VTL. Of course, this provides a compelling reason and motivation for using DSRC radios in vehicles.

Another interesting observation that can be made from Figure 5 is the fact that a large portion of the improvement with the DSRC-Actuated Traffic Control scheme occurs with modest levels of penetration (about 80% of the total improvement occurs when only 20% percent of vehicles are equipped with DSRC radios) which is a very interesting and attractive feature. In other words, with a relatively modest penetration rate of 20%, one gets a huge improvement with respect to the TL scheme. Furthermore, when one reaches 60-70% penetration ratio, if DSRC radios in certain vehicles malfunction or they get out of traffic stream, the degradation experienced is almost negligible. This shows the robustness of the proposed scheme which is again a very desirable feature.

B. Multiple Intersections With Platooning Effect

While section V-A shows the superb performance of our DSRC-actuated Traffic Control System on a single intersection with Poisson arrival, it is clear that, in an urban area, the typical route followed by vehicles may involve several intersections. In this case, Poisson arrival assumption, which assumes independence between arrivals is destroyed by the act of vehicles crossing intersections, and vehicles form platoons. Figure 6 shows such a scenario. The scenario considered in Figure 6 involves a total of 10 intersections (due to symmetry, the intersections 6-10 are not shown in the figure). It is also assumed that the intensity of Flow 1 and Flow 2 in this arterial road are approximately equal which corresponds to non-rush hour traffic during a day (e.g., between 10 AM and 3 PM). While the intersections at the two ends have a car flow based on Poisson Arrivals, the arrival pattern of the inner intersections are not Poisson, but bulk arrivals under platooning effect. Because of these assumptions, the "core node" which seems to be the most suitable intersection for measuring the performance of the proposed DSRC-actuated Traffic Control Scheme is intersection # 5. The ratio of the traffic flow on the main artery to side flows is assumed to be 4:1 in the simulations conducted. In addition, an arrival rate of 1500 cars/hr is assumed.

Observe from Figure 6 that the average waiting time of the DSRC-actuated Traffic Control Scheme improves as vehicles move from intersection 1 to intersections 2, 3, etc. Around Intersection 3, the average waiting time converges to 3.5 seconds asymptotically. Observe that intersections with arrival patterns that are subject to heavy platooning effect (intersection 3, 4, 5) perform arround 20% better than intersection with Poisson arrival (intersection 1). This result confirms intuition: when vehicles form a platoon, the presence

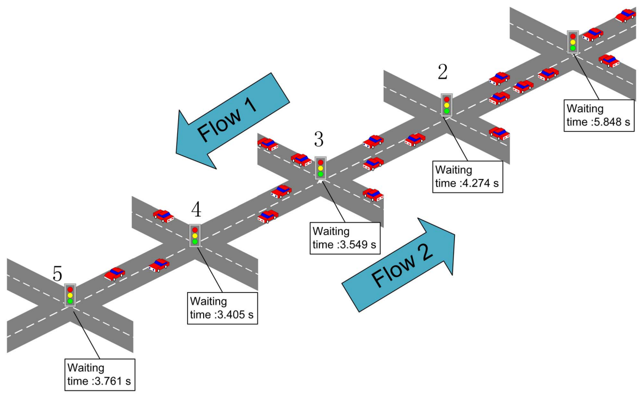


Fig. 6. Scenario showing the average waiting time performance at every intersection on an arterial road of 10 intersections. Here it is assumed that Flow 1 and Flow 2 are comparable which corresponds to non- rush hour traffic conditions in a city. The core node for measuring the performance is intersection 5 due to the symmetry of flows. Observe that the average waiting time stabilizes around 3rd intersection.

TABLE I
AVERAGE COMMUTE TIME RESULTS

Experiment Number	1	2	3	Average Commute Time(in seconds)
Traffic Light	330.64s	260.65s	429.50s	340.26
DSRC-ATL	186.70s	181.23s	184.56s	184.16s

TABLE II
SYSTEM OUTPUT RATE (VEH/S)

Time Interval (sec)		0 - 600 sec	600 - 1200 sec	1200 - 1800 sec
Traffic Lights	Exp. 1	0.443	0.560	0.512
	Exp. 2	0.467	0.592	0.548
	Exp. 3	0.440	0.570	0.520
DSRC-ATL	Exp. 1	0.558	0.687	0.693
	Exp. 2	0.565	0.680	0.745
	Exp. 3	0.566	0.683	0.732

of even one DSRC-equipped vehicle in the platoon will improve the performance of the whole platoon, thus giving better performance than Poisson arrival, where the arrivals of DSRC-equipped vehicles and arrivals of DSRC-unequipped vehicles are independent.

Hence, the performance improvement of the proposed scheme amounts to about 60% in terms of waiting time. Even when one considers the time to travel the physical distance from the 1st intersection to the 5th intersection also, the new DSRC-actuated Traffic Control Scheme provides a benefit of about 30%. This assumes a speed of 11 m/s (25mph) and a block size of about 125 m. When the total number of intersections on the arterial road exceeds 10 intersections, then the overall benefit is larger than 40%.

C. Rush Hour Performance

To see the performance of the the DSRC-actuated Traffic Control system during rush-hours, additional simulations were performed. The details of the scenario considered in our simulations and the assumptions made are as follows:

Assume an arterial road with 5 intersections and a major car flow on the arterial road (i.e., traffic in one direction during rush hour will be dominant compared to the other direction). The traffic crossing the arterial road will contribute a small amount to the total car flow. In our simulation experiments, the ratio of arterial car flow to orthogonal (crossing the arterial road) car flow is assumed to be 5:1.

In the simulations, we gradually increase the car flow for the DSRC-actuated traffic intersections and note that at around 3200 cars/hr the system approaches saturation. It is interesting to observe that the new system with DSRC-actuated intersections becomes half-full after 600 seconds; i.e., when t=600 s, and completely full when $t = 1800\ s$ (i.e., after 30 min). Hence, we set the simulation time as 30 min and repeat the experiment for 3 times. Then, we record the results of our simulation experiments. To make a fair and meaningful comparison, we use the same car flow and topology for normal traffic lights (TL) and randomly set the offset values between 5 intersections and then record the results. We again repeat the experiment for 3 times. The results obtained are shown in Table I. Hence, the average commute time of DSRC-Actuated Traffic Lights is 184.16 sec. while the average commute time of regular Traffic Lights is 340.26 sec. This corresponds to an improvement of about 46% which is quite significant.

As another performance metric, we have also measured the performance of the proposed system in terms of the system output rate (veh/s) over a period of 30 min. The results obtained are shown Table II.

As mentioned before, the period between 0 - 600 seconds corresponds to the regime when the arterial road becomes half-full at t=600 sec whereas the period 1200 - 1800 sec corresponds to the period when the arterial road becomes full slightly before 1800 sec. The results in Table II show that the proposed system provides an improvement of about 37.5% in terms of system output rate when the system gets congested. The same benefit is about 25% when the system is half-full.

D. Overall Performance

After quantifying the performance of the new system during rush hours and non-rush hours, we extended our experiments to a larger arterial road with 24 intersections, which corresponds to an urban road segment of 3 km. The main purpose of using this new scenario is to quantify the overall performance of a more realistic and significant route in urban areas throughout the day.

For this new scenario, it is assumed that 20% of vehicles will be equipped with DSRC radios. It is also assumed that during the rush hour, 5 of these 24 intersections will be in congested mode while the others are under heavy flow but not congested. Furthermore, it is assumed that drivers will have to drive on and off the arterial road and go through some unsignalized intersections as well. Assuming this time to be 2 minutes during non-rush hours (i.e., between 10 AM - 3 PM), 1 minute for midnight, and 5 minutes for rush hours, the results obtained are shown in Table III.

TABLE III

OVERALL PERFORMANCE OF THE DSRC-ACTUATED TRAFFIC LIGHTS IN TERMS OF AVERAGE COMMUTE TIME DURING A DAY

	7-9 AM, 4-6 AM (rush hours)	9 AM - 4 PM	8 PM - 6 AM
DSRC-ATL	14.2 min	8.8 min	8.9 min
DSRC-Equipped Vehicles	13.8 min	8.1 min	5.7 min
Unequipped Vehicles	14.3 min	9.3 min	9.7 min
Regular Traffic Lights	22.0 min	12.2 min	9.7 min

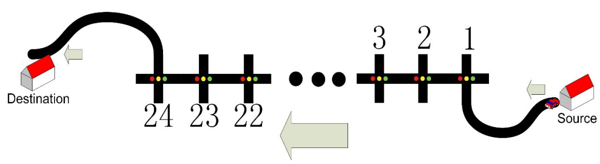


Fig. 7. Scenario showing an artery with 24 intersections with a source and destination.

The considered scenario is shown in Figure 7 and encompasses an arterial road which is 3 km long. Clearly, for most cities this is a significant route segment within a city.

Observe that the benefit of the new system proposed and the underlying trends are quantified for the whole day which involves three different regimes:

Table III shows that the benefit of the DSRC-Actuated Traffic Control system during rush hours (i.e., between 7 AM - 9 AM and 4 PM - 6 PM) is about 35.5%, while during the non-rush hour period of 10 AM - 4 PM, the benefit of DSRC-actuated new system is about 27.8%. Finally, in the third regime that encompasses the period of 8 PM to 6 AM, the benefit of the proposed system is about 8.3%.

E. Simulations Using a Real Map With Real Demand

Finally, we check our simuation model and assumptions with an independent set of data obtained from TAPAS, Cologne, Germany which involves a high level of realism. The road topology is imported from Open Street Map (OSM), and includes the whole city of Cologne, Germany. The traffic demand is generated by Travel and Activity Patterns Simulation (TAPAS). Since the topology of the data is real and the demand generated is credible, the scenario considered corresponds to a high degree of realism. We substitude the traffic light algorithm used at two chosen intersections with our traffic control scheme, intersection 286801827 (denoted as intersection A in the remainder of our paper) and intersection 365854 (denoted as intersection B in the rest of the paper). Intersection A is an intersection with medium balanced car flow while intersection B is an un-balanced intersection of an arterial road and a secondary road. The simulation is run on a set of 24-hour data, namely, the performance is evaluated over a whole day. The actual traffic signal plan in the map might differ from the real city and the actual arrival pattern might not be exactly the same as reality. However, since it uses a real map, with a highly credible demand generation model, the traffic volume and arrival pattern will be similar; hence, it's reasonable to conclude that the performance in the real intersection will be very similar.

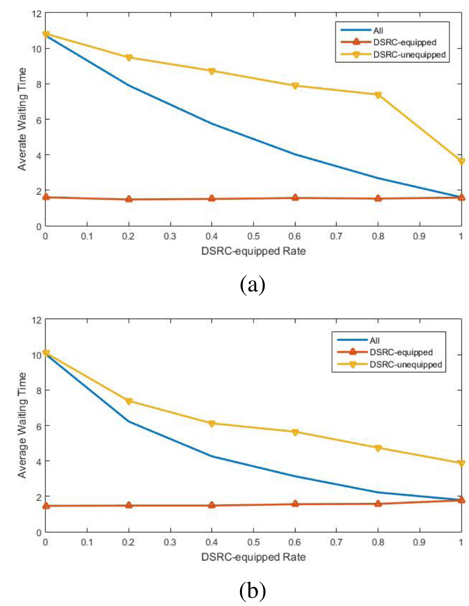


Fig. 8. Simulation result of waiting time on intersection A and intersection B from TAPASCologne 24-hour scenario. (a) Simulation result for intersection A. (b) Simulation result for intersection B.

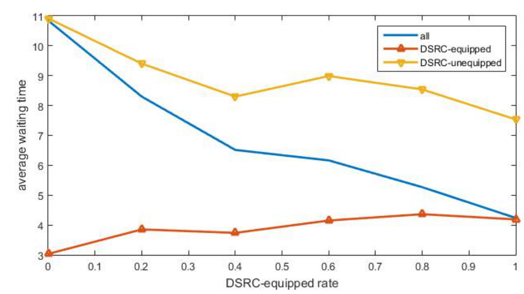
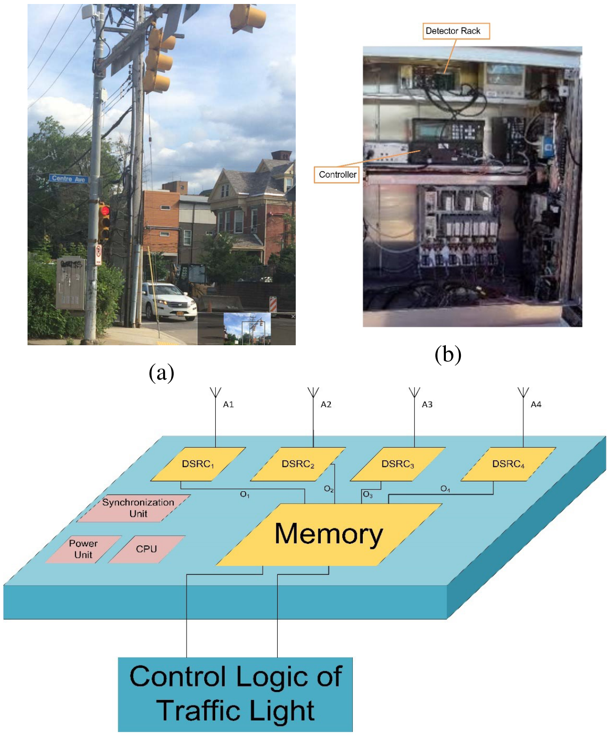


Fig. 9. Simulation result on collected vehicle arrivals at intersection of Shady Avenue and Northumberland Street in Pittsburgh.

Figure 8 shows the simulation results, where Figure 8a shows the result of intersection A and Figure 8b shows the result for intersection B, respectively. We observe similar trends as in Fig.5 This reconfirms the validity of our approach, assumptions used in the simulations, and the numerical results reported earlier in Section V-A.

We also collected empirical data on the traffic arrivals to intersections on Shady Avenue and Northumberland Street in Pittsburgh, PA, on November 28, 2017. The result is shown in Figure 9. One can observe similar trends in Figure 9 as reported in the previous sections of our paper. These 2 new independent simulation results using real traffic data thus provide strong evidence on the validity of the approach used, the underlying model and assumptions used in the simulations, and the numerical results obtained. The consistency we observe in the results obtained is excellent.



(c)

Fig. 10. One of the possible system implementations showing (a) the location of Control Box [14]; (b) the subsystems in the Control Box [14]; (c) and how the line card will interface with the 4 Antennas and the controller. In Figure 10c observe that the line card will have 4 DSRC radio transceivers (chips), a memory unit, a power unit, a synchronization unit, and a CPU in addition to all the other necessary electronics.

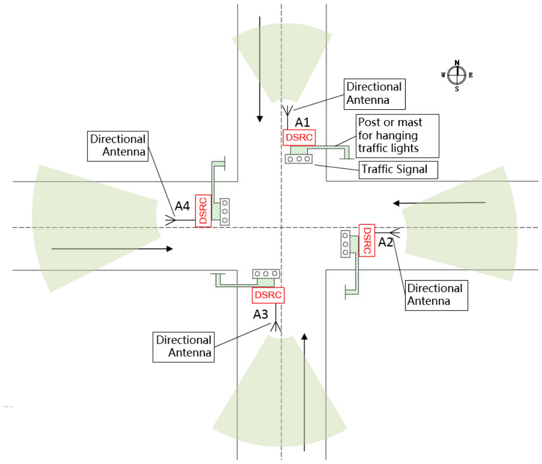


Fig. 11. A different system implementation of DSRC-actuated Traffic Control where the four DSRC receivers are placed on the mast arms of an intersection supporting the existing traffic signals. The coverage area of directional antennas are shown with green cones. While in this figure A3 is shown to detect the presence of DSRC-equipped Northbound vehicles, with the necessary RF arrangements, it should be clear that one could easily use A1 (instead of A3) to detect the DSRC-equipped vehicles that are moving to the North (Northbound). Similarly, while in the figure A1 is detecting Southbound vehicles equipped with DSRC radios, one could use an alternative configuration as well whereby DSRC-equipped Southbound vehicles can be detected by A3.

VI. Discussion

One of the possible system implementations of the proposed approach is depicted in Figure 1. In this configuration, 4 directional antennas are placed on the mast arms holding or supporting the current traffic lights. While the underlying geometry could vary from intersection to intersection, placing the antennas on the 4 mast arms could be a viable solution. These antennas are then connected to their corresponding DSRC receiver (one DSRC receiver per antenna) through some wiring. As an example, it is possible to put these 4 DSRC receivers (essentially DSRC transceiver chips) with all the associated electronics and control circuitry onto a single board and place this board as a "line card" into the Detector module of current Control Boxes that exist at every intersection equipped with traffic lights.

This "line card" implementation is very attractive as the bulk of the solution can be placed into the control box that exists at every traffic light in a very non-invasive manner. This minimizes the additional equipment that will be installed on the outside mast arms or traffic lights. Figure 10 depicts this system implementation and the relevant systems and subsystems:

It is worth emphasizing that several other system implementations are also possible. For example, due to the bandwidth and attenuation characteristics of the wires or cables used to connect the antennas to DSRC radios placed on a "line card" in the Control Box (see Figure 10), it might be necessary to use down-converters (microwave mixers) to bring down the frequency of the BSM arriving at 5.9 GHz to a level that can be transmitted or carried by the wiring used (e.g., twisted pair, coaxial cable, etc.).

We emphasize here that these are not the only possibilities for the system implementation of the proposed approach. Several other options for implementing the same approach and solution are clearly possible without changing the essence or the core ideas of our approach. Another attractive option for system implementation is shown in Figure 11. In this case, as opposed to the "line card" solution depicted in Figure 10, the 4 DSRC radios are placed on the mast arms. Once they detect the presence of DSRC-equipped vehicles in the corresponding approach, their decision is transmitted to the Control Box in binary form (ONE for the presence and ZERO for the absence of DSRC-equipped vehicles). The processing for deciding the right-of-way is still done in the Control Box based on the binary information transmitted by each DSRC radio to the Control Box.

One of the key advantages of the presented new approach is the fact that it does not need *all vehicles* to be equipped with DSRC radios. Even with a low percentage of DSRC-equipped vehicles (e.g., 20%), the benefit of the new scheme is significant. This is important as the current industry projections predict that it might take several years before 100% penetration of DSRC radios becomes a reality in many countries. However, DSRC-actuated traffic control works well even for low levels of penetration.

It is worth mentioning here that when there are no DSRC-equipped vehicles at an intersection, the system behaves in exactly the same way as the current timer-based traffic lights. This shows the flexibility of the proposed scheme.

The modifications needed for implementing our scheme on existing traffic lights are not large or prohibitive. With simple off-the-shelf DSRC radios, antennas, and software geared towards DSRC-based sensing, actuation, and decision making, the current traffic lights can be rendered "intelligent" while keeping the existing infrastructure related to traffic lights intact. This is a significant advantage. The simplicity and off-the-shelf nature of the required modifications also makes our approach a very *cost-effective* solution for mitigating traffic congestion when one compares it with well-established technologies such as loop detectors and cameras. The prototype of this system has been built and publicly demonstrated in Riyadh, Saudi Arabia, in July 2018 [52].

Another major advantage of the DSRC-actuated traffic control scheme is the fact that it might not need GPS information for proper operation. However, the hardware and software platforms of the proposed scheme could easily incorporate GPS information for other functionalities if need be.

The DSRC-Actuated Traffic Control scheme proposed in this paper can also be used profitably for autonomous vehicles. More specifically, DSRC-equipped autonomous vehicles will experience a reduced commute time with the proposed solution which is a significant benefit.

Finally, as the ratio of DSRC-equipped vehicles in a city increases to 100%, the overall performance of our scheme asymptotically approaches the performance of the VTL scheme. This shows that the DSRC-actuated traffic control is a viable alternative and offers a transition to the VTL scheme.

It is worth mentioning that the simulations used to evaluate the performance are under the assumption of ideal channel conditions, which may not be the case for some of the real-world implementations. It is important to understand the effect of channel imperfections to the overall system performance. Further research is needed to quantify the impact of such imperfect communications between vehicles.

It is also worth mentioning here that while the proposed system works really well for most of the practical scenarios in real life, it is not clear whether the system performance can reach the optimum. This suggests that new efforts for optimizing the performance of the proposed scheme would be interesting future work. More advanced algorithms have been proposed in our recent research based on Reinforcement Learning algorithms [53]. However, the approach and the underlying DSRC-Actuated Traffic Control algorithm proposed in this paper is much simpler and easier to implement, and, therefore, is a very attractive solution.

VII. Conclusions

In this paper, we have proposed a new approach to traffic control at signalized intersections. This approach proposes *communications-based traffic control* at intersections which is radically different from traffic control currently employed by vast majority of traffic lights in the world since they are essentially timer-based devices and they do not use communications between vehicles and traffic lights for decision making. More specifically, the proposed new approach leverages the use of DSRC radios broadcasting BSM every 100 ms for making the operation of current traffic lights "intelligent" and adaptive. By exploiting this broadcast communications mechanism, the traffic lights at a given intersection become aware of the presence of DSRC-equipped vehicles in one or more of its approaches and give priority to those approaches by displaying the green light to those approaches that have DSRC-equipped vehicles. Consequently, the green phase is actuated by the presence of DSRC-radios and this actuation completely changes the fixed-time green light phase currently employed by traffic lights.

It is shown that the waiting time at an intersection with traffic lights can be reduced significantly. This can reduce the average commute time of urban workers during rush hours significantly.

One of the key advantages of the proposed new approach is the fact that it does not need all vehicles to be equipped with DSRC radios. Even with a low percentage of DSRC-equipped vehicles (e.g., 20%), the benefit of the DSRC-actuated new scheme is significant. The modifications needed for implementing the proposed scheme on existing traffic lights are not large or prohibitive. With simple off-the-shelf DSRC radios, antennas, and software geared towards DSRC-based sensing, actuation, and decision making, the current traffic lights can be rendered "intelligent" while keeping the existing infrastructure of traffic lights intact. This is a significant advantage. The simplicity and off-the-shelf nature of the required modifications also makes the proposed solution a very cost-effective solution for mitigating traffic congestion when one compares it with alternative technologies such as loop detectors and cameras. In addition, the proposed solution can also be used profitably for autonomous vehicles. Finally, as the ratio of DSRC-equipped vehicles in a city increases to 100%, the overall performance of the DSRC-Actuated scheme asymptotically approaches the performance of the well-known VTL scheme.

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