Hybrid vehicular communications based on V2V-V2I protocol switching [*]

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Abstract–In this paper, a hybrid communication paradigm for vehicular networking is presented in which connectivity is provided by both existing network infrastructure (*e.g.*, wireless network access points) through a vehicle-to-infrastructure protocol and traditional vehicle-to-vehicle networking. Preexisting infrastructure can provide seamless connectivity, especially when vehicles are sparse or traveling in disconnected neighborhoods, while vehicular communications are available for dense traffic scenarios.

In this vision, we depict a novel heterogeneous vehicular network scenario, in which overlapping wireless networks partially cover the vehicular grid. *Vehicle-to-X* (V2X) is based on a protocol switching decision, which is achieved in a distributed fashion by each vehicle based on a cost function using path alternatives. An analytical model for protocol switching in V2X is described. Moreover, we analyze how messages are forwarded by vehicles communicating via V2X. We characterize the maximum and minimum bounds of information propagation and compare performance with traditional message propagation based on opportunistic networking.

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1 Introduction

Vehicular Ad-hoc NETworks (VANETs) are emerging as the preferred network design for intelligent transportation systems providing communications among nearby vehicles in the support of internet access, as well as a variety of safety applications [Held, 2007]. Traditionally, vehicular communications in short range are supported by vehicle-to-vehicle (V2V) protocols, considering smart vehicles equipped by on-board computers with sensors (*e.g.*, radar, ladar, etc.) and multiple network interface cards (*e.g.*, IEEE $802.11p$, Bluetooth, etc.). A dedicated short-range communication (DSRC) multi-hop mode is used for V2V communications and exploits the flooding of information of vehicular data applications [IEE, 1999].

V2V (DSRC) is envisioned by many investigators as the "traditional" protocol for VANETs and the most viable approach to low-latency short range vehicular networks. Nevertheless, connectivity disruptions in VANETs can occur due to quick topology network changes, vehicle speed and when vehicles are in sparse (*i.e.*, low density) or totally disconnected scenarios. As a consequence, vehicles are not always able to communicate to each other, and V2V is not the most appropriate interconnection scheme for some applications, especially non-safety critical ones [Chiara et al., 2009, H. Moustafa and Y. Zhang (Eds.), 2009].

A solution to longer-range vehicular connectivity should consider pre-existing network infrastructure like wireless access points (called as Road-Side Units, RSUs). Infrastructural nodes may simply emit data to the network, and thus be used for forwarding like common vehicles, or may provide access to background networks (*e.g.*, to inform a traffic operation centre about traffic and road conditions). Unlike vehicles, RSUs have widely different capabilities; for instance, RSUs are not equipped with sensors, are stationary and their position is known *a priori* [Schoch et al., 2008].

Intelligent Vehicular Ad-hoc NETworking [Saravanan et al., 2009] defines a novel way of using vehicular networking by integrating heterogeneous emerging wireless technologies, such as 3 G cellular systems, long-term evolution (LTE), IEEE 802.11 and IEEE $802.16e$, for effective vehicle-to-infrastructure (V2I) communications. The V2I protocol represents a viable solution for some applications to bridge the inherent network fragmentation that exists in any multi-hop network formed over moving vehicles through expensive connectivity infrastructure [Bychkovsky et al., 2006].

Drive-thru Internet systems represent those emerging wireless technologies providing Internet connectivity to vehicles, by temporary connections to an access point when a vehicle crosses a wireless network [Ott and Kutscher, 2004]. However, the main V2I limitations are due to particular vehicular applications required (*i.e.*, popular data such as traffic and weather alerts, and also unpopular/user-specific data such as e-mail and Internet browsing), and performance is strictly dependent on the specific wireless technology for the RSUs considered (*i.e.*, WiMax, High Speed Downlink Packet Access, Long Term Evolution, etc.).

Due to the main limitations of V2V and V2I, seamless vehicular connectivity management represents a new challenge for VANETs. To achieve the advantages of both two protocols, we propose a novel hybrid vehicular communication paradigm, named *Vehicle-to-X* (V2X). Based on V2V and V2I, V2X works in traditional VANET scenarios with an heterogeneous network environment with overlapping wireless cells and aims for vehicles to (*i*) communicate multi-hop between them when available (via V2V), and (*ii*) employ communications with network infrastructure (via V2I). As a result, V2X exploits both V2V and V2I —each vehicle can switch from V2V to V2I, and *vice versa*, on the basis of a *protocol switching decision algorithm*. This approach considers traditional vehicular network attributes (*i.e.*, traffic density and message direction) and also network connectivity (*i.e.*, displacement of neighbouring wireless access points and resource utilization). The *protocol switching decision* is taken on the basis of an *optimal path selection technique* (*i.e.*, minimizing radio resource utilization time) which matches the more appropriate vehicular communication protocol.

This paper is structured as follows. Section 2 deals with related work in vehicular communication protocols, and how messages propagate in VANETs. In Section 3, we describe via an analytical approach our proposed V2X protocol. Subsection 3.1 presents the *optimal path selection technique*. In Section 4, we give a few definitions about different data propagation rates obtained with V2X, and then we describe the main phases of V2X protocol, respectively. Simulation results are shown in Section 5 to validate the effectiveness of V2X paradigm. We also compare the performance of V2X with respect to traditional opportunistic networking techniques (*i.e.*, V2V) in terms of message dissemination in a typical VANET scenario. Finally, conclusions are drawn in Section 6.

2 Related Work

Many factors describe VANETs' topology and its dynamic behavior, such as the traffic density (*i.e.*, well-connected, sparsely connected and totally disconnected neighborhoods [Tonguz et al., 2007], the vehicles' speed (*i.e.*, low, medium and high speed) and the heterogeneous network environment (*i.e.*, the technologies of wireless networks around the VANET and their deployment). Vehicular connectivity represents then an open issue since it is not always supported, and messages can be lost or never received. Opportunistic forwarding is the main technique adopted in delay tolerant networks [Spyropoulos et al., 2005], and also extended in VANETs to achieve connectivity between vehicles via V2V and to disseminate information [Agarwal and Little, 2008, Resta et al., 2007, Tonguz et al., 2007]. Message propagation occurs through links built dynamically —a *bridging technique*— where any vehicle can be used as next hop and subsequent hops forward the message to the final destination. [Schoch et al., 2008] define the opportunistic forwarding technique in VANETs as advanced information dissemination communication pattern, whose purpose is to disseminate information among vehicles enduring a certain time. Traditionally, schemes for advanced information dissemination use single-hop broadcasts, store-and-forward technique, to forward messages multiple times to all those vehicles which were unreachable due to network partitioning.

Analysis of message propagation in VANETs via opportunistic networking (V2V) has been largely investigated in the literature. [Resta et al., 2007] deal with multi-hop emergency message dissemination through a probabilistic approach. The authors derive lower bounds on the probability that a vehicle correctly receives a message within a fixed time interval. Similarly, [Jiang et al., 2008] introduce an efficient alarm message broadcast routing protocol and estimate the receipt probability of alarm messages sent to vehicles. Other works [Chen et al., 2008, Nadeem et al., 2006, Yousefi et al., 2007] analyze the message propagation model on the basis of the main VANET characteristics such as number of hops, vehicle position, mobility, etc. [Yousefi et al., 2007] consider a single-hop dissemination protocol based on quality-of-service metrics. [Chen et al., 2008] propose a robust message dissemination technique based on the vehicles position, and [Nadeem et al., 2006] present a data dissemination model based on bidirectional mobility of paths between a couple for vehicles.

Although all the previous methods are effective with V2V for dense traffic scenarios, they are limited when vehicles are driving in low density neighborhoods. Road-side infrastructure should represent a viable solution to extend connectivity support in those scenarios where vehicles are not able to communicate via V2V. V2V and V2I communication technologies have been developed as part of the Vehicle Infrastructure Integration (VII) initiative [Dong et al., 2006]. The VII project considers the network infrastructure as composed by several RSU systems, each of them equipped with a 5.9 GHz DSRC transceiver (for communications between vehicles and RSUs) and a GPRS interface (to forward messages to the backbone networks). Though V2V and V2I can be adopted in the same vehicular environment, the two protocols are not used to cooperate for vehicular communications. [Mak et al., 2005] present a medium access control protocol to support the multi-channel operation for DSRC over IEEE 802.11 links providing high bandwidth for non-safety applications. Similarly, [Hung and Wu, 2008] introduce an heterogeneous wireless network infrastructure by integrating a wireless metropolitan area network with VANET technology, but again, no cooperation between V2V and V2I has been proposed.

The use of a vehicular grid together with an opportunistic infrastructure placed on the roads can be a good solution to guarantee seamless connectivity in dynamic vehicular scenarios, as described in [Gerla et al., 2006, Marfia et al., 2007]. Our approach relies on the network scenario depicted by [Gerla et al., 2006], to assure a seamless vehicular connectivity. We focus on a hybrid vehicular protocol (V2X) which provides switching from V2V to V2I, and vice versa, for dense and sparse traffic neighborhoods with an heterogeneous wireless network infrastructure with overlapping wireless cells [1].

V2X transports data through the network to a destination (a vehicle or RSU), via unicast routing. According to [Schoch et al., 2008], V2X should be classified as advanced information dissemination communication pattern, but dedicated to unicast data communications. The effectiveness of V2X for enhancement in message displacement in VANETs is analyzed and compared with a traditional opportunistic networking technique. Due to the combined potentialities of both V2V and V2I, we expect that the message propagation via V2X be improved by a correct use of vehicular communication protocols.

3 Vehicle-to-X Protocol

V2X technique is a hybrid approach to link both between vehicles (*i.e.*, V2V) and from vehicles to the infrastructure (*i.e.*, V2I) communications. The cooperation and coexistence of these two different methods can assure a good connectivity in VANET scenarios, especially in sparsely connected neighborhoods where V2V communications are not always available. The V2I represents a solution to avoid dropping connections [Ma et al., 2009].

Let us consider the vehicular scenario depicted in Figure 1. It represents a *hybrid model* in which several RSUs of different wireless technologies are deployed, partially covering a given area [Tonguz et al., 2007]. The *local information*—assumed as global—comprises the key data

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[1] No fixed displacement of access points in the ground has been considered, as assumed in [Agarwal and Little, 2008]. Our scope is to represent a real outdoor and urban network scenario, with overlapping wireless networks partially or totally covering the vehicular grid (see Figure 1).

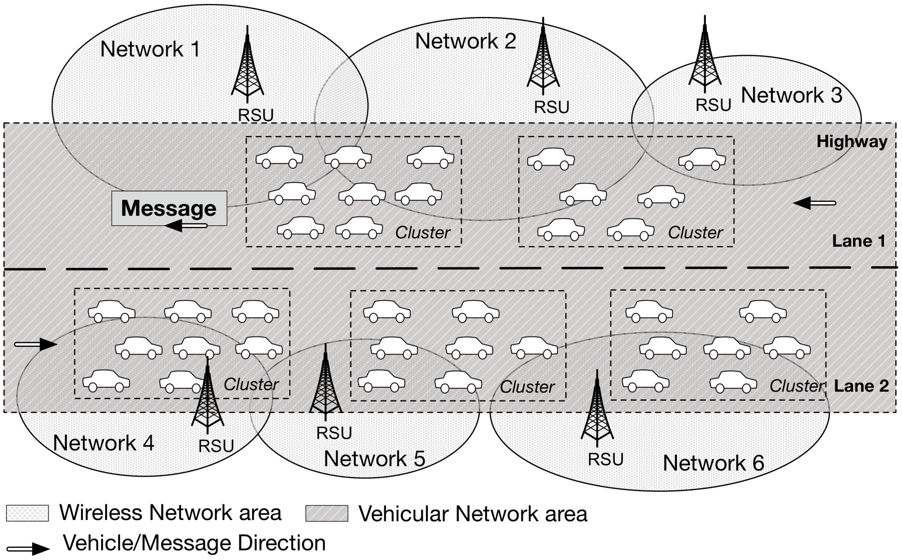

Figure 1: Vehicular grid with an heterogeneous overlapping wireless network infrastructure.

defining the network scenario. This scenario describes the traffic density as directly experienced by the vehicle. Since each vehicle continuously monitors its local connectivity by storing the received "HELLO" broadcast messages, it is able to establish if it is within a cluster or is traveling alone on the road. In contrast, a vehicle will know about neighbouring wireless networks on the basis of broadcast signalling messages sent by the RSUs.

Each vehicle driving in the grid can know about any RSUs in the range by a routing parameter that we define as *Infrastructure Connectivity* (IC). This parameter gives information about the ability of a vehicle to be directly connected with one or more RSUs. The IC assumes two values, *i.e.*, $IC = \{0, 1\}$. If a vehicle has $IC = 1$, then the vehicle is driving inside the radio coverage of a wireless cell and is potentially able to directly connect to the RSU associated with the neighbouring wireless cell. Otherwise, the value of IC is 0 when no available wireless cell is available to access.

3.1 Optimal path selection technique

In this section, we introduce the optimal path selection technique adopted by V2X, allowing protocol switching to vehicles communicating via V2V or V2I, and vice versa.

Let us assume a vehicle lays in a state $\mathrm{s} = \{\mathrm{s}_{\mathrm{V2V}}, \mathrm{s}_{\mathrm{V2I}}\}$, when is connected via V2V or V2I, respectively. The handover mechanism from a serving protocol to a new one (*i.e.*, from V2V to V2I, or vice versa) is achieved by an action a, called as state switching. Figure 2 shows the relationships among states and actions.

Each vehicle will take an action a on the basis of a decision policy, namely *optimal path selection technique*. We now describe this proposed criterion.

In the literature, many techniques for optimal path selection in a network have been presented [Kherani et al., 2006, Kumar et al., 2006], but no channel measurements have been considered. In contrast, our approach is based on a total cost function, *i.e.*, a linear combination of two physical parameters, such as (*i*) the radio resource utilization time, and (*ii*) the time interval needed to transmit a message over a path.

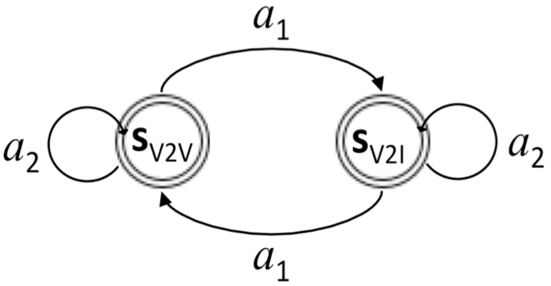

Figure 2: Relationship among states and actions.

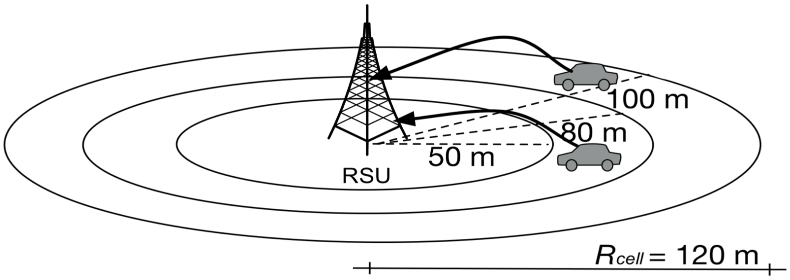

Figure 3: *DRR* parameter depending on the distance from a vehicle to the RSU.

An optimal path connecting the i-th vehicle to the k-th RSU via multi-hop is selected on the basis of a minimization process of the total cost function.

The *optimal path selection technique* represents a policy to decide for the optimal vehicular communication protocol (*i.e.*, V2V or V2I) between two end nodes (*e.g.*, from V2V or from V2I). Basically, for V2I communications, the optimal path selection provides how a vehicle can be connected to a selected RSU which is placed along the same moving direction of the vehicle.

For the connectivity link from the i-th to the j-th vehicle, we define *link utilization time* $\delta_{(i,j)}$ [s] as the time needed to transmit a message of length L [bit] from the i-th to the j-th vehicle at data rate $f_{(i,j)}$ [Mbit/s]. This is expressed as:

$$\delta_{(i,j)} = \frac{L}{f_{(i,j)}}. \tag{1}$$

Notice that for a link between a vehicle and an RSU, $f_{(i,j)}$ is obtained by the nominal data rate $\breve{f}_{(i,j)}$ by applying a *data rate reduction factor* (*DRR*) (*i.e.*, $\rho_{(i,j)}$) that depends on the distance from the vehicle to the RSU:

$$f_{(i,j)} = \rho_{(i,j)} \breve{f}_{(i,j)}. \tag{2}$$

The *DRR* factor is an indicator of data rate reduction percentage, increasing when a vehicle is laying in the bound of a wireless cell, due to path loss (see Figure 3). Table 1 collects our assumptions for the *DRR* factor, where R_{cell} is the wireless cell range corresponding to the nominal data rate $\breve{f}_{(i,j)}$ for a given wireless access technology.

Table 1: Data rate reduction factor vs. the path length.

Wireless Network	R_{cell} (m)	*Distance vehicle-RSU* (m)	*Data Rate Reduction* (%)
Wi-Fi	120	$[0, 50)$	10
		$[50, 80)$	15
		$[80, 100)$	30
UMTS	600	$[0, 300)$	20
		$[300, 400)$	25
		$[400, 600)$	35

Let us consider a cluster C composed by a set S of vehicles (*i.e.*, $S = \{1, 2, \ldots, n\}$). Moreover, m RSUs (*i.e.*, $m < n$) are displaced in the network scenario as depicted in Figure 1. Each vehicle is able to communicate with neighbouring vehicles via V2V on the basis of a connectivity bond—inter-vehicle distance— [Agarwal and Little, 2008]. We assume that only a limited subset of vehicles in the cluster C (*i.e.*, $S' = \{1, 2, \ldots, l\} \subset S$, with $l < n$) is able to connect to an RSU via V2I. For example, not all the vehicles might have an appropriate network interface card and/or be in the range of an RSU.

In such a scenario, we define the following *transmitting data rate matrices*, respectively, for V2V (*i.e.*, $\mathbf{N}_{[n \times m]}$), and V2I (*i.e.*, $\mathbf{M}_{[n \times m]}$) communications, as follows. Let $\mathbf{N}_{[n \times m]}$ be the matrix of the *V2V transmitting data rate*s $f_{(i,j)}$ between vehicles in the cluster C:

$$\mathbf{N}_{[n \times n]} = \begin{bmatrix} 0 & f_{(1,2)} & \cdots & f_{(1,n)} \\ f_{(2,1)} & 0 & \cdots & f_{(2,n)} \\ \cdots & \cdots & 0 & \cdots \\ f_{(n,1)} & f_{(n,2)} & \cdots & 0 \end{bmatrix}, \tag{3}$$

where n is the number of vehicles in the cluster C, $f_{(i,j)} = 0$ for $i = j$, while $f_{(i,j)} > 0$ for $i \neq j$ with $i, j = \{1, 2, \ldots, n\}$.

Let $\mathbf{M}_{[n \times m]}$ be the matrix of *V2I transmitting data rates* $g_{(i,k)}$:

$$\mathbf{M}_{[n \times m]} = \begin{bmatrix} g_{(1,1)} & \cdots & g_{(1,m)} \\ g_{(2,1)} & \cdots & g_{(2,m)} \\ \cdots & \cdots & \cdots \\ g_{(n,1)} & \cdots & g_{(n,m)} \end{bmatrix}, \tag{4}$$

where m is the number of RSUs displaced in the network scenario, $g_{(i,k)}$ is the data rate associated to the link from the i-th vehicle to the k-th RSU (*i.e.*, $k = \{1, 2, \ldots, h\}$, with $h < m$). Elements $g_{(i,k)}$ in matrix $\mathbf{M}_{[n \times m]}$ are null when there is no connection between i-th vehicle to k-th RSU, while l is the maximum number of available connectivity links (*i.e.*, $g_{(i,k) \neq 0}$ for $i = \{1, 2, \ldots, l\}$) [2].

From (3) and (4), we define the matrix $\mathbf{D}_{[n \times m]}$ of transmitting data rates for the i-th vehicle in the cluster C as follows:

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[2] Notice that according to typical cellular systems like UMTS, a vehicle can be simultaneously connected to more than one single RSU, whenever it is crossing an area with overlapping wireless cells.

$$\mathbf{D}_{[n\times m]} = \left[\mathbf{N}_{[n\times n]} \middle| \mathbf{M}_{[n\times m]}\right] = \left[\begin{array}{cccc|ccc} 0 & f_{(1,2)} & \cdots & f_{(1,n)} & g_{(1,1)} & \cdots & g_{(1,m)} \\ f_{(2,1)} & 0 & \cdots & f_{(2,n)} & g_{(1,1)} & \cdots & g_{(2,m)} \\ \cdots & \cdots & 0 & \cdots & \cdots & \cdots & \cdots \\ f_{(n,1)} & f_{(n,2)} & \cdots & 0 & g_{(n,1)} & \cdots & g_{(n,m)} \end{array}\right], \qquad (5)$$

where each element represents the direct link from the i-th vehicle to the j-th vehicle, or to the k-th RSU (*i.e.*, $f_{(i,j)}$, or $g_{(i,k)}$, respectively). When a vehicle is transmitting a message towards a destination, message forwarding occurs via multi-hop between vehicles communicating via V2V. The sequence of hops necessary for transmitting the message from a source to a destination represents a *path*, defined as follows:

Definition (*Path*): *A path $\Gamma_{(i,j)}$ in a vehicular grid from the i-th to the j-th node, either vehicle or RSU, comprised of a sequence of M hops $[u_1, u_2, \ldots, u_t, u_{t+1}, \ldots, u_M]$ with $u_1 = i$, and $u_M = j$, will exist if for each hop the transmitting data rate is non-null.*

The path length represents the number of M hops for a single path. It follows that, the maximum number of directed links from a vehicle to an RSU is $d = l \cdot h$, while the maximum number of potentially available paths connecting the i-th vehicle to the k-th RSU is $n \cdot d$. This represents an upper bound for the maximum number of paths, easier to reach in a dense traffic scenario, than in sparse traffic environments.

Now, we denote $\Gamma_{(i,k)}^{(\lambda)}$ as the λ-path, with $\lambda = \{1, 2, \ldots, n\dot{d}\}$, from the i-th to the k-th RSU. We assume a first partition of $\Gamma_{(i,k)}^{(\lambda)}$ into Φ sets $\gamma_{\varphi}^{(\lambda)}$, with $\varphi = \{1, 2, \ldots, \Phi\}$; each set consists of those $\mu_{\varphi}^{(\lambda)}$ links sharing the same frequency band F_{φ} [Hz], namely:

$$\gamma_{\varphi}^{(\lambda)} = \left\{\mu_1^{(\lambda)}, \mu_2^{(\lambda)}, \ldots, \mu_{\Phi}^{(\lambda)}\right\}, \qquad (6)$$

where $\mu_{\varphi}^{(\lambda)} = \left(u_{i,(F_{\varphi})}, u_{j,(F_{\varphi})}\right)$, is the φ-th link from the i-th to the j-th node, transmitting at the frequency F_{φ} [Hz]. Equation (6) can be re-written as [3]:

$$\gamma_{\varphi}^{(\lambda)} = \left\{\left(u_{i,(F_1)}, u_{j,(F_1)}\right), \left(u_{i,(F_2)}, u_{j,(F_2)}\right), \ldots, \left(u_{i,(F_{\varphi})}, u_{j,(F_{\varphi})}\right)\right\}, \qquad \varphi = 1, 2, \ldots, \Phi \qquad (7)$$

For each set $\gamma_{\varphi}^{(\lambda)}$, let $\nu_{\varphi}^{(\lambda)}$ be the number of subsets $\eta_s^{(\lambda,\varphi)}$ (*i.e.*, $s = \left\{1, 2, \ldots, \nu_{\varphi}^{(\lambda)}\right\}$), such that

$$\eta_s^{(\lambda,\varphi)} = \left\{q_1^{(\lambda,1)}, q_2^{(\lambda,2)}, \ldots, q_s^{(\lambda,\varphi)}\right\}, \qquad (8)$$

where the s-th subset $\eta_s^{(\lambda,\varphi)}$ consists of those $q_s^{(\lambda,\varphi)}$ links for which simultaneous use of the wireless channel is not possible. This is, for instance, the case of IEEE 802.11 links connecting a given node to its 1-hop neighbors.

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[3] Each subset $\mu_{\varphi}^{(\lambda)}$ is homogeneous with respect to the wireless technology and standard (*e.g.*, IEEE 802.11 p, GSM, GPRS, UMTS, HSDPA, UMTS LTE, WiMAX, etc.).

Analogously to (1), for each set $\gamma_{\varphi}^{(\lambda)}$ we define *radio resource utilization time* (*i.e.*, $Q_{\varphi}^{(\lambda)}$ [s]) for a message of length equal to L [bit] as the quantity:

$$Q_{\varphi}^{(\lambda)} = \underset{1 \le s \le \nu_{\varphi}^{(\lambda)}}{Max} \left[\sum_{q_s^{(\lambda,\varphi)} \in \eta_s^{(\lambda,\varphi)}}^{nd} \frac{L}{f_{\left(q_s^{(\lambda,\varphi)}\right)}} \right], \tag{9}$$

where $f_{\left(q_s^{(\lambda,\varphi)}\right)}$ represents the data rate for each link $q_s^{(\lambda,\varphi)}$.

It follows that, for each path $\Gamma_{(i,k)}^{(\lambda)}$ we define as *weighted total utilization time* (*i.e.*, $\tilde{Q}_{(i,k)}^{(\lambda)}$, [s]) the sum of each weighted *radio resource utilization time* that comprises the path:

$$\tilde{Q}_{(i,k)}^{(\lambda)} = \sum_{\varphi=1}^{\Phi} C_{\varphi} \cdot Q_{\varphi}^{(k)}, \tag{10}$$

where C_{φ} is the relative *cost*, expressed in terms of protocol overhead or latency, and associated to the φ-th frequency band. In general, the cost will be proportional to the allocated bandwidth, depending on the access network technology (*e.g.*, Wi-Fi, and UMTS).

In addition, let us denote with $D_{(i,k)}^{(\lambda)}$ the time needed to transmit over $\Gamma_{(i,k)}^{(\lambda)}$ a message of length equal to L [bit]. Apart from latencies introduced by node processing and queuing, the following relation represents the *delay factor* $D_{(i,k)}^{(\lambda)}$ on the λ-th path $\Gamma_{(i,k)}^{(\lambda)}$:

$$D_{(i,k)}^{(\lambda)} = \sum_{\varphi=1}^{\Phi} \sum_{\mu_{\varphi}^{(k)} \in \gamma_{\varphi}^{(k)}}^{nd} \frac{L}{f_{\left(\mu_{\varphi}^{(k)}\right)}}. \tag{11}$$

From (10) and (11), we finally define $\Lambda_{(i,k)}^{(\lambda)}$ [s] as the *total cost function* associated to the path $\Gamma_{(i,k)}^{(\lambda)}$ [s], such that:

$$\Lambda_{(i,k)}^{(\lambda)} = \alpha \tilde{Q}_{(i,k)}^{(\lambda)} + (1-\alpha) D_{(i,k)}^{(\lambda)}, \tag{12}$$

where $0 \le \alpha \le 1$ is a weight given to $\tilde{Q}_{(i,k)}^{(\lambda)}$ with respect to the *delay factor*. For different values of α (*i.e.*, $\alpha = [0, 0.5, 1]$), (12) becomes:

$$\Lambda_{(i,k)}^{(\lambda)} = \begin{cases} D_{(i,k)}^{(\lambda)}, & \alpha = 0 \\ \alpha \tilde{Q}_{(i,k)}^{(\lambda)} + (1-\alpha) D_{(i,k)}^{(\lambda)}, & 0 < \alpha < 1 \\ \tilde{Q}_{(i,k)}^{(\lambda)}, & \alpha = 1 \end{cases} \tag{13}$$

From (13) we define an *Optimal Path* as:

Definition (*Optimal Path*): *Given a pair of nodes (i,k), the optimal path will be the one, among all the $n \cdot d$ paths, minimizing the total cost function, such as*

$$\min_{\lambda=1,2,\ldots,nd} \Lambda^{(\lambda)}_{(i,k)} = \begin{cases} \min\limits_{\lambda=1,2,\ldots,nd} D^{(k)}_{(i,k)}, & \alpha = 0 \\ \alpha \cdot \min\limits_{\lambda=1,2,\ldots,nd} \tilde{Q}^{(\lambda)}_{(i,k)} + (1-\alpha) \cdot \min\limits_{\lambda=1,2,\ldots,nd} D^{(\lambda)}_{(i,k)}, & 0 < \alpha < 1 \\ \min\limits_{\lambda=1,2,\ldots,nd} \tilde{Q}^{(\lambda)}_{(i,k)}, & \alpha = 1 \end{cases} \tag{14}$$

In this paper we evaluate simulation results by accounting for the delay factor only (*i.e.*, $\alpha = 0$).

4 Data Propagation Rates

In this section, we illustrate how a message is propagated in a VANET incorporating an heterogeneous network infrastructure where vehicles communicate via V2X. For our purposes, we give several definitions of message dissemination rates for different cases.

In Figure 4 vehicles move in clusters in two separated lanes (*i.e.*, lanes 1 and 2), where north (*i.e.* N) and south (*i.e.* S) represent the directions of lanes 1 and 2, respectively. The message propagation direction is assumed for this case to be N. We assume the vehicles are traveling at a constant speed c [m/s], while v [m/s] is the message propagation rate within a cluster, such as

$$v = \frac{x}{t}, \tag{15}$$

where x is the transmission range distance between two consecutive and connected vehicles (*i.e.*, $x \leq 125$ m, [Tonguz et al., 2007], and t [s] is the time necessary for a successful transmission, which depends on the single link of connected vehicles. From (15), the average message propagation rate within a cluster (*i.e.* v [m/s]) should consider each single contribution due to each single link (i, j):

$$v = \frac{1}{h} \sum_{i,j} v_{(i,j)} = \frac{1}{h} \sum_{i,j} \frac{x_{(i,j)}}{D_{(i,j)}}, \tag{16}$$

where $v_{(i,j)}$ [m/s] is the message propagation rate for the link (i, j), and h is the number of hops occurred within a cluster. The message propagation rate v [m/s] depends on the average message propagation rate for each hop within a cluster and increases for a low number of hops h. From (11), we obtain $D_{(i,j)}$ as the delay factor over a single link, *i.e.*, a pair of vehicles (i, j).

Now, let us consider v_{RSU} [m/s] as the *message propagation rate within the network infrastructure* [4], as

$$v_{\text{RSU}} = \frac{d}{T_{\text{RSU}}}, \tag{17}$$

where d is the distance between two consecutive RSUs, and T_{RSU} is the time necessary to forward a message between two consecutive RSUs. T_{RSU} is defined as the ratio between the message length L [bit], and the effective data rate B [bit/s], for the link between the m-th and $(m + 1)$-th RSU:

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[4] v_{RSU} is strictly dependent on the message propagation direction: a message is forwarded to an RSU if it is placed along the same message propagation direction

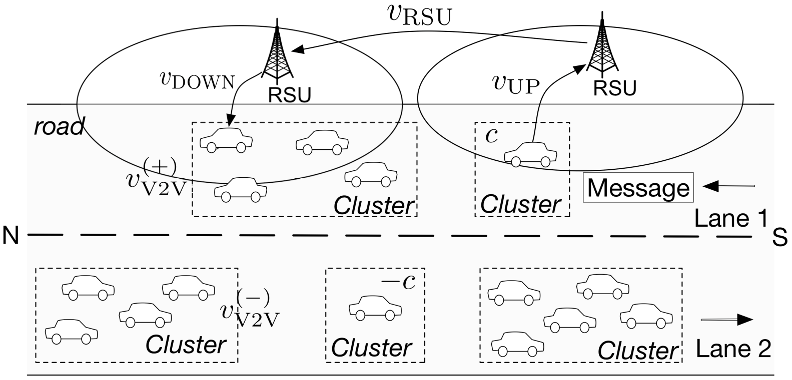

Figure 4: Data propagation rates in VANET scenario with network infrastructure.

$$T_{\mathrm{RSU}} = \frac{L}{B}. \tag{18}$$

In Figure 4, we show the data propagation rates for the considered VANET scenario. Notice that each message forwarded by an RSU to the next RSU has been previously sent by a vehicle driving inside the wireless cell of the RSU. Moreover, each time an RSU receives a message from another RSU, it sends the message (*i*) to the destination vehicle if it is driving inside the actual RSU coverage, and (*ii*) to the next RSU.

In the first case, the message propagation rate will depend on a downlink connection from RSU to a vehicle, while in the second case the message propagation rate will be equal to v_{RSU}. By leveraging these considerations, we define the *message propagation rate in uplink* (*downlink*), when a vehicle sends a message to an RSU (and vice versa) as:

$$v_{\mathrm{UP}} = \frac{x_r}{L} \cdot g_{(i,m)}, \quad v_{\mathrm{DOWN}} = \frac{x_r}{L} \cdot g_{(m,i)}, \tag{19}$$

where x_r is the distance that separates the i-th vehicle and the m-th RSU, while $g_{(i,m)}$ and $g_{(m,i)}$ are the effective transmission data rate for the link (i,m) (*uplink*), and (m,i) (*downlink*), respectively.

From (17) and (19), it follows that the *message propagation rate* v_{V2I} [m/s] for communications between vehicles and RSUs via V2I depends on the effective transmission data rates in uplink and downlink and on the effective data rate for intra-RSU communications, or:

$$v_{\mathrm{V2I}} = v_{\mathrm{UP}} + v_{\mathrm{RSU}} + v_{\mathrm{DOWN}} = \frac{1}{L}\left[d \cdot B + x_r \cdot \left(g_{(i,m)} + g_{(m,i)}\right)\right]. \tag{20}$$

After defining message propagation rates for communications via V2I, we introduce the message propagation rate for communications via V2V (*i.e.*, v_{V2V} [m/s]) as

$$v_{\mathrm{V2V}}^{(\pm)} = \pm(v + c), \tag{21}$$

which depends on the constant velocity c of vehicles and on the effective transmission data rates within a cluster C, according to (16). The positive or negative sign of v_{V2V} is due by the message propagation direction. Finally, when no connectivity occurs (*i.e.*, a vehicle is traveling alone in the grid), the message propagation rate is equal to $\pm c$, which depends on message propagation direction [5].

In our assumptions, we considered two message propagation directions (*i.e.*, *forward* and *reverse* propagation). In *forward message propagation*, each vehicle is assumed to travel in the N direction at speed c [m/s], and the message is propagated in the N direction as well. The message propagation rate has a minimum value due to the speed of the vehicle (*i.e.*, c [m/s]), since the message is traveling along the vehicle. When a connection between two consecutive vehicles traveling in the N direction is available, the message will be propagated via V2V at a rate $v_{\mathrm{V2V}}^{(+)}$. Moreover, if no vehicle connection is available, the bridging technique can attempt to forward a message to clusters along the S (opposite) direction, whenever they are overlapping with the cluster along the N direction.

Analogously, in reverse message propagation, each vehicle is assumed to travel in the S direction at speed $-c$ [m/s], and the message is propagated in the S direction as well. The message propagation rate will have a minimum value due to the speed of the vehicle (*i.e.*, $-c$ [m/s]), and a maximum bound when a message is propagating via V2V at a rate $v_{\mathrm{V2V}}^{(-)}$. Again, if no vehicle connection is available, a message will be forwarded via bridging to clusters along the N (opposite) direction, whenever they are overlapping with the cluster along the S direction. Such considerations occur for vehicles communicating via V2V and when opportunistic networking is available.

In contrast, when vehicles are communicating via V2I, the *forward message propagation* will have a maximum bound equal to v_{V2I}, while for *reverse message propagation* range the maximum bound is $-v_{\mathrm{V2I}}$. The definitions for *forward* and *reverse message propagation rates* are given below, respectively.

Definition (Forward message propagation rate): *The forward message propagation rate, when a vehicle is communicating via V2V, is in the range* $[c, v_{\mathrm{V2V}}^{(+)}]$. *In contrast, when a vehicle communicates via V2I, the forward message propagation rate is in the range* $[c, v_{\mathrm{V2I}}]$.

Definition (Reverse message propagation rate): *The reverse message propagation rate, when a vehicle is communicating via V2V, is in the range* $[-c, v_{\mathrm{V2V}}^{(-)}]$, *while for vehicles communicating via V2I, the range of reverse message propagation rate is* $[-c, -v_{\mathrm{V2I}}]$.

5 Simulation Results

In this section, we show results of V2X performance expressed in terms of (*i*) *total cost function* for protocol switching decisions, and (*ii*) *message propagation* [6], in *dense* and *sparse* traffic scenarios, respectively.

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[5] The behavior of the whole system can be characterized in terms of six transition states as described in [Vegni and Little, 2010].

[6] We recall the simulation results in [Vegni and Little, 2010] by comparing our technique with traditional opportunistic networking scheme in VANET [Agarwal and Little, 2008].

We consider a set S of vehicles (*i.e.*, $S = \{s_1, s_2, \ldots, s_n\}$), and m RSUs available to V2I communications. Without loss of generality, we consider $n = 10$ vehicles. Our scope is to depict a *dense* and a *sparse* traffic scenarios by varying the availability of connectivity links between vehicles and from vehicles to RSUs. Thus, we assume S' (*i.e.*, $S' = \{s_1, s_3, s_5, s_7, s_9\}\,,\ \ S' \subset S$) as a subset of vehicles with a direct connection with the k-th RSU.

From the definition of path, the maximum number of directed links from a vehicle to the RSU is $d = 5$. In the following simulation results, we considered the transmission ranges for V2I communications equal to 10 [Mbit/s] (*e.g.*, assuming a WiMax connectivity link), while the transmission ranges for V2V communications are in the range $[6.0, 20.5]$ [Mbit/s], [IEE, 1999]. We evaluated the *total cost function* for $\alpha = 0$, which corresponds to the delay factor, *i.e.*, $\Lambda_{i,k}^{(\lambda)} = D_{i,k}^{(\lambda)}$ as expressed in (13).

Tables 2 and 3 collect the values of the total cost function in a dense traffic scenario, for all the paths originated from vehicles with $IC = 1$ (*i.e.*, vehicle $\#2$, $\#4$, $\#6$, $\#8$ and $\#10$), and $IC = 0$ (*i.e.*, vehicle $\#1$, $\#3$, $\#5$, $\#7$ and $\#9$), respectively. The maximum value of the delay factor (*i.e.*, 30 ms) is obtained when a vehicle with $IC = 1$ is connected via V2I (*e.g.*, path 1 from vehicle $\#2$ to the RSU), while low values in the range $[11.76, 13.95]$ ms are for vehicles with $IC = 1$ connected via V2V, (*e.g.*, paths 25 from vehicle $\#2$ to the RSU). Vehicles connected to the RSU via V2V follows paths with low delays (see paths 25 in Table 3), while for vehicles connected via V2I the total cost function has high value (see path 1 in Table 2). Finally, by comparing Table 2 with Table 3, we evince that in a dense traffic scenario low values of the *total cost function* are obtained with V2V, while the maximum value is for V2I.

In Table 4, we collect the values of $\Lambda_{i,k}^{(\lambda)}$ for $\alpha = 0$, in a *sparse* traffic scenario for vehicles with $IC = 1$. The maximum value of the delay factor is still 30μs, obtained when a vehicle is connected via V2I, while low values are obtained when a vehicle is in V2V state. We can assess that also in a *sparse* traffic scenario for vehicles with $IC = 1$, V2V shows high performance with respect to V2I.

A different result is obtained in the *sparse* traffic scenario for vehicles with $IC = 0$. Table 5 lists the values of the *total cost function* for different paths; the maximum value occurs for several paths when a vehicle is connected via V2V and the number of hops increases. In contrast, low values of the *total cost function* are obtained when a vehicle communicates via V2V for just one single hop.

As a conclusion, both in *sparse* and *dense* traffic scenarios, the optimum path can guarantee a minimum total *cost function* approximately equal to 11.5μs for vehicles connected via V2V. High values of the *total cost function* are obtained with V2I in a *dense* traffic scenario, and with V2V in a *sparse* traffic scenario for increasing number of hops. It follows that V2V is most suitable in *dense* scenarios, and in *sparse* traffic neighborhoods for path with a limited number of hops; while V2I could be the most appropriate protocol in *sparse* scenarios when the number of hops linking a source to a destination is increasing.

After showing V2X performance in terms of optimal path selection, we present the *message displacement* via V2X. Basically, we recall the algorithm for V2X technique previously described in [Vegni and Little, 2010] by its pseudocode. The message displacement (*i.e.*, X [m]) is a linear function, depending on time, and varying for different traffic scenarios, message propagation speeds and network conditions. We simulated a typical vehicular network scenario as depicted in [Vegni and Little, 2010] and compared with traditional opportunistic networking technique in

Table 2: Values of *total cost function* [μs] for vehicles with $IC = 1$ in a *dense* traffic scenario.

Vehicle's ID	*Path 1*	*Path 2*	*Path 3*	*Path 4*	*Path 5*
$\#2$	30	12.76	12.5	12.5	13.3
$\#4$	12.76	30	11.76	11.76	13.04
$\#6$	12.5	11.76	30	11.76	11.76
$\#8$	12.5	11.76	11.76	30	11.76
$\#10$	13.33	13.04	11.76	11.76	30

Table 3: Values of *total cost function* [μs] for vehicles with $IC = 0$ in a *dense* traffic scenario.

Vehicle's ID	*Path 1*	*Path 2*	*Path 3*	*Path 4*	*Path 5*
$\#1$	13.95	13.33	12.76	13.33	13.33
$\#3$	13.33	12.76	11.76	12.76	13.04
$\#5$	13.04	13.04	11.76	11.76	11.76
$\#7$	12.5	11.76	11.76	11.76	11.76
$\#9$	13.33	11.76	11.76	11.76	11.76

Table 4: Values of *total cost function* [μs] for vehicles with $IC = 1$ in a *sparse* traffic scenario.

Vehicle's ID	*Path 1*	*Path 2*	*Path 3*	*Path 4*	*Path 5*
$\#2$	30	14.28	16.21	14.28	12
$\#4$	14.28	30	18.75	18.75	11.3
$\#6$	16.21	18.75	30	18.75	18.75
$\#8$	14.28	18.75	18.75	30	18.75
$\#10$	12	11.32	18.75	18.75	30

Table 5: Values of *total cost function* [μs] for vehicles with $IC = 0$ in a *sparse* traffic scenario.

Vehicle's ID	*Path 1*	*Path 2*	*Path 3*	*Path 4*	*Path 5*
$\#1$	30	12	30	12	13.63
$\#3$	30	30	18.75	30	14.28
$\#5$	11.32	30	30	18.75	30
$\#7$	30	18.75	30	30	18.75
$\#9$	12	30	18.75	30	30

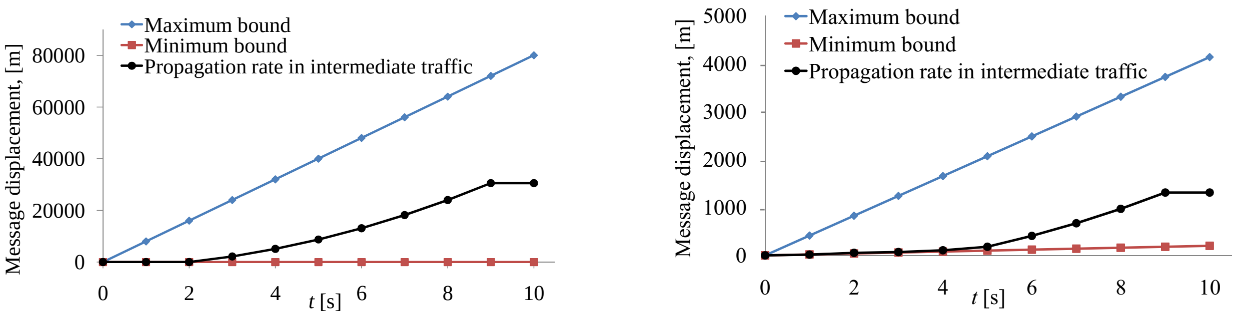

Figure 5: Forward message propagation with (*left*) V2X protocol, (*right*) traditional opportunistic networking.

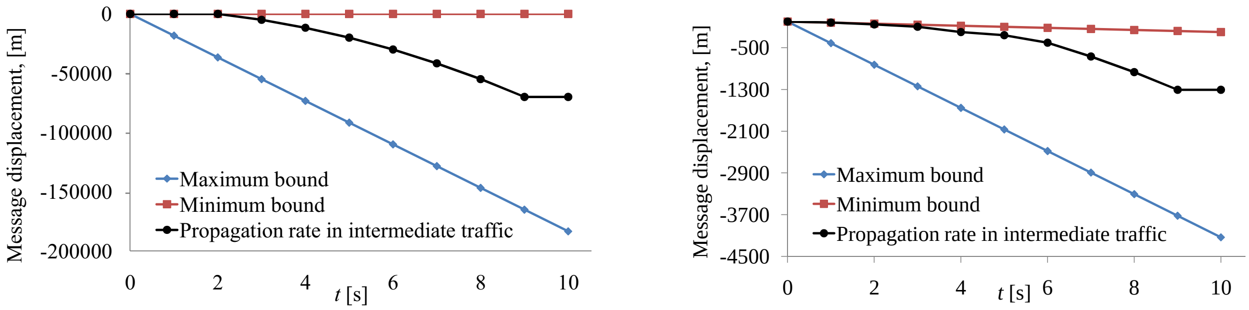

Figure 6: Reverse message propagation with (*left*) V2X protocol, (*right*) traditional opportunistic networking.

VANETs [Agarwal and Little, 2008].

Figure 5 (*left*) depicts the maximum and minimum message propagation bounds for V2X in *forward message propagation* mode. Notice a strong increase in the message propagation with respect to other forms of opportunistic networking: after $t = 10$ s, the message has been propagating for ~ 30 km in V2X (Figure 5 (*left*)), while only 1.5 km in traditional V2V (Figure 5 (*right*)). The high performance gap is mainly due to the protocol switching decision of V2X, which exploits high data rates from wireless network infrastructure. In contrast, opportunistic networking with V2V is limited to use only DSRC protocol.

Analogously, we consider a *reverse message propagation* mode, in which vehicles travel in an opposite direction. While V2X assures high values for message displacement (*i.e.*, at $t = 10$ s, a message has been propagated up to around 70 km as shown in Figure 6 (*left*)), traditional V2V can achieve low values (*i.e.*, at $t = 10$ s, messages have reached 1.3 km far away from the source vehicle (see Figure 6 (*right*)). Notice that the fluctuations of message displacement in forward and reverse cases with V2X (*i.e.*, 50 and 70 km, respectively) are mainly due to traffic density and inter-RSU distance.

6 Conclusions

In this paper, a novel hybrid vehicular communications paradigm has been proposed. This technique, called as V2X, aims to switch between performance regimes of both V2V and V2I to yield improved overall performance based on opportunistic use of moving vehicles and available wireless network infrastructure. Based on a switching protocol decision metric between V2V and V2I, V2X represents a dynamic communication paradigm for vehicular networking. It selects the most appropriate protocol (V2V or V2I) to employ for a vehicle driving in a particular network scenario (*i.e.*, *dense* and *sparse* traffic scenario). The protocol selection is driven through a proposed *optimal path selection technique*, which is mainly based on physical parameters (*i.e.*, delay and radio resource utilization time).

V2X has been investigated in terms of (*i*) how it selects V2V or V2I protocol, and (*ii*) how messages are propagating in dense and sparse traffic scenarios. V2I performance depends on the data rate over a direct link to an RSU, while V2V performance is strictly dependent on the number of hops composing a path from a source to a destination. We also characterized the upper and lower bounds for message displacements in different traffic scenarios. Validation of V2X has been undertaken via simulation, that show how the V2X protocol improves network performance with respect to traditional opportunistic networking techniques applied in VANETs.

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