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RESEARCH ARTICLE (draft version)

Vehicle to Internet communications using the ETSI ITS GeoNetworking protocol

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ABSTRACT

Vehicular Ad hoc NETworks (VANETs) allow the exchange of information between vehicles to improve road safety. In addition, vehicles can be connected to the Internet through gateways placed alongside the roads, which allow drivers to use common Internet services and new applications specifically oriented to them. The ETSI TC ITS has standardized the architecture and the communication protocols for an Intelligent Transport System (ITS), considering both safety applications and communications with the Internet. The GeoNetworking protocol (GN) has been designed to forward packets inside the VANET taking safety requirements as the main concern. This paper analyzes the GeoNetworking protocol (GN) focusing on the provision of Internet connectivity to vehicles. The main contributions of this work are the identification of sources of performance losses when using the GN protocol in communications with Internet and the proposal of different mechanisms to improve its performance in this type of communications. The evaluation of the GN protocol and the proposed improvements is conducted by means of extensive simulations.

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1. INTRODUCTION

Ad hoc networks are infrastructure-less networks where nodes communicate among them using wireless interfaces and packets travel through the network following a multi-hop path between source and destination. A Vehicular Ad hoc NETwork (VANET) is an ad hoc network formed by vehicles where links among nodes are especially unstable due to their continuous movement. VANETs are a promising technology to provide vehicles with communication capabilities for the exchange of information.

Since vehicles can exchange information between them, drivers could be informed about road hazards detected by other vehicles ahead (e.g., a sudden stop due to a traffic jam). This way, road safety applications could be deployed over VANETs with the intention of reducing traffic accidents and decreasing road casualties. Although improving road safety is the biggest focus of VANETs due to its social impact, VANETs also enable the deployment of non-safety applications (infotainment and traffic efficiency applications) based on Internet connectivity. On the one hand, Internet access from vehicles allows drivers to use common Internet services and, on the other hand, it opens the market to new Internet applications tailored for drivers. Content distribution by message store-carry-and-forward is an interesting scheme that is being studied to provide infotainment applications in VANETs (see for example [1]). In this scheme contents are assumed to be of interest to a number, or even to all, vehicles in the VANET, so the aim is to opportunistically distribute the contents to reach as many vehicles as possible in the shortest possible time. Instead, in this paper we focus on non-safety applications based on communications addressed to particular vehicles, which requires a routing protocol to find out how to forward packets to reach the intended destinations.

The ETSI TC ITS (European Telecommunications Standards Institute Technical Committee Intelligent Transport System) [2] has defined the architecture and the communication protocols for a standardized ITS. Inputs from automobile manufacturers and industry have been considered, such as those suggested by the Car-to-Car Communication Consortium (C2C-CC) [3]. The ETSI TC ITS has standardized the GeoNetworking protocol (GN) [4] for routing packets through the VANET in its system architecture [5]. The GN protocol adopts the geographic routing paradigm where packets are forwarded based on the geographical location of network nodes and the packet's destination

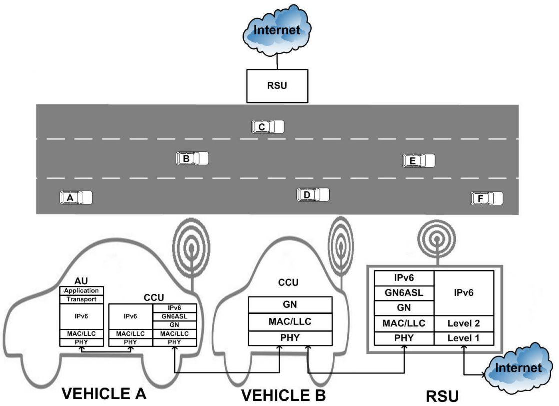

Figure 1. Communications with the Internet in the ETSI ITS

position. Internet connectivity is provided to vehicles of the VANET by means of gateways placed alongside roads.

Although ETSI ITS standards consider both safety applications and communications with the Internet, the ETSI GN protocol has been designed with the main focus on safety requirements. In this article, we pay attention to Internet connectivity aspects for non-safety applications, analyzing the performance of the ETSI TC ITS architecture and specifically the GN protocol when providing Internet access to VANET vehicles in highway scenarios. We identify the sources of performance losses when using the GN protocol for vehicle communications with Internet and propose mechanisms to tackle them. These mechanisms greatly improve the performance of the GN protocol in this type of communications. The analysis of the GN protocol and the proposed improvements has been conducted by means of simulation.

The paper is organized as follows: Section 2 introduces the ETSI TC ITS architecture and the ETSI GN protocol. In Section 3 we present the simulation scenario used to evaluate the performance of the GN protocol. Also, we analyze the results of the GN protocol simulations when vehicles of the VANET communicate with the Internet. In Section 4, the sources of performance losses when using the GN protocol are identified and mechanisms to enhance its performance are presented and evaluated. Section 5 summarizes our conclusions.

2. BACKGROUND

The ETSI TC ITS architecture and the ETSI GeoNetworking protocol are described in this section.

2.1. ETSI TC ITS Architecture

The ETSI TC ITS has standardized an architecture [5] for an Intelligent Transport System that is based on the recommendations from automobile manufacturers and industry, such as those suggested by the Car-to-Car Communication Consortium (C2C-CC) [3]. The scenario of communications with the Internet in the ETSI TC ITS architecture is depicted in Figure 1. Vehicle ITS stations are equipped with a Communication & Control Unit (CCU) that implements the ETSI communication protocol stack. The CCU uses in-vehicle interfaces for communications with the Application Units (AUs) inside the vehicle and external short-range wireless interfaces for communications with other ITS stations of the VANET. An AU is a device (e.g., a computer on the dashboard or a passenger's smart-phone) with a standard IPv6 protocol stack that executes a set of applications that benefit from the communication capabilities provided by the CCU. AUs are connected (via a wired or wireless technology) to the in-vehicle interfaces of the CCU, which acts as a gateway (optionally with NEMO [6] extensions) for AUs' communications.

The ITS ad hoc network is also formed by roadside ITS stations or Road Side Units (RSUs) that, together with CCUs, form a VANET that enables decentralized inter-vehicle communications. RSUs are located alongside roads and also implement the ETSI communication protocol stack, further increasing network connectivity. In addition, RSUs are connected to the infrastructure of a network operator, so that they could act as gateways to provide Internet connectivity to VANET vehicles.

The ETSI TC ITS has also standardized the ETSI GeoNetworking protocol (GN) [4] to forward packets in the ITS architecture. The GN protocol is a geographic routing protocol located between the link and network layers of the communication protocol stack (see Figure 1). Given the popularity of GPS devices, it is assumed that all nodes know their own geographical position. Besides, they learn the position of their direct neighbors (nodes that are one hop away). Nodes use this geographic information to forward packets through the VANET following a multi-hop path from source to destination. There are two main types of packet deliveries: Geo-unicast and geo-broadcast. In geo-unicast, the packet is forwarded hop by hop towards the position of the destination and delivered to that specific node. In geo-broadcast, the packet is first geo-routed to a target geographic zone, and then delivered to all nodes located inside the destination area. Next subsection describes the GN protocol in more detail.

Additionally, the ETSI TC ITS has standardized the integration of the ITS ad hoc network with the Internet [7], which allows vehicle ITS stations communicating with other nodes in the Internet. A GeoNetworking to IPv6 Adaptation Sub-Layer (GN6ASL) has been introduced with a set of mechanisms for the transmission of IPv6 packets over GeoNetworking protocols, which avoid modifications to the standard IPv6 protocol. The GN6ASL is in charge of coupling the IPv6 layer with the GN level, so that from the point of view of IPv6, the GN layer plays the role of a sub-IP layer. The GN layer receives IPv6 datagrams, encapsulates them into GN packets adding a GN header and then, routes them. The resolution from a

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destination unicast IPv6 address to the corresponding GN address is direct since the interface identifier part of the IPv6 address maps to one and only one GN address, i.e., the destination GN address can be directly derived from the destination IPv6 address. Thereby, the IPv6 layer perceives the VANET as a flat network topology thanks to the GN layer. In this way, two IPv6 neighbors can be separated more than one GN hop away from each other, but the GN layer makes this transparent to upper layers, so from the IPv6 layer perspective, they belong to the same link. In Figure 1, the vehicle A and the RSU are neighbors at IPv6 level, but actually the GN layer of vehicle B acts as a forwarder and establishes a multi-hop GN path between them.

This specification has adopted the Geographically Scoped stateless Address Configuration (GeoSAC) [8] mechanism for automatic IPv6 address configuration. GeoSAC adapts the IPv6 SLAAC [9] [10] mechanisms to the geographic addressing and networking scenario by defining a geographical virtual link. A geographical virtual link is defined as the restricted geographical zone where the GN protocol delivers multicast packets to all nodes inside it by means of geo-broadcasting, so all nodes inside the area of a geographical virtual link belong to the same IPv6 subnet. Hence, different geographical virtual links are defined as non-overlapping geographic areas, with an RSU acting as the access router that provides Internet connectivity to vehicles inside such area. Each RSU is in charge of a specific area of influence, i.e., a geographical virtual link. Since RSUs act as access routers, they periodically distribute Router Advertisement (RA) messages that are delivered by the GN layer to all nodes situated within its geographic area by means of geo-broadcasting. This way, vehicles can configure a global IPv6 address following the IPv6 SLAAC [9] [10] mechanisms[*]. Some optimizations have been proposed to this mechanism such as [11]. Note that vehicles move among different geographical virtual links (different areas) while they travel. Vehicles' CCUs can detect a change of area because the RAs broadcast by RSUs include in the GN header the scope of the geographical virtual link and the position of the serving RSU. Network Mobility Basic Support (NEMO BS) [6] is the candidate protocol for managing the mobility between different geographical virtual links (RSUs), although other mobility solutions like MIPv6 [12] or PMIPv6 [13] could also be applied.

We rely again on Figure 1 to explain how packets are routed inside the VANET. If an AU of vehicle A sends a packet to another node in the Internet, A's CCU should send the packet to the access router of its geographical virtual link, the RSU. Since the vehicle A and the RSU are attached to the same geographical virtual link, the RSU is the IPv6 next-hop of vehicle A, although they may be separated by more than one GN hop. Thus, the packet is forwarded by the GN layer of vehicle B forming a multi-hop path between vehicle A and the RSU. Then, the RSU removes the GN header and routes the IPv6 packet to the Internet through the network operator infrastructure. In case the destination of the IPv6 packet is a vehicle within the same geographic area as vehicle A, for example vehicle D, the packet is routed directly to the destination vehicle by the GN protocol, without traveling through the access router (RSU), because vehicles A and D are in the same IPv6 link i.e., vehicle D is in the same IPv6 subnet than vehicle A. When an IPv6 packet comes from the Internet and is addressed to vehicle A, it is first forwarded by the RSU. Thus, the GN layer of the RSU adds the GN header and sends the packet to vehicle B, which finally forwards it to vehicle A.

2.2. ETSI GeoNetworking protocol

The ETSI GeoNetworking protocol (GN) [4] is a geographic routing protocol that routes packets through the VANET based on the geographical position of nodes. It is assumed that nodes obtain their own geographical location by means of a location system, like the Global Positioning System (GPS). Additionally, every node maintains a Location Table (LT) that has information about other ITS stations in the VANET, including the position of its direct neighbors (those nodes that are one hop away). The position of the direct neighbors is obtained by means of a beaconing algorithm that works as follows: Periodically, every node broadcasts a beacon message advertising its GN address and its current position, speed, heading, station type, and so on, to all its direct neighbors. This way, nodes store in their LT the information extracted from these messages. Since beacons are sent periodically, nodes maintain their LT updated with the current position of other nodes. However, this beaconing algorithm generates some network overhead. Thus, there is a trade-off between the network overhead produced by the beaconing algorithm and the freshness of the information stored in the LT, which is needed for the appropriate operation of the GN protocol. The higher beacon frequency, the fresher information in the LT, but also the higher network overhead. Nevertheless, the GN standard proposes to reset the beacon timer whenever a GN packet is sent with the goal of reducing the network overhead produced by the beaconing algorithm. This is due to the fact that the protocol uses beacon piggybacking and the information of a beacon is also included in the GN common header of all GN packets. In addition, the LT may include geographical position information about nodes located more than one hop away. This information is discovered using the Location Service (LS), which is described later.

Due to the high mobility of vehicles in the VANET, the LT information may become obsolete quickly, so every LT entry has a lifetime. When the lifetime of an

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[*] Note that to autoconfigure an IPv6 address, the interface identifier part of the IPv6 address is uniquely derived from the GN address of the node. As GN addresses are unique in the VANET, IPv6 Duplicate Address Detection could be disabled saving the flooding of Neighbor Discovery messages, which is costly in VANETs.

entry expires, it is removed from the LT. The LT entry lifetime also has an impact on the performance of the GN protocol since it influences the freshness of the LT information. If this lifetime is too long, old neighbors in the LT can be considered valid ones when actually they are no longer reachable due to their movement. On the contrary, the shorter the LT lifetime, the lower the beacon interval needed, with the associated increase of the network overhead. Besides, if the lifetime is too short, leading to network congestion, the LT cannot be updated properly if there are losses of beacon messages due to collisions in the wireless channel.

The GN protocol defines different kinds of packet delivery services: Geo-unicast, topologically-scoped broadcast, single hop broadcast, geo-broadcast and geo-anycast. We have focused on geo-unicast and geo-broadcast because they are the most common GN services. In geo-unicast, the destination of the packet is a node located at a specific position. The destination location is conveyed in the GN header and is used to forward the packet towards the destination using one of the two forwarding algorithms defined in the specification: The greedy forwarding algorithm and the Contention-Based Forwarding algorithm (CBF). This paper is focused on the greedy forwarding algorithm, leaving the CBF algorithm for future work. The greedy forwarding algorithm selects as the next-hop of a GN packet the neighbor in the LT that is the closest one to the destination coordinates.

With geo-broadcast delivery, a packet targets all nodes inside a specific geographic area. The parameters that describe the target area are included in the GN header of the packet and are used to forward the packet towards it. The geo-broadcast packet is first forwarded like a geo-unicast packet (using the greedy forwarding algorithm) until it reaches the target zone. Then, the geo-broadcast packet is delivered to all nodes within the destination area by simple flooding.

In order to discover the position of another ITS station, for instance when sending a geo-unicast packet to a destination that is not in the LT, the source node uses the Location Service (LS), which works as follows: The source node that needs to discover the geographic position of another node broadcasts a LS request packet indicating the GN address of the target node (the node whose position is requested). The LS request packet is further broadcast by intermediate nodes until it reaches the target node. The target node replies with a LS reply packet including its position that is sent back to the requesting node as a geo-unicast packet. This can be done because the LS request packet includes the position of the source node. When the source node receives the LS reply packet, it creates a new entry in the LT for the destination node, which will be valid until its lifetime expires. If the source node does not receive a LS reply packet, it continues sending LS request packets each LS retransmission interval until it receives a LS reply packet or the retransmission counter reaches the maximum LS retransmissions.

The GN protocol defines multiple packet buffers: A LS buffer, a unicast buffer, a broadcast buffer and a CBF buffer (used if CBF is enabled). The LS buffer is used to store packets while the LS resolves the geographic position of a destination node. The unicast and broadcast buffers are useful to store geo-unicast and geo-broadcast packets when the forwarding algorithm fails finding a valid neighbor to route the packet towards the destination. These buffers are flushed when the LT is updated with information about packets' destination, so packets can be forwarded. Storing packets into buffers avoids dropping them when there are no valid neighbors due to temporal disconnections among nodes of the VANET, which is more likely in low density scenarios.

3. ETSI GEONETWORKING PROTOCOL PERFORMANCE EVALUATION

The goal of our work is to evaluate the performance of the ETSI TC ITS architecture and specifically of the ETSI GN protocol when it is used for communications between vehicles and the Internet in highway scenarios. We also propose some enhancements to improve the performance of the ETSI GN protocol in these scenarios.

3.1. Simulation Scenario

The scenario used to evaluate the performance of the ETSI GN protocol is described in this section. In order to obtain results as close as possible to a real scenario, we use the well-known OMNeT++ simulator[†]. We developed our own implementation of the ETSI TC ITS GN protocol [4] as well as GN6ASL [7] for the transmission of IPv6 packets on top of the GN protocol. This implementation has been integrated with the INETMANET framework[‡]. Our analysis is focused on the scenario where an RSU provides Internet connectivity to vehicles inside its assigned geographic area (shown in Figure 1). Our simulation scenario is a 2000-meter stretch of highway with three lanes, where an RSU serves all vehicles in the road stretch, i.e., the RSU is located in the middle of the highway stretch and its assigned area is the 2000-meters highway segment. The performance of the GN protocol when vehicles are connected to the Internet can be evaluated using just one RSU/area because the GN protocol only provides communication among nodes within the same area. Therefore, inter-area mobility is out of the scope of this paper. Vehicle traces are generated synthetically following an exponential distribution for the vehicle inter-arrival time [14], that is adjusted to obtain a particular vehicle density in vehicles per kilometer. When not stated otherwise, we use a vehicle density of 45 veh/Km in our experiments. The depart lane of

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[†] OMNeT++ Network Simulator Framework: http://www.omnetpp.org/

[‡] INETMANET for OMNeT++ 4.x: https://github.com/inetmanet/inetmanet/wiki

each vehicle is selected randomly following an uniform distribution. The target speed of the vehicles is obtained randomly with a Gaussian distribution centred on 110 Km/h and a standard deviation of 10 Km/h [15]. Since there is a relationship between the speed of vehicles and vehicle density, we have used [16] to select realistic values of speed and density. These vehicle traces are injected into the SUMO traffic simulator[§], which is coupled with the OMNET++ simulator to reproduce a realistic driver's behavior. For example, vehicles use preferably the right lane and, a fast vehicle that encounters a slower vehicle ahead, will reduce the speed and try to overtake when circumstances allow it. All vehicles and the RSU are equipped with an IEEE 802.11g[¶] link layer operating at a fixed 54 Mbps bit rate. The transmission power of the nodes is adjusted to provide around 200 meters of radio coverage [17, 18].

When vehicles enter the simulation, they move along the geographic area of the RSU until they leave the highway stretch. To avoid the interaction of the IPv6 address configuration mechanism with the performance of the GN protocol, nodes enter the simulation scenario with a predefined globally-routable IPv6 address. We still consider the overload produced by the signaling needed for the GeoSAC-based IPv6 configuration, i.e., the RSU periodically distributes RA messages with the IPv6 prefix used in its zone by means of geo-broadcast. The RA interval of the RSU is uniformly selected between RA_{min}=2.75s and RA_{max}=3.25s, so the mean RA interval is 3 seconds. In order to avoid collisions in the wireless channel when the RSU sends a RA packet, a delay chosen uniformly between 0 and 5 milliseconds is introduced before retransmitting a geo-broadcast packet. Regarding the ETSI GN protocol, all parameters are set according to its specification [4], unless stated otherwise.

In order to evaluate the performance of the ETSI GN protocol when it is used for communications between vehicles and the Internet, Constant Bit Rate (CBR) UDP flows are established between selected vehicles in the VANET and a Correspondent Node (CN) in the Internet. To focus on the evaluation of the performance in the VANET, this CN is directly connected to the RSU in the simulation. When a vehicle is selected to communicate with the CN, two independent CBR UDP flows are established between the CN and the vehicle, one in each direction. The traffic pattern of the CBR UDP flows is chosen to model a VoIP communication so packets are sent every 20 milliseconds with a payload of 160 bytes (G.711 codec). Vehicles that receive and send data traffic are selected randomly following a geometric distribution that is adjusted to obtain a specific amount of vehicles communicating with a CN. Multiple simulation runs have been executed varying the percentage of vehicles that communicate with a CN during the simulation. Each simulation is repeated 30 times using different random seeds (95% confidence intervals are provided). Statistics are taken during 200 seconds of simulation once the highway stretch is populated with vehicles to recreate a real scenario where vehicles have other vehicles ahead and behind. For each vehicle, the measurements are taken from the moment the vehicle enters the highway stretch until it exits the simulation scenario.

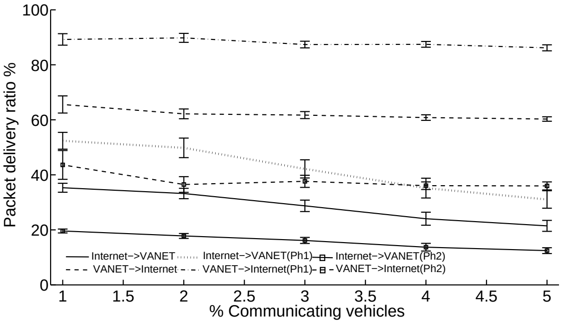

Figure 2. Packet delivery ratio of ETSI GN protocol

3.2. Simulation results analysis

In this section, we evaluate the performance of the ETSI GN protocol when providing Internet connectivity to vehicles of the VANET by analyzing the results of the simulations of the scenario described above.

Figure 2 shows the packet delivery ratio of the CBR UDP flows measured in the two directions (from the Internet to the VANET and vice versa) against the percentage of vehicles of the highway stretch that communicate with a CN. It can be seen that the packet delivery ratio decreases when the number of vehicles that communicate with a CN increases, due to the fact that total data traffic in the network increases and the resources have to be shared among more nodes trying to communicate. Moreover, the packet delivery ratio of Internet-VANET flows is significantly lower than the one of VANET-Internet flows. A thorough study of the traces of the GN simulations revealed the explanation to this poor performance. Most of packet losses are produced by two main reasons: 1) Packets are dropped at the MAC layer of the nodes because it is not possible to deliver them to the next-hop (the greedy forwarding algorithm selects invalid neighbors as next-hop many times); and 2) Packets are discarded in the Internet-VANET direction at the MAC layer of the RSU because its transmission queue is full. This means that the RSU cannot forward all traffic it receives from the Internet (Section 4 goes deeper into this saturation problem). Note that the RSU concentrates all the traffic between the Internet and the VANET, so the RSU has to access to the wireless channel more times than a vehicle because it handles more traffic. This makes the

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[§] SUMO Simulation of Urban MObility: http://sumo.sourceforge.net/

[¶] ETSI standards consider the use of the GN protocol over different short-range wireless access technologies. In our simulations nodes use IEEE 802.11g interfaces, whose usage is widespread and are available at a reduced price.

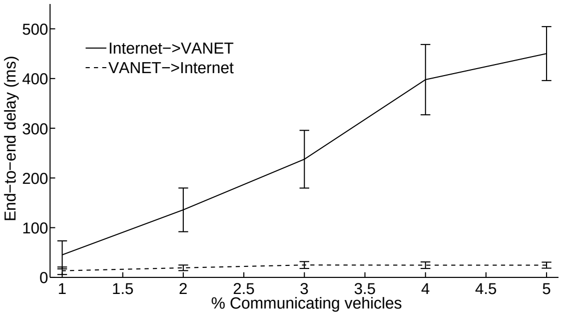

Figure 3. End-to-end delay of ETSI GN protocol

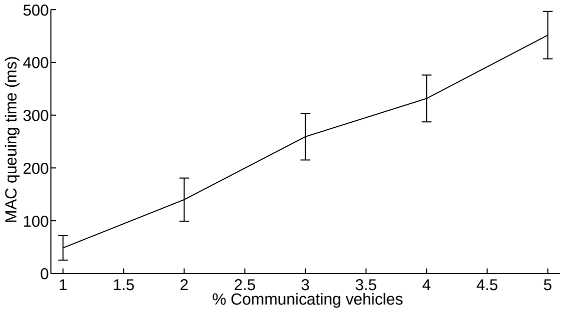

Figure 4. Queuing time of ETSI GN packets in the MAC layer of the RSU

RSU more vulnerable to saturation because vehicles and the RSU share the same opportunity of accessing to the wireless channel.

To better understand the packet losses due to selection of invalid GN neighbors, we have further studied the performance of the GN protocol taking into account the location of the RSU regarding to the vehicles of the VANET. In this way, the simulation scenario is divided in two phases: 1) Vehicles that communicate with a CN while traveling towards the RSU and 2) vehicles that communicate with a CN while moving away from the RSU. The packet delivery ratio for both, Internet-VANET and VANET-Internet flows as a function of the percentage of vehicles that communicate with a CN differentiating between phase 1 (Ph1) and phase 2 (Ph2) is also shown in Figure 2. As it can be seen in the figure, there is a significant difference in the performance of the two phases. In the case the communicating vehicle travels towards the RSU, the RSU selects as the next-hop for Internet-VANET packets the closest neighbor to the destination, which is also moving towards the RSU. This next-hop neighbor is reachable continuously until a new next-hop is selected because it travels deeper into the radio coverage area of the RSU with its movement. However, when the destination vehicle moves away from the RSU, the next-hop selected by the RSU is also moving away, so the next-hop will quickly become invalid when it exits the radio coverage of the RSU. Hence packets will be dropped until the RSU selects another valid next-hop to reach that destination. Note that the same reasoning is valid the other way around, when VANET vehicles try to reach the RSU for sending packets to the Internet. This is why the packet delivery ratio is better when vehicles that are communicating travel towards the RSU than when they move away from the RSU. This is an interesting insight on the behavior of the GN protocol.

We have also studied the behavior of the GN protocol regarding the end-to-end delay. Figure 3 presents the end-to-end delay suffered by data packets for both, Internet-VANET and VANET-Internet flows versus the percentage of vehicles communicating with a CN. The greater number of vehicles communicating with a CN, the higher end-to-end delay because the data traffic in the network increases, so the wireless channel is shared among more nodes trying to transmit packets. Again, there is a significant difference between the Internet-VANET direction and the VANET-Internet directions. As it can be seen in Figure 4, which shows the queuing time of packets in the MAC layer of the RSU against the percentage of vehicles communicating with a CN, the biggest component of the delay suffered by Internet-VANET packets is the time that they wait in the MAC layer queue of the RSU, that is longer when the number of vehicles that communicate with a CN increases.

Another interesting point is the influence of the beacon interval on the performance of the GN protocol. We have repeated the simulations in Figures 2-4 with different beaconing intervals and the results show that the performance of the GN protocol in our scenario is independent of the beacon interval. The reason is that IPv6 Router Advertisement (RA) messages also play the role of GN beacon messages. According to the beacon piggybacking mechanism defined by the specification, nodes periodically broadcast beacon messages every beacon interval, unless another GN packet is sent, in which case the beacon timer is reset because beacon information is included in the GN header. Since the RSU sends RA packets periodically, which are distributed to all vehicles of the area by means of flooding, the Location Table (LT) is updated with neighbor information every time a RA is geo-broadcast by the RSU. Thus, we conclude that beaconing is automatically disabled in scenarios where packets are geo-broadcast periodically using flooding, which is the case when connecting VANETs to the Internet (RAs are needed for vehicles to configure an IPv6 address).

We can conclude that the performance of the ETSI GN protocol as specified in [4] has plenty of room to be improved for the scenario of providing Internet connectivity to vehicles of the VANET. In the next section, a further analysis of the ETSI GN protocol is presented in which we determine the causes of performance losses when vehicles communicate with Internet, and we identify mechanisms to enhance this performance.

4. IMPROVING THE PERFORMANCE OF THE ETSI GN PROTOCOL

4.1. Location Table lifetime analysis

As introduced previously, one of the two main reasons of most packet losses in the simulations is that packets are dropped at the MAC layer of nodes because it is not possible to deliver them to the next-hop. Although packets are lost at MAC layer, the actual cause comes from the GN protocol layer. The greedy forwarding algorithm selects as the next-hop of a GN packet the neighbor in the LT that is the closest one to the destination. When a neighbor is discovered, the corresponding entry is stored in the LT, and is considered as valid for its whole lifetime. However, some neighbors in the LT that are considered by the greedy forwarding algorithm as next-hops could become unreachable because they have moved away from the radio coverage. We could think that decreasing the beacon or the RA interval (note that RA packets act as beacons) would solve the problem because the information of the LT would be more up-to-date. However, since the neighbors that have exited the radio coverage cannot update their positions, a decreased update interval does not help, because the problem is deleting outdated entries in the LT, which is done by the lifetime of LT entries that has a long default value in the standard (20 seconds). Thus, neighbors are maintained in the LT for a long time even if they are not reachable any more, so that the greedy forwarding algorithm selects unreachable next-hops to route packets with high probability. The problem is not solved until a new best neighbor appears or the entry of the previous best neighbor expires. This does not only make packets to be discarded while another reachable neighbor is selected, but also contributes to increase the traffic in the wireless channel because the MAC layer tries to send each packet up to seven times before discarding it if no link layer ACK is received (as stated in the IEEE 802.11 standard). In addition, this has the further pernicious effect of increasing the MAC queuing time at the RSU reaching a saturation state where packets are discarded because the queue is full (see Figure 4). Moreover, the greedy forwarding algorithm is especially prone to this problem because it has the tendency to select as a next-hop the closest neighbor to the limit of the radio coverage, so that the selected next-hop usually leaves the radio coverage area soon after.

We have studied the effect of the lifetime of LT entries. Figure 5 shows the packet delivery ratio of the CBR UDP flows measured in both directions (from the Internet to the VANET and vice versa) as a function of the lifetime of the entries of the LT when 3% of vehicles of the VANET are communicating with the CN. The packet delivery ratio improves when the LT lifetime is decreased. The explanation is that if invalid entries are removed faster from the LT, the probability of choosing an invalid neighbor decreases. Thus even in the case the greedy forwarding algorithm selects an unreachable neighbor as next-hop for packets towards a specific destination, the situation is solved faster because the unreachable neighbor's lifetime expires sooner. However, the performance of the GN protocol is still not good enough even if the lifetime is decreased to 5 seconds, which is the best simulated case. The packet delivery ratio peaks at 72% in the VANET to the Internet direction and 39% for the Internet to VANET flows. Note that the LT lifetime has to be greater than the update period (the average RA interval is 3 seconds) so the least lifetime that has been considered is 5 seconds.

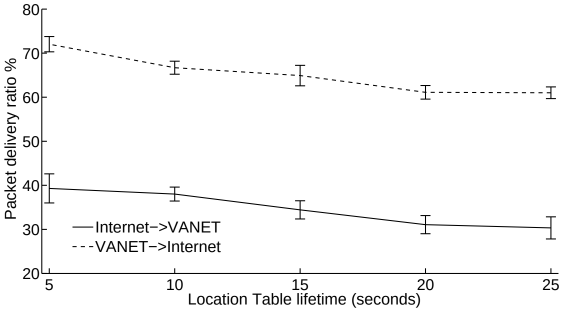

Figure 5. Location Table lifetime analysis

However, since the LT is also used for storing position information about destinations discovered by the Location Service (LS) mechanism, the LT lifetime has to be configured with this in mind. The idea is that a destination's location discovered by means of the LS mechanism has to be stored while the destination is reachable by a packet addressed to that position despite of destination's movement. In other words, the destination's location has to be deleted from the LT when the geographical point where the packet is addressed to is outside the radio coverage of the destination node. This way, the LT lifetime is given by equation (1), where R is the radius of the radio coverage and V_{max} the maximum speed of vehicles on the road:

$$t_{lt} \leq \frac{R}{V_{max}} \tag{1}$$

In our scenario, with 200 meters of radio coverage and an average maximum speed of 120 Km/h., we set the LT lifetime to 6 seconds from now on. Note that vehicles could obtain the maximum speed of the road by different ways, for instance: 1) It could be included into the messages broadcast by the RSU, 2) vehicles could estimate it taking into account the information included into the GN header of packets received from direct neighbors, or 3) the maximum speed of the road could be obtained from the digital maps of the GPS navigator database.

4.2. Neighbor position prediction and cross-layer based neighbor loss detection

In order to further improve the performance, we propose the usage of a cross-layer based neighbor loss detection and a neighbor position prediction mechanisms. These mechanisms were introduced in [19][‖] as two separate methods intended to tackle the problem of choosing invalid neighbors. The mechanisms themselves are not novel and, for example, [20] already mentioned the use of MAC-layer failure feedback with greedy forwarding. Additionally, cross-layer feedback is dependent on specific functionality at layer 2, which can explain why it is not mentioned in the ETSI GN standard. Nevertheless, it is important to understand the impact that these two mechanisms, cross-layer based neighbor loss detection and neighbor position prediction, have on the performance of the GN protocol when used for communications with Internet. In this section, we study their interaction and propose their combination to enhance the GN protocol performance.

The cross-layer based neighbor loss detection mechanism avoids discarding packets when the greedy forwarding algorithm selects an unreachable neighbor as next-hop. When a packet is discarded at the MAC layer because the next-hop is not reachable (i.e., the MAC layer has tried to send the frame seven times without receiving an ACK), the MAC layer alerts the GN layer to erase the invalid neighbor information from the LT. In this way, packets may be routed through other available neighbors avoiding packet losses. In addition, a new feedback connection from the MAC layer to the GN layer has been introduced to avoid losing the packet after the seventh sending attempt. Hence, besides deleting the invalid neighbor information from the LT, the packet is re-injected in the GN layer to be forwarded again through another next-hop.

The neighbor position prediction mechanism follows the same idea, but it is applied at GN level. This algorithm tries to predict the current position of the neighbors present in the LT to select the next hop. The current position is calculated by means of a simple operation (it does not introduce noticeable complexity) taking the last position, speed and heading that are stored in the LT: assuming that vehicles move at constant speed, the current position is estimated calculating the shift of the vehicle between the time-stamp of the LT entry and the present [21]. This way, the greedy forwarding algorithm only considers neighbors that are predicted to be still inside of the radio coverage.

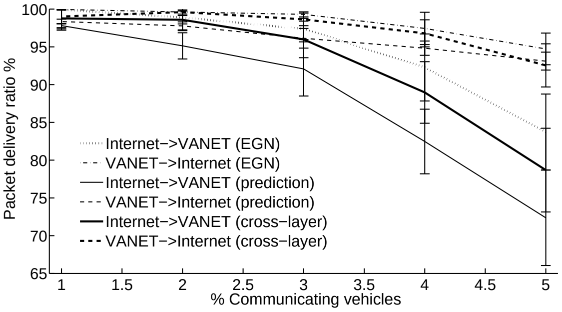

Figure 6. Packet delivery ratio of cross-layer neighbor loss detection, neighbor position prediction, and combination (EGN)

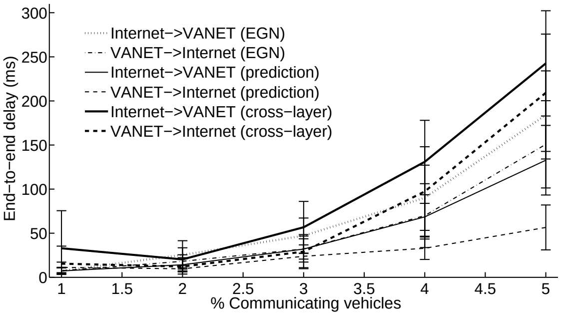

Figure 7. End-to-end delay of cross-layer neighbor loss detection, neighbor position prediction, and combination (EGN)

Since the cross-layer based neighbor loss detection and the neighbor position prediction mechanisms tackle the same problem following different approaches, we compare them separately, but also study their interaction. Figures 6 and 7 present the packet delivery ratio and the end-to-end delay of the CBR UDP flows measured in both directions (from the Internet to the VANET and vice versa) against the percentage of vehicles of the highway stretch that communicate with a CN. We first consider the application of the cross-layer based neighbor loss detection and the neighbor position prediction mechanism separately. In addition, we use an enhanced duplicate packet detection mechanism that considers the sequence numbers of all received packets to avoid discarding out-of-sequence packets as duplicates (a cause of non-negligible losses in the specification of the standard that only stores, for duplicate detection, the sequence number of the last received packet from each source). As mentioned above, the LT lifetime is set to 6 seconds. Since both mechanisms are complementary, we propose their combination to enhance the GN protocol performance. From now on, we will refer to this as the Enhanced GN (EGN) protocol (cross-layer based neighbor loss detection mechanism combined with neighbor position prediction plus enhanced duplicate packet detection mechanism), and its performance is also shown in Figures 6 and 7.

It can be seen that the cross-layer based neighbor loss detection is better than the neighbor position prediction in terms of packet delivery ratio whereas it is worse considering the end-to-end delay. The cross-layer based neighbor loss detection avoids discarding packets when the next-hop is not reachable, but the MAC layer tries to send a packet seven times before deleting the invalid next-hop from the LT. This increases the forwarding delay and the load in the wireless channel. The neighbor position prediction does not introduce extra delay in the forwarding, but it can fail in the prediction and loose packets forwarding them to invalid neighbors.

[‖] In [19] we studied the mobility management problem in VANETs. We adapted PMIPv6 to the multi-hop ETSI TC ITS architecture and we found that the performance of the GN protocol was not as expected, which is the motivation of this paper: To analyze in a systematic way the behavior of the protocol, its limitations and how to tackle them.

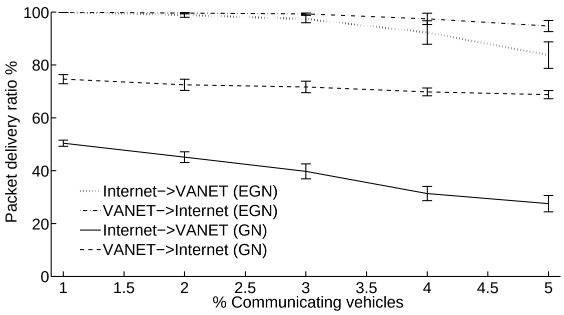

Figure 8. Packet delivery ratio (Enhanced GN and standard GN protocols)

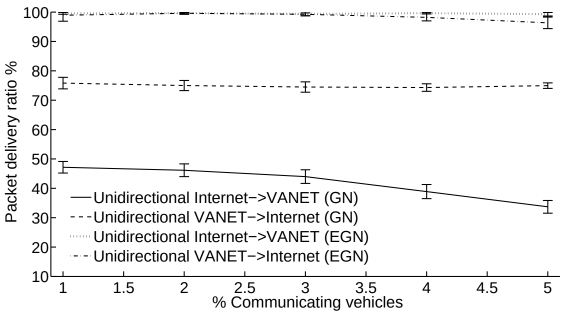

Figure 9. Packet delivery ratio for unidirectional flows

The combination of both mechanisms in EGN improves the packet delivery ratio. Regarding the end-to-end delay, EGN is between the cross-layer based neighbor loss detection and the neighbor position prediction. The neighbor position prediction serves as a first filter to discard invalid neighbors. This reduces the forwarding delay and the overload produced in the wireless channel by the cross-layer based neighbor loss detection (i.e., seven sending attempts at MAC layer before declaring a neighbor as unreachable). In case the neighbor position prediction fails, the problem is solved by the cross-layer based neighbor loss detection which deletes the invalid next-hop from the LT, although it introduces some extra delay.

Figure 8 shows the comparison of the packet delivery ratio achieved by the EGN and GN protocols as a function of the percentage of vehicles that communicate with a CN. The EGN protocol outperforms the standard GN protocol, reaching packet delivery ratio values close to 100% for both Internet-VANET and VANET-Internet flows when the percentage of vehicles communicating with a CN is low. However, the packet delivery ratio decreases when the percentage of vehicles communicating with a CN increases beyond 3%. There are several reasons for this: 1) The saturation of the RSU. The queuing time of packets in the MAC layer of the RSU increases with the percentage of vehicles communicating with a CN because the more traffic the RSU handles, the more times it has to compete for the wireless channel and, although the RSU concentrates all Internet traffic, it has the same opportunity of accessing the wireless channel than a vehicle. This makes the RSU to reach a state where packets are dropped because the MAC transmission queue is full. Nevertheless, the RSU can forward more amount of traffic running the EGN protocol because the combination of the cross-layer based neighbor loss detection and the neighbor position prediction mechanisms reduces the pernicious effect of selecting invalid neighbors as the next-hop (the selection of invalid neighbors contributes to the saturation of the RSU). 2) The problem of selecting unreachable neighbors as the next-hop is more critical when the data traffic in the network increases because the MAC layer tries to send each packet up to seven times before executing the cross-layer based neighbor loss detection mechanism. In saturation conditions, the cross-layer based neighbor loss detection has a double-edged sword effect. On the one hand, it helps to mitigate the problem of selecting invalid neighbors and protects against packet drops produced by continuous collisions in the wireless channel. This is because, in EGN, when a packet is dropped at MAC layer due to continuous collisions, it is re-injected again in the GN layer so the number of attempts to send the packet increases. On the other hand, the re-injection of the packet in EGN contributes to increase the data traffic in the wireless channel.

Regarding the performance of the EGN protocol as a function of the location of the RSU with respect to the vehicles of the VANET, the simulations revealed that the packet delivery ratio is similar for both phases, when communicating vehicles travel towards the RSU and when they move away from the RSU. The cross-layer based neighbor loss detection and the neighbor position prediction mechanisms avoid the above mentioned problem of discarding packets when the greedy forwarding algorithm selects invalid neighbors as next-hop that are not reachable, which is more pronounced when vehicles move away from the RSU.

4.3. Unidirectional data traffic

We have also studied the behavior of the standard GN and the EGN protocols when there exists only unidirectional data traffic from the Internet to the VANET or vice versa. This kind of traffic can be generated by real-time applications like video streaming or a VoIP conversation with silence suppression. Figure 9 presents the packet delivery ratio when data traffic is unidirectional from the vehicles of the VANET to the Internet, without data traffic sent from the Internet to the VANET in the simulation. The opposite case where data traffic is only directed from the Internet to the VANET is also shown in Figure 9. We have measured the packet delivery ratio as a function of the amount of vehicles that communicate with a CN considering the use of the standard GN protocol and the EGN protocol.

In the case data traffic is only sent from the VANET to the Internet, the packet delivery ratios for the standard GN and EGN protocols are logical considering the values obtained for bidirectional flows in previous analysis. Note that we have to be careful comparing the results of the simulations with unidirectional flows and bidirectional flows directly because the data traffic load conditions are different, indeed the packet delivery ratio slightly increases respect to the bidirectional case because the data traffic in the network is lower (half of bidirectional case). The EGN protocol obtains a packet delivery ratio close to 100% while the standard GN protocol achieves a packet delivery ratio around 76%.

The same can be said when data packets are only addressed from the Internet to the vehicles of the VANET without any data flow from the VANET to the Internet. The EGN protocol obtains a packet delivery ratio close to 100% while the standard GN protocol achieves a packet delivery ratio around 47% (best case).

4.4. Location Service Keep Alive mechanism

During the analysis of unidirectional data traffic we discovered an interesting issue: In the case data traffic is unidirectional from the Internet to the VANET, the LS mechanism generates noticeable network overhead because the RSU needs to discover the geographic position of each destination continuously. The RSU uses the geographic position of a destination stored in the LT until its LT entry expires. At that moment, the next data packet addressed towards the destination will trigger the LS mechanism again. This way, the RSU executes the LS every time the lifetime of a destination's LT entry expires. Note that when the traffic is bidirectional, the LS is not executed periodically because the traffic in the other direction keeps updating the position of the vehicle in the RSU, so the RSU always has an accurate knowledge of the position of communicating vehicles. Hence, the shorter LT lifetime, the higher network overhead produced by the broadcasting of LS request messages for each communicating vehicle. In addition, if the LT lifetime is short, the beaconing algorithm (or the geo-broadcasting of RAs) has to send control messages more frequently to update the nodes' LT, further increasing the network overhead.

On the contrary, if the LT lifetime is long, the network overhead is lower, but it is possible that the RSU routes packets to an old geographic position, where the destination is not reachable anymore because it has moved. This would cause forwarding errors until the destination's LT entry expires and the LS is executed again to discover the current destination's position.

Note that the above mentioned problems only occur in the scenario where the data traffic is only sent from the Internet to the VANET. In the reverse case, where the data traffic is issued only in the VANET to the Internet direction, the problem does not appear because the RSU is a fixed node, so vehicles, that send data packets to the RSU to reach the Internet, always know the RSU location accurately. Besides, the LT entry of the RSU in all vehicles is refreshed by the RA packets that the RSU geo-broadcasts periodically, so once vehicles discover the geographic position of the RSU, they do not need the LS to discover the RSU location.

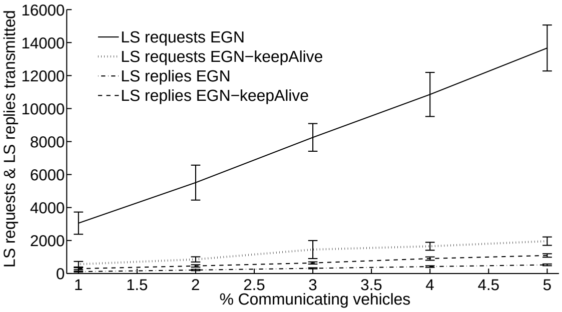

Figure 10. Number of LS request and LS reply messages transmitted Internet-VANET unidirectional flows (LT lifetime = 6 seconds)

We propose a Location Service keep alive mechanism that is useful for Internet-VANET unidirectional data flows to 1) mitigate the network overhead produced by the LS mechanism and 2) avoid possible forwarding errors produced by the use of obsolete destination position information.

The aim of this mechanism is to refresh in the RSU the location information of destination nodes. This is achieved by sending keep alive messages that update in the RSU the LT entries of vehicles that are communicating. The ETSI GN protocol already specifies a type of message that is perfect for this purpose: The LS reply that includes the geographic position of the source of the message and is sent by geo-unicast to the destination (the LS request uses broadcasting/flooding that consumes more resources in the wireless channel). The proposed LS keep alive mechanism works as follows. When a vehicle receives a data packet from the RSU it sets a keep alive timer. The vehicle sends a LS reply message every keep alive interval to update its LT entry in the RSU (we have set the keep alive interval to 3 seconds in our simulations). Thus the RSU can send data packets to the refreshed location of the vehicle. To avoid unnecessary overhead, if the vehicle sends any data packet to the RSU, the keep alive timer is reset because such data packet already updates the vehicle LT entry in the RSU. Moreover, if the vehicle stops receiving data packets from the RSU, the vehicle stops sending LS reply messages.

In order to compare the network overhead introduced by the LS keep alive mechanism, we have run simulations where data traffic is only sent from the Internet to the VANET. Figure 10 presents the number of LS request and reply messages that are transmitted considering the use of the EGN protocol. Results are presented for the cases when the LS keep alive mechanism is used or is not.

As it can be seen in the figure, the application of the LS keep alive mechanism reduces the network overhead that

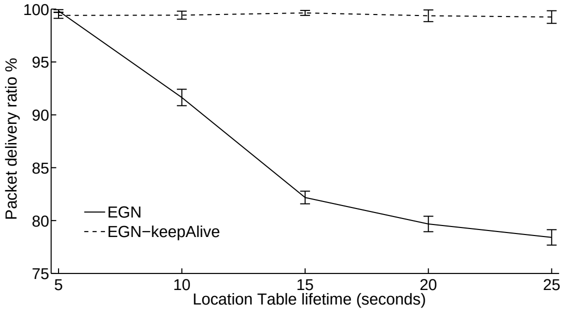

Figure 11. Packet delivery ratio Internet-VANET unidirectional flows (LS keep alive mechanism)

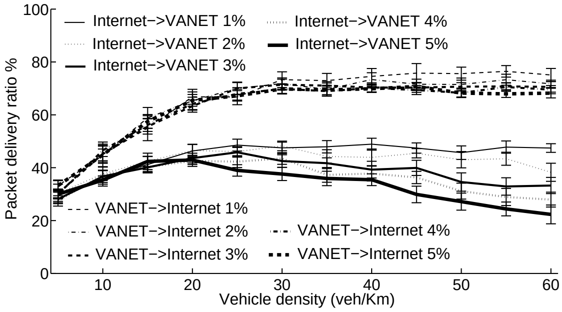

Figure 12. Packet delivery ratio standard GN protocol (vehicle density analysis)

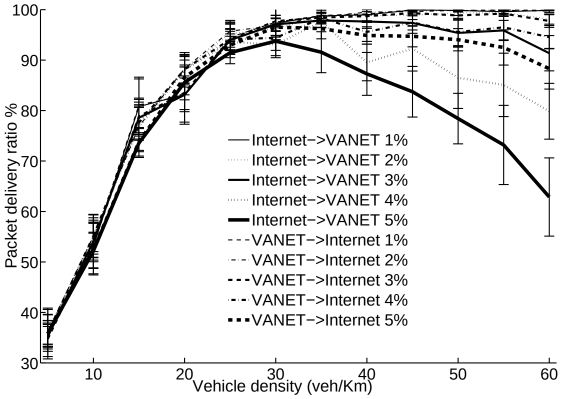

Figure 13. Packet delivery ratio Enhanced GN protocol (vehicle density analysis)

is produced by sending LS request messages every time a VANET destination's entry expires and it is erased from the RSU's LT. On the other hand, the overhead introduced by LS reply messages increases when the LS keep alive mechanism is used. However, note that LS requests are distributed by broadcasting/flooding which is costly for the wireless channel while LS replies are sent by geo-unicast.

Instead of using the LS keep alive mechanism, we could try to reduce the overhead of the LS request messages by extending the LT lifetime. However, this would not work because the RSU would send packets to an outdated geographic position, where the destination is not reachable anymore because it has moved, causing forwarding errors. This effect can be observed in Figure 11, which shows the packet delivery ratio with unidirectional data traffic from the Internet to the VANET as a function of LT lifetime. The results of the EGN protocol are shown when 3% of vehicles receive traffic from a CN. When the LS keep alive mechanism is not applied, the EGN protocol suffers a degradation of performance if the LT lifetime rises because destination LT entries are outdated.

The LS keep alive mechanism helps reducing network overhead, which is a critical issue in VANETs to obtain an appropriate performance, especially when a lot of vehicles try to communicate, jeopardizing the capacity in the VANET. In addition, the LS keep alive mechanism has to be applied in the case of having unidirectional data flows from the Internet to the vehicles of the VANET to avoid the RSU sending packets to an outdated destination position. From now on, we will also apply the proposed LS keep alive mechanism in the EGN protocol.

4.5. Vehicle density analysis

One of the parameters that have a significant influence on the performance of VANET protocols is the density of vehicles that travel through the road. In scenarios where the vehicle density is too low, the performance decreases due to disconnections between parts of the VANET. On the contrary, when the vehicle density is too high, a performance fall can also occur due to the collisions in the wireless channel caused by too many vehicles trying to transmit packets simultaneously. Figures 12 and 13 show the packet delivery ratio of bidirectional flows (Internet-VANET and VANET-Internet) as a function of the vehicle density on the road. Results are obtained for different percentage of vehicles communicating with a CN considering the use of the standard GN protocol (Figure 12) and the EGN protocol (Figure 13).

Regarding the behavior of the standard GN protocol with the density, we can observe that the packet delivery ratio has some dependence on the density of vehicles. This dependence is more remarkable in the VANET-Internet direction than in the Internet-VANET one. As explained before, an important amount of packet losses in the Internet-VANET direction is produced at the RSU because the GN protocol selects invalid neighbors as next-hops, so there is no a significant effect produced by the variation of the vehicle density because those packets are discarded in the first hop. On the contrary, the impact of the vehicle density on the packet delivery ratio in the VANET-Internet direction is more appreciable. The lower vehicle density, the smaller packet delivery ratio. If the vehicle density is low, the disconnections between parts of the VANET make impossible to form a multi-hop chain from the source vehicle to the RSU. The higher vehicle density, the greater probability of forming a multi-hop chain from the source to the destination. Thus, the packet delivery ratio continues increasing with the vehicle density until a bound where the connectivity from the source to the destination through the multi-hop chain is guaranteed, so a further increase in vehicle density does not bring additional benefits. However, for percentages of vehicles communicating with a CN above 3%, the packet delivery ratio falls with the vehicle density because the wireless channel is shared among more vehicles trying to communicate (more collisions). For the same reason, the higher percentage of vehicles communicating with a CN, the lower packet delivery ratio.

In the EGN protocol case, the packet delivery ratio in both, Internet-VANET and VANET-Internet directions, varies with vehicle density. The probability of forming a multi-hop chain from the source to the destination increases with the vehicle density. Hence, the greater density of vehicles, the higher packet delivery ratio. However, as in the standard GN protocol case, the higher percentage of vehicles communicating with a CN, the lower packet delivery ratio. Focusing on the cases of 3%, 4% and 5% of vehicles communicating with a CN in the Internet-VANET direction, the packet delivery ratio decreases when the vehicle density rises beyond a threshold. This is due to network congestion, specially in the RSU. The decrease is more apparent than in the GN case, because the EGN achieves better absolute performance so it uses more of the capacity of the VANET and congestion makes a bigger impact. However notice that RSU saturation is not a problem of the GeoNetworking layer itself, but a wireless capacity issue. Therefore the solutions to this congestion problem should be better addressed at layer 2 by increasing the effective capacity of the RSU.

4.6. Data traffic pattern analysis

This section analyzes the influence of the data traffic pattern on the performance of the EGN protocol. For this analysis, we only consider the EGN protocol because it clearly outperforms the performance of the standard GN protocol. We have considered the use of UDP and TCP transport protocols. In addition, to study the effect of RSU density, we analyze the results for the cases where the highway stretch that serves the RSU is 1000-meter and 2000-meter long.

4.6.1. UDP traffic

In order to study the influence of the UDP traffic pattern on the performance of the EGN protocol, we have varied the VoIP G.711-like UDP packet size and inter-arrival time maintaining the same traffic rate. We have considered 3 different bidirectional UDP Constant Bit Rate (CBR) patterns: 1) Packets sent every 20 milliseconds with a payload of 160 bytes, 2) packets sent every 40 milliseconds with a payload of 320 bytes and 3) packets sent every 60 milliseconds with a payload of 480 bytes. Figures 14 and 15 show the packet delivery ratio in the Internet-VANET and VANET-Internet UDP directions against the percentage of vehicles that are communicating with a CN. Figure 14 corresponds to the case where the highway stretch is 2000-meters long, whereas Figure 15 is the case of 1000 meters.

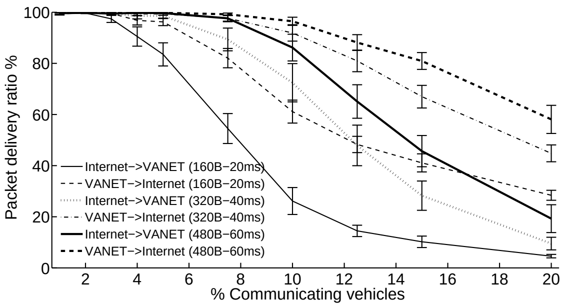

Figure 14. UDP traffic pattern density analysis (2000 meters)

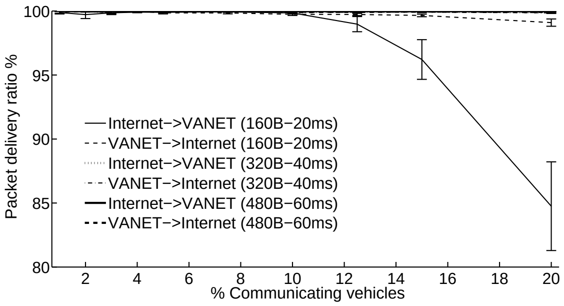

Figure 15. UDP traffic pattern density analysis (1000 meters)

Focusing on the 2000 meters case, we can see that the shorter interval between packets, the lower packet delivery ratio. A shorter inter-packet interval implies a higher number of transmissions in the wireless channel, which thus increases the probability of collision among frames. Although a bigger packet also increases the probability of collision, it can be seen in the figure that the inter-packet interval has more influence. On the other hand, the packet delivery ratio decreases with the percentage of communicating vehicles. As the network load rises, the collision probability increases, which degrades the performance. Collisions imply not only the loss of data packets, but also the incorrect refresh of neighbor information due to control packet losses, which entails even more performance degradation. In the worst case, the packet delivery ratio in the Internet-VANET direction is only 10%. The network overhead is extremely high and collisions make the communication impossible. Packets are dropped because MAC queues are saturated. However, this is a problem of available capacity in the VANET, not of the routing protocol itself.

When the RSU covers 1000 meters of highway, the number of hops from vehicles to the RSU is lower. Besides, the RSU serves fewer vehicles and thus, this entails lower congestion in the wireless channel. It can be observed in Figure 15 that EGN reaches a packet delivery ratio near to 100%, except when packets are sent each 20 ms. In that case, an abrupt fall of the performance is perceived in the Internet-VANET direction with the increase of communicating vehicles due to the congestion of the RSU transmission queue. Although this is not a problem of the routing protocol, we can conclude that capacity in the VANET is a serious limitation for a correct communication between vehicles and the RSU. This highlights the necessity of increasing the capacity in the wireless channel (enhancements in the access technology that would increase its capacity) or distributing the available capacity in a proper way to improve the communications by mean of congestion control mechanisms like the works that are being carried on by the ETSI [22, 23]. We are interested in analyzing the impact of congestion control mechanisms in future work.

4.6.2. TCP traffic

For the analysis of the behavior of the EGN protocol with TCP traffic, we have recreated a scenario where passengers are surfing the web. 100% of vehicles that enter into the simulation perform an HTTP transaction against a web server in the Internet at a certain moment. The instant in which vehicles start the HTTP transaction is uniformly distributed between the moment they enter the simulation until they exit the highway segment. The size of the HTTP GET message follows a normal distribution with mean 350 bytes and standard deviation of 20 bytes (the distribution is truncated to non-negative values). The size of the downloaded web page follows an exponential distribution with variable mean. This allows us to study the effect of bursty TCP traffic in the VANET, besides the previous experiments with CBR UDP traffic. However, when dealing with TCP, it does not make sense to talk about packet delivery ratio because TCP performs retransmissions when data do not reach the destination. Thus, we instead measure the download delay. This delay is measured from the moment the vehicle sends the HTTP GET message to the web server until it receives the web page completely (HTTP 200 OK)[**]. Figure 16 presents the download delay as a function of the web page size (mean of the exponential distribution) for the cases in which the RSU covers 1000 or 2000 meters of highway.

Results show that the download delay increases with the web page size. This is logical because a bigger web page implies more network traffic which produces higher transmissions delays. In addition, the download delay is longer when the RSU serves 2000 meters of highway. There are more hops from vehicles to the RSU, so the network overhead is greater and nodes have more difficulty to transmit packets in the wireless channel because of possible collisions. This is more relevant for the RSU because it concentrates all traffic of the highway stretch. Thus, RSUs should have higher priority to access the wireless channel than regular vehicles because they handle more traffic. We obtain download delays that would not offer an adequate user experience. As mentioned above, although it is not a problem of the routing protocol, some mechanisms are needed to improve and control the capacity of the VANET, such that a better communication between vehicles and the RSU can be provided.

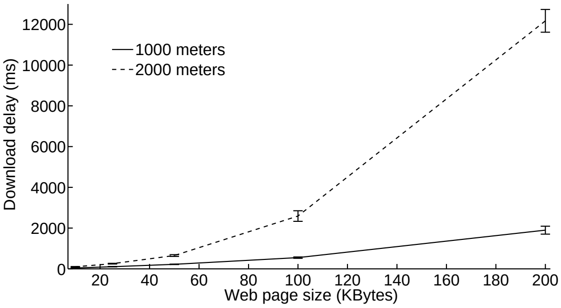

Figure 16. TCP traffic pattern density analysis

4.7. Evolution of the GeoNetworking protocol standard

The current version of the GN protocol standard is V1.1.1. A new version, V1.2.1 [24], is at the time of this writing, in the final stages of specification. The main modifications are:

- **Advanced geo-broadcasting:** A new advanced geo-broadcasting algorithm is introduced as default mechanism. Nevertheless, the distribution of packets within the destination area using simple flooding is still considered.
- **Packet data rate and geographical area size control:** In order to confront DoS attacks, nodes do not forward packets coming from neighbors that exceed an specified packet data rate or that send geo-broadcast packets to a large zone.
- **Protocol header changes:** beacon information, including the geographic position of the last forwarder, has been removed from GN protocol headers. This way, nodes cannot update neighbor information in their LT upon reception of every GN packet, but only when receiving beacon messages or single hop broadcast packets.
- **New duplicate packet detection algorithm:** the duplicate packet detection algorithm has been modified to consider the time stamp included in the packets. This modification does not solve the problem of discarding out-of-sequence packets as duplicates, mentioned in Section 4.2.

Next, we evaluate the impact of those modifications that can affect the connectivity of vehicles to the Internet: protocol header changes and the new duplicate packet detection algorithm. We have updated our implementation

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[**] Note that a browser usually issues different HTTP GET messages to different web servers. In order to simplify the simulation without affecting the goal of the analysis, vehicles send a single HTTP GET message.

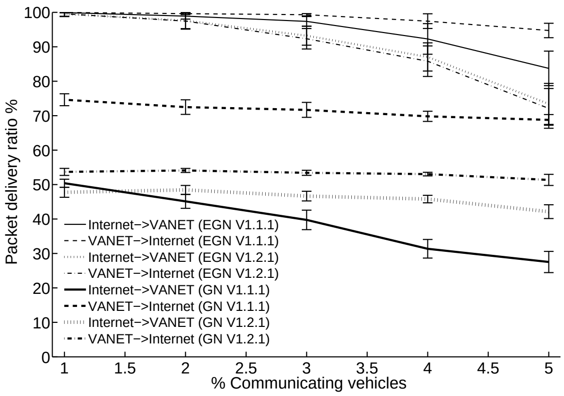

Figure 17. Packet delivery ratio V1.1.1 versus V1.2.1

following the draft of the new version of the protocol, V1.2.1.

Figure 17 shows the packet delivery ratio of the GN and EGN protocols as a function of the percentage of vehicles that communicate with a CN. Both versions of the standard, V1.1.1 and the new one V1.2.1, are considered. The LT lifetime is set to 6 seconds in all cases. Focusing on the GN protocol, V1.2.1 obtains better packet delivery ratio than V1.1.1 in the Internet-VANET direction, but it is lower in the VANET-Internet direction. We found the explanation to this behavior after a deep analysis of the results of the simulations. Due to the protocol header changes introduced in V1.2.1, nodes only update neighbor information in their LT when receiving beacon messages. In V1.1.1, nodes take benefit from the reception of any GN packet to update their LT instead, including the frequent reception of geo-unicast data packets. The limitation of information sources in V1.2.1 degrades neighbor information accuracy, which makes the packet delivery ratio decrease in the VANET-Internet direction, so packets are discarded before reaching neighbors located close to the RSU. This way, the collision probability in the wireless channel around the RSU is lower, so the RSU can forward higher amount of data traffic. This implies a higher packet delivery ratio in the Internet-VANET direction. On the other hand, the new duplicate packet detection algorithm does not produce any impact on the results of the simulations. As mentioned previously, out-of-sequence packets are still discarded because they are considered duplicates.

Regarding the EGN protocol, it can be seen that the limitation of information sources to update the LT in V1.2.1 produces a degradation of the packet delivery ratio in both, Internet-VANET and VANET-Internet flows.

From these results, we can conclude that removing beacon information from the protocol header (beacon piggybacking) produces a negative impact on the performance of communications of vehicles with Internet.

5. CONCLUSIONS

In this paper, we have thoroughly analyzed by means of simulation the performance of the ETSI TC ITS architecture and specifically the behavior of the GN protocol when providing Internet access from VANETs. We have identified sources of performance losses when using the standard GN protocol in communications with Internet. In addition, we have described mechanisms that can be applied to the GN protocol to enhance its behavior for this kind of communication. We have also studied the performance of the proposed enhancements to the GN protocol with simulations. The main conclusions that we extract from our analysis are:

- If the VANET is connected to the Internet, beaconing is automatically deactivated without causing any impact on the GN protocol performance due to its overlapping with the distribution of RA messages, needed for the vehicles to autoconfigure a global IPv6 address. RSUs periodically flood RA messages using geo-broadcast that update neighbours information in the Location Tables of the nodes. Therefore, in this scenario RAs play the role of beacon messages.
- Using the ETSI GN protocol as specified in [4] to provide Internet connectivity to vehicles of a VANET results in significant packets losses and long delays. Thus, there is room to improve its performance.
- Most packet losses are caused because the GN protocol selects neighbors as next-hops that are out of the radio coverage due to the long lifetime of the LT entries (neighbors are maintained in the LT for a long time, even when they are not reachable anymore).
- We have showed that a combination of cross-layer neighbor loss detection and neighbor position prediction mechanisms greatly improves the performance of the GN protocol.
- The RSU is prone to saturation when the percentage of vehicles communicating with a Correspondent Node (CN) in the Internet increases, which produces a degradation of the performance, especially in the Internet-VANET direction. The RSU is at a disadvantage in comparison with other vehicles because, although the RSU concentrates all Internet traffic, it has the same opportunity of accessing the wireless channel than a vehicle. This is not a specific problem of the GN protocol, but a limitation of the wireless communication technology, in our case IEEE 802.11g, although in practical terms it must be considered when using a VANET in communications with Internet. Also, in some situations the behavior of the GN protocol, such as when having excessive retransmissions because bad selection of neighbors, can worsen the situation.

- In general, VANET geographic routing protocols have a remarkable different performance when comparing the following situations: 1) Vehicles that communicate with a CN travel towards the RSU, or 2) vehicles that communicate with a CN move away from the RSU. The performance is better when communicating vehicles travel towards the RSU because of the lower probability of selecting an invalid next-hop. This could be taken into account when designing routing protocols for VANETs.
- In a VANET, a pattern of unidirectional data traffic in the Internet to VANET direction creates considerable control traffic overhead. This is due to the need of the RSU to do constant Location Service requests to locate the destination nodes of the traffic. We have proposed a Location Service (LS) keep alive mechanism that solves this problem, reducing the overhead without decreasing the performance.
- Our vehicle density analysis confirms that with a low vehicle density, the packet delivery ratio can be low, because the disconnections between parts of the VANET make impossible to form a multi-hop chain from the source to the destination. However, if the vehicle density is too high, the performance decreases due to the amount of vehicles trying to communicate and the resulting lack of capacity in the VANET.
- Our data traffic pattern analysis exposes that the capacity in the VANET is a significant limitation for a correct communication between vehicles and the RSU for certain patterns and amounts of traffic. There is a need for mechanisms that increase the capacity in the wireless channel or that distribute the available capacity in a proper way to improve the communications in the VANET.
- In our opinion, beacon information should be maintained inside GN protocol headers (beacon piggybacking) in the new version of the standard when it is used in communications with Internet. This allows nodes to obtain more accurate position information about their neighbors. Besides, since the beacon timer is reset whenever a GN packet is sent, network overhead introduced by the beaconing algorithm is reduced.

In the future we plan to analyze the performance of GN protocol when the Contention-Based Forwarding (CBF) algorithm is used instead of the greedy forwarding algorithm. In addition, in this paper we have assumed that every vehicle is willing to cooperate and forward the traffic of other vehicles, but in practice this may not happen. In the best case this could result in lower effective vehicular density, and in the worst case it could result in disturbances in the network behavior. We intend to study the problem of selfish, or even malicious, nodes in vehicular networks [25].

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