A V2X-based approach for reduction of delay propagation in Vehicular Ad-Hoc Networks *

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Abstract–In this paper we investigate the time delay propagation rates in a Vehicular Ad-Hoc Network, where vehicular connectivity is supported by both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) protocols. In our vision, seamless connectivity issues in a VANET with nearby network infrastructure, can be fixed by an opportunistic choice of a vehicular protocol between V2V and V2I. Such a decision is taken by each vehicle whenever it needs to transmit messages. Our technique —called as Vehicle-to-X— represents a *handoff* procedure between V2V and V2I, and vice versa, in order to keep vehicles connected independent of mobility issues and traffic scenarios.

We investigate the time delay as a performance metric for protocol switching, and present the time propagation rates which occur when vehicles are transmitting warning messages, via V2V or V2I. Simulation results show how the simultaneous usage of pre-existing network infrastructure, together with inter-vehicular communications, provides low delays; while traditional opportunistic vehicular communications increases the transmission time delays and does not guarantee seamless connectivity to vehicles.

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1 Introduction

Vehicular Ad-Hoc NETworks (VANETs) are an emerging class of wireless networks, providing data communications among nearby vehicles in the support of Internet access, as well as a variety of safety applications [1]. Inter-vehicular communications relay on Dedicated Short-Range Communication (DSRC) multi-hop mode, which exploits the flooding of information of vehicular data applications. However, message transmissions among vehicles is commonly affected by quick disconnections, mainly due to high vehicle speeds, long inter-vehicle distances and vehicles density. For instance, in either very low traffic or even totally-disconnected scenarios [2], inter-vehicle communications are difficult to maintain, and the use of network infrastructure can represent a viable solution —if not the only one— for some applications to bridge the inherent network fragmentation that exists in any multi-hop network formed over moving vehicles.

Drive-thru Internet systems represent those emerging wireless technologies providing Internet connectivity to vehicles, by providing temporary connections to a Road Side Unit (RSU) when a vehicle crosses a wireless network via Vehicle-to-Infrastructure (V2I) protocol [3]. Aiming to connect vehicles to the preexisting cellular and Wi-Fi cells, V2I is exploited specially in emergency scenarios where Vehicle-to-Vehicle (V2V) communications are not available [4]. Taking V2V or V2I as the unique communication protocol does not assure a seamless connectivity inside a VANETs. Both in V2V and V2I models, vehicular connectivity management represents a new challenge for VANETs. Exploiting both V2V and V2I represents an effective solution for avoiding disconnections and guaranteeing data communications independently on traffic scenarios (*i.e.* dense, sparse and totally disconnected neighborhoods, [2]).

Different approaches rely on hybrid communication protocols, based on both V2V and V2I, like [5, 6, 7]. V2V and V2I are then assumed to complement each other, working together in an hybrid vehicular communication approach. We propose a *handover* [1] technique, which decides for a protocol switching between V2V and V2I, in order to avoid disconnections due to low traffic density. Particularly, we present an analytical study of time delay propagation which occurs when a vehicle transmits a message via V2V and V2I, respectively. This paper represents a more detailed study on a previous work on V2X approach [7]. In the following sections we shall limit on describing the main aspects of V2X technique, since it has already been largely introduced in [7]. Basically, we shall focus on time delay propagation rates obtained for vehicles communicating via V2X.

The paper is structured as follows. Section 2 investigate the main issues of seamless connectivity in VANETs, and highlights some related work on hybrid vehicular communications protocols. Section 3 gives an analytical model for our proposed V2X technique, particularly focusing on time delay propagation rates. The proposed handover technique is then validated through simulation results as shown in Section 4. The average message propagation delay has been evaluated for different vehicle densities and speeds. Finally, conclusions are drawn in Section 5.

[1] Note that the *handover* mechanism takes origin in cellular systems, where user service is maintained in mobility scenarios [8]. In this work we relay on handover concept to identify a protocol switching that guarantees seamless connectivity in VANETs.

2 Related Work

Achieving seamless connectivity in vehicular ad-hoc networks is a challenge, due to the mainly high dynamic network topology that is constantly changing, and the heterogeneous vehicular density. Many authors investigated novel techniques in order to allow vehicles to be connected to one another. Basically, such approaches rely on using portions of both V2V as well as V2I techniques. This combination is commonly referenced as V2X.

In [5], the authors propose a Cooperative Infrastructure Discovery Protocol, called CIDP. It allows vehicles to gather information about encountered RSUs through direct communication with the network infrastructure, and subsequent message exchanges with neighboring vehicles via V2V. The authors show the effectiveness of this approach, but it seems to be limited to message exchange about infrastructure discovery. Our approach instead relies on an hybrid communication protocol, such as a vehicle can dynamically switch from V2V to V2I whenever the *handover* decision allows. In [6], Seo *et al.* analyze the simulation performances of a general V2X communication protocol, based on the IEEE $802.11p$ WAVE (Wireless Access in Vehicular Environments) system. Their contribution mainly addresses packet error rates for the proposed method, while connectivity issues and reliability of vehicles have not been discussed. In contrast, our approach focuses on a protocol switching aiming seamless connectivity, which needs to be independent of any specific traffic scenarios and vehicle speeds. Finally, the idea proposed by Wedel *et al.*, in [9], is the usage of V2X communications for an enhanced navigation system which smartly help drivers to circumnavigate congested roads and avoid traffic congestions. Their contribution highlights the advantages of V2X communication protocols for safety applications.

In this paper we investigate a hybrid approach for enhancing connectivity among vehicles. It consists of a handover procedure that helps vehicles decide which protocol to use (V2V or V2I). Our protocol-switching based approach results in improving opportunistic connectivity with respect to traditional inter-vehicles communications.

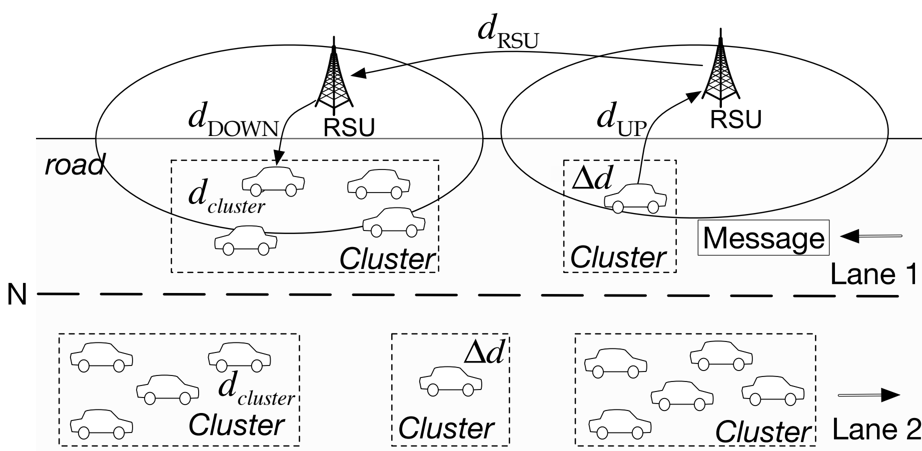


Figure 1: VANET scenario with pre-existing wireless network infrastructure.

3 Delay Propagation Rates

In this section we investigate the time delay propagating in a VANET grid, supported by a heterogeneous network infrastructure. Figure 1 depicts a vehicular network scenario in which a wireless network infrastructure partially covers the VANET. Vehicles move in clusters in two separated lanes (*i.e.*, lane 1, and 2), where north (*i.e.*, N), and south (*i.e.*, S) represent the directions of lane 1, and 2, respectively. The message propagation direction is assumed to be N and vehicles are traveling at a constant speed c [m/s].

The time delay for a message propagating within a cluster C is d [s], which is defined as the difference between the time-stamps of message reception (*i.e.* t_{Rx}), and transmission (*i.e.* t_{Tx}), respectively

$$d = t_{Rx} - t_{Tx}. \tag{1}$$

Equation (1) can be also expressed as the necessary time interval $d_{(i,j)}$ [s] for a successful end-to-end transmission of a message of length L [bit] between a couple of vehicles (i, j), where the i-th vehicle transmits a message to the j-th vehicle at a transmission data rate $f_{(i,j)}$ [Mbps], such as

$$d_{(i,j)} = \frac{L}{f_{(i,j)}}. \tag{2}$$

By assuming the cluster C comprises of a set of vehicles connected each other through h hops (*i.e.* $h = \{1, 2, \ldots, H\}$), the average time delay propagation rate within a cluster (*i.e.*, d [s]) should consider each single contribution due to each single link (i, j), such as

$$d = \sum_{i,j} d_{(i,j)} = L \sum_{i,j} \frac{1}{f_{(i,j)}}, \tag{3}$$

where $d_{(i,j)}$ [s] is the time delay propagation rate on the connectivity link from the i-th vehicle to the j-th vehicle. Assuming a constant transmission data rate (*i.e.* $f = f_{(i,j)}$) for each connectivity link (i, j) in the cluster C, (3) becomes

$$d = \frac{L \cdot h}{f}. \tag{4}$$

Now, let us consider d_{RSU} [s] as the time delay propagation rate within the network infrastructure, as

$$d_{\text{RSU}} = \frac{L}{f_{\text{RSU}}}, \tag{5}$$

which is defined as the ratio between the message length L [Bit], and the effective data rate f_{RSU} [bit/s], for the link between the m-th and $(m + 1)$-th RSU. It represents the time necessary to forward a message of length L between two consecutive RSUs at rate f_{RSU} [Bit/s]. The potential for communications between RSUs is introduced in this work in order to avoid connectivity interruptions caused by low traffic densities, and that the V2V protocol cannot always solve.

Equation (5) represents the time delay propagation rate within the preexisting network infrastructure. According to Figure 1 we shall also consider the time delay propagation rate in *uplink* (*downlink*), when a vehicle sends a message to an RSU (and vice versa), such as:

$$d_{\text{UP}} = \frac{L}{g_{(i,m)}}, \quad d_{\text{DOWN}} = \frac{L}{g_{(m,i)}}, \tag{6}$$

where $g_{(i,m)}$ and $g_{(m,i)}$ is the effective transmission data rate for the link (i,m) (*uplink*), and (m,i) (*downlink*), respectively.

From (5) and (6), it follows that the time delay propagation rate d_{V2I} [s] for communications between vehicles and RSUs via V2I depends only on the effective transmission data rates in uplink and downlink (*i.e.* d_{UP} and d_{DOWN}, respectively), and on the effective data rate for intra RSU communications (*i.e.* d_{RSU}), such as

$$\begin{aligned} d_{\mathrm{V2I}} &= d_{\mathrm{UP}} + d_{\mathrm{RSU}} + d_{\mathrm{DOWN}} = \\ &= L\left(\tfrac{1}{g_{(i,m)}} + \tfrac{1}{f_{\mathrm{RSU}}} + \tfrac{1}{g_{(m,i)}}\right). \end{aligned} \tag{7}$$

As an analogy, we define the time delay propagation rate for communications via V2V (*i.e.*, d_{V2V} [s]), as

$$d_{\mathrm{V2V}} = d + \Delta T, \tag{8}$$

where d [s] is the time delay propagation within a cluster, as defined in (3), and ΔT [s] is the minimum time interval necessary to connect a couple of vehicles traveling at speed c [m/s] and separated at distance Δx [m]. ΔT is defined as

$$\Delta T = \frac{\Delta x}{c}. \tag{9}$$

Notice that when no connectivity occurs (*i.e.*, a vehicle is traveling alone), the time delay propagation rate is equal to ΔT [s]. In V2V communications the time delay propagation rate strongly increases for low traffic density scenarios.

In our vision, we can model the overall system as an alternating renewal process, where vehicular connectivity cyclically alternates between three phases, such as:

1. **Phase 1** (*No connectivity*): a vehicle is traveling alone in the vehicular grid. It represents a typical totally-disconnected traffic scenario, where no connectivity via V2V is available. Moreover, we assume that no connectivity via V2I is assumed to be available during this phase (no network infrastructure);

2. **Phase 2** (*Short-range connectivity*): a vehicle is traveling and forming a cluster with other vehicles. V2V connectivity is available if the inter-vehicle distance is below a fixed connectivity upper bound (*i.e.* ≤ 125 m). No connectivity via V2I is assumed to be available during this phase;

3. **Phase 3** (*Long-range connectivity*): a vehicle is traveling and forming a cluster with other vehicles. It enters a wireless cell and can connect with the associated RSU via V2I. No connectivity via V2V is assumed to be available during this phase. Vehicles are forced to connect with available network infrastructure.

Each phase is described as follows. During Phase 1, the vehicles are completely disconnected, due to very low vehicle density and no available network infrastructure. Data packets are cached within a node and traverse the network, until a connectivity link becomes available. The minimum time necessary to a vehicle to be connected with a neighbouring vehicle is ΔT [s], which depends on the inter-vehicle distance Δx [m] and the vehicle speed c [m/s], as expressed in (9). When a vehicle reflects to be in Phase 2, the messages are able to propagate multihop via V2V within a cluster. The transmission time delay to forward a message within a cluster comprised h hops is d [s], which depends on the effective transmission data rates for each hop within the cluster, as already defined in (4).

We assume that *traditional* opportunistic networking in VANETs relays on exploiting connectivity in both Phase 1 and Phase 2. In order to avoid disconnections, the *bridging* technique connects separated vehicles in Phase 1 with those in Phase 2. It follows that the time delay propagation rate via V2V (*i.e.* d_{V2V} [s]) comprises both two components from Phase 1 (*i.e.* ΔT [s]), and Phase 2 (*i.e.* d [s]), respectively. Finally, in Phase 3 the time period necessary to a vehicle to transmit a message via V2I to an RSU is d_{UP} [s], which depends on the RSU's wireless technology. The end-to-end time delay between two separated vehicles for communications via V2I comprises the uplink (*i.e.* d_{UP}), the inter-RSU link (*i.e.* d_{RSU}), and the downlink (*i.e.* d_{DOWN}) time delays.

By leveraging such assumptions, we shall define the *average transmission time delay propagation rate* (d_{avg} [s]) as the average time delay necessary to propagate a message in a vehicular network, where vehicles are able to opportunistically communicate both via V2V and V2I [2]. Basically, the average time delay alternates between (*i*) the time delay occurring in Phase 1 (*i.e.* ΔT [s]), (*ii*) the multihop time delay in Phase 2 (*i.e.* d [s]), and (*iii*) the time delay in Phase 3 via V2I (*i.e.* d_{V2I} [s]), respectively.

Let us denote $T_\tau^{(n)}$ with $\tau = \{1, 2, 3\}$ the random amounts of time a vehicle spends in one of the three phases, during the n-th cycle. $T_\tau^{(n)}$ are i.i.d. variable, due to the memoryless assumption on the inter-vehicular distances, and the expected time spent in the τ-th phase is $E\left[T_\tau^{(n)}\right]$. It follows that the long-run fraction of time spent in each of these phases is respectively

$$p_\tau = \frac{E\left[T_\tau\right]}{\sum\limits_{\tau} E\left[T_\tau\right]}, \tag{10}$$

where $E\left[T_\tau\right]$ has been assumed to approximate $E\left[T_\tau^{(n)}\right]$.

We are now able to compute the average time delay propagation rate d_{avg}, which occurs in a vehicular scenario, where connectivity is alternating between three main phases, as

$$d_{avg} = p_{(\tau=1)}\Delta T + p_{(\tau=2)}d + p_{(\tau=3)}d_{\mathrm{V2I}}. \tag{11}$$

Each contribution in (11) represents the effective time delay propagation which occurs each time a vehicle is in a specific connectivity phase *i.e.*, for $\tau = \{1, 2, 3\}$. The probability that a vehicle lays in one of the three phases can be expressed as the probability that a vehicle is not connected, connected with neighbors and RSUs, respectively.

In order to determine the probability that a vehicle is connected with other vehicles traveling in the same or opposing direction, it is useful to assume the vehicular grid has a discretization in terms of number of cells, that is the distance gap between two vehicles is equivalent to N cells. Basically, we considered two bounds for the cell size *i.e.*, R, an upper bound, and $R/2$, a lower bound.

[2]Notice that the ratio behind the protocol switching decision from V2V to V2I, and vice versa, in out of the scope of this paper. It has been investigated in [7].

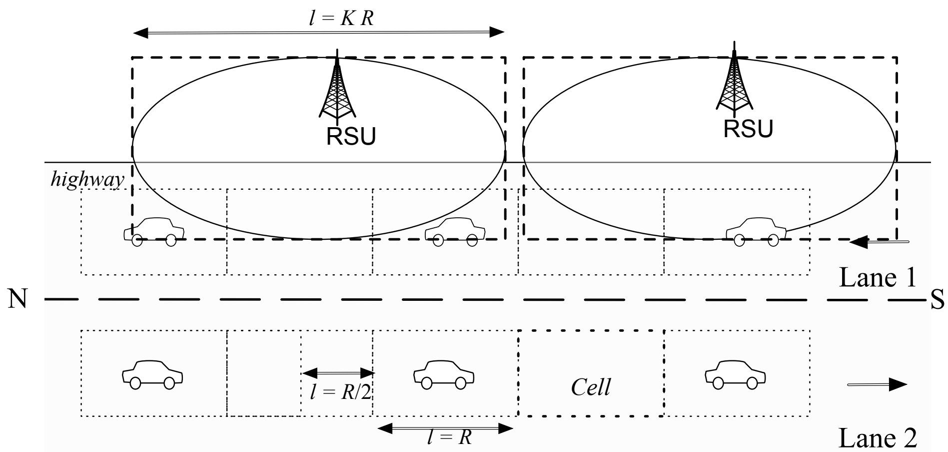


Figure 2: Vehicular grid comprised of R-size virtual cells. The probability that a vehicle is connected via V2V and V2I depends on the cells occupancy.

Figure 2 depicts how the vehicular grid is assumed to be composed of cells. Each cell has a size l [m]. We consider a cell to be occupied if one or more vehicles are positioned within that cell.

In the Phase 1 for a vehicle traveling alone on the eastbound (westbound), the probability that it will be connected via multihop with a next vehicle on the eastbound (westbound) depends on if each of the N eastbound (westbound) cells in the distance gap is occupied by at least one vehicle, such as

$$(p_{e,w})^N = (1 - \exp(-\lambda_{e,w} R))^N, \tag{12}$$

where $\lambda_{e,w}$ is the traffic density distribution on eastbound (westbound). In this case the number of cell is $N = 1$ since the gap equals the minimum inter-vehicle distance, *i.e.* $G = R$ [m]. Equation 12 becomes

$$p_{e,w} = (1 - \exp(-\lambda_{e,w} R)). \tag{13}$$

Again, in the Phase 2 the vehicles along eastbound (westbound) are connected via V2V if each of the N westbound (eastbound) cells in the gap is occupied by at least one vehicle. This is an event which occurs with probability as expressed in (12), but the number of cell N is equal to

$$N = \left\lfloor \frac{G}{R} \right\rfloor, \tag{14}$$

where G [m] is the gap between two separated vehicles. However, in the event that not all of the N cells in the westbound direction are occupied, the vehicles along eastbound are deemed to be disconnected. A message is then buffered in the vehicle's cache until connectivity is achieved again.

Finally, in the Phase 3 the probability that a vehicle traveling in the westbound (eastbound) will be connected via V2I with a next vehicle, still on the westbound (eastbound), depends on if each of the N westbound (eastbound) cells in the distance gap is occupied by at least one RSU, such as

$$(p_{w,e})^N = (1 - \exp(-\lambda_{w,e} R))^N, \tag{15}$$

where in this case the number of cell N is

$$N = \left\lfloor \frac{G}{K \cdot R} \right\rfloor, \tag{16}$$

since we assumed the wireless networks have a larger cell size than that in the vehicular grid *i.e.*, $l = K \cdot R$ [m], with $K > 0$.

We can now give the following Theorem:

Theorem (Average Time Delay Propagation): *The average time delay necessary to a vehicle, driving in a vehicular grid partially covered by a wireless network, to forward a message of length L is:*

$$d_{avg} = p_{e,w}\left(\lfloor N = 1 \rfloor\right) \cdot \Delta T + p_{e,w}\left(N = \lfloor G/R \rfloor\right) \cdot d + p_{w,e}\left(N = \lfloor G/(KR) \rfloor\right) \cdot d_{\mathrm{V2I}}. \tag{17}$$

Notice that since we introduced two bounds for the cell size (*i.e.* the upper and lower one, for $l = R$ and $l = R/2$, respectively), the average time delay propagation in (17) will be comprised between a lower and upper bound.

4 Simulation Results

In order to properly evaluate our theoretical model, we have performed extensive simulations. In this section, we compare the delay propagation rates in a VANET scenario using different communication methods as defined by the three phases of connectivity previously described in Section 3.

The following Subsection 4.1 and 4.2 introduce the simulation setup and the obtained results, respectively.

4.1 Simulation setup

We developed our own simulator, written in the C language, which includes the highway model scenario with 4 different car speeds. The simulator measures the propagation delay as main performance metric.

We considered both asymmetric and symmetric bidirectional traffic flows, where the traffic density on eastbound and westbound traffic is different and assumed equal, respectively. However, in this paper we assumed the symmetric traffic flow scenario, that is a typical configuration illustrating the propagation behavior and message transmission performance when cars are faced with during the all three *connectivity phases*.

We simulated a typical file sharing service, where messages are propagating in the vehicular grid. A large number of simulations were performed, in order to decrease random fluctuations. Then, we assumed perfect conditions, that is no dropped packets, contention or interference occurrence has been introduced. This ideal situation represents the first scenario to simulate in order to understand how delay is affected in the best case. The vehicle density on highways was varied from as low as 1 vehicle per kilometer, up to 100 vehicles per kilometer, and speed covers from 15 up to

Parameter	*Value*
Length of simulation	10000 seconds
Number of runs	200
Vehicular Tx Range	125 m
Infrastructure Tx Range	500 m
File size	9 Mbytes
Packet size	400 bytes
Vehicle speeds	15 to 35 m/s
Vehicle density	1 to 100 vehicles/km

Table 1: Parameter setup used in simulations.

35 [m/s]. These values represent typical highway conditions of sparse, medium and heavy traffic conditions on the roadways. The vehicular traffic has been obtained through a random exponential distribution, which generated the inter-vehicle distances on the highway. The exponential distribution has been largely shown to be in good agreement with real vehicular traces for uncongested traffic conditions, *i.e.*, up to 1000 vehicles per hour. The inter-arrival time of vehicles is calculated based on vehicle density and speed of vehicle over the highway distance. For these reasons however, network connectivity is not always guaranteed. Consequently, there is a non-zero possibility that a partition may exist in the network at any given time.

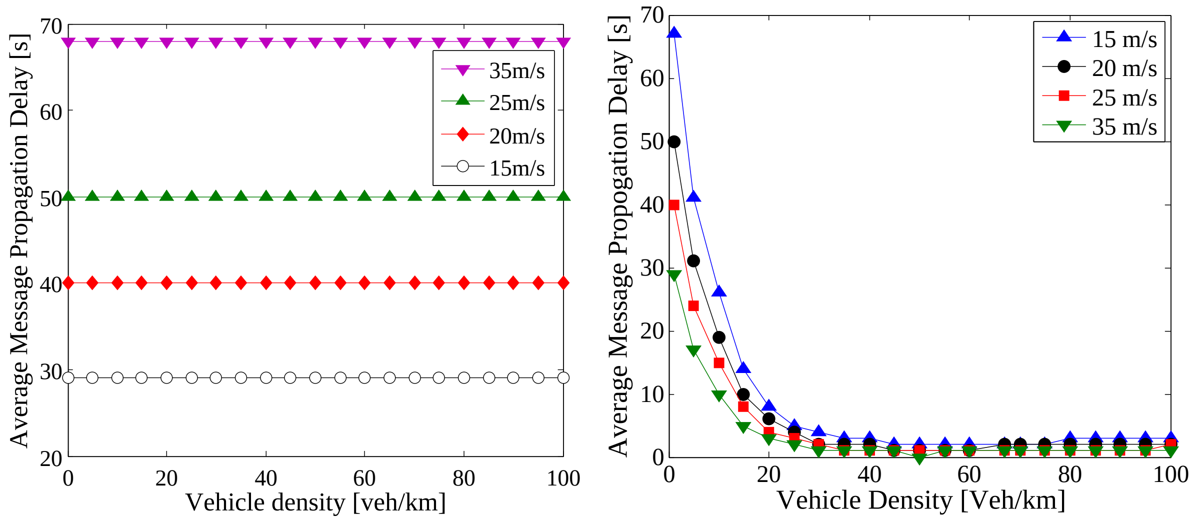
For each scenario, the simulation was run for 10000 seconds, and the average delay was calculated from 200 different iterations to account for the randomness of the simulation. Distance between access points is 500 [m] and they are distributed uniformly. Complete details about the simulation setup are presented in Table 1.

4.2 Simulation results

We compared the delay propagation rates in the three different *connectivity phases* for a typical file sharing application in VANETs. However, to better understand and validate the simulator, we also included a "limited" Phase 2 that allows transmission to a single direction only, so the message propagates strictly in an *ad-hoc* hop-to-hop fashion from vehicle to vehicle on a single direction of the highway. This allows results to be analyzed in light of (*i*) no connectivity; (*ii*) limited one-direction communication; (*iii*) vehicle communication that allows transmissions to both directions through *bridging*; and finally (*iv*) a hybrid V2X model in which a message can propagate using all possible transmission means, be it *ad-hoc* or through the infrastructure whenever available.

Due to space restrictions, we use the following legends in the graphs: "V2V" represents the single-direction message propagation; "V2V Bridged" represents Phase 2; and "V2X" our hybrid model.

Our results show that as the vehicle density increases, the delay decreases. The delay also decreases as the vehicle speed increases as shown in Figure 3 (*a*). This graph represents a typical behavior occurring in Phase 1. The delay in the no connectivity phase is the ratio of physical distance covered over the vehicle speed. Thus, the delay is significantly large as compared to Phase 2 and 3. Notice that in this phase the time delay propagation does not depend on vehicles' density, since no connectivity is assumed to be.



(*a*) (*b*)

Figure 3: (*a*) Average message propagation delay for increasing vehicle density, and speed, for Phase 1 (no connectivity) at different speeds (*i.e.* 15, 20, 25 and 35 m/s). (*b*) Average message propagation delay for increasing vehicle density at different traffic speeds using V2V communication.

Propagation delay also depends on vehicle speed. To better understand this correlation between the delay and the vehicle speed, we have simulated vehicular movement and the delay at four different vehicle speeds relying solely on a single-direction of communication. The simulation results unambiguously show that the delay reduces with increase in vehicle speed as shown in Figure 3 (*b*). As a consequence, Figure 4 (*a*) depicts the average time delay propagation for a message traveling at vehicle speed, and the vehicle density is low. The time delay results in an average delay smaller than that of Phase 1 with no connectivity. Moreover, by modifying the speeds of the vehicles, the maximum time delay changes. As the vehicle density increases the average delay decreases, as probability of connectivity among cars increases and thus the message travels faster than the vehicle speed.

Figure 4 (*a*) shows that in low density situations the average delay follows an increasing order. This is clearly expected and helps corroborate the correctness of our simulator. What results show is that under high density conditions majority of vehicles are inter-connected and the message travels at radio speed. Beyond this level, effect of increasing vehicle density seems non-beneficial. Obviously, as vehicle density increases more and more vehicles are connected and the message can travel at radio speed majority of time.

Finally, in Figure 4 (*b*) we compare the message propagation delay for V2I communications only, since it collects the best and worst cases of time delay propagation. As a matter, V2I performance are not affected by the vehicle density since it does not rely on any multihop vehicle communications. It is only affected by variations of uplink and downlink data rates of the network infrastructure. The transmission rates used are the combinations of the maximum uplink and downlink rates for the infrastructure in order to demonstrate the different thresholds. The uplink data rate ranges from 0.2 Mbps to 2.7 Mbps, and the downlink ranges from 5 Mbps to 12.2 Mbps.

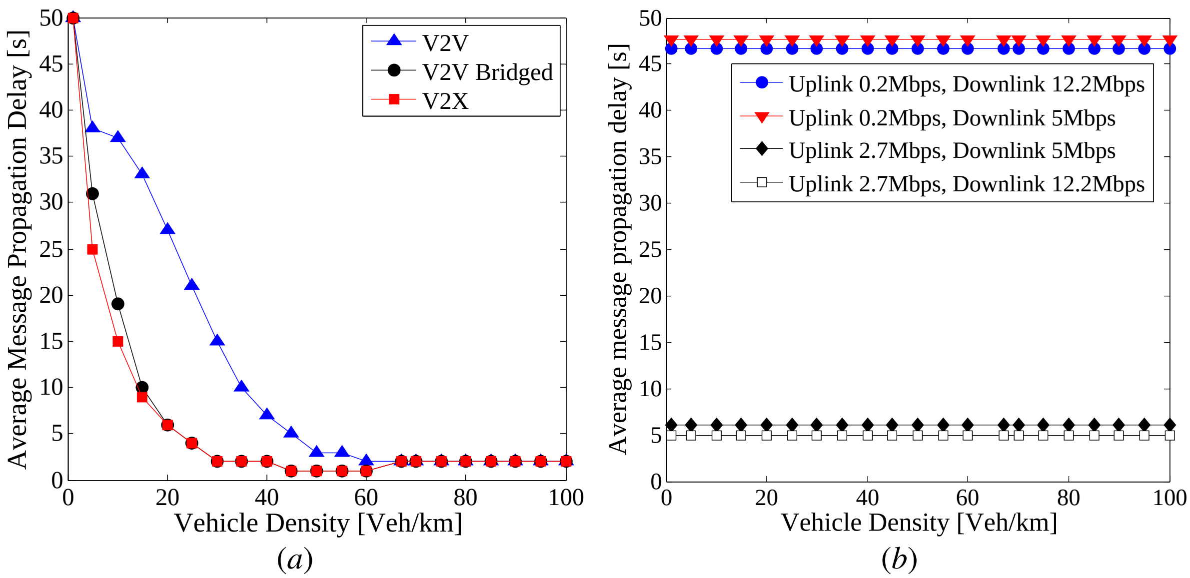


Figure 4: (*a*) Average message propagation delay for increasing vehicle density for V2V, V2V Bridged and V2X at fixed speed. (*b*) Average message propagation delay for increasing vehicle density in V2I communications at different uplink and downlink rates.

Notice the V2I shows the best (*i.e.* 5 s) and worst (*i.e.* 48 s) time delay cases for low (*i.e.* uplink 0.2 Mbps, and downlink 5 Mbps) and high (*i.e.* uplink 2.7 Mbps, and downlink 12.2 Mbps) values of data rates, respectively.

Comparing Figure 4 (*a*) and (*b*) we are then able to establish thresholds for handover between a purely infrastructure-based connection to any of the other options.

5 Conclusions

In this paper we investigated an hybrid vehicular communication protocol relaying on both V2V and V2I approaches. In order to avoid disconnections and maintain a seamless connectivity, vehicles should exploit any available connectivity link occurring in the vehicular grid. Our approach represents an handoff mechanism between V2V and V2I, based on a decision criterion previously discussed in [7].

In this paper we have proven the effectiveness of such technique in terms of time delay transmission rates. Simulation results have shown how hybrid approaches enhance connectivity support specially in high mobility and low density traffic scenarios, with respect to traditional opportunistic V2V techniques. Future work will consider a real-world implementation, in order to properly reflect a more realistic scenario.

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