Reliable Intersection Protocols Using Vehicular Networks

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***Abstract*—Autonomous driving will play an important role in the future of transportation. Various autonomous vehicles have been demonstrated at the DARPA Urban Challenge [3]. General Motors has recently unveiled their Electrical-Networked Vehicles (EN-V) in Shanghai, China [5]. One of the main challenges of autonomous driving in urban areas is transition through cross-roads and intersections. In addition to safety concerns, current intersection management technologies such as stop signs and traffic lights can introduce significant traffic delays even under light traffic conditions.**

Our goal is to design and develop efficient and reliable intersection protocols to avoid vehicle collisions at intersections and increase the traffic throughput. The focus of this paper is investigating vehicle-to-vehicle (V2V) communications as a part of co-operative driving in the context of autonomous vehicles. We study how our proposed V2V intersection protocols can be beneficial for autonomous driving, and show significant improvements in throughput. We also prove that our protocols avoid deadlock situations inside the intersection area. The simulation results show that our new proposed V2V intersection protocols provide both safe passage through the intersection and significantly decrease the delay at the intersection and our latest V2V intersection protocol yields over 85% overall performance improvement over the common traffic light models.

I. Introduction

Road intersections are currently managed by stop signs and traffic lights. These technologies have been designed to manage traffic and increase the safety at intersections, but there is a growing concern about their efficiency and safety. Each year, more than 2.8 million intersection-related crashes occur in the United States, accounting for more than 44% of all reported crashes [6]. In addition, the delays introduced by stop signs and traffic lights significantly increase trip times. This leads to a huge waste of human and natural resources. The 2011 Urban Mobility Report, published by the Texas Transportation Institute, illustrates that the amount of delay endured by the average commuter was 34 hours which costs more than $100 billion each year [2].

Past work in this domain includes the use of Vehicle-to-Infrastructure (V2I) communications by having a centralized system in which all vehicles approaching an intersection communicate with the intersection manager. The intersection manager is a powerful computational infrastructure installed at intersections that tells all vehicles crossing the intersection [10, 16] when they should cross or stop. Installing a centralized infrastructure at every intersection is somewhat impractical due to the prohibitively high total system costs Also, as in all centralized systems, the intersection manager is a single point of failure, and vehicles must somewhat coordinate on their own, in the case that the intersection manager fails. To address these shortcomings, in our previous work, we have introduced a family of vehicular network protocols to manage the safe passage of traffic across intersections [14, 15]. These completely distributed protocols rely on vehicle-to-vehicle (V2V) communications and localization to control and navigate vehicles within the intersection area. Autonomous vehicles approaching an intersection use Dedicated Short Range Communications (DSRC) and Wireless Access in a Vehicular Environment (WAVE) [4] to periodically broadcast information such as position, heading and intersection crossing intentions to other vehicles. The vehicles then decide among themselves regarding who crosses, who stops, etc.
However, communication reliability is crucial for safety applications such as intersection collision avoidance. High packet loss will affect approaching vehicles' communication across the intersection corners. In urban intersections, signal propagation within DSRC channels may get affected by fading. Line-of-Sight (LOS) conditions are not always available due to the presence of big buildings and other obstacles at intersection corners. In our current work, we have therefore designed and developed a new intersection protocol with a realistic channel propagation model. They have been implemented in our hybrid emulator-simulator for vehicular networks, called AutoSim. The propagation model is based on the *Nakagami-m* model [11] that has been proven to significantly match with empirical results for signal propagation using DSRC/WAVE.

We formally prove the deadlock-freedom property of our family of intersection protocols, we also perform many experiments to study the effects of packet loss on our V2V intersection protocols and measure the reliability of these protocols in the presence of channel impairments.

The rest of this paper is organized as follows. Section II includes our latest V2V Intersection protocols and the deadlock-freedom analysis and proofs. Section III includes the *Nakagami-m* propagation and communication loss model. Section IV includes the implementation of our V2V intersection protocols and the DSRC channel propagation model in AutoSim. In Section V, we evaluate these protocols under various wireless communication conditions. Section VI describes our conclusion and future work.

II. V2V INTERSECTION PROTOCOLS

A. Collision Detection

In this section, we describe the two generations of our V2V intersection protocols. These protocols have been designed to increase the throughput at intersections while avoiding collisions. Vehicles use V2V communications using DSRC/WAVE to broadcast intersection safety messages to other vehicles in their communication range. These protocols enable co-operative driving among approaching vehicles to ensure their safe passage through the intersection. Our assumption is that all the vehicles are equipped with Global Positioning System (GPS) devices and have access to a digital map database, which provide them with critical information such as position, heading, speed, road and lane details. Intersection safety messages are broadcast at 10Hz and they contain the trajectory details of the sender along the intersection area. The format of these safety messages is defined by SAE's J2735 standard [4] and we use the second part of Basic Safety Messages (BSM) for the extra information in our intersection safety messages. We have assumed that, in all our protocols, all vehicles have similar shape and physical dimensions. [1]

The intersection area is modeled as a grid which is divided into small cells. Each cell in the intersection grid is associated with a unique identifier. Figure 1 shows an intersection with two lanes entering the intersection grid from all four directions. The *Trajectory Cells List (TCL)* is defined as the ordered list of the cell numbers which will be occupied by a vehicle along its trajectory inside the intersection box. In this example scenario, vehicle A's TCL is 8,7,6,5 and vehicle B's TCL includes cell numbers 15,11,7,3.

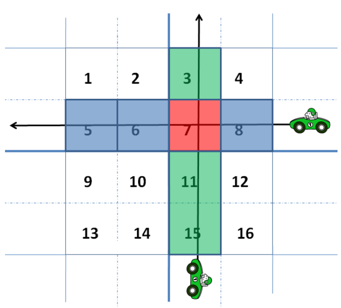


Fig. 1: Intersection Grid

Our proposed V2V intersection protocols make use of our Collision Detection Algorithm for Intersections (CDAI) [14]. CDAI runs on all vehicles, using the information obtained from received safety messages broadcast by surrounding vehicles. The algorithm uses the TCLs of the sender and the receiver of the safety messages and by comparing the two lists, it determines if there is any common cell along their trajectories while crossing the intersection. If a potential collision is detected by CDAI, the algorithm returns the *first* conflicting cell number which we refer to as *Trajectory Intersecting Cell (TIC)*. For example in Figure 1, cell number 7 is the TIC between vehicles A and B.

When no potential collision is detected among the sender and the receiver(s) of intersection safety messages, they can safely cross the intersection concurrently without stopping or slowing down. This behavior increases the throughput of the intersection by decreasing any unnecessary delays faced by approaching vehicles. But if a potential collision is detected, vehicles identify the common cell(s) among their TCLs. In this case, vehicles use a pre-designed priority policy and follow the assigned Intersection Protocol (IP) rules to cross the intersection area. We have implemented a First-Come, First-Served (FCFS) as our priority policy, in which priorities are assigned to vehicles based on their arrival time to the intersection. In the case that two or more vehicles arrive at the intersection almost at the same time, ties can also be broken in favor of vehicles on a main road. If there is still a tie, it is broken by Vehicle Identification Number (VIN), which is uniquely assigned to each vehicle.

In our intersection protocols, each vehicle uses 3 types of intersection safety messages to interact with other vehicles within its communication range.

1) An ENTER message is used to inform the neighboring vehicles that the vehicle is approaching the intersection area with specific crossing intentions. The ENTER message contains 9 parameters: *Vehicle ID, Current Road Segment, Current Lane, Next Road Segment, Next Vertex, Arrival-Time, Exit-Time, Trajectory Cells List,Cells Arrival Time List, Message Sequence Number and Message Type*, which is ENTER in this case.
2) A CROSS message is to inform that the vehicle is inside the intersection grid, this message contains the sender's identification and trajectory details, identifying the space that will be occupied by the vehicle while crossing the intersection. The CROSS message contains the same parameters as the ENTER message. Its Trajectory Cells List contains the updated list of trajectory cells and their related arrival times for the current cell and remaining cells along the vehicle's trajectory through the intersection area, and the *CROSS Message Type*.
3) An EXIT message indicates that the vehicle has exited the intersection boundaries. The EXIT message contains 3 parameters: *Vehicle ID, Message Sequence Number, and EXIT Message Type*.

Every vehicle uses its own GPS coordinates, speed and also the map database to compute the distance to the approaching intersection and the distance passed from the previous intersection. We consider three *intersection states* for each vehicle based on its relative location to the intersection area.

- *Intersection-Approach*: when vehicle's distance to the approaching intersection is less than a threshold parameterD_{ENTER}.
- *Intersection-Enter*: when the vehicle is inside the intersection grid's boundaries.
- *Intersection-Exit*: when the vehicle exits the intersection, until it travels farther than a threshold value D_{EXIT} from the exit point of the intersection.

We have categorized our intersection protocols based on the actions taken by potentially conflicting vehicles to avoid collisions. Potentially conflicting vehicles are those vehicles which have trajectory conflicts with one or more crossing vehicles through the intersection area and may get into a potential collision. The first category includes Through-

[1]Relaxing this assumption is the subject of ongoing work.

put Enhancement Protocol (TEP) and Concurrent Crossing-Intersection Protocol (CC-IP) [14, 15]. In this category, the conflicting vehicle with higher priority can ignore the intersection safety messages from other lower-priority vehicles and cross the intersection without slowing down or stopping. However, any lower-priority vehicle is super-cautious and when it loses a competition, it comes to a complete stop before entering the intersection boundaries, and waits till it receives a CLEAR message, from the higher-priority vehicle. This message informs the lower-priority vehicle that the higher-priority vehicle has crossed the intersection and now the intersection area is safe for its passage. This protocol is applied across all priority levels.

The second category of Intersection Protocols is referred to as Spatio-Temporal Intersection Protocols (STIP). The main goal is to increase the parallelism inside the intersection area by allowing more vehicles to cross the intersection at the same time. STIP includes the Maximum Progression Intersection Protocol (MP-IP) and the Advanced Maximum Progression Intersection Protocol (AMP-IP). We will present both these protocols in this paper and study their properties.

B. *Maximum Progression Intersection Protocol (MP-IP)*

MP-IP is designed to increase the intersection throughput by allowing even potentially conflicting vehicles to progress inside the intersection area, when the primary goal of safe passage of all vehicles across the intersection can be satisfied. Here we define the terms that will be used in our theorems.

- P_v: Priority of vehicle *v*. This is determined by the priority policy.
- S_v: Set of cells required for vehicle *v* to cross the intersection. It consists of the current cell and next cells that will be occupied by vehicle *v*.
- C_v: Current cell occupied by vehicle *v*.
- N_v: Next cell that will be occupied by vehicle *v*.
- $TIC_{v,y}$: Trajectory Intersecting Cell between the higher-priority vehicle *v* and lower-priority vehicle *y*.

Based on the above definitions, one can derive the following logical relations:

$$C_v \neq N_v \text{ and } C_v \in S_v \text{ and } N_v \in S_v$$

The following rules are applicable to all vehicles:

Algorithm 1 MP-IP, Sender Vehicle

Input: Vehicle's *intersection state*
Output: Broadcast intersection safety message
if STATE=Intersection-Approach **then**
  Broadcast ENTER message
else if STATE=Intersection-Enter **then**
  Broadcast CROSS message
else if STATE=Intersection-Exit **then**
  Broadcast EXIT message

And here are the rules applied to a vehicle B when it receives intersection messages from a vehicle A, where (A $\neq$ B).

Algorithm 2 MP-IP, Receiver Vehicle

Input: Safety message received from vehicle A, *RM*
Output: Vehicle B's movement at the intersection
if $(RM = ENTER$ or $RM = CROSS)$ **then**
  Run CDAI to detect trajectory conflicts with vehicle A and find $TIC_{A,B}$
  if $(TIC_{A,B} = NULL)$ **then**
    Cross the intersection
  else
    Run FCFS priority policy
    if $(P_B > P_A)$ **then**
      Cross the intersection
    else
      Progress and stop before entering $TIC_{A,B}$
else if $RM = EXIT$ **then**
  if $TIC_{A,B}$ is cleared **then**
    Cross the intersection

We now illustrate MP-IP with an example. Figure 2 shows two vehicles A and B, approaching an intersection. We assume that vehicle A has higher priority than vehicle B. In this case, vehicle A gets to cross the intersection without stopping or even slowing down. Vehicle B shall progress inside the intersection grid and stop before entering the TIC with vehicle A, which is cell number 6. As vehicle A leaves cell number 6, it updates its TCL to [10,14] and sends a CROSS message. This informs vehicle B that the TIC is now clear and it can continue its trajectory through the intersection by proceeding to cell number 6.

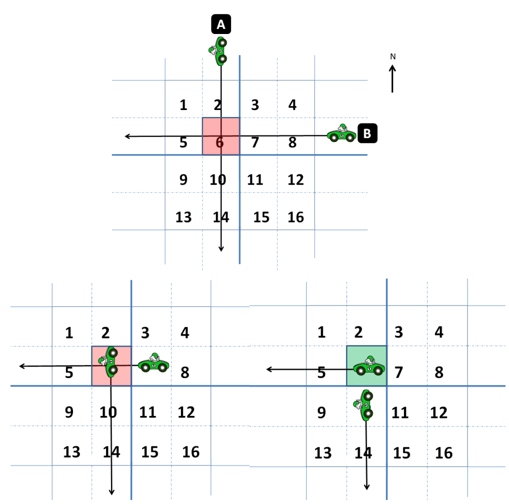


Fig. 2: An example scenario for MP-IP

C. *MP-IP Freedom from Deadlock*

A deadlock is a situation in which two or more competing actions are each waiting for another to finish, and thus neither ever does. A deadlock situation can occur inside the intersection area, among the vehicles which are trying to cross the intersection at the same time. To better explain such scenarios, we use *wait-for* graphs. A *wait-for* graph is a directed graph used for deadlock detection in operating systems and relational database systems. A deadlock exists if the graph contains any cycles.

We now investigate a possible deadlock scenario, in which all vehicles progress inside the intersection area as much as possible without getting into a collision. As we can see in Figure 3, vehicle A's next cell is occupied by vehicle D, vehicle D's next cell is occupied by vehicle C, vehicle C's next cell is occupied by vehicle D, and finally vehicles B's next cell is occupied by vehicle A. This means that none of these vehicles can progress inside the intersection grid as each of their next cells are occupied by other vehicles.

For the purpose of this paper, we define the elements of our intersection *wait-for* graph as follows. Vehicles are represented as the nodes of our *wait-for* graph, and an edge from vehicle B to vehicle A implies the vehicle A is holding a cell that vehicle B needs, to complete its trajectory through the intersection grid. Thus, vehicle B is waiting for vehicle A to release (leave) that specific cell. It can be seen clearly in Figure 4 that the corresponding *wait-for* graph contains a cycle and therefore it is a deadlock situation.

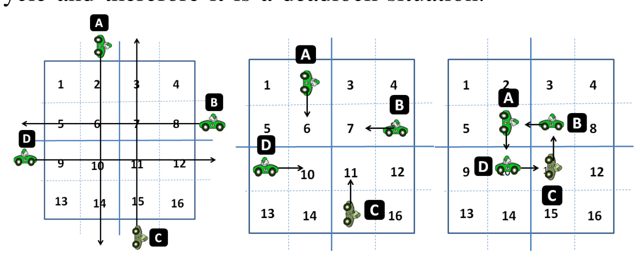


Fig. 3: A Deadlock scenario

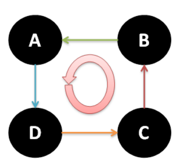


Fig. 4: Wait-for graph for an example deadlock scenario

Definition 1. ***Trajectory Dependency:***
Vehicle A's trajectory depends on vehicle B's trajectory iff two conditions are true at the same time:

1) *The priority of vehicle A is lower than the priority of vehicle B.*
2) *There is a common cell along their trajectory cells.*

The above statement can be written as:

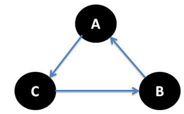
$$[(P_A < P_B) \text{ and } S_A \cap S_B \neq \phi] \iff A \rightarrow B$$

Rule 1. ***MP-IP Rule:***
If vehicle A's trajectory depends on vehicle B's trajectory, then vehicle A cannot enter any of the cells reserved by vehicle B.

$$(A \rightarrow B) \Rightarrow C_A \notin S_B$$

Theorem 1. *Without loss of generality, the MP-IP is deadlock-free.*

Proof: We prove the theorem by contradiction. Suppose we have two vehicles. Deadlock condition is as follows:
$C_A = N_B$ and $C_B = N_A$



Suppose that $P_A > P_B$
and we have,

$$C_B = N_A \Rightarrow S_A \cap S_B \neq \phi \quad (1)$$

Based on the Trajectory Dependency and MP-IP Rule, from Equation (1):

$$B \rightarrow A \Rightarrow C_B \notin S_A \quad (2)$$

But from deadlock conditions, we have $C_B = N_A$, so:

$$C_B = N_A \Rightarrow C_B \in S_A \quad (3)$$

(2) and (3) cannot be true at the same time. This is a contradiction. So $C_B = N_A$cannot be true while $C_A = N_B$.

We now consider the deadlock situation with *n* vehicles, $n > 2$. We must therefore have

$C_A = N_B$ and $C_B = N_C$ and ... $C_Y = N_Z$ and $C_Z = N_A$.

Suppose that $P_A > P_B > P_C > ... > P_Z$

So we have: $P_A > P_B > P_C > ... > P_Z \Rightarrow P_A > P_Z$

$$C_Z = N_A \Rightarrow S_A \cap S_Z \neq \phi \quad (4)$$

Based on the Trajectory Dependency and the MP-IP Rule, from (4):

$$Z \rightarrow A \Rightarrow C_Z \notin S_A \quad (5)$$

But deadlock conditions, states that $C_Z = N_A$, so:

$$C_Z = N_A \Rightarrow C_Z \in S_A \quad (6)$$

(5) and (6) are contradictory. So $C_Z = N_A$ cannot be true while $C_A = N_B$ and $C_B = N_C$ and $C_Y = N_Z$ So we can conclude that the deadlock situation is avoided by applying the *MP-IP Rule*. ■

We now apply MP-IP to the deadlock scenario of Figure 3. Figure 5 shows that vehicle A can progress without worrying about other vehicles, as it has the highest priority among them. Vehicle B progresses to cell number 7, and stops before entering cell number 6, since it is a part of vehicle A's TCL. The same MP-IP rule applies to vehicles C and D. Since D has potential conflicts with vehicles A and C, and both of them have higher priorities than D, then D has to stop before entering any of those conflicting cells, numbers 10 and 11. As cell number 10 is the first conflicting cell along vehicle D's trajectory, it stops before entering this cell and waits in cell 9 until A crosses and leaves cell 10. So, no cycle is formed and the highest-priority vehicle A has all the cells cleared for its trajectory through the intersection area. After the last step showed in Figure 5, all the vehicles can progress to the next cell along their trajectory and cross the intersection area safely, without causing any deadlock situation.

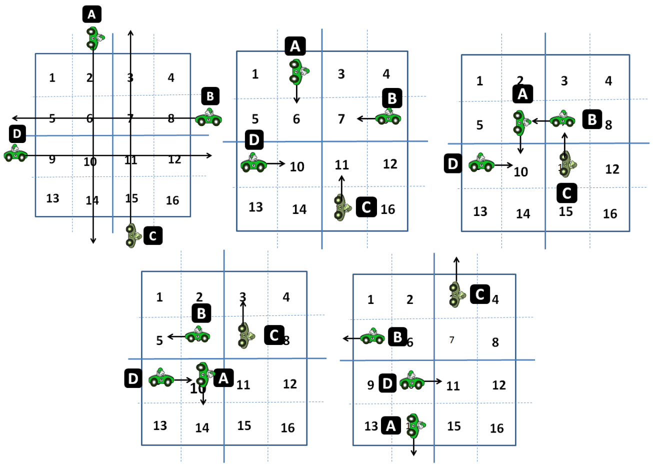


Fig. 5: Deadlock is avoided by the MP-IP Rule

D. Advanced Maximum Progression Intersection Protocol (AMP-IP)

This protocol is built based on MP-IP's key idea that conflicting vehicles can make concurrent progress inside the intersection grid when collisions can still be avoided. Additionally, AMP-IP has the advantage of allowing the lower-priority vehicles to cross the conflicting point and clear the conflicting cell before the arrival of the higher-priority vehicle to that cell.

Each vehicle uses its GPS coordinates, controller model parameters and digital map information to calculate its current position, velocity and distance to any point at the intersection grid. All this information is used as inputs to measure the exact arrival time of the vehicle to each cell along its trajectory while crossing the intersection area. When a vehicle detects a potential collision with a higher-priority vehicle, it compares its own arrival time at the conflicting cell with the arrival time of the higher-priority vehicle to the same cell. If its arrival time is sufficiently earlier than the arrival time of the higher-priority vehicle, then it can go ahead and cross the conflicting cell without stopping for the higher-priority vehicle.

To ensure the safe passage of both the potentially conflicting vehicles, we use a **Safety Time Interval** to increase the safety and make sure that the lower-priority vehicle has enough time to leave and clear the conflicting cell completely, before the arrival of the higher-priority vehicle to that cell.

Based on the Newtonian equations of motion, we set the *Safety Time Interval* as follows:

$$D(t) = D_0 + V_0 t + 1/2at^2$$
$$t = \frac{-V_0 + \sqrt{{V_0}^2 + 2aD}}{2a} \tag{7}$$

As of year 2010, the amount of time that an average vehicle takes to accelerate from 0 miles per hour (mph) to 60 mph is about 8.95 seconds. This value has been calculated by averaging the acceleration parameter of 1,807 car records [1]. Using this value, we calculate the maximum acceleration to be approximately $2.9969\frac{m}{s^2}$. The width of each cell is assumed to be 5 meters. The worst-case scenario is when the initial speed of the vehicle is 0 $\frac{m}{s}$ and the time to cross the cell is the maximum possible. By replacing these values in Equation (7), the *Safety Time Interval* is calculated as 1.8266s, which has been rounded up to 2s for our protocol.

We now define the terms that will be used in our proof.

- $TIC_{V,Y}$: Trajectory Intersecting Cell between the higher-priority vehicle V and lower-priority vehicle Y.
- $AT_{V,c}$: Arrival Time of vehicle V to cell c.
- $ET_{V,c}$: Exit Time of vehicle V from cell c.
- Θ: The *Safety Time Interval*.

Similar to MP-IP, vehicles make use of the intersection safety messages to inform their neighbors about their intentions to enter, cross and finally exit the intersection area. In AMP-IP, the ENTER and CROSS safety messages contain additional information about the cells that will be occupied by the vehicle while crossing the intersection grid. This information includes the estimated arrival time of the vehicle to each of the cells in its TCL through the intersection grid. The same rules as in Algorithm 1, apply to all sender vehicles.

The following rules are applied to a vehicle B when it receives intersection messages from a vehicle A, where (A $\neq$ B).

Algorithm 3 AMP-IP, Receiver Vehicle

Input: Safety message received from vehicle A: *RM*
Output: Vehicle B's movement at the intersection
if $RM = ENTER$ or $RM = CROSS$ **then**
  Run CDAI to detect trajectory conflicts with vehicle A and find $TIC_{A,B}$
  if $(TIC_{A,B} = NULL)$ **then**
    Cross the intersection
  else
    Use FCFS priority policy
    if $(P_B > P_A)$ **then**
      Cross the intersection
    else
      $c = TIC_{A,B}$
      if $([AT_{B,c} + \Theta] < AT_{B,c})$ **then**
        Cross the intersection
      else
        Progress and stop before entering $TIC_{A,B}$
else if $RM = EXIT$ **then**
  if $TIC_{A,B}$ is cleared **then**
    Cross the intersection

Figure 6 shows the same scenario as Figure 2 but, with vehicles following AMP-IP rules. As before, since vehicle A has a higher-priority than vehicle B, it gets to cross the intersection without stopping or even slowing down. Vehicle B compares its own arrival time to the TIC, which is cell number 3 with the arrival time of vehicle A to the exact same cell. In the case that vehicle B arrives there earlier, and has enough time to clear the cell before the arrival of vehicle A, then instead of progressing only up to the TIC, it can progress into and clear the conflicting cell number 3.

So, by using AMP-IP, we allow the lower-priority vehicle to go ahead and cross the conflicting cell before the arrival of the higher-priority vehicle. This action decreases the delay

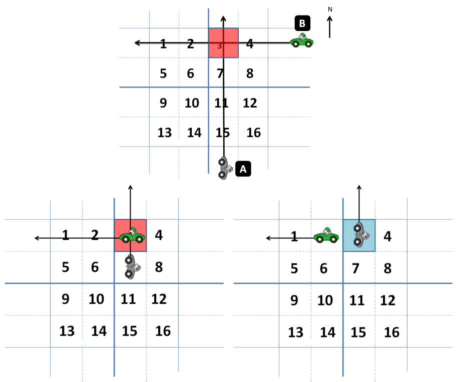


Fig. 6: An example scenario for AMP-IP

time faced by this vehicle and increases the total throughput of the intersection.

E. AMP-IP Freedom from Deadlock

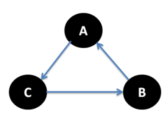
In this section, we prove that using AMP-IP cannot lead to a deadlock situation.

Rule 2. ***AMP-IP Rule:***
If vehicle A's trajectory depends on vehicle B's trajectory, then A cannot enter the $TIC_{B,A}$, unless it is able to leave $TIC_{B,A}$ before B arrives to that cell.

Suppose that $n = TIC_{B,A}$. The AMP-IP rule can also be stated as:

$$\{(A \rightarrow B) \text{ and } (ET_{A,n} > AT_{B,n})\} \Rightarrow C_A \notin S_B$$

Theorem 2. *There is no deadlock under AMP-IP.*



Proof. We prove these properties using contradiction. Suppose we have two vehicles. Deadlock condition is as follows:
$C_A = N_B$ and $C_B = N_A$

Suppose that $P_A > P_B$

Based on the trajectory dependency:

$$[P_A > P_B \text{ and } S_A \cap S_B \neq \phi] \Rightarrow B \rightarrow A \tag{8}$$

From Deadlock conditions, we have $C_A = N_B = TIC_{A,B}$, so vehicle A is already in cell $TIC_{A,B}$:

$$C_A = N_B \Rightarrow ET_{B,TIC_{A,B}} > AT_{A,TIC_{A,B}} \tag{9}$$

By AMP-IP rule and from Equations (8), (9):

$$C_B \notin S_A \tag{10}$$

From Deadlock, we have:

$$C_B = N_A \Rightarrow C_B \in S_A \tag{11}$$

(10) and (11) cannot be true at the same time. This is a contradiction. So $C_B = N_A$cannot be true while $C_A = N_B$.

Now consider the deadlock situation with n vehicles, $n > 2$.

$C_A = N_B$ and $C_B = N_C$ and ... $C_Z = N_A$

Suppose that $P_A > P_B > P_C > ... > P_Z$

Based on the Trajectory Dependency,

$$[P_A > P_Z \text{ and } S_A \cap S_Z \neq \phi] \Rightarrow Z \rightarrow A \tag{12}$$

From Deadlock conditions, we have $C_A = N_Z = TIC_{A,Z}$, so vehicle A is already in cell $TIC_{A,Z}$,

$$C_A = N_Z \Rightarrow ET_{Z,TIC_{A,Z}} > AT_{A,TIC_{A,Z}} \tag{13}$$

By AMP-IP rule and from equations (12), (13):

$$C_Z \notin S_A \tag{14}$$

From the deadlock condition, we have:

$$C_Z = N_A \Rightarrow C_Z \in S_A \tag{15}$$

(14) and (15) are contradictory. So $C_Z = N_A$ cannot be true while $C_A = N_B$ and $C_B = N_C$ and $C_Y = N_Z$. □

Let us apply the AMP-IP rule to the deadlock scenario of Figure 3. Since vehicle D does not have enough time to clear $TIC_{C,D}$ before vehicle C arrives at that cell, it will not even enter the first TIC, which is $TIC_{A,D}$. So the trajectory is not blocked for the higher-priority vehicle A and deadlock does not happen. Hence the same scenario as in Figure 5 occurs. However, if vehicle D has enough time to clear both $TIC_{A,D}$ before vehicle A gets there and clear $TIC_{C,D}$ before vehicle C gets there, it will cross both conflicting cells. As we can see in Figure 7, this behavior of vehicle D, will allow the road to be clear for higher-priority vehicles A and C, and again no deadlock occurs.

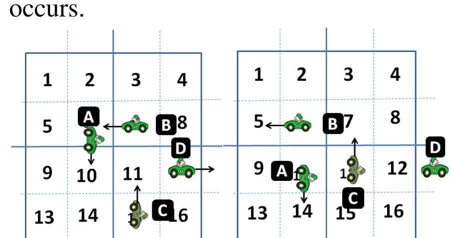


Fig. 7: An example scenario for AMP-IP

III. V2V Signal Propagation Using DSRC Channels

As explained in Section II, our intersection protocols rely on vehicle-to-vehicle communications. All vehicles use V2V messages to interact with one another and use the information within these messages to control their movements such as adjusting their speed during their trajectory through the intersection area. We know that wireless communication is not perfect and channel impairments decrease the reliability of vehicular communications. As vehicles approach an intersection with relatively high speeds, it is vital to receive the intersection safety messages within a very short time interval to be able to react, and get to a full stop before entering the intersection area when necessary. Channel impairments such as fading will decrease the communication reliability by increasing the packet loss ratio. Therefore, a high rate of packet loss will affect the communication as vehicles do not receive the information soon enough to avoid collisions at the intersection.

Figure 8 illustrates an intersection crossing scenario from our hybrid emulator-simulator, AutoSim. In this scenario, vehicle A is attempting to enter the intersection from the North and turn left heading east. Vehicle B arrives at the intersection slightly after vehicle A, and attempts to go straight. As they have a trajectory conflict, they may get to a potential collision if they attempt to cross the intersection at the same time. When the communication medium is perfect and there is no packet loss, vehicle B will receive the intersection safety messages from vehicle A. As vehicle B is assigned a lower priority based on its arrival time, it allows vehicle A to safely cross the intersection first. In contrast, when the packet loss rate is too high, intersection safety messages among these vehicles can be lost, and vehicle B has no information about the higher-priority vehicle, A. So, it attempts to cross the intersection without stopping or slowing down and this leads to a collision between vehicles A and B.

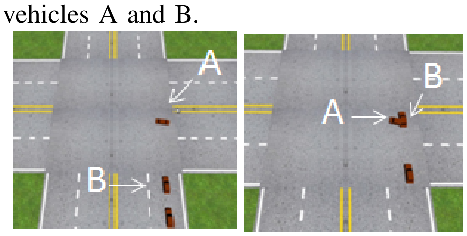


Fig. 8: Snapshots from AutoSim simulator. V2V intersection management: (a) No packet loss and safe passage of vehicles (b) High packet loss rate results in an accident

An often used realistic and probabilistic model for wireless signal propagation using DSRC channels is the *Nakagami-m* model. This model estimates the received signal strength in multipath environments, in which the channel is influenced by various degrees of fading. *Nakagami-m* fading with the shape parameter m and distribution spread parameter is expressed as:

$$f(x) = \frac{2m^m x^{(2m-1)}}{\Gamma(m)\Omega^m} exp\frac{(mx^2)}{\Omega}, x > 0, \Omega > 0, m > \frac{1}{2}$$

When the signal amplitude follows the *Nakagami* distribution, the power follows the Gamma distribution,

$$p(x) = (\frac{m}{\Omega})^m \frac{x^{(m-1)}}{\Gamma(m)} exp(-\frac{mx}{\Omega})$$

where $\Gamma(m)$ is a complete gamma function of parameter m. Taliwal et al. [17] have shown that this model agrees with empirical data. Figure 9 shows the probability of reception based on the distance between the transmitter and the receiver for various values of m and the communication range of 500 meters. Yin et al. [8, 9] have performed statistical fading analysis based on DSRC empirical data. Their analysis shows that, for distances less than 100m, the fading appears to follow a Rician fading distribution, in which $m > 1$. When the distance is greater than 100m, it generally follows a Rayleigh fading distribution, in which $m = 1$ and it models a harsh Non-Line-Of-Sight (NLOS) scenario.

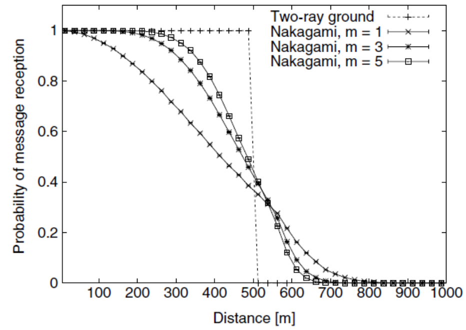


Fig. 9: Probability of successful packet reception.

We will use the *Nakagami-m* model to study the impact of imperfect V2V communication on our intersection protocols. We will assume a deterministic model for the transmission power for the *Nakagami-m* model, that is, the power necessary to reach a communication range of certain meters. Increasing the transmission power will eventually increase the communication range. This results in higher Packet Delivery Ratio (PDR) and communication reliability. In sparse traffic conditions, the channel load is light and increasing the transmission power does not carry negative consequences. When dealing with busy urban intersections in which the traffic is dense, a high number of safety messages is broadcast, and results in higher channel load and may lead to channel congestion. We will evaluate such environments in the next section.

In scenarios where V2V communications has a high packet loss ratio due to obstacles or channel congestion, local-sensing technologies can be used to avoid collisions at the intersection. We believe that by combining V2V communications with local-sensing information obtained by sensors, cameras, radars and thermal images, highly reliable collision avoidance is achievable even in extreme environment scenarios.

IV. Implementation

In this section, we describe the implementation of the V2V protocols and the V2V communication model. In order to analyze our intersection protocols and their communication reliability, the DSRC propagation model and the traffic flow at intersections need to be studied. For this purpose, we use a tool called AutoSim. This simulator-emulator is an extension to GrooveNet [12, 13].

AutoSim is a hybrid emulator-simulator for vehicular communication and interaction. It facilitates protocol design as well as in-vehicle deployment and uses real street-map-based topography. This enables city-wide simulations using different types of trip and messaging models. The simulator uses a model-based approach where different models interact with each other resulting in vehicular movement. Each simulated vehicle is made up of several types of models. The core individual modules are control, communication, mobility and pose estimation. The mobility models within AutoSim are used to implement different types of intersection protocols.

AutoSim also has real-time emulation capability wherein real and simulated cars can co-exist and interact with each other. The communication interfaces for DSRC communication as well as peripheral sensory interfaces are implemented to enable real cars instrumented with DSRC to react in real-time with simulated cars. The communication protocol uses Basic Safety Messages (BSM) [4] that are broadcast as part of the WAVE mechanism. A brief description of the relevant models follows:

- *Traffic light model*: This model simulates the traffic light intersections in the real world. We have used the two most common green light durations of 10 seconds and 30 seconds.
- *V2V Intersection models*: These models have been designed to implement our CC-IP, MP-IP and AMP-IP protocols. All vehicles use pure V2V communication to interact with each other.
- *Controller model*: This realistic model has been designed to control the movement of vehicles based on their speed, acceleration and deceleration profiles. This impacts the movement of vehicles through intersections. In our current work, all vehicles are assumed to have from similar shape, physical dimensions and dynamic capabilities.
- *Communication model*: This model has been used to simulate the wireless communication among the vehicles using DSRC/WAVE technologies. This model includes the *Nakagami-m* propagation model that matches with empirical results for vehicle-to-vehicle (V2V) communications.

V. Evaluation

In this section, we evaluate the proposed protocols using various propagation models and mobility models that we have designed and simulated in AutoSim.

A. Metric

We define the *trip time* for a vehicle, as the time taken by that vehicle to go from a fixed start-point before the intersection to a fixed end point after the intersection. We calculate the trip time for each simulated car under each model and compare that against the trip time taken by the car assuming that it stays at a constant street speed and does not stop at the intersection. The difference between these two trip times is considered to be the Trip Delay due to the intersection. We take the average trip delays across all cars in a simulation sequence as our metric of comparison. Our other metric is Packet Delivery Ratio (PDR). PDR has been widely used as the major metric to evaluate radio channel characteristics. PDR is defined as the probability of successful packet reception and is measured as the ratio of the successfully received packets to the total number of packets transmitted within a pre-defined time interval.

B. Scenarios

Since there is a large variation in intersection types, we restrict our attention to Four-way Perfect-Cross Intersections, in which the intersection legs are at perfect right angles to the neighboring leg. In our simulations, the traffic generation follows the Poisson random distribution. We have looked at a wide range of traffic densities. Our simulations include very sparse traffic rural intersections with the mean value of 0.1 cars per second in each direction of the intersection, and also very busy urban intersections with the mean value of 1 car per second in each direction. We run all our simulations on 4-lane roads, with 2 lanes in each direction. The intersection type, vehicle routes and turn-types are generated offline. Each vehicle is removed from simulation when it reaches its destination. Each simulation run uses 1000 vehicles, and each run is terminated when the last vehicle reaches its destination.

C. Experimental Results

We have compared the traffic light model to our proposed V2V-based protocols, the Concurrent Crossing-Intersection Protocol (CC-IP), the Maximum Progression-Intersection Protocol (MP-IP) and the Advanced Maximum Progression-Intersection Protocol (AMP-IP). Figure 10 shows this comparison for a perfect-cross intersection. The traffic is assumed to be symmetric, meaning equal amount of traffic volume in every direction and an equal amount of turn ratios. The X-axis is the traffic volume determined as cars per second and the Y-axis is the delay in seconds.

All our V2V-based models outperform the traffic light models. CC-IP, MP-IP and AMP-IP have respectively 48.78% and 70.82% and 85.75% overall performance improvements over the traffic light model with a 10-second green light time. The average delay is very negligible for lower traffic volumes in MP-IP and AMP-IP V2V-based models. Under MP-IP and AMP-IP, the delays stay very low even with higher traffic volumes. AMP-IP outperforms CC-IP and MP-IP respectively by 69.94% and 51.15%. Based on our results under AMP-IP, the average delay faced by vehicles at the intersection, even in very high traffic densities, is as low as 22 seconds. Note that this traffic volume is significantly higher than the traffic density in Manhattan area during rush hour.

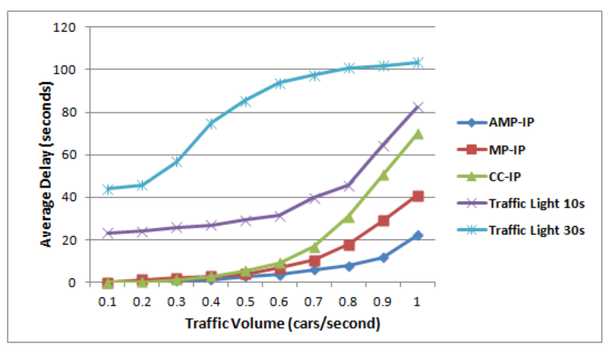


Fig. 10: Delay comparison among different mobility models

We next studied the case where the traffic volume is significantly different on the intersection roads. We assume that the North-South directions of the intersection has higher traffic density and the intersecting East-West directions has the roads with lower traffic on them. However, the roads have the same type and priority to cross the intersection. Figure 11 shows that the Advanced Maximum Progression-Intersection Protocol (AMP-IP) performs better than other V2V-based models and also outperforms the traffic light model significantly. Figure 12 illustrates the performance comparisons between the asymmetric traffic (various traffic volumes among the intersection roads) and the symmetric traffic under the rule of AMP-IP and the traffic light model. As we expect, the vehicles arriving on the higher traffic density roads face higher delays which increases the overall average delay. In the case of the traffic light model, this difference is huge and unfair, since vehicles arriving from the higher volume traffic direction are forced to face much higher delays. However, AMP-IP results in more fair passage of vehicles through the intersection.

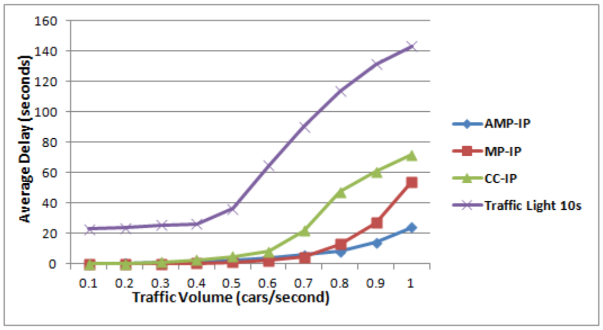


Fig. 11: Delay comparison for asymmetric traffic.

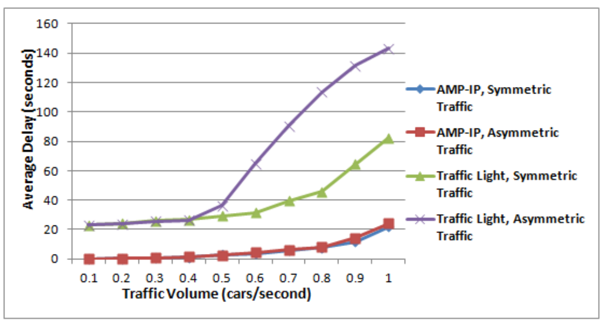


Fig. 12: Delay comparison between traffic light and AMP-IP in symmetric and asymmetric traffic.

We finally studied the scenario in which higher priorities have been assigned to high-traffic-volume roads, in order to allow more vehicles to cross the intersection coming from the higher-density roads. This reduces the backed-up traffic and accordingly increases the overall throughput of the intersection. Figure 13 shows the comparisons between two different scenarios using AMP-IP. Note that assigning higher priorities to higher traffic volume roads outperforms the scenario that all legs of the intersection have the same priority. The improvement is small at low volume traffic but it increases significantly as the traffic density increases. These results highlight the importance of an appropriate priority policy and how assigning higher priorities to vehicles on the high-volume traffic roads can decrease the overall delay and increase the throughput of the intersection significantly while dealing with a large number of vehicles at the intersection.

We now measure the PDR value based on the distance between the transmitter and the receiver of intersection safety messages in various traffic scenarios. We look at the intersections with different amounts of obstacles which lead to different multipath degrees. To simulate a harsh NLOS environment, we use $m = 1$ in our *Nakagami-m* propagation model and bigger values of m are used to model the intersections with less number of obstacles such as tall buildings. We use three values for the fading parameter m = 1, 2, 3 and transmission power of 20dBm. A deterministic Two-ray Ground propagation model has been assumed for the transmission power for the *Nakagami* model. Using this model, we have set the effective Communication Range (CR) of 200m in our simulation. Figure 14 shows the PDR comparison among intersection environments with different fading degrees. Based on the results of the *Nakagami-m* propagation model and as we expected, for the lower values of fading parameter m, the PDR values drop faster as the distance increases between the transmitter and the receiver of the intersection safety messages.

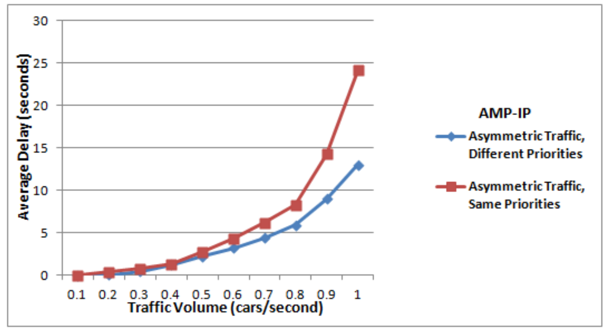


Fig. 13: AMP-IP Average delays. Higher priority for higher volume roads.

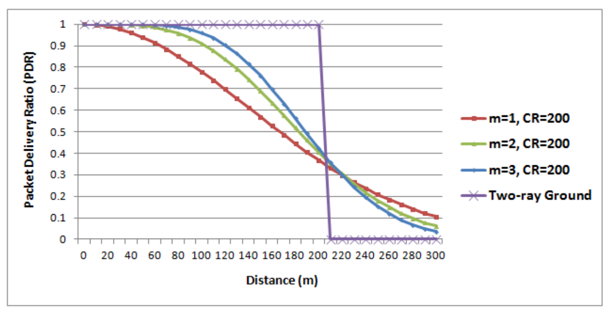


Fig. 14: Packet Delivery Ratio with communication range of 200 meters

The results in Figure 14 confirm that by increasing the transmission power and hence increasing the communication range, the PDR values are significantly higher for various distances between any transmitter and receiver pairs. But the main drawback is that in dense traffic environments, increasing the transmission power ends in involving more vehicles and higher chance of channel congestion as the channel load increases significantly.

We have logged the statistics for all simulated vehicles such as their position information at any moment while crossing the intersection. This information has been used to log any accidents among the vehicles trying to concurrently pass through the intersection area.

Our results show that absolutely no accidents happen in any tested traffic volumes at the intersection. All the vehicles make their decision about how to cross the intersection, while they are approaching it and, based on the intersection safety messages sent by other vehicles every 100ms. This surprisingly positive result is because of receiving at least one safety message from any other approaching vehicle is sufficient to detect any potential collisions using the CDAI, and to come to a complete stop before entering the intersection boundaries. Since it takes seconds to cross an intersection, at least one such message is received on time.

Fan Bai et al. [7] define the Safety application reliability as the probability of successfully receiving at least one single packet from neighbor vehicles during the tolerance time window T. This is calculated as follows:

$$P_{Application} = 1 - (1 - P_{Comm})^N$$

Where, N is the number of messages sent during the time window T and P_{Comm} is the communication reliability which is calculated as the probability of successfully receiving each packet. In our proposed protocols, vehicles start broadcasting the safety messages when their distance to the entrance of the intersection is less thanD_{ENTER}, which is set to 20 meters in our simulations. As these safety messages are transmitted with the frequency of 10Hz, the tolerance time window T is at least 500ms. This has been calculated based on vehicle's speed and deceleration parameters, and the safe distance to get to a complete stop before entering the intersection box. Figure 15 shows the measured safety application reliability for our intersection protocols in various multipath environments. We notice that our proposed V2V intersection management protocols have the average application reliability very close to 100%, for distances of up to 100m between the transmitter and the receiver vehicles.

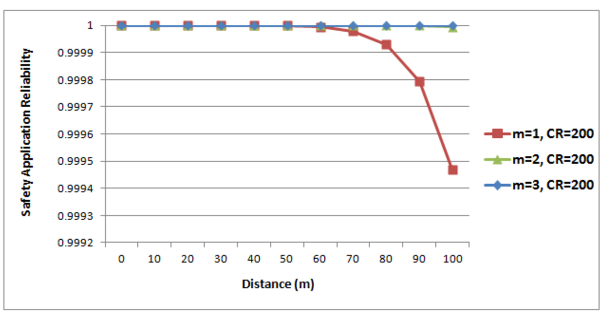


Fig. 15: Application reliability, with communication range of 200 meters.

We therefore conclude that our proposed intersection protocols support safe traversal through intersections at substantially higher throughput even with imperfect and practical wireless environments.

VI. Conclusions and Future Work

More than 44% of all reported vehicle crashes occur at intersections. This shows that current technologies such as traffic lights and stop signs are not so efficient in managing traffic safely and they also increase trip times significantly. In this paper, our goal was to design new V2V-based intersection protocols which significantly increase the throughput of the intersections and avoid collisions. We have also implemented DSRC signal propagation models and studied the effects of channel impairments such as packet loss due to fading on our V2V protocols. Our results indicate that our protocols benefit from properties such as freedom from deadlock and high application reliability even in harsh NLOS environments such as intersections with tall buildings at all corners. Significant increase in traffic throughput with the least dependency on static infrastructure is the other benefit of using these intersection management protocols. Although our protocols are designed for autonomous vehicles that use V2V communication for co-operative driving in future intelligent transportation systems, they can be adapted to a driver-alert system for manual vehicles at traffic intersections.

In our ongoing work, we are addressing the following limitations. As mentioned in this paper, we currently do not deal with position inaccuracies. Position accuracy will affect the protocols since each vehicle depends on its position and the known position of the other vehicles to make safety-critical decisions. We believe that in extreme environment scenarios where the channel is congested and the packet loss rate is very high, local sensing technologies such as cameras, radars, lasers and thermal images can be combined with V2V and V2I communications to avoid any potential collisions.

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