Fuzzy Logic Based Traffic Surveillance System Using Cooperative V2X Protocols with Low Penetration Rate

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***Abstract*—In this paper, we studied the relationship between Vehicle Total Time (VTT) and the traffic conditions for signalized intersection. VTT is the duration that a vehicle remains associated with road side unit RSU through group leader. As the vehicle travels along an intersection and encounters different degrees of delay (i.e. different traffic conditions), the value of VTT varies accordingly. Intuitively, the higher value of VTT indicates the worse degree of traffic condition. This study, investigates the ways to estimate the traffic condition of an intersection based on the measurements of VTT taken from Vehicle to Everything V2X protocol of the COLOMBO project. Specifically, we estimate the traffic conditions of an intersection based on average speed and its derivative (acceleration) using fuzzy logic. The proposed method is evaluated using a well known network simulator benchmark (ns3). The simulation results reveal that VTT can be used with data fusion techniques to estimate the traffic conditions of an intersection with good accuracy even under low penetration rates (PR). This is comparable to a similar technique used in COLOMBO to abstract the traffic conditions of an intersection based on average speed. As a result, this study suggests a potential use of VTT as traffic indicator for signal control design in the future work.**

I. Introduction

The need for wide area traffic surveillance to capture traffic dynamics has led to the growing interest in vehicle adhoc networks VANET communications. Such emerging cooperative techniques, like Vehicle-to-Everything V2X communication, open new channels for delivering information. It is necessary that such information have a good accuracy with limited V2X communication capable vehicle PR. This paper proposes a traffic surveillance technique capable of estimating traffic conditions of an intersection with low V2X communication capable vehicle PR that can be directly used for signal control design.

Traffic surveillance using V2X communication is merged very recently[1]. For instance, the FP7 COLOMBO project[2] used V2X protocols for smart traffic lights in order to determine traffic surveillance information about local queue length, with the goal to use such traffic indicators to dynamically adapt traffic light control. COLOMBO project deal with two traffic management topics: traffic surveillance and advanced traffic light control algorithms using cooperative data. In this paper the first topic is analyzed for the purpose of replacing traditional detection V2X protocols using the more detailed information that cooperative detection can offer. Traditionally, the main function of this detection for adaptive control is the estimation of queue length and arrival patterns. Ideally, a birds-eye view of the traffic network with speed, position and route information about each vehicle should be available. Using this information the traffic light controller knows exactly how many vehicles are waiting or approaching each signal group. Both traditional detection V2X protocols and standard cooperative systems cannot deliver this[3] even with full PR. This means that traffic control algorithms rely on estimation of traffic conditions to divide the arrival flow between signal groups. COLOMBO uses swarm intelligence algorithm to estimate the abstract of this traffic condition (called it pheromone) based on average speed. Swarm intelligence, as an optimization algorithm taking inspiration from the collective behavior of social insects such as ants, is time consuming and requires a lot of traffic data to be aggregated in offline (i.e. static) or online (i.e. dynamic) approach. One drawback of these approaches that rely on traffic condition estimation comes from defining the sample aggregation areas. In offline approaches[4], [5], [6] the challenge is to determine the area length that is neither too large nor too small. Online approaches[7], [8] adjust to true traffic conditions, the challenge is to dynamically build and maintain clusters and cluster leaders. Another issue, to avoid same vehicles impacting different traffic conditions in space or time, traffic conditions need to be mutually exclusive.

In this paper, an online strategy is followed. The physical relation between the data dissemination time of each vehicle and the underlying traffic speed/density observed by COLOMBO project is used for estimating the traffic conditions. Fuzzy logic with data fusion technique is used to avoid same vehicles impacting different traffic conditions in space or time. This is done by differentiating between approaching and leaving flow condition for each cluster (or group) based on average speed and their derivative (acc./deceleration) through online time updating with respect to their traffic density.

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The simulation results show that the proposed technique is superior to the Swarm optimization technique used in COLOMBO project. Compared to COLOMBO project, in the proposed technique determining the traffic conditions does not require any optimization and therefore it is a more simple task.

The rest of this paper is organized as follows. In section 2, a selection of existing research efforts in the field of traffic surveillance using V2X protocol is presented. The proposed protocol is also explained in this section in an abstract perspective. In section 3, the protocol performance and reports the primary experimental results obtained so far are analyzed. Comparison with COLOMBO project approach is presented in Section 4. Discussions on ongoing research and concluding remarks are given at the end of the paper.

II. Traffic Surveillance using V2X protocol

Cooperative V2X technology can monitor an intersection approach continuously and thus provide extensive information of approaching vehicles. V2X capable vehicles frequently transmit a Cooperative Awareness Message (CAM) containing all required relevant information (e.g. speed, position, ...etc.). A convenient method to acquire data from cooperative vehicles is to receive CAM messages with Road Side Units (RSU). After receiving the message, the RSU extracts the most important information that is suitable for a traffic light controller.

A. Related works

In most countries, especially in the United States and Europe, several researchers are worked on traffic surveillance of intersections using V2X protocols. Generally speaking, two different approaches for traffic surveillance can be observed: topology based or dissemination based. This observation based on whether knowledge of the traffic conditions related with messages dissemination time of V2X protocol or not. Topology-based approach is based upon clustering vehicles for a compress description of the traffic condition. This is capable for determining traffic efficiency performance indicators without involving a RSU. Therefore, it may be applied for monitoring parts of the road network with a sparse RSU coverage for computing average speed and number of vehicles. In this context, by elected leaders [9] explored the benefits from local preprocessing of GPS probe data. While [4], [5] divide roads into fixed sections, to consolidate traffic volumes in vehicles, either directly or through a zone leader. Another example, [1], [10],[11], [12] let a sampler (or group leader) to estimate traffic density by broadcast a message and count the returned messages. Similar approaches, [6],[7], [8] showed to be more adapted to dynamic traffic by clustering vehicles according to similar properties rather than static road. [13], [14] use the V2X Local Dynamic Map (LDM), populated by periodic CAM/Basic Safety Message (BSM) to estimate local traffic conditions.

On the contrary, in dissemination based approach no counting is needed, vehicles send messages and the density/speed can be estimated using message propagation speed (e.g. [15]), which may be implemented on top of n-hop communication protocols. Studies presented in [16],[17],[18], [19] characterized the relationship between traffic density and information dissemination delay under the assumption of an exponential inter-distance, and prove the existence of a density threshold below which dissemination is linear, and above which dissemination becomes exponential. The exponential inter-distance with any general distribution is relaxed by [20]. Further investigation on this relationship is done by [21], [18],[22] and the impact of a low PR of the V2X technology on the dissemination speed had been modeled.

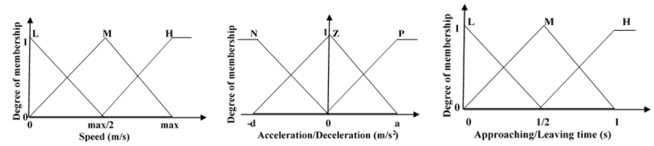
B. Our approach

In this paper, we propose to follow a new strategy by using message dissemination time as well as average speed and number of vehicles to estimate the traffic conditions. Unlike [23], we propose to use RSU to evaluate traffic conditions rather than vehicles. Unlike [24], we propose to use fuzzy logic to evaluate traffic conditions for each direction of an intersection rather than traffic congestion for each vehicle in highway scenario. And finally unlike COLOMBO traffic surveillance algorithms [2] that uses swarm optimization algorithm to abstract adapted traffic condition, we do not use any optimization algorithm and get adaptable results in comparison with them. Our approach uses the V2X protocol that is also used in COLOMBO project, mainly for average speed estimation purposes, to monitor the road traffic conditions. These conditions are monitored locally by the RSU of an intersection. However, in contrast to COLOMBO, we employ fuzzy logic to locally detect a potential direction traffic condition. When a different direction situation is detected, we sum the individual estimations made locally by different directions to collaboratively and accurately detect and characterize the whole intersection traffic conditions.

1) Traffic conditions local estimation: From an abstract perspective, our protocol operate as in [1]. Protocol in [1] can be summarized in two protocol sets: group formation and group life-cycle management. Group formation protocol set consists of two main phases: the first one adopts a simple flooding protocol to discover and activate all nearby vehicles that can be grouped together (i.e., that are traveling along the same path), while the second phase takes over the group leader election. In group life-cycle management protocol set the leader is responsible for harvesting and processing the available sensor information from all the group members as well as determining when the group can be safely disposed. Since positions of vehicles are neither lane level accurate nor accurate enough to determine the exact amount of vehicles at a certain distance to the stop line. We used their estimated number of vehicle per direction to estimate the approaching time and leaving time for whole approaching and leaving directions respectively. Also, [1] protocol keeps the times at which a vehicle entered and left the communication range for ***group life cycle management***, in our protocol the VTT can be computed (as done in COLOMBO framework but not used), albeit only for the roads that are within the communication range. Still, one further issue should be named. The VTT can be only directly computed if a vehicle passes the communication range or direction within it completely. In order to overcome this issue fuzzy logic with data fusion technique have been introduced to differentiate between "approaching time" and "leaving time". This will be done in the RSU so that the summation of them (i.e. approaching and leaving time) can be evaluated with VTT extracted from ns3 benchmark continually. Thus, VTT can be defined as the duration that a vehicle remains associated with RSU directly or through group leader. Approaching time can be defined as the time required for each vehicle to approach to the RSU. And finally leaving time can be defined as the time required for each vehicle to leave the RSU. For each second the information of the group is sent to the RSU that joins the intersection. The RSU use the incoming information including VTT as an indicator for estimating the traffic conditions by estimating approaching and leaving time continuously. As the vehicle travels along an intersection encounters different degrees of delay (i.e. different traffic conditions), so the value of VTT varies accordingly. Intuitively, the higher value of VTT indicates the worse degree of traffic condition. When introducing a fuzzy logic, it is possible to detect the halts of equipped vehicles based on their average speed and derivative (acceleration/deceleration). As previously explained, each RSU implementing our solution to estimates its local approaching and leaving time based on its average vehicles speed and their derivative (acceleration/deceleration). The average vehicles speed can be easily obtained from the [1] protocol. We used a discrete derivative,since our system is discrete, computed as the difference between the average speed at two subsequent time instants divided by the interval between them (since our solution follow the COLOMBO's one for the sake of comparison we also use time steps of a fixes length of one second, i.e. the division is always by 1). Therefore, in each road (i.e. direction) we can estimate its approaching and leaving time in terms of its average vehicles speed and their derivative, and then feeds these values into the fuzzy system. The input variables, as in any fuzzy system, are first classified into different categories or fuzzy sets. Possible fuzzy sets for speed are L for low, M for medium, and H for high. For speed derivative, the defined fuzzy sets are N for negative, Z for zero, and P for positive. In addition, output fuzzy sets corresponding to approaching and leaving estimated time have also been defined for one second time span, with L for low, M for medium and H for high. One of the main particularities of fuzzy logic is that a fuzzy set can contain elements with partial degree of membership, and consequently, an input value can belong to several fuzzy sets at the same time. For example, a speed value of 6.9445m/s (i.e. with maximum speed equal to 13.889m/s) could be member of both medium and low/high speed fuzzy sets. membership functions are employed, in order to determine the degree of membership of the input values to each of the fuzzy sets. The membership functions used in our solution have been implemented based on simple rating system, illustrated in Fig. 1(a), Fig. 1 (b) (with average acceleration a=2.8 and deceleration d=4.8 determind from [25] based on simple rating) and Fig. 1(c). Finally, fuzzy rules that relate input (speed and its derivative) and output fuzzy sets (approaching and leaving time per second) have been established and are displayed in Table I. The fuzzy rules have been designed based on the speed, its derivative and approaching/leaving time physical relationship. For example:

If Speed is *H(igh)* and it's Derivative is *P(ositive)* then Approaching time is *L(ow)* and Leaving time is *L(ow)*

As Fig. 1(c) illustrates, the output of the fuzzy system is a continuous value within one second interval [0,1] indicating the approaching and leaving time per second.



(a) Speed sets (b) Derivative sets (c) Output sets

Fig. 1: Fuzzy-based estimation system

TABLE I: Fuzzy rules relating input (speed and its derivative) sets with output (approaching and leaving time) sets

Approaching time/ Leaving time		Speed Derivative		
		N	Z	P
Speed	L	H/L	H/L	M/M
	M	H/L	M/M	L/H
	H	M/M	L/H	L/L

2) Online adaptation with data fusion technique: The proposed approach allows online evaluating the individual estimations that different participating directions make locally. As described in the previous section, every RSU in an intersection continuously monitors the individual traffic conditions for each direction, and estimates through the fuzzy-based system the current estimation of approaching and leaving time. Only when the sum of the traffic estimation exceeds a predefined VTT, RSU activate the cooperative traffic information update with data fusion mechanism. VTT corresponds to the sum of approaching and leaving time, to be monitored for each direction, varied depending on traffic management policies. Our solution does not generate any additional communications overhead when traffic conditions are normal or not, since the data fusion procedure is launched without any additional information. The data fusion mechanism is based on messages which are exchanged when the leader updates the group fused data and sends it to the corresponding RSU. These messages are employed to send local number of vehicles estimated made by different directions (i.e direction in [1] protocol), and VTT for each vehicle left the corresponding direction. In addition, and as novelty with respect to other proposals, the quantity of last vehicles updating is also exchanged to quantify the average level of approaching and leaving time estimation and its value. To this aim, message updates the traffic information included in the packet based on its own approaching and leaving time estimation. Finally, RSU situated in the center of an intersection will get a global and complete vision of the level of approaching and leaving time for whole the intersection. In order to determine the value of all the incoming and outgoing direction of the intersection, estimated approaching and leaving time averaged respectively. A key aspect in our solution is to identify the approaching and leaving time (i.e. VTT) close to the RSU of the intersection that will change the data fusion procedure. Data fusion technique defines a procedure that is open for further optimization. For example, which vehicles that have recently passed the stop line or stay in the traffic jam direction, will be responsible for increasing (or decreasing) the VTT values of the next vehicles. To this aim, every road direction evaluates its local traffic estimation for a certain period of time. The road direction is considered to have increase value of approaching and leaving time. This is done if its previous local estimations sustainable reported some stayed vehicle from previous cycle. Thus, such intersection controller is not operated well to clear all the vehicles. The vehicles at the stop line of the corresponding direction will periodically generate VTT messages at a configurable frequency rate which allows selecting the periodicity of the traffic information updates. Since our solution has to be robust to low PRs, instead of using the number of cars only, the updating of approaching and leaving time is also computed with suitable traffic measurement for each direction. The current approach for measuring traffic associated to each direction is called CTF (Cars-Times-Fuzzy). Every direction has a counter associated to it that is either increased by approaching time when the direction has red light or decrease by the leaving time after the related direction is executed in green light. This counter is updated according to the following equation:

$$CTF_d(k) = CTF_d(k-1) + Cars_d(k) * F_d(v(k), k);$$
$$CTF_d(0) = 0$$

where $CTF_d(k)$ is the new value of the CTF counter for direction d, $CTF_d(k-1)$ is the value of the counter at the previous time-step and $Car_d(k)$ is the number of cars on the target direction d, and finally $F_d(v(k), k)$ is the estimated approaching time for red light period and the estimated leaving time for green light period respectively.

III. Simulation Results

For evaluating the protocol, a simple scenario consisting of one intersection was taken from COLOMBO simulation system (called Rilsa intersection [25], as shown in Fig. 2). This is done for two reason, comparability and traffic realistic (although it is synthetic but traffic is configured to be realistically reflect urban intersection traffic, and has been used as a baseline traffic scenario in COLOMBO). The quality of the performed surveillance is not effected by neither infrastructure nor traffic light settings. The time-space patterns (such as the number of vehicles on the regarded road or their speed) are quite complex yielding in strong fluctuations of the performance indicators (i.e. approaching and leaving time), due to being limited by the traffic light.

All communications, at the network level, are performed by the ns-3 standard **yans** WiFi model using IEEE 802.11p with ETSI ITS G5 standards. A 6 Mbps bandwidth rate with OFDM and default log-distance propagation model is used to compute signal loss. The main configurations and parameters used in our simulations reported in Table II. concisely.

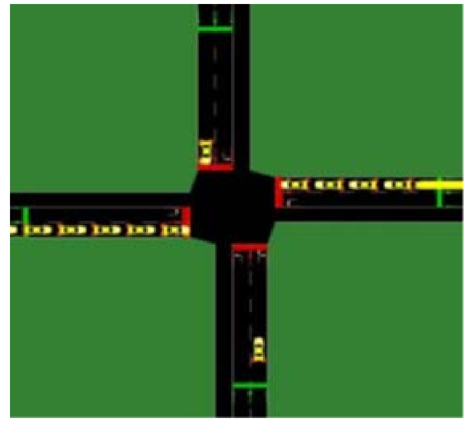


Fig. 2: RILSA Intersection from [25]

TABLE II: Communication parameters configuration used

Parameter	Value
Wifimode	802.11p
Transmission mode	6 Mbps (OFDM)
Node radius	170 m
Propagation loss	Logarithmic
Propagation speed	Constant ($3*10^8$ m/s)

We use SUMO as the urban mobility simulator to supply our simulation environment, considering that ns-3 does not provide a realistic model to simulate vehicular behavior in a city network. All simulations were performed in the same one hour time span. Vehicle densities change during time according to a wave trend that follows the green and red timings controlled by the traffic light. In a first step, we compare the VTT from COLOMBO-ns3 framework with the estimated one (i.e. summation of approaching and leaving time from our solution) with real number of cars (i.e. 100% PR with precise position data) in order to test fuzzy system ability to reflect traffic conditions. In a second phase, in order to evaluate the capability of our solution to follow and emulate realistic conditions with localization affected by errors,we make PR vary (from 100% to 10%) with position sampling error using COLOMBO framework. Relates to the first step,

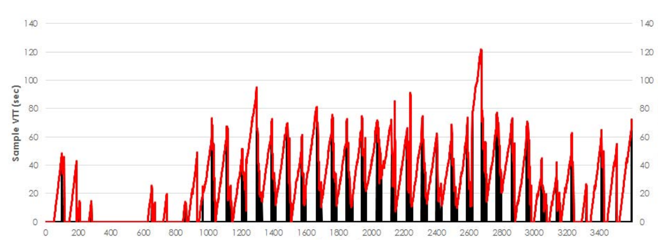


Fig. 3: Estimated VTT with Sample VTT for one direction

Fig. 3 depicts the VTT raw samples received by the RSU (black line) with the estimated one from our solution (red line). We can observe that our fuzzy system estimate the VTT accurately and continuously. Another important notice, our estimated solution does not drop to zero as the sample VTT in cases where the vehicles need more than one cycle to leave the intersection (e.g. between 1000 and 3400 sec in Fig. 4). Although at some situation (e.g. between 2400 and 2600 sec), it seems does not react to large varying states but having a look at the real number of cars in Fig. 4, we can see that this comes from the fast increase in traffic density (i.e. real number of cars with time). For the second phase, Fig. 4 depicts the real number of cars approached and estimated by COLOMBO framework (black line) with the approaching time estimated from our solution (red line), with a 170 meters range from the inspected RSU. This value of 170 meters is chosen to match the maximum communication range of a mobile node used in COLOMBO framework.

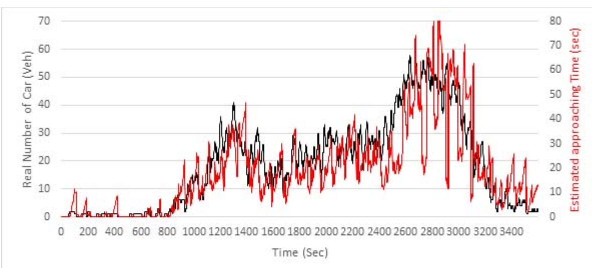


Fig. 4: Approaching time estimated with real number of car

The same thing can be done for the whole leaving directions for Rilsa intersection as shown in Fig. 5.

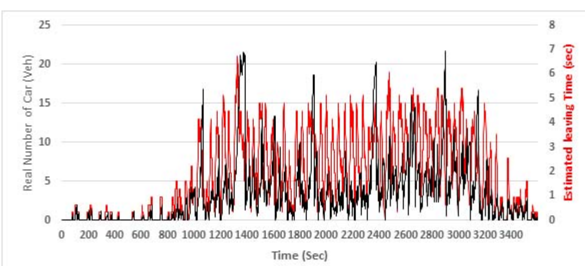


Fig. 5: Leaving time estimated with real number of car

In addition, other relevant experimental results that we collected refer to the investigation of our solution behaviors with different PRs shown in Fig. 6.

IV. COMPARISON

In order to have a simple comparison with COLOMBO results, Fig. 7 depicts the pheromone that was computed with COLOMBO project by the following equations:

$$f_l(k+1) = f(k) + v(l,k); f_l(0) = 0$$
$$\text{where } v(l,k) = \frac{(maxSpeed(l) - MeanVehicleSpeed(l,k))}{\frac{dMeanVehicleSpeed}{dk}}$$

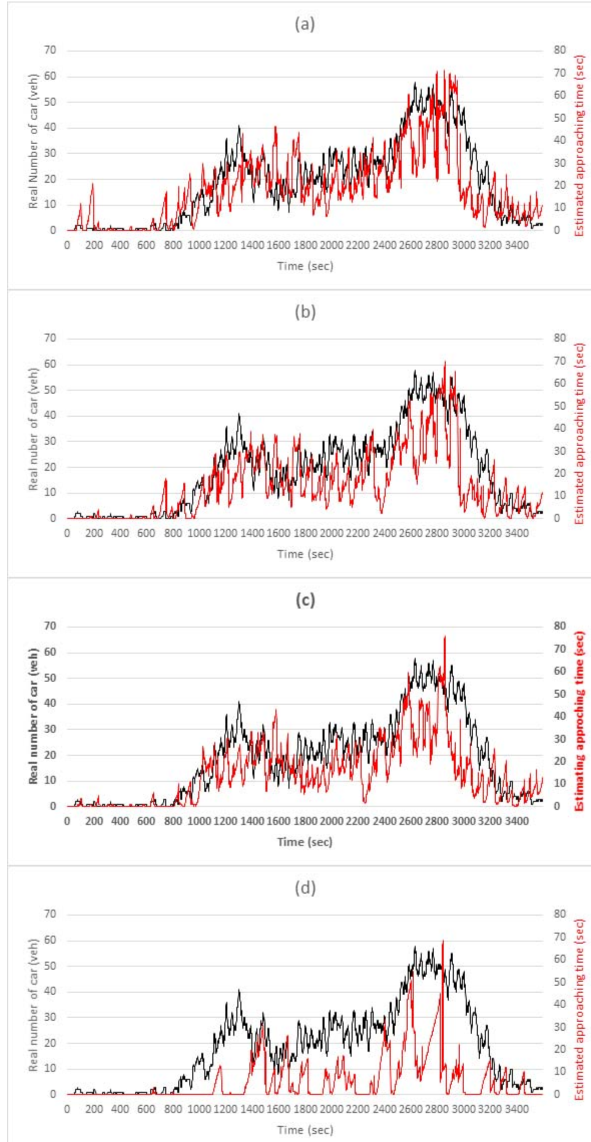


Fig. 6: Approaching time estimated with (a)100%, (b)50%, (c)20%, and (d)10% PRs

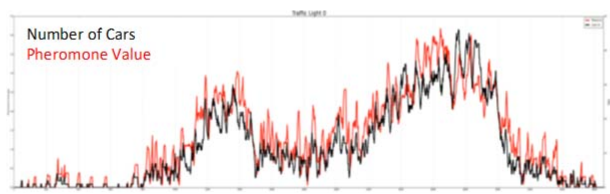


Fig. 7: Depicts the pheromone value and the real number of cars. Taken from [2] COLOMBO D7.6 final report

From our simulation results, a simple comparison can be made between our traffic surveillance solution and COLOMBO's. In Table III the main differences between them are summarized.

TABLE III: Main differences between our solution and COLOMBO

Characteristics	COLOMBO	Ours
Approaches followed	Topology-based or Dissemination-based	Topology-based and Dissemination-based
Data required	Speed and/or Number of Vehicles	Speed, Number of Vehicles As well as vehicle total time
Surveillance data type	Pheromone	Approaching and leaving time
Algorithm used	Swarm intelligence	Fuzzy logic
Disadvantage	Time consuming with optimization	Without optimization
Advantage	Dynamically adapted with traffic flow	Dynamically adapted with traffic flow
Penetration rate	Effected	Not effected a lot
Data quality	Close to benchmark (SUMO)	Close to benchmark (COLOMBO, more specifically ns3)

V. Conclusion

Our traffic surveillance solution includes several simplifications compared to the one used in COLOMBO project. Consequently also some of the COLOMBO's traffic surveillance are used in ours. The optimized procedure in COLOMBO however, is often not relevant to the calculation of traffic surveillance data. Our solution can exchange data even only when one vehicle is under the RSU's communication range. This motivates the solution to be used even for rapid decrease of the number of vehicles. At the same time, focusing on approaching and leaving time measurements are less dependent on the PR; in fact, as shown in Fig. 6(d) following the closely real behavior up to 20%, and having reasonably good results. As shown, already deployed V2X road side units can be a source of information about traffic efficiency. The PR is the major factor that influences the quality of the surveillance, but as well the aggregation interval (for both approaching and leaving time) to report should be taken into account. One obvious issue where no equipped vehicle was sensed is the lack of data for that intervals . Depending on the aggregation interval's duration and the PR, the probability to have no data for an interval will be changed. For this reason, low PRs show lack of data at times where no equipped vehicle has been within the communication range. As a result, our solution can provide the traffic light controller with a fairly good estimation of the approaching and leaving time with real traffic flow. These results were confirmed using simulations. Further investigations should be performed that use our solution to evaluate the performance under more realistic conditions.

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