Evaluation of Broadcast Storm Mitigation Techniques on Vehicular Networks Enabled by WAVE or NDN

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Abstract. A vehicle in a vehicular ad-hoc network (VANET) can perform wireless broadcasting by flooding to find a route to a node or to send an emergency warning, for example. However, this is usually a very demanding operation because it may originate broadcast storms, with high impact on redundancy and collision of packets, as well as channel bandwidth waste. Diverse strategies have been proposed by the research community to mitigate the broadcast storm problems. To contribute to this important topic, this work evaluates on a simulation scenario the network performance of a VANET in terms of content delivery time, signal-to-interference-plus-noise ratio (SNIR) packet loss and duplicate packets, considering the use of broadcasting by flooding on two prominent network paradigms: wireless access in vehicular environment (WAVE) and named data networking (NDN). Afterwards, these network technologies are used to study two distinct strategies to mitigate the flooding problems. One strategy uses a counter-based scheme and the other a geographic location scheme. Simulation results show that both strategies are effective in mitigating the broadcast storm problems in terms of the considered metrics.

Keywords: Vehicular ad-hoc network (VANET) · Broadcast storm · Named data networking (NDN) · Wireless access in vehicular environment (WAVE)

1 Introduction

A vehicular ad-hoc network (VANET) is formed by vehicles equipped with one or more wireless communication devices, named on-board units (OBU). Vehicles can communicate one another without any infrastructure support, or with the infrastructure through a fixed road side unit (RSU), or with electronic devices able to connect to a VANET, such as smart-phones carried by pedestrians. Therefore, VANETs include vehicle-to-everything (V2X) communications, which is a collective name for vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P) communications. Vehicles can communicate directly if they are within signal range, or using multi-hop routes computed in a cooperative way through specific routing protocols. Since vehicles may move at high speeds along restricted and predictable road paths, VANETs

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have distinctive characteristics and communication requirements, such as, short contact time, connectivity disruption, and dynamic topology. Another characteristic of VANETs is the communication heterogeneity, as vehicles may have multiple interfaces with distinct wireless communication technologies, as discussed next.

Ideally, a vehicle should be able to choose the best technology or use multiple technologies in parallel to communicate with other nodes. The most prominent communication technologies for VANETs are currently the long term evolution - vehicle (LTE-V) [1], dedicated short-range communications (DSRC) [2], and intelligent transport systems - 5 GHz band (ITS-G5) [3]. LTE-V is a modified version of LTE [4] to provide the high speed, and low latency communications required by VANETs [5]. DSRC is a set of standards to allow short-to-medium range wireless communications with high data transmission in V2X environments. It is based on IEEE 802.11p and the IEEE 1609 family of standards, which constitute the key parts of the wireless access in vehicular environment (WAVE) protocol stack [6]. ITS-G5 is a V2X European wireless short-to-medium range communication technology for fast transmission of small size messages using the IEEE 802.11p. All those characteristics make VANETs a very challenging communication environment. Furthermore, named data networking (NDN) [7] is a recent communication architecture focused on content delivery by naming, which has been proposed as an alternative to the end-to-end connection paradigm of TCP/IP. Due to the viability of NDN becoming the future network paradigm, diverse works have been published on the use of NDN in VANETs environments [8].

Besides the communication technology to be used, the broadcast nature of the wireless communications should be also considered in order to optimize the communication performance in VANETs. A simple solution for wireless communication in VANETs is broadcasting by flooding. However, broadcasting has inherent drawbacks, namely unreliability due to its unacknowledged mode, increment of potential collisions in the wireless channel, packet redundancy, and channel bandwidth waste. Therefore, new strategies and/or mechanisms are required to control collisions and packet redundancy.

In light of such considerations, the goal of the present paper is the following. Firstly, a traffic scenario, based on a use-case, is deployed in a VANET simulator and then the network performance is evaluated in terms of content delivery time, signal-to-interference-plus-noise ratio (SNIR) lost packets, and duplicate packets, considering the use of broadcast by flooding in two distinct network paradigms: NDN, and DSRC/WAVE (hereafter named WAVE, for simplicity's sake). Afterwards, the VANET performance is evaluated for both NDN and WAVE using two distinct mitigation techniques against broadcast storm. One strategy uses a counter-based scheme and the other a geographic location scheme, as discussed later.

The rest of this paper is structured as follows: Sect. 2 presents an overview of the WAVE communication technology, NDN architecture, NDN in VANETs, as well as the relevant aspects regarding broadcast storm mitigation techniques, and the related work. Section 3 presents the two strategies evaluated in this paper to mitigate broadcast storm problems in VANETs; Sect. 4 introduces the connected ambulance use-case, and its implementation in the VANET simulator. Section 5 shows the results obtained in the simulated VANET scenario; Sect. 6 analyses these results; and, finally, Sect. 7 presents the conclusions and the future work.

2 Background and Related Work

The WAVE and NDN technologies are discussed generically next, as well as NDN enabled VANETs. A brief overview of the relevant aspects regarding broadcast storm mitigation techniques is also presented.

2.1 Communication Architecture for VANETs

The WAVE standard was designed to support public safety operations in V2X communication environments. It was developed to meet the short latency requirement for road safety messaging and control. The allocated spectrum is structured in 10 MHz wide channels, with one control channel (CCH) and multiple service channels (SCHs). The CCH is dedicated for safety communication with low latency and for initialization of regular communications. The SCHs are used for safety and non-safety exchange of data. The physical and medium access control (MAC) layers are defined by the IEEE 802.11p standard [6]. At scenarios with high densities of vehicles, the wireless channels can become very congested, which leads to a high probability of packet collisions. To prevent this phenomena, IEEE 802.11p uses the carrier sense multiple access/collision avoidance (CSMA/CA), combined with a random back-off procedure, to reduce packages collisions and to ensure latency and accuracy requirements of vehicle safety applications. Over the IEEE 802.11p plays the IEEE 1609.4 standard, which enables multi-channel operations without requiring knowledge of the physical layer parameters. Then comes the IEEE 1609.3 standard, which defines the network and transport layer services, including addressing and routing. It also defines the WAVE Short Messages Protocol (WSMP) to support secure data exchange without using IP addresses. WSMP supports high priority and time sensitive communications. IEEE 1609.3 specifies a maximum WSMP message size of 1400 bytes.

2.2 Named Data Networking Architecture

The communications in NDN involve the exchange of interest packets and data packets between consumers and producers. Basically, a consumer sends an interest packet to the network asking for a content and a data packet carrying the requested content is replied by a provider. No IP addresses are carried by these packets. Both the requested data and the replied data are identified by hierarchical names. The data packet contains the name, the content, and a signature. An interest packet is uniquely identified by the combination of name and nonce. The nonce is a random number used to detect looping interests. Data and interest packets are forwarded by the routers based only on the names. NDN also provides data muling, which allows a moving node to be a physical carrier of data packets. These nodes are called packet mules.

Three major data structures are present in the NDN routers: content store (CS), pending interest table (PIT), and forwarding information base (FIB). The CS is a temporary cache of data packets received by the router, and it is used to satisfy future interests. The PIT stores the names of all interest packets received by the router that were not still satisfied and the respective incoming interfaces (face, in NDN terminology). The PIT table is used to register the return path for possible data packets in response to the interests forwarded upstream. The data mules cache all data packets heard over a broadcast channel, even if there is no matching pending interest in the PIT. The interest lifetime field in the interest packet defines for how long the interest packet is hold in the PIT. The FIB stores information related with routing, namely the outgoing faces to forward the interests that match the longest name prefix. A name prefix in the FIB can have multiple output faces.

When a NDN router receives an interest packet, it checks firstly the CS in order to find the requested content. If this is cached in the CS, the router returns a data packet through the interface that received the interest. Else, the router checks the PIT for a matching record of the interest name. If the record exists in the PIT, it adds the incoming face of the interest to the record, and discards the packet. In the absence of a matching entry, a new record is created in the PIT, and then the FIB is checked to find out where the interest should be forwarded to. If no face is found in the FIB, then the interest is dropped and a negative acknowledgement (NACK) of the interest is sent to the downstream node. When a router receives interests for the same name from multiple downstream nodes, it forwards only the first interest upstream towards the data producer. When a data packet arrives to an NDN router, this finds the matching PIT entry and forwards the data to all downstream interfaces listed in that PIT entry. It then removes that PIT entry, and caches the data in the CS to satisfy future interests.

There are several cache placement strategies proposed in literature [9]. Leave copy everywhere (LCE) is the default cache placement policy used in the NDN architecture, whereby a data packet will be cached in all active routers between the producer and consumer, without any selection criterion. However, this simple scheme may produce significant cache redundancy. Moreover, due to the limitation of cache size, caches need a replacement policy, such as first-in-first-out (FIFO), least recently used (LRU), least frequently used (LFU), most frequently used (MFU), and most recently used (MRU). The replacement policies more used in NDN are LRU and LFU.

2.3 Named Data Networking in VANETs

Vehicular networking is a domain where the NDN architecture may offer diverse advantages over the TCP/IP architecture, such as reduced delay, robustness to disruptions, increased content availability, and content decoupling from producers. Although NDN can improve the connectivity, there are still a number of challenges to solve due to the variable network densities, network partitions (caused by vehicles being unable to send/forward packets to other subsequent vehicles), message redundancy, broadcast storms, security and privacy. As a car in vehicular NDN can play the role of producer, consumer, forwarder and data mule, the high mobility of the receiver and/or producer must be also considered carefully in the deployment of NDN over VANETs. It is claimed in [10] that, in the NDN-enabled VANETs, the packets are usually flooded, because there is no role for the FIB in these environments. As the cache size of vehicles is very large, the placement strategy usually adopted in VANETs is the LCE.

According to [11], modifications to the regular NDN operations are necessary for VANET environments. Instead of only accepting data with matching entries in PIT, a vehicle should cache all received data, in order to facilitate rapid data dissemination in highly dynamic environments. Vehicles should also serve as data mules in order to carry a copy of the content to other areas. Moreover, since it is very difficult to run a routing protocol to build and maintain the FIBs in a VANET, due to the high dynamics of connectivity among vehicles, other means to forward interest packets should be developed.

A few works have studied the performance of NDN over VANETs, such as [11, 12]. Although these works experimentally demonstrated the effectiveness of VANET via NDN with infrastructure support, no performance comparative study was conducted with host-centric networks. In [13], a comparison study for two connected vehicle systems powered by NDN and IP solutions, respectively, was conducted for image dissemination. The simulation results showed that the NDN may be effectively a promising alternative to the conventional IP networking.

2.4 Broadcast Storm Mitigation Techniques

In a traffic scenario with high density of vehicles, the wireless channel can become very congested, which leads to high probability of packet collisions and broadcast storms. Hence, strategies to mitigate these problems are required. As discussed in [14], there are a few schemes proposed to alleviate the broadcast storm problem, namely the (*i*) probabilistic, (*ii*) counter-based, and (*iii*) distance-based schemes. Basically, these schemes try to inhibit some hosts from rebroadcasting in order to reduce the redundancy and collision of packets.

The simplest way to reduce the number of rebroadcasts is to use probabilistic rebroadcasting. According to this method, after receiving a message, a host will rebroadcast it with a defined probability. The distance-based scheme measures the relative distance between hosts to decide whether a packet should be rebroadcast or not. It is based on the fact that when the distance between two cars is very small, there is little additional coverage provided by the rebroadcasting of one of those cars.

Another way is to use a counter-based scheme, as described in [14]. A defer time is calculated before each packet transmission, and if the same packet is overheard during the defer time a certain number of times, the transmission is canceled.

Other mechanisms have been proposed to decide which nodes should forward the packets in order to alleviate the broadcast storm problem. For instance, candidate forwarders could be the vehicles that have maximum connectivity time and good link quality with the consumer [15], or only the vehicles in the path towards the data producer, as discovered during a preliminary flooding stage [12]. A scheme based on hop counts to control the packet flooding/broadcast storms is proposed in [16]. As discussed in the next section, a broadcasting mechanism based on geographical location (geolocation) of the vehicles is also considered in this paper to reduce the broadcast storm problems.

A nonce is a random number that can be used just once in the network. Nonces may be used, for example, in cryptography and networking. Nonces are used in NDN to discard duplicate packets received over different paths [7]. As the nonce allows a packet being retransmitted by the intermediate nodes only once at most, then nonces may be used to reduce the number of (re)broadcast packets too.

The geolocation and the counter-based schemes will be evaluated in this work, as well as the effect in the network performance of the use of nonces.

3 Evaluated Strategies to Mitigate Broadcast Storms in VANETs

This work evaluates two strategies to mitigate the broadcast storm problems in VANETs enabled by WAVE and NDN: (*i*) the counter-based strategy; and (*ii*) the geolocation strategy. The effect in the network performance of the use these strategies with nonces is also evaluated.

The counter-based strategy was implemented following the algorithm proposed in [14]. Basically, as a host may hear multiple times the same message from other hosts before starting to transmit its message, a counter keeps track of the number of times the broadcast message is received during a certain time interval. If this counter reaches a predefined value, then the rebroadcasting is canceled.

The geolocation strategy is a broadcasting solution based on geographical location. According to this strategy, the producer and the consumer communicate each other using preferably the vehicles circulating on a set of roads connecting the producer and the consumer. In case of communication failure after a number of trials using the geolocation transmission mode, the packet is rebroadcast by flooding. The set of roads is chosen through an algorithm that takes into consideration, for example, the minimum distance between the producer and the consumer and/or the density of vehicles in the roads. By receiving an interest packet containing the GPS location of the consumer, the producer is able to define a list of contiguous roads and send this list in the data packet. In the same way, by receiving a data packet containing the GPS location of the producer, the consumer is able to define such list and send it in the interest packet. When the forwarder nodes receive a data/interest packet, only those located in the roads defined in the list are allowed to rebroadcast it. Otherwise, the forwarder node discards the received packet.

4 Connected Ambulance Use-Case

In order to evaluate the efficiency of the counter-based and geolocation strategies against broadcast storm, a use-case inspired on a connected ambulance care assistant was considered for this work, as described next.

During the trip of an ambulance transporting a patient to the hospital, the electronic equipment of the paramedics in the ambulance send patient's data, such as video images of patient's injuries and data of vital signs, to the health specialists in the hospital, allowing them to know more exactly the clinical health state of the patient carried in the ambulance. In this way, the first aids can be properly carried out in the ambulance, and when this vehicle arrives to the hospital everything is ready to receive the patient. The data is sent to the hospital through a wireless communication infrastructure. A similar use-case is considered in the SliceNet Project [17].

The consumer (receiver) of the content (hospital) is static and the producer (ambulance) is dynamic. Since NDN communications are driven by the consumers, in the NDN scenario the producer only sends a data packet after receiving the respective interest from the consumer. In the WAVE scenario, the ambulance only sends the data packet of sequence number n after receiving the ACK of the packet $n - 1$ from the hospital.

This work considers the transmission from the ambulance to the hospital of a certain number packets, each one containing a set of physiological signals of the patient, such as the electrocardiography (ECG), arterial pressure, oximetry, respiration rate, heart rate, and body temperature.

4.1 Use-Case Simulation

In order to evaluate the performance of the geolocation and counter-based strategies, it was considered a VANET with an ambulance able to provide the service described above. This scenario was implemented in a simulator. The simulation setup and the simulation test conditions are presented next.

Simulator. It was used the simulator Veins-4.7.1. This is a vehicular network simulation framework that couples the mobility simulator SUMO [18] with a wireless network simulator built on the discrete event simulator OMNeT++. Veins has a manager module to synchronize the mobility of the vehicles between the wireless network simulator and SUMO. Veins implements fully detailed models of IEEE 802.11p and IEEE 1609.4 DSRC/WAVE network layers, including multi-channel operation.

The simulator was programmed so that cars take diverse actions to help decrease the ambulance trip delay, as described next. The use-case was implemented over this functionality. During the trip, the OBU of the ambulance broadcasts periodically emergency warning messages using the WAVE short message protocol (WSMP) [19] over IEEE 802.11p. In each warning message is sent the current road and next $n - 1$ roads of the ambulance. For example, if the number of roads is equal to two, then the current road and the next road of the ambulance are sent in the message. Basically, when a car receives an emergency warning message from a nearby ambulance, it checks if the car is moving in the same direction of the ambulance. If this is true, and if the car is moving ahead the ambulance, then the car checks if the ambulance is not overtaking. If true and if the current road of the car is included in the set of ambulance next n roads, then the car tries to change lane to pull to the road side. If this is done with success, then the car stops until being passed by the ambulance. If the car and the ambulance are moving in crossing or opposite directions, then if the next junction is the same for the car and the ambulance, and if the car is near this junction, then the car stops at the end of the road to let the ambulance pass. The cars moving in the opposite direction of the ambulance also stop at the road end to make easier the flow of the cars moving ahead the ambulance. This helps to reduce the traffic volume ahead the ambulance. When the ambulance is overtaking, the cars rolling in the opposite road also tries to change lane and stop, in order to leave the road free to the ambulance.

If the RSU of a traffic light receives the emergency warning message from an ambulance, the traffic light switches as soon as possible to green in the direction of the emergency vehicle and to red to block the vehicles in the crossing directions. The signal keeps green while the ambulance does not pass through the traffic light. Once crossed by the ambulance, the traffic light runs the regular sequence loop of color light signals.

Road Grid. The simulation was carried on a road grid with seven horizontal roads and seven vertical roads, as shown in Fig. 1*a*. The length of each road is 200 m. To simulate the pull of the car to the side of the road in order to give way to the ambulance, the roads of the grid have two lanes, as shown in Fig. 1*b*. Although a map with two lanes in every road is not very representative of a city, where often only one lane exists, it should be noted that all cars in the simulation roll mostly on the internal lanes, and the external lanes are only used by cars to help free the internal lanes to the approaching ambulance. An ambulance never uses the external lanes. So, the external lanes are used to simulate the real situation of cars pulling to the side of the road to let the ambulance pass.

Routes. Along the simulation time, the ambulance follows a predefined closed pattern, covering most of the grid edges. After running a sinuous trajectory through 56 edges, which corresponds to a distance of 11.11 km, the ambulance reaches the start position, thus completing one cycle. Then, it starts another cycle, repeating again the same closed pattern route. This scheme continues until the simulation time is over. The routes of the cars were generated with the SUMO traffic generator (randomTrips.py). A route with a new traffic profile is generated every time a simulation is run.

Number of Vehicles. Simulations were run for 200, 400, 600, and 800 vehicles in the road grid. The ambulance started rolling and transmitting messages only when the stipulated number of vehicles was present in the road grid.

NDN. The essential aspects of the NDN architecture were implemented at Veins. The CS can store 1000 data packets, and the PIT 1000 interest packets. For simplicity's sake, LCE and FIFO were the strategies used for the cache placement and the cache replacement, respectively. As OBUs have only one face to receive and transmit packets, the FIB role was not considered in this work, just as in [11, 12, 20]. The mule strategy was also not implemented.

Communications. All vehicles had an OBU with IEEE 802.11p. The transmission power was 20 mW, which corresponds to a signal range of 530 m. The total length of the MAC frames containing the warning messages was 166 bytes. The service channel was not used, the simple path loss propagation model was used, and no buildings were considered in the simulation scenario. As Veins does not simulate acoustic signals, these were simulated using wireless communication messages. The cars able to "listen" the siren are those that receive such messages directly from the ambulance. It should be noted that the siren messages are always transmitted via WSMP, even when NDN is used in the VANET to access the producer's content.

Traffic Lights. Simulations were carried out with three traffic lights. One traffic light was placed exactly at the central junction of the grid and the other two at the junctions indicated in Fig. 1*a*. The traffic lights switch between red and green every 50 s. For simplicity, the yellow light was not used. The ambulance crosses twice each junction with traffic lights during a complete route cycle (Fig. 1*b*).

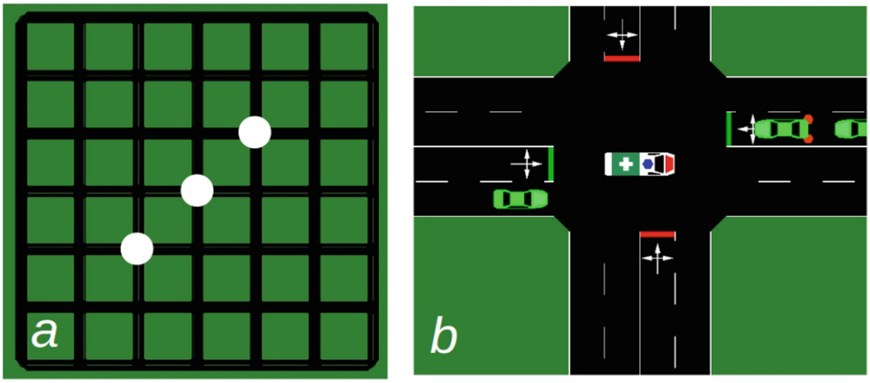

Fig. 1. (*a*) Road grid of size 7 × 7, with white dots marking the location of the traffic lights. (*b*) Ambulance crossing a junction with traffic lights. Note the two lanes per edge. (Color figure online)

Parameters. The values of the parameters used in the simulations are shown in Table 1. The simulation finishes when the consumer receives the full content from the producer. It is required 1000 packets to transmit the full content. Each packet carries an application payload of 100 bytes. This size is enough to contain a sample set of physiological signals of the patient, because the arterial pressure, oximetry, respiration rate, heart rate, and temperature are quantified by decimal values.

Table 1. Parameterization used in the simulated scenario.

Parameter	Value		Parameter	Value
road grid size	7 x 7		communication protocol	IEEE 802.11p
number of traffic lights	3		service channel (SCH)	unused
road length	200 m		MAC frame size	166 bytes
number of hundreds of vehicles	2, 4, 6, 8		application payload size	100 bytes
minimum car trip distance	2000 m		transmission data rate	18 Mbps
vehicle velocity	10 m/s		transmission power	20 mW
vehicle acceleration	3 m/s^2		time-to-live (TTL)	31
vehicle deceleration	10 m/s^2		data payload size	100 bytes
lane stay time	6 s		full content size	1000 packets
emergency warning period	0,2 s		CS size	1000 data packets
max. time for car to change lane	20 s		PIT size	1000 interests
time for car to send change lane mesgs.	3 s		PIT entry lifetime	1 s
change lane warning mesg. period	1 s		packet retransmission period	0,1 s
traffic light changing period	50 s		cache placement	LCE
number of ambulance roads (*n*)	2		cache replacement	FIFO

5 Simulation Results

The wireless communication performance was evaluated on the simulated emergency scenario considering the use of V2X communications in WAVE and NDN environments, combined with the use of the counter-based or geolocation strategies, as well as the nonces. The use of nonces means that every time the consumer or the producer needs to send a packet, a number is generated randomly by that node and sent in the packet. The results obtained for the content delivery time, the SNIR lost packets, and the duplicate packets are presented next. The results represent the average values of multiple simulations, each one with a different traffic profile. All results are relative to the content consumer (hospital). The number of cars in the road grid is constant along the simulation. The results were obtained considering respectively the presence of 200, 400, 600, and 800 cars on the road grid. As a guideline rule, the lower are the heights of the bars, the better is the communications performance of the VANET in terms of the considered metrics.

The bar graphics of Figs. 2, 3, 4, 5 and 6 show the results obtained for the proposed use-case, using both WAVE and NDN technologies. In all graphics, the x-axis contains the number of cars, and the y-axis the percentage values of the considered performance metrics. The meaning of the three bars obtained for each specific number of cars in the road grid is presented next.

The blue bar (at left) shows the content delivery time, which is the time required to receive the full content from the producer. It is expressed in a percentage relatively to a reference time, which is equal to the maximum content delivery time found in all simulations. Considering all 292 simulations carried out in this work (see Table 2), the maximum content delivery was equal to 1434,0 s, which occurred for a test in NDN with 600 cars, using the counter-based strategy with nonces. For example, if the blue bar indicates 40%, it means that the average content delivery time for this particular case was 1434,0 × 0,40 = 573,6 s. So, the content delivery time is calculated by:

$$content\,delivery\,time = delivTime/refTime * 100\% \tag{1}$$

where *delivTime* was the time required to deliver the full content from the producer to the consumer, and *refTime* is the reference time (1434,0 s).

The red bar (at middle) shows the average SNIR lost packets at the producer (*P*) and the consumer (*C*). This parameter reflects the number of collisions on the OBUs of both nodes, and may be used as an indirect indication of the bandwidth occupancy of the wireless channel, in that the higher is its value, the more occupied is the wireless channel used by both OBUs. The SNIR lost packets (%) is calculated by:

$$SNIR\,lost\,packets(\%) = (SNIRlostPkts(P) + SNIRlostPkts(C))/2 \tag{2}$$

where SNIRlostPkts(X) means “SNIR lost packets at X”, with X = {*P*, *C*} (*P* is the producer, *C* is the consumer), and is calculated by this expression:

$$SNIRlostPkts(X) = SNIRlostPkts(X)/(SNIRlostPkts(X) + recvdPkts(X)) * 100\% \tag{3}$$

where recvdPkts(X) means “received packets by X”, with X = {*P*, *C*}.

The orange bar (at right) shows the duplicate packets sent in average by the producer (data packets) and the consumer (ACK packets). Note that the value shown in the graph must be multiplied by four to get the real value of duplicate packets. The duplicate packets (%) is calculated by the expression:

$$duplicate\,packets(\%) = (duplPkts(P) + duplPkts(C))/2 \tag{4}$$

where *duplPkts*(X) means “duplicate packets sent by X”, with X = $\{P, C\}$, and is calculated by this expression:

$$duplPkts(X) = (nrSentPkts(X) - nrUniquePkts(X))/nrUniquePkts(X) * 100 \tag{5}$$

where nrSentPkts(X) is the number of packets sent by X and nrUniquePkts(X) is the number of unique packets sent by X, with X = $\{P, C\}$. The number of unique packets is equal to the number of packets used to transmit the full data content, which is equal to 1000 packets.

The meaning of the legends in the bar graphics is the following:

(i) *flood* means that all packets were sent in broadcast by flooding. This is obviously the transmission mode more susceptible to originate broadcast storms in the VANET.

(ii) *geoX* means that the flooding mode is used after X trials in geolocation mode without successful delivery of the packet to the destination node. This is valid to all packet types, i.e. interest, data, and acknowledgement packets. So, if $X > 1$, the first packet is sent in geolocation mode, as well as the eventual next $X - 1$ retransmissions of this packet, and the eventual retransmission number X is done in flooding mode. The eventual retransmission number $X + 1$ is done again in geolocation mode, restarting in this way the retransmission mode cycle. For example, *geo10* means one transmission in geolocation mode followed by nine eventual retransmissions in geolocation mode too, and then one eventual retransmission in flooding mode. Afterwards, the cycle restarts again.

(iii) *cntX* means that the counter-based strategy is used with a counter threshold equal to X for all types of messages (*i.e.*, data and interest packets in NDN, WSM and ACK packets in WAVE).

(iv) *non* means that a nonce is attributed to each packet sent by the producer or the consumer, so that a packet is retransmitted by the intermediate nodes only once at most. So, each packet has a sequence number and a nonce. If the consumer or the producer retransmits a packet, this packet is sent again with the same sequence number of its last transmission, and a new nonce.

Table 2 shows the number of simulations run, with distinct traffic profiles, for each type of transmission strategy with a specific number of cars. For example, fifteen simulations were run using geo10 with nonces (geo10 non) on a scenario with two hundred cars. A few simulations were run just a little number of times, or not run at all, because they require a very long time to finish. For example, a conventional laptop requires more than one month to run in WAVE the flooding strategy with 600 cars. In this very specific case, the results were linearly extrapolated from those obtained with the flooding strategy in WAVE using 200 and 400 cars.

Figures 2, 3, 4, 5 and 6 show the bar graphics of the average values obtained for the three evaluated metrics, which are discussed in the next section.

Table 2. Number of simulations run in WAVE and NDN for each transmission mode with a specific number of cars.

	WAVE					NDN			
	200	**400**	**600**	**800 cars**		**200**	**400**	**600**	**800 cars**
flood	1	1	0	0		1	1	1	0
flood non	3	0	0	0		1	0	0	0
cnt1	16	13	16	10		17	10	10	5
cnt1 non	11	4	2	3		10	4	2	1
geo10	14	10	5	4		14	10	10	12
geo10 non	15	10	10	4		10	10	9	2

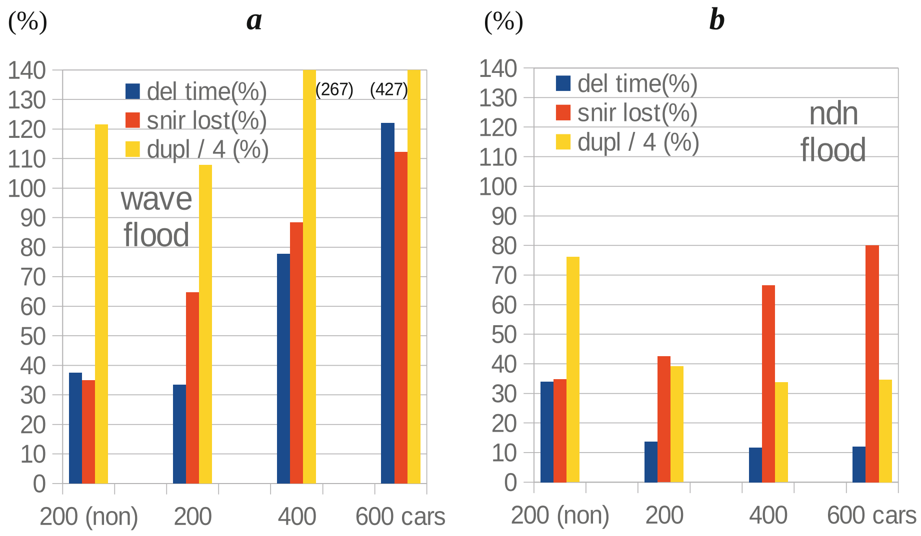

Fig. 2. Results for flooding in WAVE (*a*) and NDN (*b*), with nonces (non) for 200 cars, and without nonces for 200, 400 cars, and 600 cars. The results for WAVE with 600 cars were extrapolated. For WAVE with 400 and 600 cars, the *dupl/4* bar gets 267% and 427%, respectively. (Color figure online)

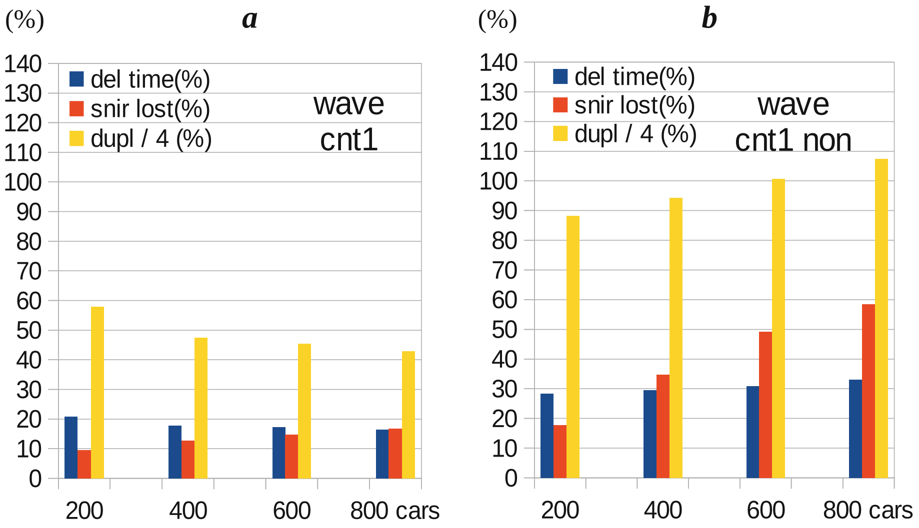

Fig. 3. Results for counter-based strategy in WAVE, with counter threshold equal to one (cnt1), without nonces (*a*), and with nonces (non) (*b*). (Color figure online)

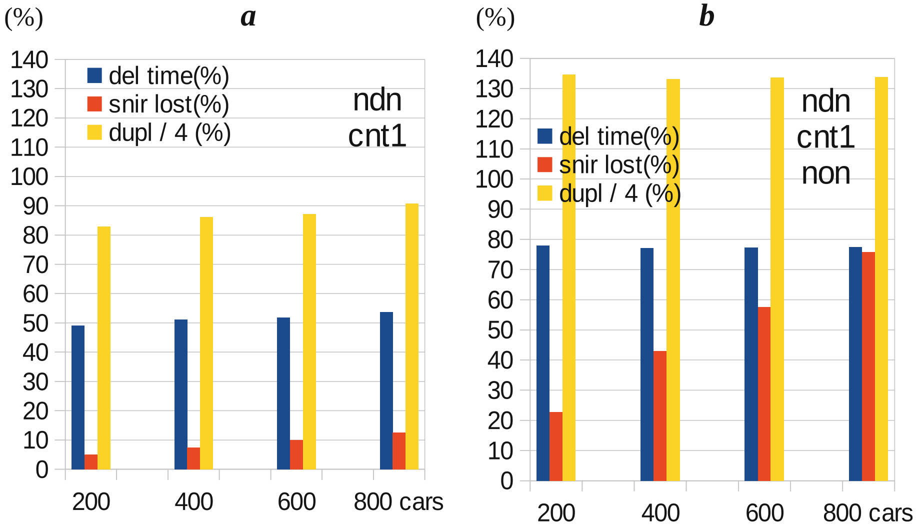

Fig. 4. Results for counter-based strategy in NDN, with counter threshold equal to one (cnt1), without nonces (*a*), and with nonces (non) (*b*). (Color figure online)

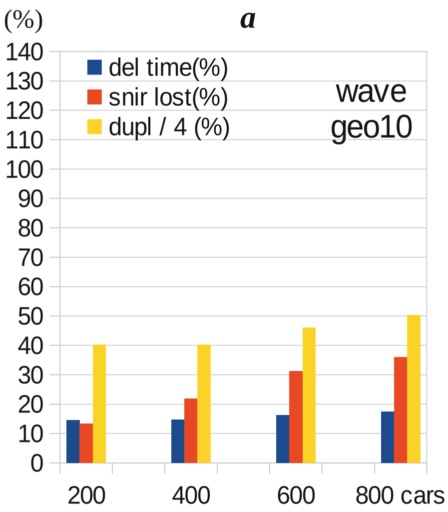

Fig. 5. Results for geolocation strategy in WAVE, without nonce (*a*), and with nonces (non) (*b*). Flooding is used after ten trials in geolocation mode without successful delivery of the packet to the destination node (geo10). (Color figure online)

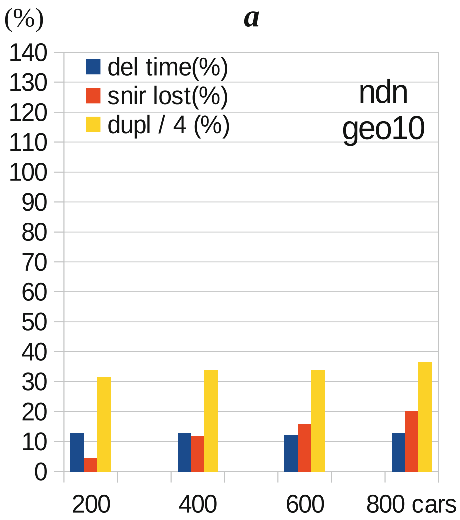

Fig. 6. Results for geolocation strategy in NDN, without nonces (*a*), and with nonces (non) (*b*). Flooding is used after ten trials in geolocation mode without successful delivery of the packet to the destination node (geo10). (Color figure online)

6 Analysis of the Results

The results obtained in the simulated VANET scenario for NDN and WAVE are discussed next. It is analyzed firstly the NDN results, and then the WAVE results.

When flooding is used in NDN without nonces (Fig. 2*b*), it is noted that the network performance, regarding the three considered metrics, was clearly better than that obtained with WAVE (Fig. 2*a*). This is justified by the operation of PIT in NDN. Indeed, all interest packets already registered in the PIT are discarded, because a similar interest packet has already been sent to the network. So, the number of broadcasts in the VANET becomes lower. Moreover, Fig. 2*b* (and Fig. 2*a*) shows that, when 200 cars are rolling in the road grid, the use of nonces in NDN (and WAVE) does not help to decrease neither the content delivery time nor the duplicate packets, comparatively to the situation where the nonces were not used. When nonces are not used, Fig. 2*b* shows that the SNIR lost packets increases considerably with the number of cars, which does not occur for the content delivery time and the duplicate packets. When compared with the flooding results, Fig. 6*a* shows that the use of geolocation strategy reduces considerably the SNIR lost packets, although the content delivery time and the duplicate packets do not change so considerably. Figure 4*a* shows that the use of the counter-based strategy in NDN presents a considerably higher content delivery time and duplicate packets when compared with the use of flooding and geolocation transmission schemes, but the SNIR lost packets is smaller than that obtained with these two schemes. Comparing Fig. 4*a* with Fig. 4*b*, it is noted that the use of nonces in the counter-based strategy increases clearly the SNIR lost packets, the content delivery time, and the duplicate packets. However, the use of nonces in the geolocation strategy (Fig. 6*b*) helps to decrease the SNIR lost packets, but increases considerably the content delivery time and the duplicate packets too, when compared with the geolocation strategy without nonces (Fig. 6*a*). So, the best global performance in NDN was obtained with the use of the geolocation strategy without nonces.

Let us analyze now the results obtained with WAVE. When flooding is used in WAVE without nonces (Fig. 2*a*), the content delivery time, the SNIR lost packets and the duplicate packets increase considerably with the number of cars. When the geolocation scheme is used without nonces, Figs. 5*a* and 6*a* shows that the most significant difference between WAVE and NDN is the SNIR lost packets, which is almost the double in WAVE than in NDN. The duplicate packets are also higher in WAVE than in NDN. In WAVE, the use of nonces in the geolocation scheme (Fig. 5*b*) helps to decrease the SNIR lost packets, but increases the content delivery time and increments considerably the duplicate packets, when compared with the geolocation without nonces (Fig. 5*a*). In WAVE, the use of the counter-based strategy revealed lower SNIR lost packets than the geolocation strategy. However, the counter-based and the geolocation strategies present similar performances in terms of content delivery time, specially when there are at least four hundred cars in the road grid. Once again, Figs. 5*a* and *b* show that the use of nonces on the geolocation scheme helps to decrease the SNIR lost packets, but increases the content delivery time and the duplicate packets, comparatively to the geolocation without nonces. Figure 3*b* shows that the use of nonces on the counter-based strategy deteriorated the performance of all parameters when compared with Fig. 3*a*, where nonces are not used. In WAVE, without nonces, the difference observed in the network performance between the counter-based and geolocation strategies is not so notorious as that observed in NDN. However, one may say that the best global performance in WAVE was obtained with the counter-based strategy without nonces, since it presents a significant smaller SNIR lost packets than the geolocation strategy. This is particularly true when there are at least four hundred cars rolling in the road grid.

Tables 3 and 4 summarize the analysis of the results for each broadcast strategy in the form of replies to the following questions. Table 3 answers to the question: "Using the considered transmission strategy, had NDN better performance than the WAVE in terms of content delivery time, SNIR lost packets, and duplicate packets?" Table 4 answers to the question: "For the WAVE/NDN technology, had the transmission strategy B globally better performance than the transmission strategy C in terms of the considered three metrics?" The meaning of the replies is the following: *Y* means "yes"; *YY* means "yes, considerably better"; *N* means "no"; *NN* means "no, considerably worst"; and ≈ means "almost equal", where "considerably" means a difference, in module, above twenty percentage points (pp). Table 4 is composed of two subtables: table A for WAVE, and table B for NDN. For example, table A indicates that, in WAVE, the geolocation strategy (geo10) performed worst (*N*) than the counter-based strategy (cnt1). Yet, table B indicates that, in NDN, geo10 performed considerably better (*YY*) than cnt1. Table 4 does not consider "flooding with nonces", because the results available for this case are limited to 200 cars in the road grid.

In summary, the best global performance was obtained in NDN with the geolocation strategy, {NDN geo10} (Fig. 6*a*), and in WAVE with counter-based strategy, {WAVE cnt1} (Fig. 3*a*), both without nonces. Comparing Fig. 3*a* with Fig. 6*a*, it is noted that the content delivery time was always lower in {NDN geo10}, with differences to {WAVE cnt1} between 3,5 pp and 8,1 pp. The duplicate packets was also always lower in {NDN geo10}, with differences to {WAVE cnt1} between 6,2 pp and 26,5 pp. The SNIR lost packets was lower in {NDN geo10} for 200 and 400 cars, but higher than {WAVE cnt1} for 600 and 800 cars, with differences, in module, below 5,1 pp. So, globally, the NDN with the geolocation strategy performed moderately better than the WAVE with counter-based strategy, in terms of the considered metrics.

Table 3. Summary of the results in the form of replies to the formulated question (*Y* = yes; *YY* = "yes, considerably better"; *N* = no; *NN* = "no, considerably worst"; ≈ = almost equal).

Had NDN better performance than WAVE ?			
transmission strategy	**content delivery time**	**SNIR lost packets**	**duplicate packets**
flooding	*YY*	*Y*	*YY*
counter	*NN*	*Y*	*NN*
counter with nonce	*NN*	*N*	*NN*
geolocation	*Y*	*Y*	*Y*
geolocation with nonce	*N*	*Y*	≈

Table 4. Summary of the results for WAVE (table A) and NDN (table B) in the form of replies to the formulated question (*Y* = yes; *YY* = "yes, considerably better"; *N* = no; *NN* = "no, considerably worst").

Had the transmission scheme at the column better performance than the scheme at the row ?										
WAVE						NDN				
table A	cnt1	cnt1 non	geo10	geo10 non		cnt1	cnt1 non	geo10	geo10 non	table B
flood	*NN*	*NN*	*NN*	*NN*		*Y*	*Y*	*NN*	*Y*	flood
cnt1	*	*YY*	*Y*	*Y*		*	*YY*	*NN*	*N*	cnt1
cnt1 non	*NN*	*	*NN*	*N*		*NN*	*	*NN*	*NN*	cnt1 non
geo10	*N*	*YY*	*	*Y*		*YY*	*YY*	*	*YY*	geo10

7 Conclusions and Future Work

In this paper, an evaluation study was conducted for two mitigation strategies against broadcast storm problems on a VANET enabled with NDN and WAVE technologies. For this goal, a connected ambulance care assistant was implemented on a vehicular simulated scenario. The results show that the best global performance in NDN was obtained with the use of the geolocation strategy without nonces. In WAVE the best global performance was obtained with the counter-based strategy without nonces, although the difference to the geolocation strategy is more contained than that observed in NDN. Globally, the geolocation strategy in NDN performed moderately better than the counter-based strategy in WAVE, regarding the considered three metrics.

The use of nonces in the geolocation and counter-based schemes tends to increase the content delivery time and the duplicate packets, and so they do not help to improve the global network performance. Comparatively to the broadcast by flooding, the results show that, in WAVE, the geolocation and counter-based strategies are effective in mitigating the broadcast storm problems in terms of the considered metrics. In NDN, the geolocation strategy is able to improve the network performance by reducing significantly the SNIR lost packets obtained with flooding.

This study was conducted for a specific use-case. The efficiency of the geolocation and counter-based strategies should be tested with other use-cases, including scenarios with a fraction of cars equipped with V2X communications, and different road configurations. The effect of the buildings along the roads on the radio signals should be also considered. Other strategies based, for example, on probabilities and distances should be evaluated too, as well as the use of different strategies operating together in a VANET scenario. These issues should be tackled in future work.

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References

1. Araniti, G., Campolo, C., Condoluci, M., Iera, A., Molinaro, A.: LTE for vehicular networking: a survey. IEEE Commun. Mag. **51**(5), 148–157 (2013)
2. Kenney J.: Dedicated short range communications (DSRC) standards in the United States. In: Proceedings of the IEEE, pp. 1162–1182 (2011)
3. ETSI Intelligent Transport Systems (ITS): European profile standard for the physical and medium access control layer of intelligent transport systems operating in the 5 GHz frequency band. ETSI Draft - ES 202 663 v1.1.0. European Telecommunication Standards Institute, Sophia Antipolis, France (2009)
4. Sesia, S., Toufik, I., Baker, M.: LTE: The UMTS Long Term Evolution. Wiley, Hoboken (2009)
5. Chen, S., et al.: Vehicle-to-everything (V2X) services supported by LTE-based systems and 5G. IEEE Commun. Stand. Mag. **1**(2), 70–76 (2017)
6. Weigle, M.: Standards: WAVE/DSRC/802.11p. Vehicular Networks CS, vol. 795, p. 895 (2008)
7. Zhang, L., et al.: Named data networking. ACM SIGCOMM Comput. Commun. Rev. (CCR) **44**, 66–73 (2014)
8. Liu, X., Li, Z., Yang, P., Dong, Y.: Information-centric mobile ad hoc networks and content routing: a survey. Ad Hoc Netw. **58**, 255–268 (2017)
9. Zhang, G., Li, Y., Lin, T.: Caching in information centric networking: a survey. Comput. Netw. **37**(16), 3128–3141 (2013)
10. Deng, G., Xie, X., Shi, L., Li, R.: Hybrid information forwarding in VANETs through named data networking. In: Proceedings of the 26th IEEE International Symposium on PIMRC, pp. 1940–1944 (2015)
11. Grassi, G., Pesavento, D., Pau, G., Vuyyuru, R., Wakikawa, R., Zhang, L.: VANET via named data networking. In: IEEE INFOCOM 2014 Workshops, pp. 410–415, April 2014
12. Amadeo, M., Campolo, C., Molinaro, A.: Enhancing content-centric networking for vehicular environments. Comput. Netw. **57**(16), 3222–3234 (2013)
13. Xu, X., Jiang, T., Pu, L., Qiu, T., Hu, Y.: A comparison study of connected vehicle systems between named data networking and IP. J. Internet Technol. **16**(2), 343–350 (2015)
14. Ni, S., Tseng, Y., Chen, Y., Sheu, J.: The broadcast storm problem in a mobile ad hoc network. Wirel. Netw. **8**(2/3), 153–167 (2002)
15. Ahmed, S.H., Bouk, S.H., Yaqub, M.A., Kim, D., Song, H.: DIFS: distributed interest forwarder selection in vehicular named data networks. IEEE Trans. Intell. Transp. Syst. **19**(9), 1–5 (2018)
16. Ahmed, S.H., Bouk, S.H., Yaqub, M.A., Kim, D., Song, H., Lloret, J.: CODIE: controlled data and interest evaluation in vehicular named data networks. IEEE Trans. Veh. Technol. **65**(6), 3954–3963 (2016)
17. SliceNet Project. https://slicenet.eu/5g-ehealth-smart-connected-ambulance-use-case. Accessed 15 June 2019
18. Krajzewicz, D., Erdmann, J., Behrisch, M., Bieker, L.: Recent development and applications of SUMO-simulation of urban mobility. Int. J. Adv. Syst. Meas. **5**(3–4), 128–138 (2012)
19. 1609.3-2010 - IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services, pp. 1–144 (2010)
20. Duarte, J.M., Braun, T., Villas, L.A.: Receiver mobility in vehicular named data networking. In: Proceedings of the Workshop on Mobility in the Evolving Internet Architecture (MobiArch 2017), pp. 43–48. ACM, New York (2017)