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Seamless Connectivity Techniques in Vehicular Ad-hoc Networks

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1. Introduction

Emerging Vehicular Ad-hoc NETworks (VANETs) are representing the preferred network design for Intelligent Transportation Systems (ITS), mainly based on Dedicated Short-Range Communications (DSRC) for Vehicle-to-Vehicle (V2V) communications (Held, 2007). Future vehicles will be fully networked, equipped with *on-board* computers with multiple Network Interface Cards (NICs) (*e.g.*, Wi-Fi, HSDPA, GPS), and emerging wireless technologies (*e.g.*, IEEE 802.11p, WiMax, LTE).

Although V2V is potentially the most viable approach to low-latency short-range vehicular networks, connectivity in VANETs is often not available due to quick topology network changes, random vehicle speed, and traffic density (*i.e.* sparse, dense, and totally disconnected neighbourhoods) (Chiara *et al.*, 2009). As an alternative, longer-range vehicular connectivity are supported by a Vehicle-to-Infrastructure (V2I) protocol (Held, 2007), which exploits a pre-existing network infrastructure, for communications between vehicles and wireless/cellular access points (referred to Road Side Units, RSUs). As a further benefit, V2I protocols allow access to the Internet and delivery of traditional applications in addition to dedicated applications for ITS, thus making vehicle communications more versatile.

Both the paradigms —V2V and V2I— exhibit connectivity problems. Different speed and traffic densities result in low vehicular contact rate, and limit communications via V2V protocol, while V2I communications are reduced, especially in highway scenarios, by the low number of RSUs displaced on the roads. Moreover, V2I limitations are due to particular vehicular applications, and performance is also strictly dependent on the specific wireless technology for the RSUs. It can then become advantageous to adopt hybrid schemes combining V2V and V2I communication into a single protocol and allowing fast migration from V2I to V2V connectivity depending on the operation context (high/low density, high/low velocity). Such mechanism is the so-called Vertical Handover (Pollini, 1996).

In this chapter we shall describe the traditional techniques —Vertical Handover algorithms— used for seamless connectivity in heterogeneous wireless network environments, and in particular adopt them in VANETs, where V2V and V2I represent the main communication protocols. Section 2 deals with the basic features of Vertical Handover (VHO) in the general context of a hybrid wireless network environment, and it discusses how decision metrics can affect handover performance (*i.e.* number of handover

occurrences, and throughput). Instead, Section 3 briefly introduces two proposed techniques achieving seamless connectivity in VANETs. The first technique is a vertical handover mechanism applied to V2I-only communication environments; it is presented in Section 4 via an analytical model, and main simulated results are shown in Subsection 4.1. The second approach is described in Section 5. It addresses a hybrid vehicular communication protocol (*i.e.* called as Vehicle-to-X) performing handover between V2V and V2I communications, and vice versa. Subsection 5 illustrates how messages can be propagating via V2X, while Subsection 6 shows the main phases of V2X algorithm and the simulation results. Finally, we conclude this chapter in Section 6.

2. Vertical Handover mechanism

Next generation wireless networks adopt a heterogeneous broadband technology model in order to guarantee seamless connectivity in mobile communications. Different network characteristics are basically expected for different multimedia applications, and ubiquitous access through a single network technology is not always guaranteed because of limitation of geographical coverage. Moreover, since mobile applications require Quality-of-Service (QoS) continuity in a ubiquitous fashion, cooperation of access networks in heterogeneous environments is an important feature to assure.

A Vertical Handover (VHO) is a process preserving user's connectivity *on–the–move*, and following changes of network (Pollini, 1996). In this context, VHO techniques can be applied when network switching is needed (*i*) to preserve host connectivity, (*ii*) optimize QoS as perceived by the end user, and (*iii*) limit the number of unnecessary vertical handover occurrences (*i.e.* the well-known *ping-pong effect*) (Inzerilli & Vegni, 2008).

VHO schemes can be classified on the basis of the criteria and parameters adopted for initiating a handover from a Serving Network (SN) to a new Candidate Network (CN). Namely, we can enlist the following main metrics whose monitoring can drive handover decisions:

- *Received Signal Strength* (RSS)-based VHO algorithms: when measured RSS drops below receiver sensitivity it denotes lack of connectivity which requires necessarily a VHO (Ayyappan & Dananjayan, 2008); (Inzerilli & Vegni, 2008);
- *Signal-to-Noise and Interference ratio* (SINR)-based VHO algorithms: SINR directly impacts achievable goodput in a wireless access network. A modulation scheme can sometimes adapt transmission rate a channel coding scheme to measured SINR (Yang *et al.*, 2007); (Vegni *et al.*, 2009);
- *Multi-parameter QoS*-based VHO algorithms: VHO algorithms can be based on the overall quality assessment for the available networks obtained balancing various parameters (Vegni *et al.*, 2007); (Jesus *et al.*, 2007);
- *Location*-based VHO algorithms: they estimate network QoS on the basis of the MT location relatively to the serving access point (Kibria *et al.*, 2005); (Wang *et al.* 2001); (Kim *et al.*, 2007).

In an RSS-based VHO approach, when the measured RSS of the SN drops below a predefined threshold, the RSS of the monitored set of CNs is evaluated in order to select the best network to migrate to. The authors in (Ayyappan & Dananjayan, 2008) adopt this basic approach for VHO and evaluate the performance of a vertical handover mechanism that is based on the RSS measurements. This approach represents the traditional handover and simplest mechanism, which however does not aim to optimize communication performance.

Differently, the SINR-based approach (Yang *et al.*, 2007) compares the received power against the noise and the interference levels in order to obtain a more accurate performance assessment, which brings about a slight increase of computational cost. SINR factor is considered for VHO decisions, as it directly affects the maximum data rate compatible with a given Bit Error Rate (BER). Therefore, when the SINR of the serving network decreases, the data rate and the QoS level decrease too. As a consequence, a SINR-based VHO (Yang *et al.*, 2007) approach is more suitable to meet QoS requirements, and can be used to implement an adaptive data rate procedure. RSS-based and SINR-based schemes are both reactive approaches, which means that they aim to compensate for performance degradation when this occurs, that is whenever either the RSS or the SINR drops below a guard threshold. Moreover, we expect that a combination of different VHO decision metrics (*i.e.* location information, RSS/SINR measurements, QoS requirements or monetary cost) can generate most effective and correct VHO decisions (Vegni *et al.*, 2009).

A Multi-parameter QoS-based VHO scheme has been illustrated in (Vegni, *et al.* 2007), which is instead representative of a proactive approach performing regular assessment of the QoS level offered by the current SN, as well as by other CNs. The proposed method attempts to select the best CN at any time thus preventing performance degradation, and sudden lack of connectivity. It can be based on the simultaneous estimation of a set of parameters such as RSS, throughput and BER and in the subsequent evaluation of an objective QoS metric, which is a function of such parameters. Its effectiveness is directly dependent on the ability of the objective QoS metric to mimic subjective Quality-of-Experience of the end-users, and on the accuracy of the assessment of the parameters on which the metric is based. QoS-based VHO is well suited for multimedia applications like real-time video streaming. As a drawback, preventive approaches may lead to high handover frequency and hence lead to algorithmic instability, *i.e.* the so-called *ping-pong* effect. A hysteresis cycle or a hard limitation in maximum handover frequency in the VHO algorithm can help reducing this phenomenon (Kim *et al.*, 2007).

In location-based VHO solutions, the knowledge of location information is exploited to assess the quality of the link between SN and the MT, and to predict its future evolution to some extent on the basis of the MT estimated path. User position can be determined in several ways (Kibria *et al.*, 2005), including Time of Arrival, Direction of Arrival, RSS, and assisted GPS (Global Positioning System) techniques. Examples of location-based VHO are discussed in (Wang *et al.* 2001), though the proposed technique shows a computational complexity of the handover decision that is rather high, and establishing and updating a lookup table to support a handover margin decision turns out to be time-consuming. In (Kibria *et al.*, 2005) the authors develop a predictive framework based on the assumption that the random nature of user mobility implies an uncertainty on his/her future location, increasing with the extension of the prediction interval.

Location-based VHO solutions are the most commonly-used techniques in the VANET context, where high-mobility of nodes makes it difficult to promptly react to performance degradation purely basing on RSS measurements.

3. Seamless connectivity in vehicular ad hoc networks

In this section we are introducing two different approaches for seamless connectivity in VANET scenarios.

The first approach is a Vertical Handover technique based on vehicle speed, where a vehicle switches from a Serving Network (SN) to a Candidate Network (CN) if its speed is lower

than a fixed threshold (Vegni & Esposito, 2010); (Esposito *et al.*, 2010). Such technique *i.e.*, called as Speed-based Vertical Handover (S−VHO) mainly addresses necessary connectivity switching in vehicular environments for real-time applications, which require high QoS levels and seamless connectivity. S−VHO does not consider traditional vehicular protocol (*i.e.* V2V and V2I), but it simply guarantees a seamless connectivity when vehicles are crossing an area with overlapping wireless networks.

The problem of a seamless connectivity becomes more challenging in VANETs, because vehicles move across overlapping heterogeneous wireless cells environments. In such scenarios, frequent and not always necessary switches from a SN to a CN may occur, often degrading network performance. Vertical Handover techniques are able to fix seamless connectivity according to a well-defined decision criteria (*i.e.* the type of RSU technology, the RSS indicator, QoS metrics, and so forth (McNair & Fang, 2004)).

Traditional VHO decision metrics cannot be applied in vehicular environments, and may fail due to the speed and the time that the vehicle is going to spend in a wireless network. The problem of a seamless connectivity becomes even more challenging as vehicles move at high speed across overlapping heterogeneous wireless cells environments.

Therefore, in VANETs handovers should be performed on the basis of specific factors, such as vehicle mobility pattern, and locality information, rather than standalone QoS requirements. Past solutions have partially but not fully considered these aspects. In (Chen *et al.*, 2009) the authors deal with a novel network mobility protocol for VANETs, to reduce both handover delay and packet loss rate. In (Yan *et al.*, 2008) a vertical handover technique focuses on an adaptive handover mechanism between WLAN and UMTS, based on the evaluation of a handover probability, obtained from power measurements. In this case, the handover decision is taken by comparing the handover probability with a fixed probability threshold, which depends on the vehicle speed and on handover latency.

The second technique is a hybrid vehicular communication protocol, called as Vehicle-to-X (V2X), which achieves the advantages of both traditional V2V and V2I protocols (Vegni & Little, 2010). V2X supports VANET scenarios with a heterogeneous network environment, and aims for vehicles (*i*) to communicate between them (via V2V), and (*ii*) to connect to the Internet (via V2I). V2X permits hybrid vehicular communications, and each vehicle can switch from V2V to V2I, and vice versa, on the basis of a *protocol switching decision metric*.

We will illustrate the behaviour of V2X protocol, and analyze how information is propagated in VANETs with heterogeneous network infrastructure nearby. In the simulated scenarios, a data push communication model has been assumed, in which information messages are propagated via localized (limited range) broadcast. Effectiveness of V2X will be validated via a performance comparison −in terms of *message dissemination*− with traditional opportunistic networking technique (*i.e.*, V2V).

V2X results in a novel opportunistic forwarding technique that is the main approach to achieve connectivity between vehicles, and to disseminate information. In traditional opportunistic networking V2V communications exploit connectivity from other neighbouring vehicles by a *bridging* technique, where message propagation occurs through connectivity links which are built dynamically (Agrawal & Little, 2008). Each vehicle acts as next hop and subsequent hops form a path from a source vehicle to a destination vehicle. Because V2X does not rely only on V2V but also exploits the potentiality of V2I, it should be considered as an opportunistic forwarding technique, where messages are propagated along dynamically generated paths whose links are vehicles, as well as road side units.

4. Speed-based VHO technique

A Speed-based VHO technique (S-VHO) is now described in each single step of VHO decision (Vegni & Esposito, 2010). We recall that, as all the VHO techniques are mainly focused on maximization of network performance, and limitation of vertical handover occurrences, even for S-VHO the aim is to both minimize VHO frequency — the number of executed VHOs — and maximize the throughput measured at the vehicle.

Differently from traditional RSS-based vertical handover approaches (Inzerilli & Vegni, 2008), the proposed S-VHO method does not consider any signal strength parameters: such information might be out of date, unreliable and its variance may fluctuate significantly, especially in VANET scenarios, causing unnecessary and unwanted vertical handovers, as well as throughput degradation. With respect to traditional VHO algorithms, S-VHO takes a vertical handover decision on the basis of the estimation of the *cell crossing time* parameter, which represents the time spent in crossing a wireless cell by the vehicle. No RSS indicator is considered in such approach, and S-VHO decides to switch from a SN to a CN on the basis of throughput experienced at the vehicle receiver, and the time spent by the vehicle in a CN.

It is noticeable that S-VHO method approaches to the technique proposed in (Yan *et al.*, 2008), except that S-VHO focuses on a vehicle-controlled VHO, due to smart *on-board* computer equipped with GPS connectivity, and handover decisions are based on both vehicle speed, and handover latency (Vegni & Esposito, 2010); (Esposito *et al.*, 2010). Moreover, S-VHO differs from previous vertical handover techniques because its usefulness is extended to real time applications for vehicular scenarios (*i.e.*, video streaming, on-line gaming, Internet browsing, and so on).

We shall describe an analytical framework of S-VHO technique. First, we depict how throughput in both serving and candidate networks can be estimated; then we show analytically how a vertical handover decision is taken by the vehicle.

Figure 1 illustrates the vehicular scenario we are dealing with. We assume that a vehicle is driving at constant speed v [m/s], following a typical Manhattan mobility model, suitable for a urban area and where the vehicle's trajectory is constrained by a road grid topology, with straight paths (*i.e.* a highway composed of straight lanes). Each vehicle is equipped with a GPS receiver, and then the vehicle's location is continuously updated and tracked.

Let us denote as t_{in} and t_{out} the time instants when a vehicle enters and exits a wireless cell (*i.e.* an UMTS network), respectively. The distance the vehicle will cross inside the wireless cell during the time interval $\Delta T = t_{out} - t_{in}$ is:

$$\Delta x = \frac{v}{\Delta T}.$$ (1)

From (1) we can introduce the *Cell Crossing Time* [s] parameter, according to the following assessment, such as:

Definition *(Cell Crossing Time).* *Given a vehicle V, traversing an area covered by a wireless cell C at constant speed $\bar{v}$, the cell crossing time of V in C, denoted as ΔT [s], is the overall time that V can spend under C's coverage.*

According to Figure 1, the cell crossing time lasts since the vehicle enters the wireless cell in P_{in} at t_{in}, and then exits the wireless cell in P_{out} at t_{out}, respectively. During ΔT interval, the vehicle is crossing the Δx distance. Assuming an omni-directional radio coverage C for the wireless network, and denoting (*i*) $R \in \mathfrak{R}^+ \setminus \{0\}$ as the radius of the wireless cell, (*ii*) $\phi \in [0, \pi]$

as the angle between the vehicle's line-of-sight with the RSU and the direction of the vehicle, we can use classic Euclidean geometry to obtain
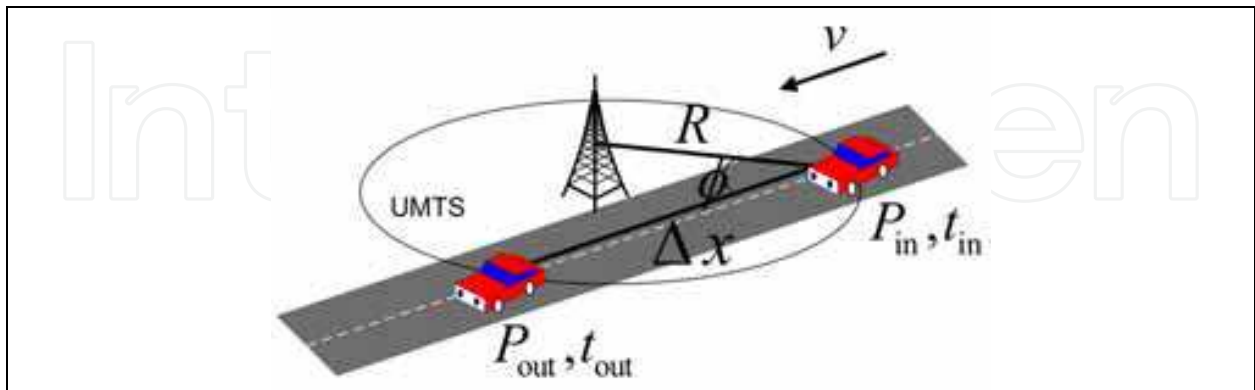
$$\Delta x = 2R\cos\phi. \tag{2}$$

Fig. 1. VANET scenario where a vehicle moves at constant speed v, following a Manhattan mobility model. P_{in} and P_{out} are the wireless cell entrance and exit points, respectively

Since we have assumed that each vehicle is equipped with a GPS receiver, the coordinates $P_{in} \equiv (x_{in}; y_{in})$ of the entrance, and $P_{out} \equiv (x_{out}; y_{out})$ of the exit point of the wireless cell, with respect to a coordinate system centered in the cell centre, are easily calculated so that Δx is known. It follows that the *cell crossing time* can be expressed as

$$\Delta T = \frac{\Delta x}{|\vec{v}|} = \frac{2R}{|\vec{v}|}\cos\left[\arctan\left(\frac{y_{out} - y_{in}}{x_{out} - x_{in}}\right)\right]. \tag{3}$$

Notice that the computation in (3) is directly performed by the vehicle by assuming constant vehicle speed, and knowledge of the wireless cell radio coverage.
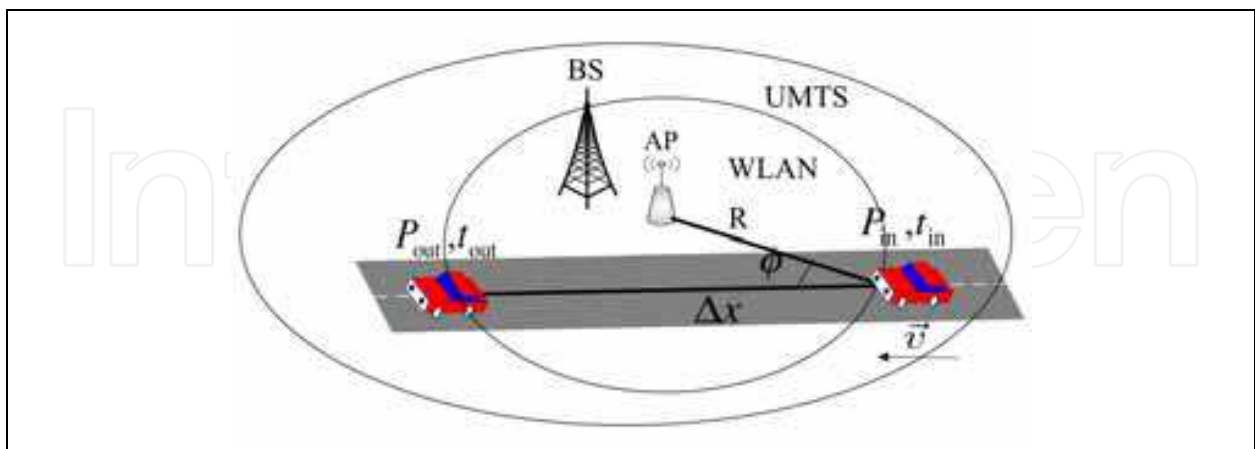

Fig. 2. VANET scenario with heterogeneous overlapping wireless networks

After defining geometric parameters, we can introduce the throughput Θ (t) [Bits], evaluated for $t = \Delta T$ [s], as:

$$\Theta(t) = B_{SN}\Delta T, \tag{4}$$

where B_{SN} [Bit/s] is the bandwidth of the actual wireless cell (*i.e.* Serving Network, SN), assumed to be constant during ΔT. Equation (4) defines the throughput Θ that a vehicle would experience by remaining connected with the actual wireless cell, during the *cell crossing time ΔT*.

Note that so far we have only modelled the throughput in a VANET network where a vehicle is crossing a single wireless network, and no overlapping cells are considered. We now extend the model to heterogeneous environments by capturing vertical handovers across different access networks as well. In this case, a vehicle is entering an area where two or more different wireless cells are co-existing and overlapped.

Figure 2 shows this vehicular scenario with heterogeneous overlapping wireless networks (*i.e.* UMTS, and WLAN).

Namely, the vehicle drawn in Figure 2 is actually connected to an UMTS network, and is entering a WLAN network in P_{in} at t_{in}. Then, UMTS represents a Serving Network (SN) while WLAN a Candidate Network (CN), respectively.

Since S-VHO aims to maximize throughput, system initiates a handover from the SN (*i.e.* UMTS) to the CN (*i.e.* WLAN), if and only if the estimated throughput measured in the CN is higher than the throughput in the current SN, such as:

$$\Theta_{CN} \geq \Theta_{SN} . \tag{5}$$

Let a vehicle be connected to a SN, entering the wireless range of a Candidate Network (CN). In this heterogeneous scenario, we model the data delivered between the two time instants t_{in} and t_{out}, as a positive range function $\gamma : \Re \rightarrow \Re^+$ defined as

$$\gamma = \alpha \cdot (B_{CN} - \delta)(\Delta T - L) + (1 - \alpha) B_{SN} \Delta T, \tag{6}$$

where α is an indicator function, such that $\alpha = 1$ when a vertical handover is executed, and zero otherwise. Note that when $\alpha = 1$, γ is equivalent to the throughput obtained in the CN, while for $\alpha = 0$, γ is the throughput in the SN. The parameter $\delta \in \Re^+$ is a hysteresis factor introduced to avoid vertical handover occurrence when the two competing networks have negligible bandwidth difference.

Function in (6) captures the data loss due to the vertical handover latency L [s], that is the time interval during which a vehicle, traversing an area covered by at least two wireless cells, does not receive any data due to control plane (socket switching) signalling messages exchange.

Since during the cell crossing time of a vehicle it is desirable to maximize throughput, S-VHO technique initiates a handover only when it represents a valid handover, that is when

$$\gamma \big| (\alpha = 1) > \gamma \big| (\alpha = 0) , \tag{7}$$

from which it follows:

$$B_{CN} > \frac{B_{SN}}{1 - \dfrac{L}{\Delta T}} + \delta , \tag{8}$$

The inequality in (8) shows that switching decisions may not be necessary even though the bandwidth B_{CN} is higher than B_{SN}. Switching becomes necessary only if the time that the

vehicle will spend in the wireless cell with higher bandwidth is long enough to compensate for the data loss due to the switching overhead, namely only if

$$1 - \frac{L}{\Delta T} > 0 \quad \Rightarrow \quad L < \Delta T. \tag{9}$$

This observation leads to the conclusion that the throughput Θ is influenced not only by the bandwidth of the considered technologies, but by a larger set of parameters, such as (*i*) the cell crossing time, (*ii*) the vehicle speed, and (*iii*) the overhead of the control-plane protocols adopted (*handover latency*). This consideration represents not only a novel definition for throughput by three previous parameters (*i.e.* cell crossing time, vehicle speed, and handover latency), but also gives an important result for vertical handover management and connectivity switching decisions in vehicular networks. By monitoring and limiting vehicle speed to a fixed upper bound, it is always possible to perform a valid handover. This result represents the following *Theorem of Speed Upper Bound* for valid VHO decisions (Esposito *et al.*, 2010).

Theorem (*Speed Upper Bound*). *Given a vehicle V, travelling with an average constraint speed $\vec{v}$ in a heterogeneous vehicular environment for a distance Δx, a valid handover for V occurs if $|\vec{v}|$ is bounded as follows:*

$$|\vec{v}| < \frac{\Delta x \left(B_{CN} - B_{SN} - \delta \right)}{\left(B_{CN} - \delta \right) L}. \tag{10}$$

Proof: the claim follows from (8), where we highlighted the term ΔT, such as

$$
\begin{aligned}
&\left(B_{CN} - \delta \right) \left(1 - \frac{L}{\Delta T} \right) > B_{SN}, \\
&\left(B_{CN} - \delta \right) \left(\Delta T - L \right) > B_{SN} \Delta T, \\
&\left(B_{CN} - B_{SN} - \delta \right) \Delta T > \left(B_{CN} - \delta \right) L, \\
&\Delta T > \frac{\left(B_{CN} - \delta \right) L}{\left(B_{CN} - B_{SN} - \delta \right)}.
\end{aligned}
\tag{11}
$$

By replacing the term ΔT from (11) in the following definition of average vehicle speed, *i.e.*

$$|\vec{v}| = \Delta \vec{x} / \Delta T, \tag{12}$$

we obtain the result expressed in (10).

The Theorem of Speed Upper Bound is useful not only for VHO management, but also in designing V2I protocols, as well as to promote vehicle safety applications. Network providers may in fact offer lower data rate in those areas where the speed limit is lower, and so induce vehicles to maintain lower speeds, in order to experience acceptable QoS levels — low jitter and high throughput— throughout valid handovers. Users should be more motivated to respect speed limits, rewarded by QoS enhancement.

S-VHO technique is based on Theorem 1 in order to manage valid handovers for fast users driving in an heterogeneous vehicular network environment. This approach is acted by the vehicle itself each time is crossing a wireless network and needs to be connected with it. S-

VHO rules according to the following algorithm drawn in Figure 3. S-VHO accepts three inputs, such as (*i*) the vehicle speed $\vec{v}$, (*ii*) the ingress time t_{in} of the vehicle into a wireless cell, and (*iii*) the GPS location information P_{in}, respectively. The algorithm then returns the handover decision variable $\alpha \in \{0, 1\}$, whose value means if a vertical handover is executed or not.

Let a vehicle be connected to a SN, driving in an area with heterogeneous overlapping wireless networks (*i.e.* UMTS, and WLAN). Due to multi-network interface cards equipping the vehicle, it is able to recognize one or more available CNs to access. A vertical handover can occur whenever the inequality in (8) is verified.

After each handover execution, the algorithm enters in *idle mode* for an inter-switch waiting time period (*i.e.* T_w [s]), that means no vertical decision is taken. For example, if a vehicle travels at 15 m/s, a 10 seconds inter-switch waiting time results in 150 meters covered by the vehicle, before the algorithm is reactivated. The idle mode approach is a well-know solution for limitation of vertical handover frequency (Inzerilli & Vegni, 2008); (Inzerilli *et al.*, 2008).

Input : $\vec{v}, t_{in}, P_{in}$

Output : α

while *inside area with at least two overlapped cells*, **do**

> **if** $\left[B_{CN} > \dfrac{B_{SN}}{\left(1 - \dfrac{L}{\Delta T}\right)} + \delta \right]$
>
> **then**
>
> > evaluate ΔT
> >
> > **if** $\Delta T > \Delta T *$ **then**
> >
> > > $\alpha \leftarrow 1$ (VHO executed)
> > >
> > > set a decreasing counter to $T_w[s]$.
> > >
> > > **while** $T_w > 0$ **do**
> > >
> > > > idle mode
> > >
> > > **end**
> >
> > **else**
> >
> > > $\alpha \leftarrow 0$ (no VHO executed)
> >
> > **end**
>
> **end**

end

Fig. 3. Speed-based Vertical Handover Algorithm

Many handover algorithms incorporate a hysteresis cycle within handover decisions, in order to prevent a mobile terminal moving along the boundary of a wireless cell to trigger handover attempts continuously. This phenomenon is well known in the literature as *ping-pong effect* (Kim *et al.*, 2007), and hysteresis is largely adopted in practical implementations.

A high number of vertical handover executions can lead to excessive network resource consumption and also affects mobile terminal's performance (*i.e.* battery life, and energy consumption).

Ping-pong effect occurs in vehicular environments, specially when vehicles travel on a border line between two wireless cells, and make frequent, often unnecessary or unwanted handovers. Limitation of handover frequency is acted by imposing a minimum interval of time between two consecutive handovers. Namely, the grater is the waiting time the smaller will be the number of vertical handovers.

S-VHO algorithm first measures the data rate from CN (*i.e.* B_{CN}), and then if inequality (8) holds, the cell crossing time ΔT is computed as shown in (3). After the cell crossing time evaluation, S-VHO decides whether the handover would be valid or not by comparing ΔT with the threshold for valid handover, (*i.e.* ΔT^*).

We can express the threshold for valid handover as

$$\Delta T^* = \frac{\Delta x}{v^*}. \tag{13}$$

The term v^* is the speed upper bound, obtained from the inequality (10) and formally expressed as

$$v^* = \frac{\Delta x (B_{CN} - B_{SN} - \delta)}{(B_{CN} - \delta)L} - \varepsilon, \tag{14}$$

where ε is a positive quantity (*i.e.* $\varepsilon \to 0$). Equation (13) becomes

$$\Delta T^* \simeq \frac{(B_{CN} - \delta)L}{B_{CN} - B_{SN} - \delta}. \tag{15}$$

The Theorem of Speed Upper Bound shows that the vehicle's speed is strictly limited by handover latency L, and the hysteresis factor δ. The impact of both two parameters and the effects on the speed upper bound are described by the following analytical results.

In Figure 4 (*a*) we show the impact of the handover latency L [s] on the speed upper bound, for a given bandwidth ratio of two available wireless technologies (*e.g.* UMTS, and WLAN[1]). The hysteresis factor δ was set to zero to isolate only the impact of handover latency, and the range of speed was bounded by 35 m/s (typical highway speed limit). As we can notice, for higher values of handover latency, the speed upper bound (*i.e.* the maximum speed at which vehicles experience valid handovers) decreases, and approaches to zero:

$$\lim_{L \to \infty} v^* = 0. \tag{16}$$

This result is reasonable since vehicles travelling at higher speed may not spend enough time under higher data-rate wireless networks to justify the degraded performance introduced by the handover overhead of the signalling messages.

For a bandwidth ratio equal to one (*i.e.* $B_{CN} = B_{SN}$), the speed bound is null as the hysteresis factor has been set to zero; in general (*i.e.* for $\delta \neq 0$), the speed bound is still approaching to zero for L approaching to infinity:

---

[1] The bandwidth ranges were chosen according to WLAN, and UMTS (Laiho *et al.*, 2005) requirements.

$$\lim_{L\to\infty} v^* = \lim_{L\to\infty} \frac{-\Delta x \delta}{(B_{CN} - \delta)L} \,. \tag{17}$$

The second result comes by observing the epigraph and hypograph — the set of points above, and below the drawn curves, respectively. Any point belonging to the epigraph represents no performance gain in initiating handovers, even if the CN has higher bandwidth than the SN. In contrast, for any point in the hypograph valid handovers occur. We can notice that the curve with zero bandwidth gap (*i.e.* $B_{CN} = B_{SN}$) has empty hypograph. This follows directly from the definition of valid handover, that means a vertical handover cannot be valid when the data rates from CN and SN are equal.
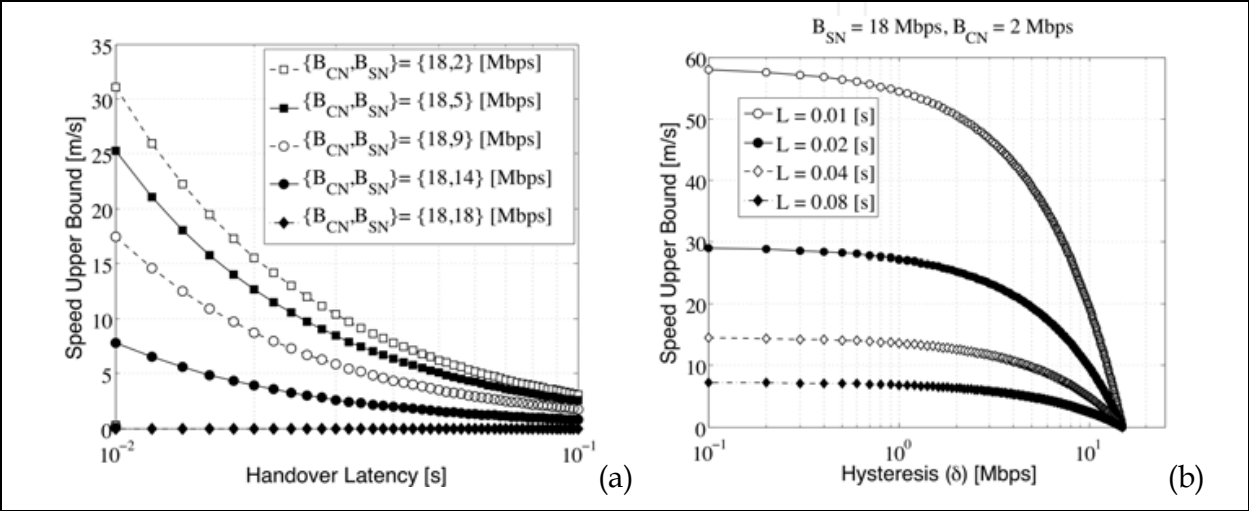
Fig. 4. Speed Upper Bound behaviour. Impact of (*a*) handover latency *L*, and (*b*) hysteresis δ

In Figure 4 (*b*) we show the impact of the hysteresis δ [Mbps] on the speed bound, for different values of the handover latency (*i.e.* L = {0.01, 0.02, 0.04, 0.08} [s]). The hysteresis range is [0, $B_{CN} - B_{SN}$]. It is useful to note that $B_{CN} - B_{SN}$ is the maximum value of δ after which no valid handover would occur. We have simulated the case $B_{CN} - B_{SN}$ = 16 [Mbps], which represents a typical gap in data rates between UMTS and WLAN.
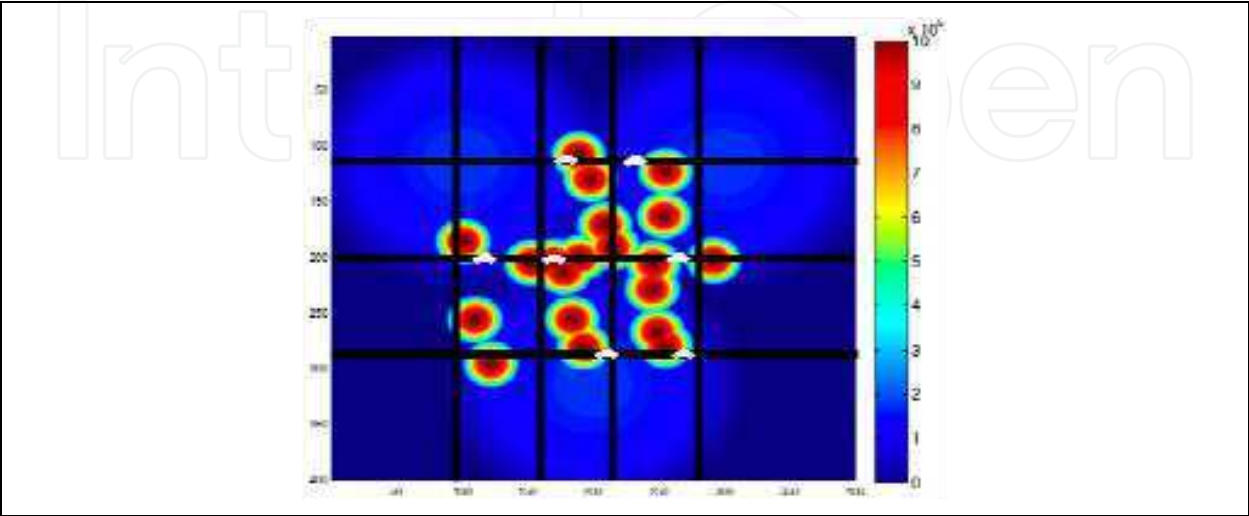

Fig. 5. Simulated VANET scenario with overlapping WLAN and UMTS cells

Notice how the hypographic area changes for different values of *L*: the lower the handover latency, the greater the hypograph. For example, when the handover latency increases (*i.e.* *L* = 0.08 [s]), the hypographic area significantly reduces. From this observation, it follows that *handover latency should be taken into account when designing protocols for seamless connectivity in VANETs*, and not only focusing on physical parameters or vehicle speed.

4.1 S-VHO simulation results

In this section we describe some simulation results for S-VHO mainly expressed in terms of throughput maximization, and limitation of *ping-pong* effect. They will show how S-VHO works for valid vertical handovers in VANETs.

Network performance, *i.e.* throughput, delay, and jitter, as well as the number of vertical handovers, have been obtained with an event-driven simulator. More details of the simulator can be found in (Vegni, 2010). The simulation scenario depicts a vehicle entering from a random location, restricted to travel along a grid of streets and intersections. The vehicle follows a random path inside a grid, according to the Manhattan mobility model, as shown in Figure 5. The event-driven simulator generates different scenarios, whose characteristics are similar to previous heterogeneous scenarios described in (Vegni & Esposito, 2010). Figure 5 depicts one of the simulated scenarios, in terms of data rate distribution from a set of three UMTS base stations, and twenty WLAN access points, modelling a 2 km² area.

The location of each wireless cell has been generated uniformly at random, and a vehicle moves in this area with speed in the range [5, 35] [m/s], capturing urban environment as well as highway scenarios. During its journey, a vehicle requires to download a series of video frames. For example, we could figure out that passengers are enjoying their travelling time by means of real time applications, *e.g.* video streaming and online gaming.

For the cell setup, we have considered typical values of WLAN and UMTS radio parameters, as described in (Vegni & Esposito, 2010). The cell radius was set to 120 [m] for IEEE 802.11/a outdoor environment, and 600 [m] for an UMTS microcell; the transmitted power in the middle of UMTS and WLAN cell has been chosen to be between 43 and 30 dBm, respectively. Finally, the average vertical handover latencies from UMTS to WLAN, and from WLAN to UMTS, have been set respectively to $L_{U \to W}$ = 2 [s], and $L_{W \to U}$ = 3 [s], while the data rate of UMTS and WLAN equal to 384 [kbps], and 11 [Mbps], respectively.

S-VHO network performance have been validated in terms of (*i*) throughput, (*ii*) jitter, and (*iii*) handover frequency. Moreover, a comparison between S-VHO and a previous vertical handover technique (Yan *et al.*, 2008), based on traditional power measurements, has been carried out. In both algorithms, the speed of the vehicle is used as handover assessment criterion. Hereafter we will name the technique described in (Yan *et al.*, 2008) as Speed Probability Based VHO (SPB). Simulated results[2] will prove the effectiveness of S-VHO for valid handovers.

Figure 6 shows the throughput expressed as cumulative received bits in a downlink connection for both S-VHO and SPB techniques, versus the inter-switch waiting time in the range [0, 50] [s]. The cumulative received bits represent the amount of received bits by a vehicle moving inside an heterogeneous wireless environment for the simulated period of time.

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[2] Results obtained by averaging 100 heterogeneous network scenarios.

The throughput performance of S-VHO outperforms at every speed the SPB algorithm. Our performance improvement are justified by the absence of received signal strength dependence in S-VHO handover assessment criteria. Moreover, the effectiveness of S-VHO is clear when vehicle speed is below a given limit (*e.g.*, 20 [m/s]).

On the other hand, SPB does not appear sensitive to either speed or inter-switch waiting time, and its throughput is limited. However, the S-VHO throughput drops when the vehicle speed exceeds the desired limit. This is justified by the Theorem of Speed Upper Bound for valid VHOs.
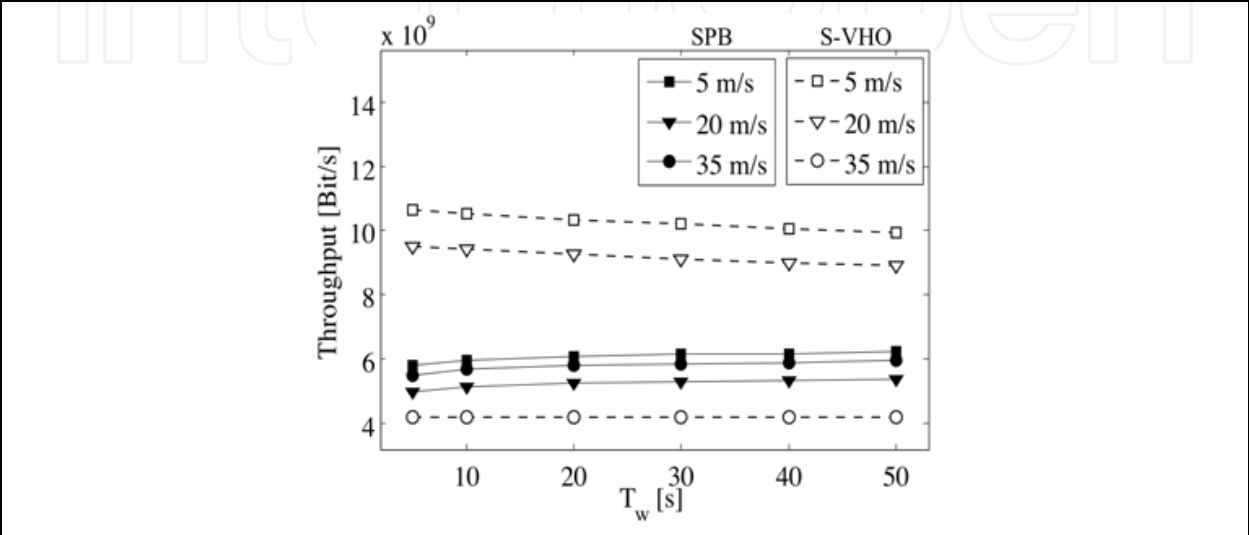
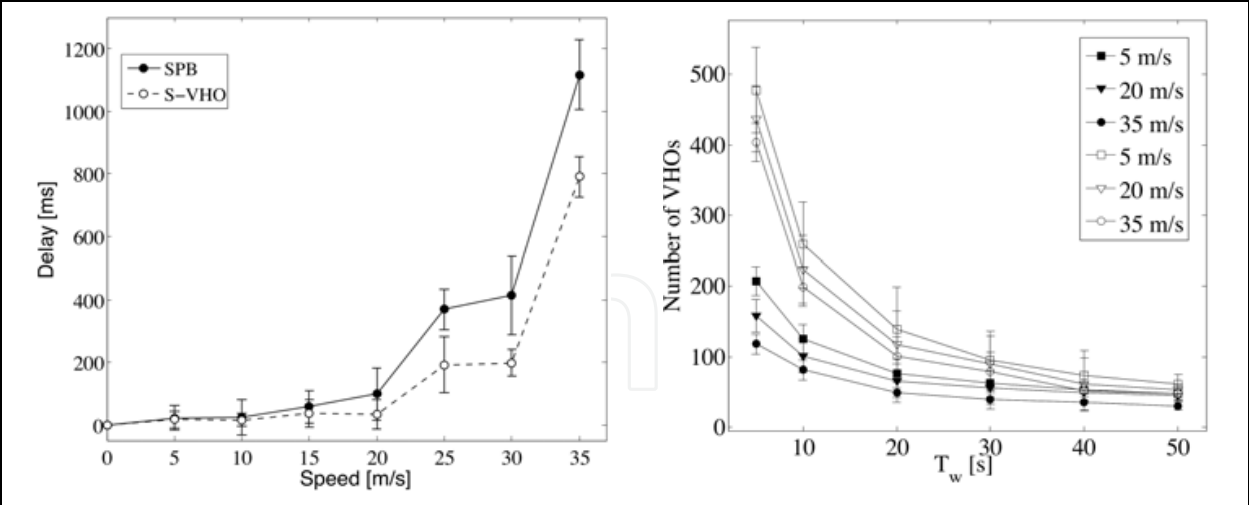Fig. 6. Comparison of throughput between S-VHO (white markers), and SPB (black markers)

Fig. 7. Comparison of (*left*) delay, and (*right*) number of vertical handover occurrences, between S-VHO (white markers), and SPB (black markers) algorithms

The average frame delay for both S-VHO and SPB is shown in Figure 7 (*left*). The 95% confidence intervals express how the average frame delay increases for higher speeds. This is because there is not enough time to download the next frame before the signal from the SN gets too weak. Moreover, S-VHO experiences lower delays compared to SPB, since on average it performs less handovers.

Figure 7 (*right*) depicts, with 95% confidence intervals, the average number of handovers for different values of inter-switch waiting time. As expected, the number of vertical handovers decreases when the system is idle for longer periods (*i.e.* when T_w increases). Since our simulations count all the handovers (valid or invalid), the gap between the S-VHO and SPB curves represents the number of invalid handovers, executed not taking into account the handover latency *L*.
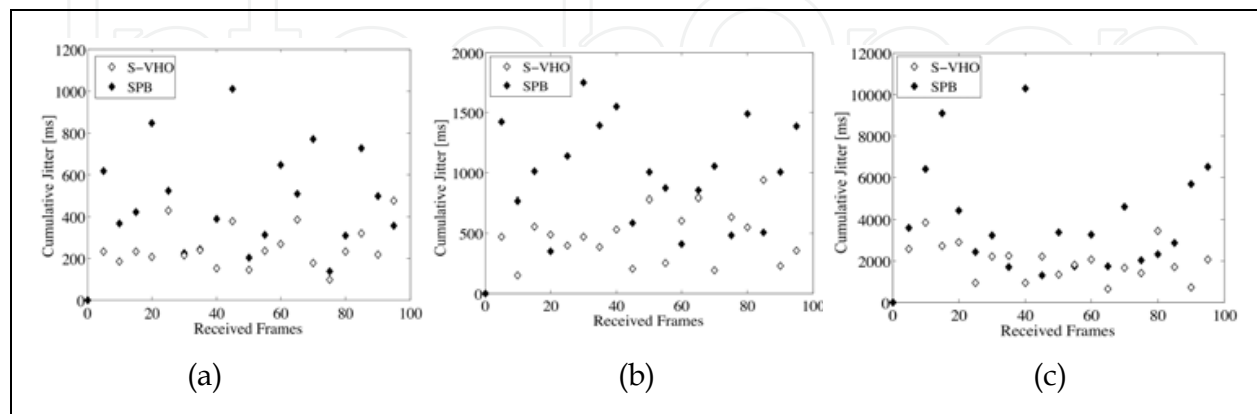

Fig. 8. Cumulative jitter experienced by a vehicle, for different speeds (*a*) $|\vec{v}| = 15$ [m/s], (*b*) $|\vec{v}| = 25$ [m/s], and (*c*) $|\vec{v}| = 35$ [m/s]

Jitter performance from S-VHO and SPB have been compared, and are shown in Figure 8 for different values of speed, and a fixed inter-switch waiting time value (*i.e.* $T_w = 10$ [s]). Each point represents the cumulative jitter, defined as the difference between maximum and minimum frame delay. Jitter increases with speed —note the scale difference among different graphs— since two frames may be more often coming from different wireless networks, and also because the cell crossing time decreases when the speed increases. For S-VHO higher speed implies higher jitter, unless the number of unnecessary handovers is reduced.

To summarize, S-VHO technique distinguishes from previous approaches by using both handover latency and cell crossing time estimation to simultaneously improve throughput and delay. It is driven by the vehicle speed, so that vehicles are required to maintain a given speed limit to maintain acceptable levels of throughput, delay and jitter. VHOs are limited to effective and necessary connectivity switching. A handover towards a CN with higher data rate does not necessary result in a throughput improvement.

S-VHO represents not only a novel VANET protocols for real-time applications, but also it could be useful for urban safety. As a matter, service providers assisted by vehicular networks could enforce speed limits and safety, while delivering real-time services as video-streaming or online gaming.

5. Hybrid vehicular communication protocols

As known (Held, 2007), one of the main characteristics of VANETs is that vehicles move in clusters —interconnected blocks of vehicles— due to different traffic scenarios (*i.e.* dense, sparse or totally disconnected traffic neighborhoods). For this reason, vehicular connectivity is not always available, and messages propagation in VANETs is still an open issue.

Many authors have addressed how to improve message forwarding by opportunistic techniques, and multi-hop approaches. In (Resta *et al.*, 2007) a multi-hop emergency message dissemination is described by means of a probabilistic approach. The authors derive lower bounds on the probability that a vehicle correctly receives a message within a fixed time interval. Similarly, in (Jiang *et al.*, 2008) an efficient alarm message broadcast routing protocol is presented. This technique estimates the receipt probability of alarm messages sent to vehicles.

In other works the message propagation model is based on the main VANET characteristics such as number of hops, vehicle position, mobility, etc. In (Yousefi *et al.*, 2007) the authors consider a single-hop dissemination protocol based on Quality-of-Service metrics, while in (Chen *et al.*, 2008) a robust message dissemination technique is illustrated, based on the vehicles position. Finally, the authors in (Nadeem *et al.*, 2006) present a data dissemination model based on bidirectional mobility of paths between a couple for vehicles.

Common aspect in all previous works is that data traffic is disseminated only through vehicles communicating via V2V; no network infrastructure nor V2I protocol have been considered.

The use of the vehicular grid together with a network infrastructure has been discussed in (Gerla *et al.*, 2006); (Marfia *et al.*, 2007). The benefits of using the opportunistic infrastructure placed on the roads result in an enhancement of message propagation. In fact, a Road-Side Unit represents a fixed node which is able to forward message information to vehicles driving inside a wireless cell.

V2X relies on the network scenario depicted in (Gerla *et al.*, 2006), but it represents a novel protocol providing switching from V2V to V2I, and vice versa. It enables vehicles to communicate via V2V or V2I on the basis of a protocol switching decision. The message propagation via V2X is then improved by a correct use of vehicular communication protocols (*i.e.*, V2V and V2I).

The heterogeneous vehicular scenario we are referring to is depicted in Figure 9. Let us consider a cluster *C* comprised of a set *S* of vehicles (*i.e.*, $S = \{1, 2, \ldots, n\}$). Then, *m* Road-Side Units (RSUs) (*i.e.*, $m < n$) are displaced in the network scenario. Each vehicle is able to communicate via V2V on the basis of a fixed transmission range radio model (Vegni & Little, 2010). 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 are not in the range of connectivity of an RSU. Analogously, we assume that only *k* RSUs (*i.e.*, $k = \{1, 2, \ldots, h\}$ with $h < m$) are available to V2I communications.

In such scenario, we are now introducing the *Protocol Switching Decision* as follows:

Definition *(Protocol Switching Decision).* *A source vehicle V_s, sending via V2V a message of length L to a destination vehicle V_d, will switch to V2I if there exists an optimal path linking V_s with an RSU. Analogously, a source vehicle V_s, sending via V2I a message of length L to a destination vehicle V_d, will switch to V2V if there exists an optimal path linking V_s with neighbouring vehicles.*

The *optimal path* will be defined hereafter.

For the connectivity link from the *i*-th to the *j*-th vehicle we define as *link utilization time* $q_{(i,j)}$ [s] the time needed to transmit a message of length *L* [bit] from the *i*-th to the *j*-th vehicle, at an actual data rate $f_{(i,j)}$ [Mbit/s], such as

$$q_{(i,j)} = \frac{L}{f_{(i,j)}}. \tag{18}$$

For a link between the i-th vehicle and the k-th RSU, the data rate $f_{(i,j)}$ is obtained by the nominal data rate $\tilde{f}_{(i,k)}$ by applying a *Data Rate Reduction* (*DRR*) factor (*i.e.*, $\rho_{(i,k)}$ [s]) that depends on the distance from the vehicle to the RSU, such as

$$f_{(i,k)} = \rho_{(i,k)}\tilde{f}_{(i,k)}. \tag{19}$$

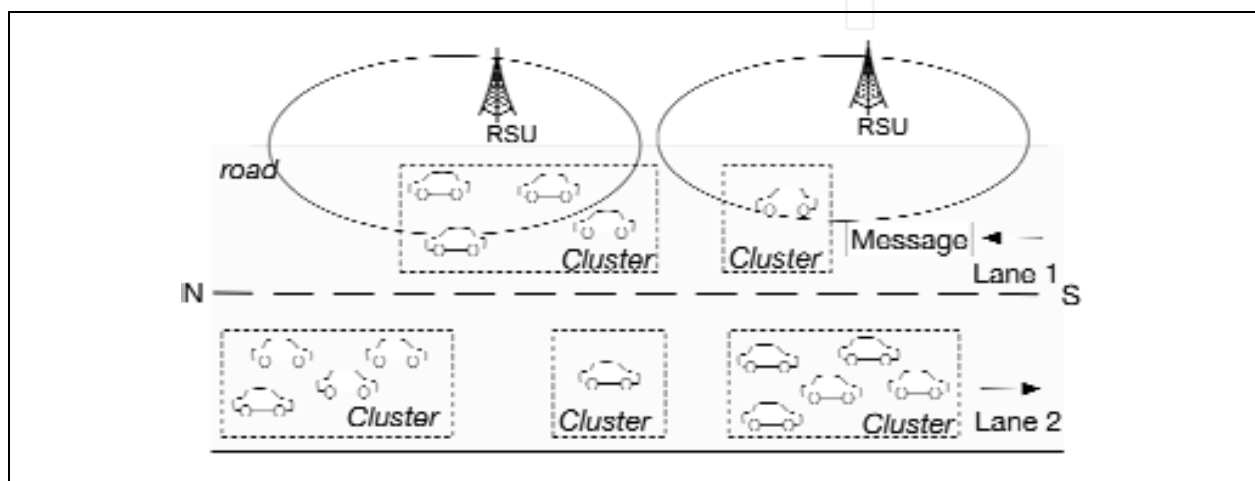The *DRR* factor increases when a vehicle is laying within the bound of a wireless cell.

Fig. 9. VANET scenario with heterogeneous wireless network infrastructure partially covering the grid

Let us now define a *Path* in a vehicular network as:
Definition (Path).   *Given the i-th vehicle and the k-th RSU, a path is a sequence of M hops connecting the i-th vehicle with the k-th RSU, where a single hop represents a link between two neighbouring vehicles. The path length represents the number of hops M for a single path.*
It follows that the maximum number of directed links from a vehicle to an RSU is $\alpha = l \cdot h$, while the maximum number of different paths that can connect the i-th vehicle to the k-th RSU is $n \cdot \alpha$.
From the definition of path, we define the *path utilization time* $Q_{(i,k)}$ [s] from the i-th vehicle to the k-th RSU as the sum of single link utilization time parameters (*i.e.*, $q_{(i,j)}$), for each hop that comprises the path, as

$$Q_{(i,k)} = q_{(i,j)} + q_{(j,x)} + \ldots + q_{(x,k)} = L\sum_{\substack{i=1 \\ x \in S}}^{n}\left[f_{(j,x)}^{-1} \right]. \tag{20}$$

The *optimal path* will be the one, among all the paths $n\alpha$, with the minimized path utilization time, such as

$$\min_{s=1,2,\ldots,n\alpha} Q_{(i,k)}^{(s)} = L \cdot \min_{s=1,2,\ldots,n\alpha} \sum_{\substack{i=1 \\ x \in S}}^{n}\left[f_{(j,x)}^{(s)} \right]^{-1}. \tag{21}$$

Equation (21) is compared with the link utilization times in V2V communications in order to detect the most appropriate vehicular protocol. It represents our criterion for the *optimal path detection technique* in VANETs where vehicles are V2X enable.

5.1 Data propagation rates

In this section we illustrate how a message is propagated in a VANET incorporating a heterogeneous network infrastructure, where vehicles are communicating via V2X. For this purpose, we shall give several definitions of message dissemination rates for different cases. The network scenario we are referring to is that one as depicted in Figure 9. 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.

Each vehicle in the grid is able to know about its local connectivity through broadcast "hello" messages forwarded in the network. Local connectivity information received by each vehicle establishes if a vehicle is within a cluster or is traveling alone on the road. In contrast, a vehicle will know if there are neighbouring wireless networks to access, on the basis of broadcast signaling messages sent by the RSUs.

Let the vehicles be traveling at a constant speed c [m/s]. The *message propagation rate within a cluster* (*i.e.*, v [m/s]) is defined as

$$v = \frac{x}{t},\tag{22}$$

where x [m] is the transmission range distance between two consecutive and connected vehicles communicating via V2V, and t [s] is the time necessary for a successful transmission, which depends on the single link of connected vehicles. Typical value of transmission range distance is $0 < x \leq 125$ m, as shown in (Agarwal & Little, 2008).

Equation (22) represents the average message propagation rate within a cluster, because it consists of each single contribution due to each single link (i, j) in the cluster, such as

$$v = \frac{1}{h}\sum_{i,j} v_{(i,j)} = \frac{1}{h}\sum_{i,j}\frac{x_{(i,j)}}{q_{(i,j)}} = \frac{1}{hL}\sum_{i,j} x_{(i,j)} \cdot f_{(i,j)},\tag{23}$$

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 within a cluster v [m/s] depends on the average message propagation rate for each single hop, and increases for a low number of hops h.

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

$$v_{\text{RSU}} = \frac{d}{T_{\text{RSU}}},\tag{24}$$

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,

$$T_{\text{RSU}} = \frac{L}{B}. \tag{25}$$

Notice that 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. The potential for communications between RSUs aims to avoid connectivity interruptions caused by low traffic densities, and that the V2V protocol cannot always solve.

In Figure 10 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 will send the message (*i*) to the destination vehicle if it is driving inside the actual RSU coverage, or (*ii*) to forward the message to 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:

$$v_{\text{UP}} = \frac{x_r}{L} \cdot \tilde{f}_{(i,m)}, \quad v_{\text{DOWN}} = \frac{x_r}{L} \cdot \tilde{f}_{(m,i)}, \tag{26}$$

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

From (24) and (26), 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, such as:

$$v_{\text{V2I}} = v_{\text{UP}} + v_{\text{RSU}} + v_{\text{DOWN}} =$$
$$= \frac{1}{L}\left[d \cdot B + x_r \cdot \left(\tilde{f}_{(i,m)} + \tilde{f}_{(m,i)} \right) \right]. \tag{27}$$

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:

$$v_{\text{V2V}}^{(\pm)} = \pm (v + c), \tag{28}$$

which depends on the constant velocity c of vehicles and on the effective transmission data rates within a cluster C, according to (23). 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.

To sum up, we characterize the behaviour of the whole system in terms of six transition states as follows:

1.   Messages are traveling along on a vehicle in the N direction at speed c [m/s];
2.   Messages are propagating multi-hop within a cluster in the N direction at speed $v_{\text{V2V}}^{(+)}$ [m/s];

3. Messages are traveling along a vehicle in the S direction at speed $-c$ [m/s];
4. Messages are propagating multi-hop within a cluster in the S direction at speed $v_{V2V}^{(-)}$ [m/s];
5. Messages are transmitted via radio by an RSU in the N direction at speed v_{V2I} [m/s];
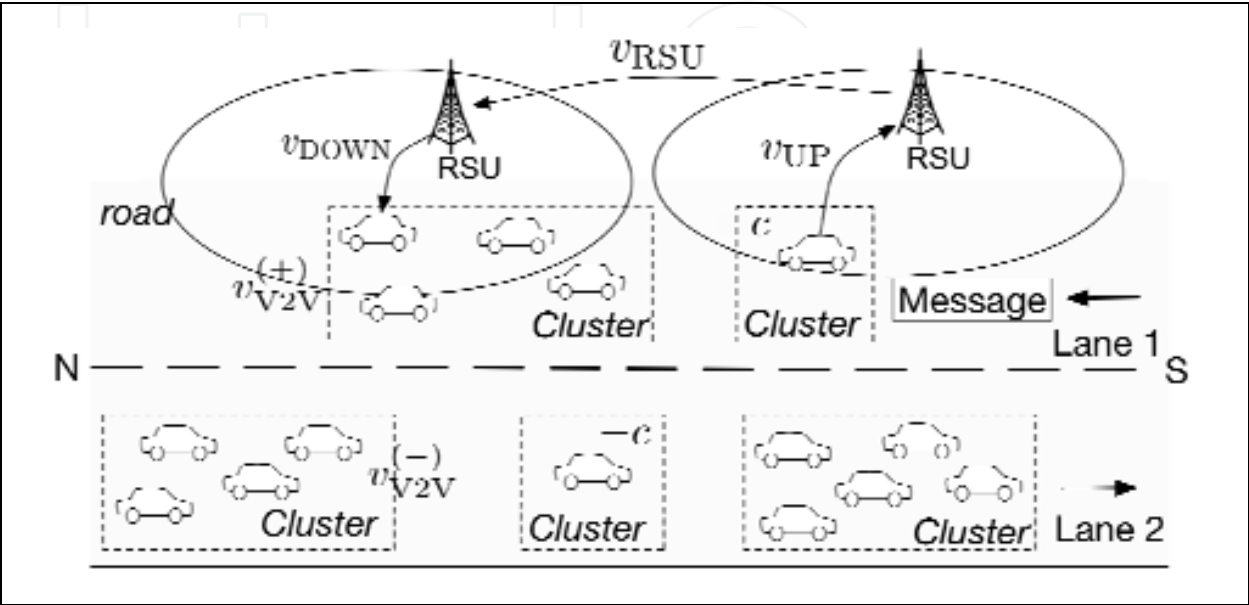6. Messages are transmitted via radio by an RSU in the S direction at speed $-v_{V2I}$ [m/s].

Fig. 10. Data propagation rates in VANET scenario with network infrastructure

States $(1-4)$ are typical for data propagation with opportunistic networking technique for vehicles communicating only via V2V, while states 5, and 6, have been added for vehicles communicating via V2I. All the six states can occur when vehicles communicate via V2X.

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 $v_{V2V}^{(+)}$.

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, it is easy to evince that 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 $v_{V2V}^{(-)}$. 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 $-v_{V2I}$.

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

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

5.2 V2X algorithm

This section illustrates how V2X takes a protocol switching decision.

The algorithm for handing over from V2V to V2I, and vice versa, is described by its pseudo-code in Figure 11. It is mainly based on (*i*) the *Infrastructure Connectivity* (*IC*) parameter, which gives information if a vehicle is able to connect to an RSU, and on (*ii*) the *optimal path detection technique*. The algorithm accepts one input (*i.e.*, the vehicle's *IC*), and returns the actual message propagation rate (*i.e.*, {v_{V2V}, v_{V2I}}).

Input: *IC*

Output: $\begin{cases} v_{V2V}, & \text{if a vehicle communicates via V2V} \\ v_{V2I}, & \text{if a vehicle communicates via V2I} \end{cases}$

while $IC = 0$ **do**
   A vehicle is connected via V2V, $\leftarrow v_{V2V}$
end
else
   if $IC = 1$ **then**
      Optimal path detection, $\leftarrow v_{V2I}$ or v_{V2V}
   end
end
if A vehicle communicates with an RSU via V2I **then**
   the RSU tracks the destination's position,
   if Destination vehicle is inside the actual RSUs coverage **then**
      Direct link from RSU to destination vehicle
   else
      The actual RSU will forward the message to next RSU
   end
end
end

Fig. 11. Algorithm for protocol switching decisions in V2X

Let us consider the following VANET scenario. A source vehicle is communicating with other vehicles (*relay*) via V2V in a sparsely connected neighbourhood, where the transmission range distance between two consecutive vehicles is under a connectivity bound, *i.e.* $x \leq 125$ m.

The source vehicle is driving inside any wireless cell, and is receiving "hello" broadcast messages from other vehicles nearby. Local connectivity information will notify the vehicle the availability of vehicles to communicate with via V2V; no RSU presence will be notify to the vehicle. In this case (*i.e.*, V2V availability, and no V2I) the *IC* parameter for vehicle *A* will be set to 0. Otherwise, when a vehicle enters a wireless network, the presence of an available RSU to access will be directly sent to the vehicle by means of its associated *IC* parameter set to 1.

Finally, a destination vehicle is driving far away from *A*, and other vehicles (*relay*) are available to communicate each other.

In such scenario, the algorithm works according to two main tasks, such as (*i*) checking *IC* parameter, and (*ii*) tracking the destination vehicle(s). Every time a vehicle forwards a message it checks its *IC* value. When *IC* = 1, the vehicle calculates the *optimal path* according to (21) in order to send the message directly to the selected RSU via V2I. Otherwise, the vehicle forwards the message to neighbouring vehicles via V2V.

By supposing the RSU knows the destination vehicle's position (*i.e.* by A-GPS), if the destination vehicle is traveling within the RSU's wireless coverage, the RSU will send the message directly to the destination vehicle. Otherwise, the RSU will be simply forwarding the message to the RSU that is actually managing the vehicle's connectivity. Finally, the message will be received by the destination vehicle.

Some simulation results are now shown in order to verify the effectiveness of V2X approach as compared with traditional opportunistic networking scheme in VANET. As a measure of performance, we calculate the *average message displacement* (*i.e. X* [m]) in VANETs via V2X. The *message displacement* is a linear function, depending on time, and varying for different traffic scenarios, message propagation speeds, and network conditions. It follows that in each of the six states listed in Section 5.1, the message displacement $X(t)$ will be as follows:

1. $X(t) = c \cdot t$, for messages traveling along on a vehicle in the N direction at speed c [m/s];

2. $X(t) = v_{V2V}^{(+)} \cdot t$, for messages propagating multi-hop within a cluster in the N direction at speed $v_{V2V}^{(+)}$ [m/s];

3. $X(t) = -c \cdot t$, for messages traveling along a vehicle in the S direction at speed $-c$ [m/s];

4. $X(t) = v_{V2V}^{(-)} \cdot t$, for messages propagating multi-hop within a cluster in the S direction at speed $v_{V2V}^{(-)}$ [m/s];

5. $X(t) = v_{V2I} \cdot t$, for messages transmitted via radio by an RSU in the N direction at speed v_{V2I} [m/s];

6. $X(t) = -v_{V2I} \cdot t$, for messages transmitted via radio by an RSU in the S direction at speed $-v_{V2I}$ [m/s].

States 1, 2, and 5 refer on a *forward message propagation*, while stated 3, 4, and 6 on a *reverse message propagation*, respectively.

We simulated a typical vehicular network scenario by the following events:

i.   at $t = 0$ s a source vehicle is traveling in the N direction and sends a message along on the same direction, (*state* 1);
ii.   at $t = 2$ s the message is propagated multi-hop within a cluster in the N direction, (*state* 2);
iii. at $t = 6$ s a relay vehicle enters an RSU's radio coverage, and the message is transmitted via V2I to the RSU. Finally, it will be received by other vehicles at $t = 10$ s, (*state* 5).

We compared this scenario with traditional opportunistic networking technique in VANETs, where the following events occur:

i.   at $t = 0$ s a source vehicle traveling in the N direction sends a message along on the same direction, (*state* 1);
ii.   at $t = 4$ s the message is forwarded to a vehicle in the S direction, (*state* 3);
iii. at $t = 6$ s the message propagates via multi-hop within a cluster in the N direction, (*state* 2). The transmission stops at $t = 10$ s.

For comparative purposes, main simulation parameters has been set according to (Wu *et al.*, 2004), including $c = 20$ m/s, $d = 500$ m, typical message size $L = 300$ bit, data rate transmission $B = 10$ Mbit/s (*e.g.*, for WiMax connectivity), and $x_r = 400$ m. The transmission rates in DSRC have been assumed equal to 6 Mbit/s (Held, 2007). We assumed a cluster size equal to $h = 5$, and different distances between couples of vehicles (*i.e.*, 100, 75, 50, 40, and 30 m). For each hop the transmission range has been hold (*i.e.* < 125 m).

Figure 12 (*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 approximately 30 km in V2X (Figure 12 (*left*)), while only 1.5 km in traditional V2V (Figure 12 (*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.
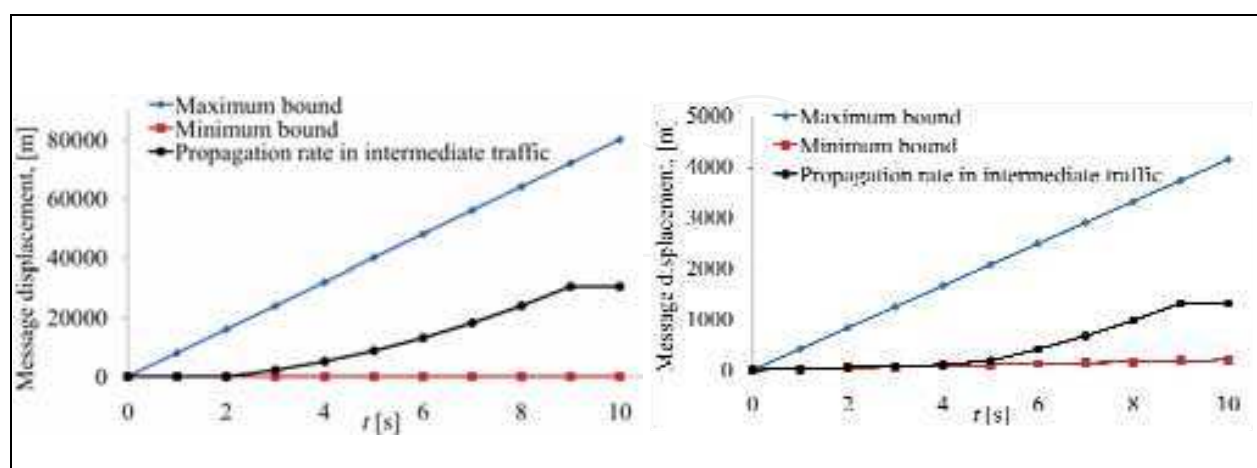

Fig. 12. Forward message propagation for (*left*) V2X protocol, (*right*) traditional opportunistic networking

Analogously, we simulated how a message is forwarded in *reverse message propagation mode*, where vehicles are traveling in an opposite direction (Figure 13). In this case, the message

propagation rates are in the range $[-c; -v_{V2I}]$ and $[-c; v_{V2V}^{(-)}]$ [m/s], for V2X and traditional opportunistic networking scheme, respectively. Once again, 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 13 (*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 13 (*right*)).

Notice the fluctuations of message displacement in *forward* and *reverse* cases with V2X (*i.e.* 50, and 70 km, respectively). They are mainly due to traffic density, and RSUs' positions (*i.e.* inter-RSU distance). In general, high performance are obtained with V2X, while low message propagation distance with traditional V2V.
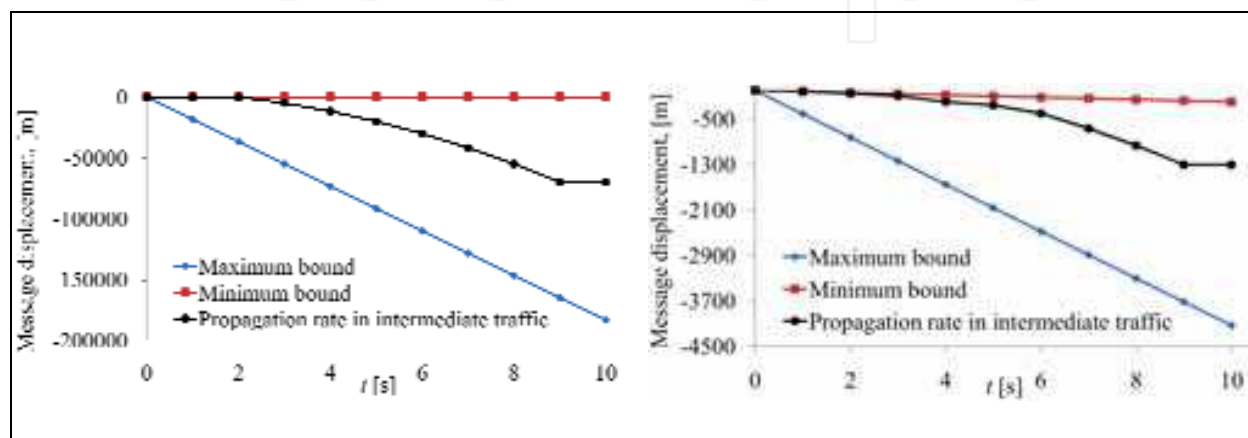

Fig. 13. Reverse message propagation for (*left*) V2X protocol, (*right*) traditional opportunistic networking

6. Conclusions

In this chapter we have discussed application of VHO in the context of VANETs in order to optimize application delivery through a mixed V2V/V2I infrastructure. Vertical handover strategies can be applied to assure VANET connectivity *context-aware*, and *content-aware*.

Various metrics can be adopted to trigger handover decisions including RSS measurements, QoS parameters, and mobile terminal location information. This last represents the most common parameter used to drive VHO decisions.

Hence, a geometrical model has been presented where GPS-equipped mobile terminals exploit their location information to pilot handover and maximize communication throughput taking into account mobile speed. The proposed technique has been described via both analytical and simulated results, and validation of its effectiveness has been supported by a comparison with a traditional vertical handover method for VANETs (Yan *et al.*, 2008).

Moreover, we have described a hybrid vehicular communication protocol V2X and the mechanism by which a message is propagated under this technique. V2X differs from traditional V2V protocol by exploiting both V2V and V2I techniques, through the use of a fixed network infrastructure along with the mobile ad-hoc network. In this heterogeneous scenario, we have characterized the upper and lower bounds for message propagation rates. Validation of V2X has been carried out via simulation results, showing how V2X protocol

improves network performance, with respect to traditional opportunistic networking technique applied in VANETs.

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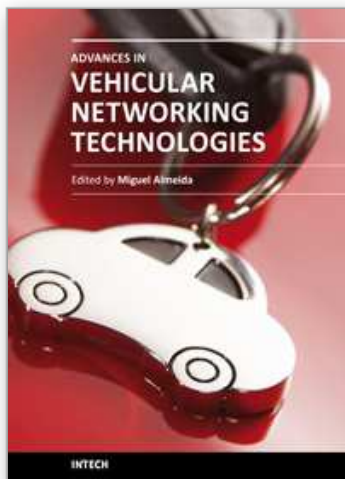
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This book provides an insight on both the challenges and the technological solutions of several approaches, which allow connecting vehicles between each other and with the network. It underlines the trends on networking capabilities and their issues, further focusing on the MAC and Physical layer challenges. Ranging from the advances on radio access technologies to intelligent mechanisms deployed to enhance cooperative communications, cognitive radio and multiple antenna systems have been given particular highlight.

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