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On the V2X speed synchronization at intersections: Rule based System for extended virtual platooning

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Abstract

Autonomous vehicles that are able to communicate together allowed the emergence of a new way of controlling intersections. Recently an active research community stakes on cooperative intersection management. Vehicles and intersection are able to communicate together in order to improve traffic condition at intersections. Many simulations have shown that the cooperative intersection management outperforms traffic lights because there are no limited stages as within traffic light and authorized movements are adapted to the current situation. This paper focusses on speed synchronization at intersections. More precisely, a virtual platoon is formed by vehicles coming from different lanes. When traffic rate is low this allows avoiding useless stops and thus the speed synchronization saves energy and increases the average speed. However, experiments showed that some parameters need to be considered. Hence, as the traffic rate grows, vehicles need to stop and speed synchronization is no more efficient. The main reason of this drawback is that the studied concepts are limited to First Come First Served or to First Out First-Served. This paper extends the virtual platooning, where new rules form new virtual platoon able to adjust dynamically the whole behavior according to the traffic flow growth under safety conditions. Simulations based on real-world experiences show that the proposed approach is very efficient by increasing the average speed while keeping a high capacity of the intersection.

Keywords: Cooperative Intersection Management, Virtual Platoon, V2X, Rules based System

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1. Introduction

With the core status in the urban traffic system, intersection management has taken a big part of research attention. The most available in the literature are traffic lights, which has helped to improve the traffic condition at intersections. However, with the constant increasing mobility and societies, new challenges have posed to traffic lights. Besides, due to the fact that with complex, changeable and randomosity traffic features, traditional traffic controls are unable to meet the traffic demands. The emerging technology that deploys in vehicles and in the intersection control system can improve the availability. Indeed, vehicles are more and more self-controlled and they are able to communicate with the surrounding vehicles and infrastructures. The wireless technologies with positioning systems have received a great attention since they offer the tremendous opportunity to connect the vehicles, the traffic environment and the control system. As a consequence, by means of the application of new technologies, an active research area, Cooperative Intersection Management, is open up.

Within Cooperative Intersection Management, its embrace remarkable novelties compared to traditional traffic control system. Firstly, instead of only city involving in traditional traffic control decision, each vehicle instantaneously participates to the decision making process. In this way, each vehicle can be considered individually, and contribute to improve the traffic conditions according to the current observed situation, for instance by yielding its right of way or by forcing the way. From this point of view, few simple rules applied individually by each vehicle can contribute to a whole efficient behavior at the intersection. Indeed, on the one hand the traffic is changing and vehicles arrive randomly. On the other hand a global optimization is time consuming because the problem is NP. Hence, it is hard to change the decision according to rapid traffic variation.

This paper assumes that vehicles are connected and adapt their speed according to other vehicles into the intersection as we have shown in ITS World Congress in 2015, where three connected driverless vehicles share an 8-shaped circuit by synchronizing their speed [1, 2]. Speed synchronization is very interesting to avoid useless deceleration and acceleration. However, the main issue is that at a high traffic rate speed synchronization is not able to perform as well as expected [3]. In this paper vehicles are able to change their ranks by themselves in order to pass before than expected. The proposed rule aims to face different traffic rate scenarios.

This paper is organized as follows. The next section gives a brief recall of the cooperative intersection management. The third section introduces speed synchronization and gives the rules. Next simulation results are presented before conclusion.

Nomenclature

V2V	Vehicle to Vehicle communication
vplps	vehicles per lane per second
vps	vehicles per second

2. Brief literature overview

Cooperative Intersection Management means that each vehicle communicates with other surrounding vehicles to obtain a right of way (see Fig 1-a). More recently, the intersection manager (RoadSide Unit: RSU) is used to avoid collision. Indeed, it allows checking the consistency of the presence list. The right of way can be a simple semaphore green or red as presented in Fig 1-b and Fig 1-c. In this case many approaches are proposed to decide the best set of vehicles that are allowed to cross simultaneously the intersection [4,5]. More complicated right of way relies on cooperative cruise control. Vehicles adapt their speed to avoid colliding with all conflicting vehicles. There are many speed synchronization protocols in the literature. In [6, 7] vehicles reserve the time they occupy the potential zone of collision. Other noticeable contributions are based on acceleration communicated by the intersection (RSU) to vehicles that must slow down [7,8]. Other papers rely on the presence list on which the rank determines the precedent vehicles that should be considered to avoid collision (see Fig 2). This is called sequence-based protocol [8]. In all cases the vehicle should adapt its speed with conflicting vehicles.

Some contributions delay a given set of vehicles by using centralized optimization approaches. However the problem is NP [4]. Hence, the optimization is based on heuristics and mainly on the cooperative cruise control approach. First Come First Served (FCFS) as well as First Out First Served (FOFS) are used. In the FCFS, The vehicles leave the intersection with respect to the order they arrive. FOFS means that vehicles able to cross the intersection first are scheduled first. FOFS results from the reservation protocol. Simulations show in many papers that cooperative speed synchronization is very efficient at low traffic flow. In order to extend the traffic efficiency of speed synchronization approach, the acceleration function was improved in [5]. However simulations were limited to no more than 0,18 vehicle per lane per second.

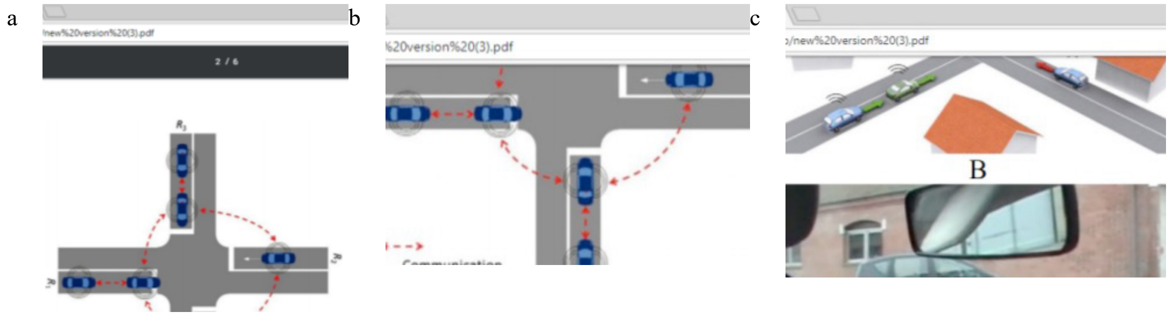

Fig. 1. (a) Cooperative Intersection Management; (b) Simulation of semaphore-based approach (c) Real tests of semaphore-based approach.

However, the performance decreases by the increasing traffic rate in such a way that we obtain more interesting results by semaphores [8, 9, 10]. Many experiences have shown that that speed adaptation with vehicles coming from other corridors (setup time) requires more time than just following a leader car in the same lane (heading time). Even if this time is less important than in semaphore based approach, it hinders the release of vehicles when the traffic flow is high. Hence, the main issue is how to change the rank of cars in the presence list to improve the traffic at high traffic rate. In [10 ,11], it was proved that when the setup time s is bigger than the headway time h, it is better to continue the green period for the following vehicle in the same lane. This is a property of the optimal solution if we aim to increase the throughput. In the following we will call it the platoon principle (PP).

3. Rule based principle

In this paper we consider that each vehicle receives a presence list of all vehicles. The presence list is an extend list built by the geonetworking standard. In the presence list, the vehicle finds all other precedent vehicles, their position, speed and desired destination, i.e. go straight, turn right and turn left. The vehicle ranked before in the presence list will cross the intersection first. The vehicle has to adapt its speed accordingly to avoid collision.

3.1. Rule 1: Cooperative cruise control

For safety reason each vehicle considers three following sets of obstacles:

- Real obstacles (r): vehicles ahead in the same lane,
- Map obstacle (m): stop line before the beginning of the potential zone of collision,
- Virtual obstacles (v): all precedent vehicles that have a conflicting destination.

Real and virtual vehicles are in the presence list. However, real vehicles are also detected by the frontal sensors of the vehicle. The map obstacle is added to allow modifying the rank of the vehicles in the presence list as it will be discussed later. Each vehicle as the green vehicle in fig 2 computes three accelerations a_r, a_m and a_v according to each set of obstacle. As shown in the Fig 2, a_r is obtained according to the leader vehicle in the same lane (blue vehicle for the green vehicle) whereas a_m is computed according to the distance between the vehicle and the stop line. a_v is computed as follows:

$$a_v = min(a_0, a_1, \dots, a_j, \dots, a_k) \quad (1)$$

where a_j is the acceleration for avoiding collision with the j^{th} virtual vehicle and k is the number of all virtual obstacles, i.e, vehicles in conflict. a_j is computed by considering the difference between the distance that separates both vehicles from the potential zone of collision $x - d_v$ as shown in fig 2. If the distance is negative we have a_j=-∞ . The acceleration applied by the vehicle is:

$$a = min(a_r, max(a_v, a_m)) \quad (2)$$

One can observe from this equation that the vehicle continues slowing down to stop at the stop line until it is able to synchronize its speed with the other vehicles coming from the other lanes. For instance, the green vehicle in Fig 2 reduces its speed to stop before the stop line because a_m until it will be able to follow the red vehicle because a_v will be bigger than a_m, as stated by equation 2. The way that a_m is computed can increase significantly the capacity of the intersection.

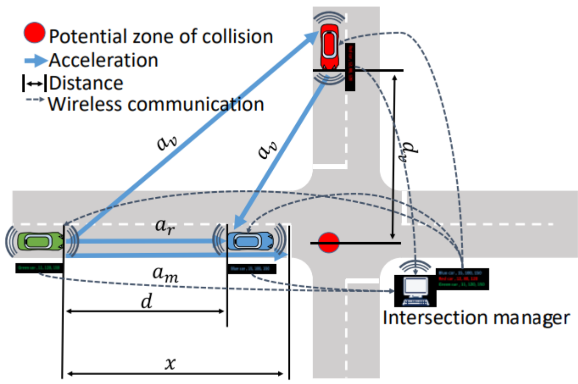

Fig. 2. Speed synchronization at intersection: in the presence list, blue car is first, red car is second and green car is the last one. Green car must consider both red and blue cars to adapt its speed. The intersection manager periodically broadcasts the updated list according to the periodically received messages from cars.

The presence list can be built either by each vehicle through V2V communication or by the intersection manager. In order to avoid consistency problem and for safety reason, we consider that each vehicle sends periodically its position, speed and the desired destination to the intersection server. When the intersection server discovers a new vehicle, with FCFS, the vehicle is automatically added at the lowest rank of the presence list. Later, the intersection server only updates the data of the vehicle, by keeping its rank. A more detailed presentation of FCFS robustness against packet loss is given at [12].

3.2. Rule 2: Extended leader

One of the most important advantages of the cooperative intersection management is that phases can be dynamically formed according to the current traffic. Hence, we extend the concept of the leader to all vehicles that are in the presence list without conflict. We draw the reader attention that the extended leader is only used to consider a team of vehicles that can cross together and it is not used for computing a_r. a_r is only computed according to the real leader.

3.3. Rule 3: high priority vehicles

In order to change the rank that allows better performance, it is important to be careful about adding a new precedent vehicle to vehicles in the other corridors. Indeed, the other vehicles should be able to adapt their speed accordingly before getting into the potential zone of collision. In order to achieve the objective, we define the expected acceleration of each vehicle as follows:

$$a_e = \begin{cases} \frac{2v_l(x \cdot s_l - (x-d) \cdot s_f)}{(x-d)^2} & if\ s_l > 0 \\ -\infty & if\ s_l = 0 \end{cases} \quad (3)$$

where s_f and v_l are the speeds of the vehicle and of its extended leader in the same lane, respectively, d is the distance between the extended leader and the vehicle and x is the distance that separate the vehicle from the stop line. All these values can be obtained by sensors in the front of each vehicle, such as radar or Lidar for the real leader or by wireless communication for all other extended leader. Vehicle continuously evaluates its a_e as given in equation (3) according to all leaders. If $a_e < 0$ then the vehicle has a flag of high priority related to a given extended leader and keeps it. It communicates its flag and the related extended leader v_{el} to the intersection manager. The negative expected acceleration allows to rank the vehicle before all common conflicting vehicles with the extend leader. However, a new rank should be studied carefully as discussed in rule 4 because of collision risks.

3.4. Rule 4: Rank in the presence list

In practice, it is possible to have many available ranks between the extended leader v_{el} and the follower in which the new incoming vehicle, called v_{new}, can be put. In Fig 3 there are three available ranks, for the new incoming green vehicle. It can be placed at the lowest rank. It can be placed also between blue and amber vehicles or between amber and red vehicle. More precisely, there is an ordered set of vehicles between the real leader (blue car) and the virtual follower (red car). Let us call the list between the extended leader and its virtual leader $l = (v0, \cdots, vk)$ and define the function $conflict(v_i, v_j) \mapsto \mathscr{B}$ with $\mathscr{B}$ is the Boolean set. l is a part of the whole presence list L, $l = (v_a, v_r)$ with v_a v_r are amber and red vehicles, respectively. Defines the set:

$$Nc = \{\forall v_j \in l / conflict(v_{el}, v_j) = 0 \wedge s_j \neq 0ms^{-1} \wedge conflict(v_{new}, v_j) = 1\} \quad (4)$$

Let $rank(v_i) \mapsto \mathbb{N}$ be the function that gives the current rank of the vehicle v_i and $newrank(v_i) \mapsto \mathbb{N}$ the new rank of vehicle with the high priority. The new rank of v_{new} is obtained as follows:

$$newrank(v_{new}) = max\left(rank(v_j)\right) + 1 \text{ with } v_j \in Nc \cup \{v_{el}\} \quad (5)$$

Let's in Fig 3 the vehicles have the following movements: the blue (v_{el}) amber and red vehicles go straight and the vehicle green vehicle (v_{new}) turns left. Their current ranks in the presence is as follows $L = (v_{el}, v_a, v_r, v_{new})$. Assumes now that v_{new} obtains a negative expected acceleration according to v_{el} that is the blue car. From (3), $Nc = \{v_a\}$ and $newrank(v_{new}) = max(rank(v_{el}), rank(v_a)) + 1 = 3$. Hence, v_{el} will be behind v_a and the new presence list is as follows $L = (v_{el}, v_a, v_{new}, v_r)$

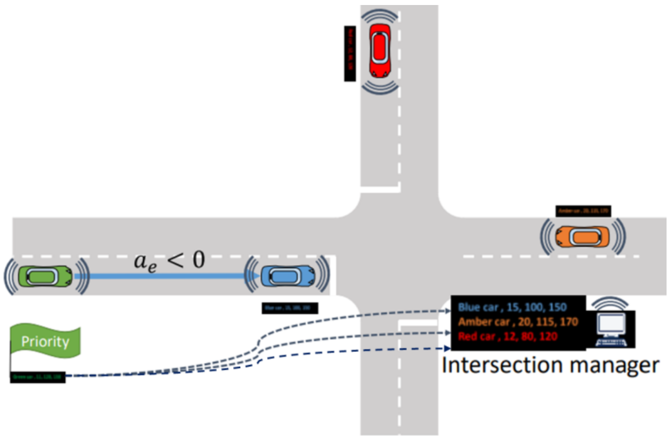

Fig. 3. Three possible rank of the green vehicle.

3.5. Rule 5: Communication

Due to packet loss, delayed vehicles may not receive the list of new virtual obstacles. Indeed, equation 1 only tells us that the conflicting vehicle is able to synchronize its speed if it has the information. Hence, it must acknowledge the new virtual obstacle before any modification in the presence list. For safety reasons, the priority vehicle is added as a new virtual obstacle only after the completion of the following process:

- The priority vehicle is added in the list according to FCFS,
- According to the received list it sends messages to all first conflicting vehicles in the list l to request an acknowledgment of the priority,
- If all vehicles acknowledge the request, the rank is modified.

Hence, there are two states of the priority flag, requested and acknowledged. Only the acknowledged status is considered by the intersection server to change the rank. The negotiation of the priority vehicle for acknowledge can be done directly through V2V communication or relayed by the intersection server. This depends on the ability of the cryptographic functions to confirm acknowledge. In simulation we consider that the server sends the request in the presence list. Acknowledge is sent by vehicles when they update their data.

4. Simulations

For the simulation environment, we considered data of real experiences. In simulation we compare three scenarios:

- DCP (Distributed Clearing Policy): the vehicles receive green or red according to the traffic situation. It was shown that the sequence of vehicles based on DCP is near to the optimal for freeing vehicles the soonest. It was also shown that DCP outperforms traffic light, even at a high traffic rate.
- FIFS: In this scenario vehicles synchronize their speed according a presence list that respects the order of the vehicle arrivals.
- PP (Platoon Policy): Vehicles synchronize their speed as in FCFS but the presence list is built according to all Rules presented in this paper.

The three scenarios are compared into a complex four ways intersection. Each way has only one lane where vehicles with three different directions cohabit. We have considered 80%, 10% and 10% of vehicles of the same lane going straight, turning left and turning right, respectively. This aims to raise the issue of the set of simultaneous authorized movements.

First we consider a variable traffic rate in order to observe the ability of PP to adapt the presence list according to the traffic variation. There are two considered values of traffic rates 0.4 vps (low traffic) and 0.8 vps (high traffic). The influx changes each 100 seconds. The comparison of the average speed is presented in fig 4-a. The presented curves are obtained from the average of five simulation runs. During the simulation run, we didn't observe particular significant different behaviors for the same scenario. Hence, the average results give a good idea about the behavior in general. One can observe that after 100 seconds FIFS is not able the recover its initial performance. Indeed, this due to the limited capacity that cannot answer a demand of 0.8 vps. Even if the traffic becomes lighter, FIFS is not able to free the accumulated vehicles. DCP behaves better but the average speed is low. Even if it becomes higher when the traffic is lighter, the average speed suffers from vehicles stopped at the intersection. PP outperforms both control approaches. The average speed grows significantly when the traffic rate is smaller, while it stills as good as DCP at a high traffic rate. PP keeps the advantage of both traffic management systems.

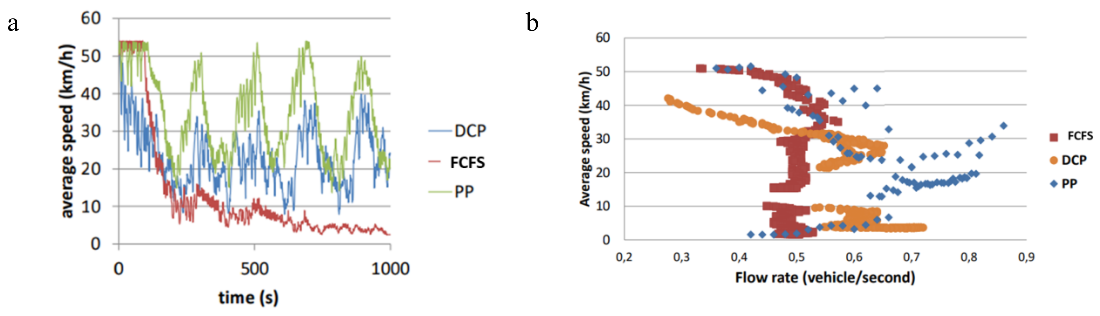

Fig. 4. Simulation results :(a) Average speed according to the periodical variation of the flow; (b) Speed flow diagram.

5. Conclusion

In this paper we introduce a rule based approach to improve the performance of cooperative intersection management. Through wireless communication these vehicles are able to synchronize their speed to avoid useless stop when the flow is low whereas they are able to form a platoon when the flow becomes higher. Simulations show that the proposed rules allows better performances than semaphores at a high flow since the time between two vehicles coming from two different road is reduced thanks to speed synchronization. This also allows energy saving at both cases, i.e. in low and high flow [13]

These interesting results deserve further investigations to reorganize platoons according to movements that can be allowed together. This can increase the capacity of the intersection to reach its maximal capacity as if there is no turning movement. Indeed, the proposed platoon is only based on the properties of the optimal scheduling. In order to improve the results, artificial intelligence can be used to be closer to the optimal solution [14, 15].

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