Computer Networks 213 (2022) 109086

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

G-3MRP: A game-theoretical multimedia multimetric map-aware routing protocol for vehicular ad hoc networks

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ARTICLE INFO

Keywords:
Vehicular ad hoc networks
Game theory
Video reporting service
Multimetric routing protocol

ABSTRACT

The particular requirements and special features of vehicular ad hoc networks (VANETs) (e.g., special mobility patterns, short link lifetimes, rapid topology changes) involve challenges for the research community. One of these challenges is the development of new routing protocols specially designed for VANETs. In this paper, we present a novel game-theoretical approach of a multimetric geographical routing protocol for VANETs to forward video-reporting messages in smart cities. Game theory is considered a very interesting theoretical framework to analyze and optimize resource allocation problems in digital communication scenarios. Our contribution has shown to enhance the overall performance of VANETs in urban scenarios, in terms of percentage of packet losses, average end-to-end packet delay and peak signal to noise ratio (PSNR).

1. Introduction

Vehicular ad hoc networks (VANETs) are a subset of mobile ad hoc networks (MANETs) [1] where nodes are vehicles. VANETs have been studied extensively in the literature during the last decade. The development of VANETs is highly motivated by a large number of interesting applications for intelligent transportation systems (ITS) [2]. In these networks, nodes are vehicles which can communicate with other vehicles directly forming vehicle-to-vehicle (V2V) communications or communicate with fixed equipment deployed along the road, referred to as road side unit (RSU), forming vehicle-to-infrastructure (V2I) communications.

V2V and V2I communications can provide a wide range of information to drivers and authorities. Smart connected vehicles have the ability to collect, process and send information about themselves and their environment to RSUs or to other neighbor vehicles in their transmission range by integrating on-board devices such as network interface, different types of sensors and GPS receivers [3]. VANET applications can be classified into:

- Safety applications: These applications use wireless communication between vehicles (V2V) or between vehicles and infrastructure (V2I) to improve road safety and avoid accidents. The main objectives are to save people's lives and provide a clean urban environment to improve the quality of life of citizens.
- Comfort applications: These applications aim to enhance traffic efficiency and mobility in the city. Furthermore, weather and traffic information can be provided to drivers and passengers so they can be alerted about bad whether or traffic jams.
- Entertainment applications: These applications aim to improve the comfort of drivers and passengers (e.g., making the journey more enjoyable). The nearest restaurant to the driver's location or a near hotel location and their prices can also be consulted. In addition, passengers can send or receive instant messages, play online games and access to the Internet.

The special requirements and characteristics of VANETs (e.g., special mobility patterns, short link lifetimes, rapid topology changes) generate challenges for the research community. One of these challenges is to provide promising multimedia services for smart cities, which requires to develop new routing protocols specially designed to provide those multimedia services over VANETs. In this work, a new proposal of a multimetric geographical routing protocol for VANETs to transmit video-reporting messages is presented. Our proposal considers several quality of service (QoS) metrics to select the best next forwarding vehicle for each packet in each hop towards the packet's destination. These metrics are properly weighted to obtain a multimetric score for each candidate vehicle in transmission range, so that the current forwarding node can take the best next hop forwarding

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https://doi.org/10.1016/j.comnet.2022.109086
Received 2 December 2021; Received in revised form 20 May 2022; Accepted 31 May 2022
Available online 7 June 2022

decision. In addition, the weights of the QoS metrics are self-configured. We have designed an algorithm to compute and update those weights throughout time so that candidate nodes would be better scored according to the current state of the environment. In this way, each time the forwarding algorithm needs to arrange nodes, a proper weight value for each metric will be updated so that the adaptive framework is able to self-configure.

Also, with the aim to attain realistic results, we include the presence of obstacles in real maps [4] so that each time a node is going to send a packet, a previous check is done to ensure that no obstacles are found between the current and the next forwarding node; otherwise, the packet would be dropped. This way, our forwarding algorithm is building-aware so that the current forwarding node can avoid vehicles behind buildings to be chosen as next forwarding nodes.

Recently, game theory is considered one of the most interesting theoretical framework to analyze and optimize resource allocation problems in digital communication scenarios [5]. For example, a shared wireless environment can be defined as a game where each node (each *player*) competes with the others for the access to the channel [6]. Besides, the effectiveness of the video transmission depends on how packets are routed and transmitted through the vehicular network, as it is shown in our proposal of a multi-metric map-aware routing protocol to transmit video messages over VANETs in urban scenarios [7]. For this purpose, we claim that game theory (GT) can notably improve the way that packets of video-reporting messages can be forwarded through VANETs aiming to improve the overall network performance.

Our research in this paper focuses on the deployment of an efficient geographical routing protocol based on a game-theoretical algorithm to forward video-reporting messages over VANETs. This contribution seeks to further enhance the overall performance of the vehicular network. As a starting point, we used our multimedia multimetric map-aware routing protocol (3MRP) introduced in [7], over which we develop our game-theoretical forwarding algorithm. Several performance metrics have been computed to illustrate the benefits of our protocol: average packet losses, average end-to-end delay and peak signal to noise ratio (PSNR).

Our main contributions in this manuscript can be summarized as follows:

- Firstly, we summarize our previous approaches (i) REVsim [4] and (ii) 3MRP [7] used in the proposal presented in this work. (i) REVsim is a tool able to analyze the presence of obstacles in a real map (e.g., obtained from OpenStreeMap [8]) so that it checks if two vehicles in transmission range can establish communication between them or not due to the presence of an obstacle. (ii) 3MRP is a multimedia multimetric map-aware routing protocol developed for VANETs that considers five metrics to select the best next node to forward video-reporting messages. Those metrics are computed from local data gathered by the periodical interchange (usually once per second) of hello messages between vehicles.
- Secondly, we present our new proposal named game-theoretical multimedia multimetric map-aware routing protocol (G-3MRP) specially designed considering the video features. Also, it includes a game-theoretical forwarding strategy according which video frames are transmitted over the vehicular network. The game-theoretical forwarding algorithm to take the next hop forwarding decision, has been designed from the inspiration in our previous proposal of a game-theoretical multipath routing protocol to provide video-warning messages in mobile ad hoc networks (MANETs) [9]. Now in this work we have developed a game-theoretical model taking into account the specific features of vehicular networks and considering only local information.
- Finally, we have carried out an extensive performance evaluation of our proposal compared to other similar proposals in realistic urban scenarios. Simulation results show the benefits of G-3MRP in terms of packet losses, packet delay and peak signal to noise ratio (PSNR), for different vehicles' densities.

1.1. Precedents

This manuscript includes two sections devoted to summaries of previously published work, plus a section derived from the first author's thesis. These three sections are necessary for understanding the manuscript and are the basis of the new proposal presented here. In Section 3 we summarize a tool named REVsim that we developed in [4] to include the presence of obstacles in our simulator to attain realistic results. In Section 4 we summarize our proposal multimedia multimetric map-aware routing protocol (3MRP) for vehicular networks that considers five metrics to score candidate nodes and be able to make forwarding decisions [7]. Section 5 is part of the Ph.D. thesis [10] of the first author not published in another manuscript. Sections 6–8 contain additional original contributions of this manuscript.

1.2. Organization

The remainder of the paper is organized as follows: Section 2 presents some related work. Then, Section 3 describes the operation of our REVsim tool to consider the presence of obstacles in realistic VANET simulations. Next, Section 4 summarizes our former proposal 3MRP [7] of a multimetric routing protocol for VANETs. After that, Section 5 presents our novel approach named game-theoretical multimedia multimetric map-aware routing protocol (G-3MRP), whereas Sections 6 and 7 explain the mathematical details of the game-theoretical forwarding model. Following, Section 8 shows a performance evaluation of our proposal. Finally, in Section 9 conclusions and future work are summarized.

2. Related work

Routing in VANETs is the process of selecting the best vehicle or vehicles in the vehicular network through which data will be forwarded towards destination. The best forwarding nodes are not necessarily the closest ones to destination, although they usually are selected using the shortest path. Similar proposals of routing protocols for vehicular ad hoc networks close to our work can be classified in two categories: (a) geographical routing protocols for VANETs; (b) routing protocols used to transmit video over VANETs; and (c) game-theoretical approaches of forwarding algorithms for VANETs. In the following we summarize some representative works related to our proposal in those three categories.

(a) Regarding geographical routing protocols, many proposals were designed in the last years for VANETs. The work in [11] shows that the best routing protocols for VANETs are based on the information of the instantaneous locations of nodes. Geographic unicast protocols for VANETs can be classified into three categories [12]: (i) greedy, (ii) opportunistic, and (iii) trajectory based. (i) The most common approach in VANETs is the greedy strategy where a node forwards packets to its closest neighbor to destination. (ii) Opportunistic strategies use the store-carry-and-forward technique to avoid dropping packets when no forwarding node is available. This strategy could incur high delays, which are not suitable for video-streaming of delay sensitive content. (iii) Using a trajectory-based strategy, a vehicle has more chances to be selected as a forwarding node if it is moving towards destination. On the other hand, greedy perimeter stateless routing (GPSR) [13] is a well-known geographic unicast protocol designed for VANETs with two different modes to forward packets: *greedy mode*, which is used by default, and *perimeter mode* used when it is not possible to use the greedy mode. Several proposals have been presented in the literature to improve the basic GPSR. Movement prediction routing (MOPR) in [14] improves the routing process of GPSR by including the link stability concept. That approach is one of the first research works that uses the link stability idea to choose the best forwarding node for unicast communications. Authors in [15] propose a modification of GPSR called greedy perimeter stateless routing with movement awareness (GPSR-MA), which exploits information about movement to improve the selection of the next forwarding vehicle. They use information about position, moving direction and speed to select the next forwarding node, improving GPSR. Authors in [16] present improvement GPSR (I-GPSR) that incorporates four metrics (distance to destination, vehicles' density, moving direction and vehicle speed) used to select the best forwarding node. In [17], authors present a proposal named multimetric map-aware routing protocol (MMMR) that uses four metrics in the process of selecting next forwarding nodes (distance to destination, vehicles' density, trajectory and available bandwidth). MMMR is map aware since it considers the possible presence of obstacles in a Manhattan scenario while looking for the next forwarding node. Conversely, our proposal is also building-aware but in a real map scenario taken from OpenStreetMaps [8]. In [18] we analyzed how buildings have an impact in the channel model of simulated VANETs in urban scenarios, since these obstacles may attenuate communications between vehicles. Finally, in [19], authors propose a position-based routing algorithm for VANETs called junction-based routing (JBR). The clue of this proposal is to make better use of the nodes located at junctions. A selective greedy forwarding is used in the routing protocol jointly with a recovery strategy. A novel minimum angle method is designed and used as a part of the recovery strategy.

(b) A few studies have been proposed about routing protocols specially designed to transmit video-streaming over VANETs. Authors in [20] presented LIAITHON, a location-aware multipath unicast scheme to transmit video over urban VANETs. Forwarding nodes are chosen depending on geographic advance, link stability and degree of closeness. LIAITHON finds out two relatively short paths with minimum route coupling effect using location information. Simulations show that LIAITHON improves the single path solution and the node-disjoint multipath solution. In addition, in [21], the authors present VIRTUS (VIdeo Reactive Tracking-based UnicaSt) to extend the duration of the decision of nodes to forward packets from a single transmission moment to a time window. Besides, that decision depends on a trade-off between link stability, vehicles' density and geographic information. In [22], authors propose a multipath solution for VANETs including link disjoint and node-disjoint schemes to provide a high quality video-streaming on VANETs. Due to the special features of VANETs and the large size of video data, extra interference and contention during the video-streaming are provoked by the redundancy of forward error correction (FEC) techniques. To cope with this issue, authors use TCP to transmit I-frames to ensure their transmissions and UDP to transmit P and B frames to reduce the delay of the transmissions. Furthermore, authors use node disjoint and link disjoint algorithms to further minimize delay by transmitting I-frames and inter-frames (P and B frames) through separate paths. Simulations show that the proposed multipath protocol provides a high video quality with an acceptable delay compared to other protocols. Authors in [7] proposed the multimedia multimetric map-aware routing protocol (3MRP) to send video-reporting messages over VANETs. Five weighed-metrics were designed and used to score each candidate node and then select the best next forwarding node to transmit each packet. These metrics are: (i) available bandwidth in the link established between source/forwarding node and each neighbor, (ii) trajectory, (iii) nodes' density, (iv) distance to destination and (v) percentage of MAC packet losses. In [23], a two-path video streaming algorithm is proposed based on node-disjointness. Seeking a high-quality video streaming service over VANETs, the video packet is split into different frames and sent through different paths. The primary route will transfer the intra-frames using TCP, and the secondary route will be in charge to send inter-frames using in this case UDP. Both routes are discovered using a combination of several QoS metrics and the discovery process is treated as an optimization problem. Ant colony optimization (ACO) is used to provide the solution of the aforementioned optimization problem. In [24], the distribution of video packets over multiple routes is formulated by the authors as an optimization problem that minimizes packet loss ratio (PLR) and frequent video playback freezing. Author's approach will help in achieving the reconstruction and playback of the video while maintaining needed QoS values. Simulation results support their proposal by obtaining enhancements in PLR, packet end-to-end delay, number of delivered video packets and freezing delay.

(c) During the last years, game theory was applied in several approaches to optimize video transmission through heterogeneous channels [25,26], or through ad hoc networks [9,27]. In this section, we report some of the most recent works that employ game theory, which has been recently an active topic in communications. Regarding these works, several distributed resource allocation strategies between multiple competing users were implemented using game theory. For example, authors in [25] propose an additive logarithmic weighting solution (ALOW) for balancing video delivery over heterogeneous networks. ALOW combines several metrics such as received signal power, network load, packet delay, user's equipment, and user's credit budget. Finally, ALOW is optimized using a cooperative game theory (GATH) approach. Experimental results show that ALOW together with GATH outperform several state of the art algorithms in terms of throughput, satisfaction index and overall video quality delivered. In [26], authors design a novel receiver-driven scheme, called Supcast, for video multicast in NOMA systems with heterogeneous channel conditions. Supcast consists of two-stage power allocation strategy as well as a near-optimal low-complexity algorithm for chunk scheduling. Simulation results show a better performance of Supcast compared to other existing schemes. Authors in [9] propose a game-theoretical multipath routing protocol to provide video-warning messages in MANETs. Author's contribution was concretely designed to prevent accidents in a smart city scenario. Simulation results show that our novel proposal based on a game-theoretical approach outperforms the case of non using that approach showing lower packet losses, average packet delay, and delay jitter. In [27], authors present a novel packet forwarding approach based on evolutionary game theory approach. Their approach imposes an incentive modeling to stimulate the cooperation between nodes over a MANET scenario. An exhaustive analysis has been made showing clearly the benefits of their work. To sum up, their proposal concludes that the reputation and trust-based game increases the utility of packet-forwarding strategy with high throughput and negligible network overhead.

(d) Additionally, some works in the literature show that game theory analysis can also be employed for load balancing purposes, such as [28], where the authors propose two game-theory based load-balancing schemes to improve the task offloading decisions in vehicular edge computing networks. The work [29] proposes a cooperative game theory approach which improves a multi-metric load balancing algorithm for mobile video service delivery over heterogeneous networks. They consider received signal power, network load, packet delay, among other metrics. In [30], authors propose game theory based decentralized learning algorithms for mobile-edge computing, to maintain the load balancing of the independent multiple cloud lets (i.e., mobility-enhanced small-scale cloud data centers located at the edge of the Internet) present in the network where mobile users perform offloading tasks randomly. Other interesting works also propose mechanisms for load-balancing, such as [31] that designs a multi-metric routing algorithm for wireless mesh networks which reduces collisions, protocol overhead, interference, energy consumption, better network organization and scalability.

In this work, we introduce a novel proposal of a game-theoretical forwarding algorithm specially designed to provide video services over vehicular networks. To the best of our knowledge, the development of an efficient geographical routing protocol based on a game-theoretical approach to efficiently forward video-reporting messages over VANETs doing load balancing, is novel.

3. REVsim operation

Considering the presence of obstacles in VANET simulations is an important issue to get realistic results in the performance evaluation of any novel proposal. In our proposal G-3MRP we include our tool REVsim [4] which is able to analyze the presence of obstacles in a real map in such a way that at each moment we can check if two vehicles are in the same transmission range and can establish communication between them or not (due to the presence of an obstacle) by checking the output file generated by REVsim. Our software REVsim depends on some parameters, such as road resolution, transmission range, Alpha and Beta parameters, to make its forwarding decision. Below we provide a brief explanation of each one of the designed parameters in the REVsim software, which are depicted in Fig. 1 over an area of the city of Barcelona.

- The "Alpha" parameter is designed to determine the maximum angle where vehicles in line X can still establish communication with vehicles in line Y.
- The "Beta" parameter is mainly used to compute the grade of curvature while passing to the following lines in the same road.
- The "Distance" parameter is used to improve the overall efficiency of REVsim operations. Based on the transmission range of nodes, this parameter will provide for every node, a list of neighboring nodes with which a communication could be established. In this way, all REVsim operations will be executed ONLY on those nodes found in the list.
- The "road resolution" parameter defines the number of discrete samples a line will be described with.

To sum up, REVsim software will generate an output file that will be used in our simulations to determine if two vehicles are in the same transmission range and can establish communication between them or not. We refer the reader to [4] for more details on how REVsim works and can be used during vehicular network simulations.

4. Multimedia multimetric map-aware routing protocol (3MRP)

Our previous proposal named multimedia multimetric map-aware routing protocol (3MRP) [7] takes the three aforementioned forwarding aspects (greedy, opportunistic and trajectory) into consideration to select the best next node to forward video-reporting messages over VANETs. In addition, we use realistic scenarios taking into consideration the presence of obstacles in real maps when selecting a forwarding node thanks to the REVsim tool, see Section 3. Five metrics to optimize the selection of the best next forwarding node are included in our proposal. These five metrics, periodically collected from the received hello messages (which are sent by default once per second) of the neighbor nodes, are:

- **Distance to destination** ($u_{dst,i}$): It is the distance between each candidate node i and the packet's destination.
- **Vehicle density** ($u_{dns,i}$): It is computed as the number of vehicles in the neighbor' list of each node i divided by $\pi \cdot TR_i^2$, being TR_i the transmission range of the candidate node i.
- **Trajectory** ($u_{trj,i}$): It is computed as a comparison of the current distance of a candidate node i to destination with a future distance between those same two nodes. This way, we detect if the candidate node is approaching or moving away from the destination.
- **Available bandwidth estimation (ABE)** ($u_{abe,i}$): ABE [32] is used to estimate the available bandwidth in the link formed between the current node holding the packet and each candidate node i.
- **MAC layer losses** ($u_{lss,i}$): Our routing protocol uses the packet losses computed at the MAC layer as a local feedback information regarding packet losses in the link formed between the current node holding the packet and each candidate node i.

This way, the vehicle currently holding the packet arranges the list of neighboring vehicles according to a multimetric score. This multimetric score is computed from the five routing metrics regarding each candidate node. 3MRP makes hop-by-hop forwarding decisions taking only this local information into account. Every node that has a packet to be sent, needs to select the optimal next forwarding node among the current list of neighbors.

Each vehicle updates its neighbors' list upon the reception of hello messages (HMs) from its neighbors within transmission range. Then, the node filters the list of candidates to be the next forwarding node using the REVsim tool to check if there are obstacles that interfere the communication witch each candidate node. After that, the node evaluates and assigns a multimetric score to each neighbor candidate to be the next forwarding node. As a first step, we assign the same weights (w_j, $1 \le j \le 5$) to each metric ($u_{dst,i}, u_{dns,i}, u_{trj,i}, u_{abe,i}, u_{lss,i}$), respectively in the multimetric score $\bar{u}_i$ of each neighbor i. Afterwards, we improve that fixed-weights scheme by including a dynamic weighing scheme in the computation of $\bar{u}_i$, which is summarized in Section 4.1.

$$\bar{u}_i = \sum_{j=1}^{5} u_{j,i} \cdot w_j = u_{dst,i} \cdot w_1 + u_{trj,i} \cdot w_2 + u_{dns,i} \cdot w_3 + u_{abe,i} \cdot w_4 + u_{lss,i} \cdot w_5 \quad (1)$$

We finally obtain a multimetric score for each candidate forwarding vehicle using Eq. (1). The final multimedia score takes values between zero and one (i.e., $0 < \bar{u}_i \le 1$). The neighbor with the highest multimetric value $\bar{u}_i$ will be selected as the best next forwarding node.

4.1. Dynamic self-configured weights (DSW)

As we have pointed out in the previous section, in Eq. (1) we have used two weighting schemes to compute a multimetric score from the combination of those five metrics: (i) fixed values $w_j = \frac{1}{5}$, $1 \le j \le 5$; and (ii) dynamic weights updated with an algorithm named dynamic self-configured weights (DSW), similarly as we did in [7]. Each time a node needs to forward a packet, that node arranges the nodes included in its neighbors' list (properly filtered using REVsim, see Section 3) from the best to the worst by computing a multimetric score using Eq. (1). In Eq. (1), the weights $w_1, w_2, \ldots, w_5$ are now computed by our algorithm DSW so that they are dynamically updated depending on the current state of the neighborhood scenario. The idea is to highlight those decisive metrics that can better help the node currently holding the packet (node S in Fig. 2) to choose the best next forwarding node among the vehicles in its neighbors' list.

We propose an algorithm to update the weights w_i dynamically and therefore re-calculate the multimetric score of neighbors $\bar{u}_i$ throughout time. The idea is that the most decisive metrics are highlighted (their weights increase) in front of the other not so determinant metrics. This way, if a metric value in a node differs significantly with respect to the average neighbors' value in that metric, we assign more importance (i.e., a higher weight) to that particular metric. To do so, we define

Fig. 1. Meaning of the parameters α, β and *road resolution* used in our REVsim [4] software to detect the presence of obstacles in vehicular network simulations using real maps.

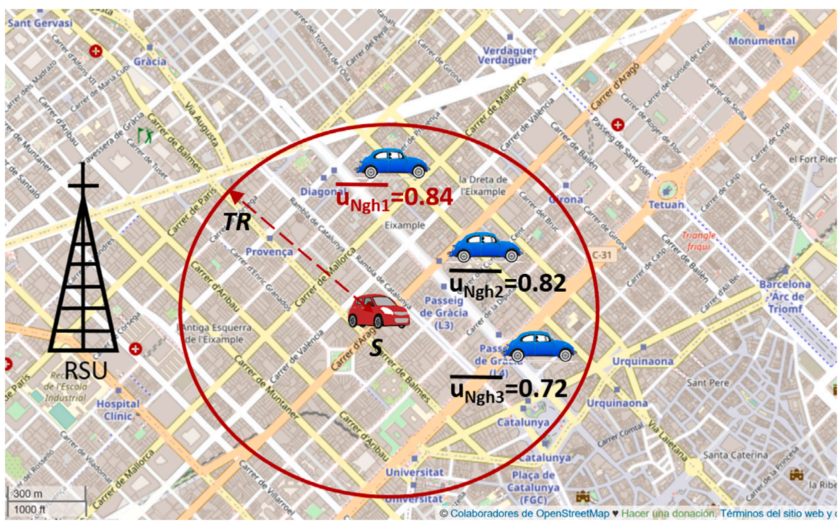


Fig. 2. The node S currently holding the packet takes a forwarding decision for that packet. Neighboring nodes within transmission range (TR) are arranged according to a multimetric score using Eq. (1).

as a decisive metric when the neighbor nodes show different values in that metric. This indicates that the value of such decisive metric could help the forwarding algorithm to better classify neighbor nodes. On the contrary, having a more constant metric value (i.e., all neighbor nodes have almost the same value in that metric) indicates that this metric should not be considered as decisive to sort the importance of neighbor nodes, thus our algorithm will give a lower value to the weight of that metric.

5. Our game-theoretical forwarding proposal included in G-3MRP

In this work we present a novel game-theoretical forwarding algorithm to further improve the performance of our previous proposal named multimedia multimetric map-aware routing protocol (3MRP) [7]. We follow a similar structure as we did in our previous proposal [9] of a game-theoretical multipath routing protocol to provide video-warning messages in mobile ad hoc networks (MANETs), which has inspired the methodology followed in this present work to develop a game-theoretical model taking into account the specific features of vehicular networks. The scenario considered is a multimedia service consisting of video reporting messages (e.g., about the traffic state or about a traffic incident in that road) transmitted from vehicles S to the closest RSU in an urban environment, see Fig. 2. Nodes S *play* a *routing game* to distribute each video packet seeking their own best performance. The *players* of the game are the VANET nodes and the *action* of the game is to select the proper next-hop forwarding node to forward their video-streams towards the closest RSU. Also, we assume that each node S selects up to three best neighboring nodes among the available nodes within transmission range. Those nodes are classified as best-quality node (B node), medium-quality node (M node), and worst-quality node (W node), through which the video frames will be sent. In this section we introduce our proposal of a game-theoretical forwarding algorithm included in our geographical routing protocol for VANETs. The new proposal is named **game-theoretical multimedia multimetric map-aware routing protocol (G-3MRP)** for VANETs.

5.1. Video reporting messages. Basic features

We assume that each vehicle S currently holding the packet (either the source node or any intermediate forwarding node) has a set of I, P and B video frames of an MPEG-based video flow to be transmitted towards the closest RSU. These three types of video frames are combined to form a group of pictures (GoP), e.g. 15 frames each. A GoP has three types of frames: I, P and B, and has a unique frame-pattern in a video repeated in each GoP. The video frames are encoded as follows: (i) Intra-coded pictures (I-pictures) that encode spatial redundancy,

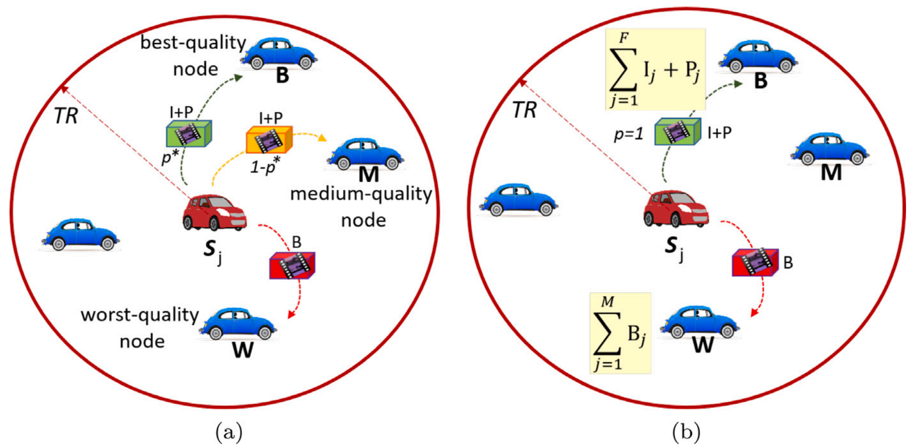


Fig. 3. (a) Proposed framework to send I+P+B video frames over the best three available forwarding nodes, which are arranged as *best-quality node* (B), *medium-quality node* (M) and *worst-quality node* (W). (b) In this case, all (I+P) frames are sent through the best-quality forwarding node (B).

form the base layer, they provide a basic video quality and carry the most important information for the decoding process at the receiving side. The whole GoP would be lost if the corresponding I frame was not available at decoding time; (ii) Predictive-coded pictures (P-pictures), which carry differential information from preceding frames; and (iii) Bidirectionally-predictive-coded pictures (B-pictures), which carry differential information from preceding and posterior (B) frames.

We have assigned different priorities for the video frames considering their importance within the video flow and their relative importance in the de-codification process. Thus, I frames will have the highest priority, P frames the medium priority and B frames the lowest priority.

5.2. Basics of our game-theoretical forwarding algorithm

In this section we describe the basics of our game-theoretical forwarding algorithm, using a simple scheme represented in Figs. 3 and 4 to explain the proposed architecture of our proposal. We assume there are N source nodes S_j, $1 \leq j \leq N$, that send each one a video reporting message to the closest RSU, see Fig. 2. It is important to highlight that it is likewise possible to apply the same forwarding scheme in any VANET, independently of the number of connections and nodes. We assume that the node currently holding a packet has three possible forwarding nodes at stake, arranged as the best-quality node (B), the medium-quality node (M) and the worst-quality node (W), see Fig. 3(a). Nodes S_j distribute their I–P–B video frames over those available forwarding nodes considering the importance of each video frame in the performance of the decoded video at destination. This way, video flows are distributed over several forwarding nodes, thus balancing the load over the VANET, which helps to improve the performance of the vehicular network. Note that the best performance of our game-theoretical forwarding algorithm assumes there are three available forwarding nodes, although it also adapts to other circumstances when there are only two available nodes (I+P video frames would be sent through the best-quality node and B video frames through the worst-quality node), or when there are only one available node (I+P+B video frames would be sent through that node) or even using store & forward operation in case node S_j has no neighbor in that moment.

By default, nodes always would try to send the most important video frames (i.e., I frames) through the best available node found by G-3MRP. This means that I frames, which are the biggest ones and carry the most important video information, would be sent through the best-quality forwarding node (B); P frames would be sent through the medium-quality node (M); whereas the least important frames (i.e., B frames) would be sent through the worst-quality node (W). Nevertheless, if each node were to send the most important frames through the best-quality forwarding node (B), this node could become congested. As a consequence, that best-quality forwarding node could suffer more losses than the others, which would lead to classify it as a worse node. This behavior could produce an oscillatory performance that might affect the video experience of users if it happened frequently.

To cope with this issue, alternatively $players$ (S) could *play a forwarding game* such that the best two nodes (excellent, good) are at stake to be chosen by each player over which the player will transmit the most important video frames (i.e., I+P frames). Accordingly, each player could sometimes transmit the most important I+P frames through the good-quality node. For the sake of simplicity, in this work we consider that B frames are always sent through the bad-quality node. Additionally, I and P frames of a same video stream will be sent together through the same node to highlight the effects of our forwarding strategy. The reason is that there are more P frames than I frames per flow. We follow an equivalent design as we did in our proposal 3MRP for mobile ad hoc networks (MANETs) [7]. In this work, we focus on the specific design of our game-theoretical forwarding algorithm for VANETs.

When a node S_j has a packet to be sent, it $plays$ our forwarding game to select the next forwarding nodes to transmit its video flows. Each node S_j sends its I+P video frames through the best available node (B) with a certain probability p and through the medium-quality node (M) with a probability $1 - p$. The idea behind this strategy is that nodes prefer to send their video frames through not heavily used forwarding nodes to have better performance. As it is shown in Figs. 3(b), 4(a) and 4(b), we have three possible cases:

(i) Without playing the game, all users would always send the most important video frames (i.e., I+P) through the best-quality (B) forwarding node (Fig. 3(b)).
(ii) Alternatively, they could play our game-theoretical forwarding algorithm. Notice that the case shown in Fig. 4(a) is worse than the one shown in Fig. 3(b) for all N users, since they are sending their I+P frames together and through the medium-quality node (M) instead of through the best-quality node (B). This case should not happen often.
(iii) In the third case (Fig. 4(b)), I+P frames will be sent through the best-quality available forwarding node by each user with a certain probability p, and through the medium-quality forwarding node with a probability $1 - p$.

Notice that $players$ (i.e., vehicles currently holding a packet to be forwarded towards its destination) must decide their strategies (i.e., their corresponding p value) simultaneously and without communicating with each other. Let F be the total number of I+P frames to be sent through the forwarding scheme depicted in Fig. 4(b). Depending

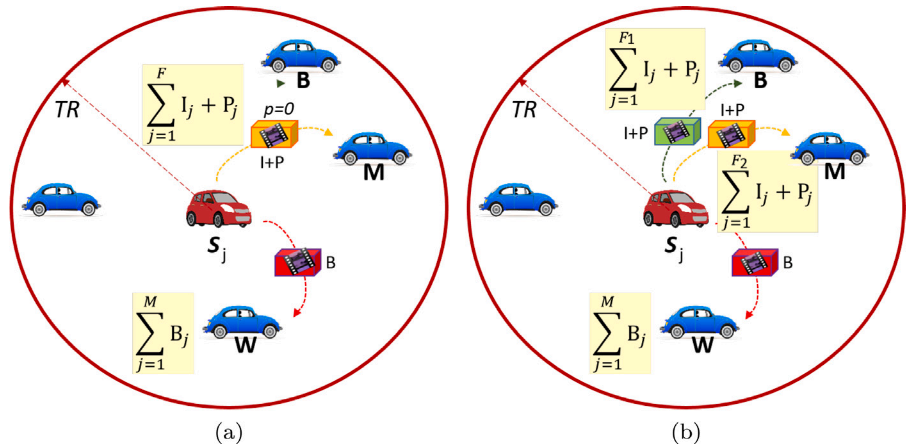


Fig. 4. (a) In this case, all I+P frames are sent through the medium-quality forwarding node (M). (b) Using our game-theoretical strategy, I+P frames will be sent through the excellent forwarding vehicle with a certain probability p and through the good-quality forwarding vehicle with a probability 1-p. F_1 and F_2 are the number of (I+P) frames sent through the excellent forwarding node and through the good-quality forwarding node, respectively. F is the total number of video frames to be transmitted, being $F = F_1 + F_2$.

on the p value, a number of I+P frames equal to F_1 will be sent through the best-quality forwarding node (B) and a number of I+P frames equal to F_2 will be sent through the medium-quality node (M), being $F = F_1 + F_2$. M represents the total number of B frames to be sent, always through the worst-quality node (W), see Fig. 4(b).

Note that, in our considered scenario, it could happen that several nearby source vehicles, which periodically send video-reporting messages to the nearest road side unit, use some common forwarding vehicles along the path towards destination. For that reason, their forwarding decisions can affect each other. Forwarding vehicles arrange their candidate neighboring vehicles according to five metrics (distance to destination, vehicle's trajectory, vehicles' density, available bandwidth and MAC layer losses). So it might happen that two close vehicles arrange in the same order their candidate next-hop forwarding nodes, and thus they make the same forwarding decision, i.e. they choose the same next hop forwarding node. Alternatively, using our proposal vehicles will consider the two best candidates at stake and choose one or the other with a certain probability computed with our game-theoretical forwarding game. We depict an example of this in Section 8.2, see Fig. 6. As a consequence, that load balancing effect will improve the whole network performance.

In the next section we will compute an optimal probability p_i^* for each vehicle currently holding a packet to be forwarded towards its destination. That probability p_i^* is the probability of sending I+P frames through the best-quality node, so that this p_i^* value produces the best outcome for that *player*.

6. Design of the game-theoretical forwarding scheme for video-reporting messages in VANETs

As a general rule, a *game* can be described by means of the *players* participating in that game, a set of *strategies* for those players, and a specific set of *payoffs* for each combination of strategies. Let S be a finite set of N players $1, \dots, N$. Each player i has a finite set of possible actions A_i. Let $a_i \in A_i$ be one of the actions chosen by player i. The action space, named as A, is the Cartesian product of all A_i, i.e., $A = A_1 \times A_2 \times \cdots A_N$. An N-tuple action, referred as a, is a specific point in the action space A. A *pure strategy* gives a full definition of how a player will play a game. Specifically, a pure strategy determines the action a player will make for any possible situation. A *mixed strategy* of player i, α_i, is a given probability, $p_i \in P = [0, 1]$, regarding each pure strategy. According to that probability, players select their strategy among the set of pure strategies. Let $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_N)$ be the mixed strategy profile, then the probability that a particular N-tuple action $a = (a_1, a_2, \dots, a_N)$ happens, $p(a)$, is computed from the product of the probabilities assigned to a by α.

Let u_i be the *utility function* of player i in the strategic form game regarding each stage. The utility function is a mathematical description of preferences to map the action space to a set of real numbers. A utility function for a given player designates a real number regarding every possible outcome of the game. Consequently, a higher number implies that the outcome is better.

$$u_i : A \rightarrow R, \quad 1 \le i \le N \tag{2}$$

$U_i(\alpha)$ is the expected utility for player i for the mixed strategy profile α:

$$U_i(\alpha) \equiv \sum_{a \in A} p_a \cdot u_i(a) \tag{3}$$

Using three primary components we can define a strategic game G: the set of players S, the action space A, and the set of individual utility functions for each player i, u_i.

$$G = (S, A, u_i) \tag{4}$$

Eq. (5) gives a mixed strategies extension to G, where U_i is the set of all expected utilities to i and $\Delta(A_i)$ is the set of all probability distributions over A_i.

$$G' = (S, \Delta(A_i), U_i) \tag{5}$$

A *best response* is a strategy that produces the most favorable result for a player considering other players' strategies as known. A *Nash Equilibrium* (NE) [33] is a solution so that each player plays a best response to the strategies of other players. Each player is assumed to know the strategies of the other players. Moreover, no player has incentive to unilaterally change their current strategy while the other players maintain theirs unchanged. Players are in equilibrium when a change in strategies by any one of them would produce that player to have a worst outcome than if they remained with their current strategy. It is a mathematical fact that every mixed extension of a strategic game has at least one *mixed strategy Nash equilibrium* [33].

In order to define best responses in general, we need a notation et of strategies to be used by all players other than player i, known as α_{-i}:

$$\alpha_{-i} = (\alpha_1, \dots, \alpha_{i-1}, \alpha_{i+1}, \dots, \alpha_N) \tag{6}$$

Strategy α_i^* is a best response for player i to the strategies of all players except i, α_{-i}^*, if:

$$U_i(\alpha_i^*, \alpha_{-i}^*) \ge U_i(\alpha_i, \alpha_{-i}^*), \quad \forall\ \alpha_i \in \Delta(A_i) \tag{7}$$

This means that if α_i^* is a best response for player i to the assumed set of strategies α_{-i}^* played by the other *N-1* players, then it will produce player i a payoff at least as high as the payoff the player would obtain if they selected any other strategy α_i from their set of available strategies. Evenly, a best response (BR) correspondence to player i is given by:

$$\alpha_i^* \in BR_i(\alpha_{-i}) = argmax_{\alpha_i \in \Delta(A_i)} U_i(\alpha_i, \alpha_{-i}) \tag{8}$$

Let us remark that $argmax_x F(x)$ is the value of x for which $F(x)$ has the largest value. A joint strategy $\alpha^* = (\alpha_1^*, \dots, \alpha_N^*)$ is a NE if, for each player i, α_i^* is a best response to α_{-i}^*.

Recall that every finite game has Nash equilibria in either mixed or pure strategies [34,35].

6.1. Benefit for a node that transmits I+P video frames

Let us start defining a parameter that evaluates the benefit for a node S_j of choosing a particular forwarding node to send the current packet prior to providing a definition of game player's utility. As we have mentioned before, we assume that there always are at least two available nodes (best-quality and medium-quality nodes) to forward packets through them. Each forwarding node will represent a specific benefit for that node S_j.

Let $\phi_{B,i}$ be the benefit for the best-quality forwarding node, and let $\phi_{M,i}$ be the benefit for the medium-quality forwarding node, where $\phi_{B,i}$ and $\phi_{M,i} \in \mathbb{R}^*$. Later, we will relate $\phi_{B,i}$ and $\phi_{M,i}$ with the global outcome obtained with G-3MRP. Strategy α_i is defined as follows:

$$\alpha_i = \begin{cases} \text{Transmit I+P frames through the best-quality node (B)} \\ \quad \text{with probability } p_i \\ \text{Transmit I+P frames through the medium-quality node (M)} \\ \quad \text{with probability } 1 - p_i \end{cases} \tag{9}$$

Probability p_i is the probability for vehicle i of sending I+P frames through the best-quality forwarding node, and probability $(1 - p_i)$ is the probability of sending those frames through the medium-quality forwarding node.

6.2. Design of the utility function of our game-theoretical forwarding algorithm

The utility function U_i designed in the game-theoretical forwarding algorithm included in our G-3MRP routing protocol, aims to minimize the percentage of I+P frames losses. The reason is that the loss of the most important video frames is most significant in video services. The proposed utility function for player i is depicted in Eq. (10). Table 1 contains the definitions of all variables presented in Eq. (10).

$$U_i = \underbrace{\left(\frac{n_{rB,i} - n_{sB,i}}{n_{sB,i}}\right) \cdot \phi_{B,i} \cdot p_i^2}_{\text{Best-quality forwarding node}} + \underbrace{\left(\frac{n_{rM,i} - n_{sM,i}}{n_{sM,i}}\right) \cdot \phi_{M,i} \cdot (1 - p_i)^2}_{\text{Medium-quality forwarding node}}, \quad 1 \le i \le N \tag{10}$$

Now, let us relate $n_{sB,i}$ and $n_{sM,i}$ with $n_{s,i}$:

$$n_{sB,i} = p_i \cdot n_{s,i} \tag{11}$$

$$n_{sM,i} = (1 - p_i) \cdot n_{s,i} \tag{12}$$

where $n_{s,i} = n_{sB,i} + n_{sM,i}$.

Substituting Eqs. (11) and (12) in Eq. (10) we get the following expression for the utility function U_i regarding the node i currently holding a packet to be forwarded:

$$U_i = \underbrace{\left(\frac{n_{rB,i} - p_i \cdot n_{s,i}}{p_i \cdot n_{s,i}}\right) \cdot \phi_{B,i} \cdot p_i^2}_{\text{Best-quality forwarding node}} + \underbrace{\left(\frac{n_{rM,i} - (1 - p_i) \cdot n_{s,i}}{(1 - p_i) \cdot n_{s,i}}\right) \cdot \phi_{M,i} \cdot (1 - p_i)^2}_{\text{Medium-quality forwarding node}}, \quad 1 \le i \le N \tag{13}$$

Table 1
Definitions of the variables described in Eq. (10).

Variable	Definition
$i = 1, 2, 3, \dots, N$	i is a generic player, while N is the number of players (vehicles sending a video-reporting message)
p_i	Probability of sending the (I+P) frames through the best-forwarding node for player i
$\phi_{B,i}$	Benefit for player i if selecting the best-quality forwarding node
$\phi_{M,i}$	Benefit for player i if selecting the medium-quality forwarding node
$n_{s,i} = n_{sB,i} + n_{sM,i}$	Number of (I+P) frames sent by player i through the best-quality and the medium-quality nodes
$n_{sB,i}$	Number of (I+P) frames sent by player i through the best-quality node
$n_{rB,i}$	Number of (I+P) frames received (at destination) from player i through the best-quality node
$n_{sM,i}$	Number of (I+P) frames sent by player i through the medium-quality node
$n_{rM,i}$	Number of (I+P) frames received (at destination) from player i through the medium-quality node

Recall that the nodes' classification will be independently computed by each vehicle, i.e., best/medium-quality candidate nodes to forward its I+P video-frames could be different for each player.

In Eq. (10), we have designed our utility function U_i to be proportional to the negative of the I+P frames losses. In Eq. (10), $\left(\frac{n_{rB,i}-n_{sB,i}}{n_{sB,i}}\right)$ is the negative of the I+P frame losses through the best-quality forwarding node and $\left(\frac{n_{rM,i}-n_{sM,i}}{n_{sM,i}}\right)$ is the negative of the I+P frame losses through the medium-quality node. This way, the utility increases as the losses decrease. The same happens for both the best-quality and the good-quality forwarding nodes. Besides, U_i is a concave function so that we ensure to have a p probability value that produces the maximum utility for that player i.

Furthermore, U_i is proportional to the benefit achieved by selecting the best-quality or the medium-quality forwarding nodes $\phi_{B,i}$ and $\phi_{M,i}$, respectively. We can see a numerical example of the utility function in Section 8.2.2.

Depending upon the values of the utilities, pure strategies may not exist, but in that case there are always mixed strategies [34,35]. The mixed strategy α_i^* is a (NE) if the utilities $U_i (i = 1, \dots, N)$, satisfy Eq. (8). If there exists a mixed Nash equilibrium, player i will have a best response. To obtain the best response, U_i must be maximized:

$$\frac{\partial U_i}{\partial p_i} = 0 \tag{14}$$

Then, merging both Eqs. (13) and (14) we obtain:

$$\frac{\partial U_i}{\partial p_i} = -2 \cdot p_i \cdot (\phi_{B,i} + \phi_{M,i}) + \phi_{B,i} \cdot \frac{n_{rB,i}}{n_{s,i}} - \phi_{M,i} \cdot \frac{n_{rM,i}}{n_{s,i}} + 2 \cdot \phi_{M,i} \tag{15}$$

$n_{sB,i}$, $n_{sM,i}$ and $n_{s,i}$ are assumed to be higher than zero since at least one frame should have been sent. This will lead to simplify the previous Equation. Let us define the following variables:

$$\hat{n}_{B,i} = \frac{n_{rB,i}}{n_{s,i}}, \ \hat{n}_{M,i} = \frac{n_{rM,i}}{n_{s,i}} \tag{16}$$

Now, we merge both Eqs. (15) and (16) and we get:

$$\frac{\partial U_i}{\partial p_i} = -2 \cdot p_i \cdot (\phi_{B,i} + \phi_{M,i}) + \phi_{B,i} \cdot \hat{n}_{B,i} - \phi_{M,i} \cdot \hat{n}_{M,i} + 2 \cdot \phi_{M,i} \tag{17}$$

Finally, if we combine both Eqs. (14) and (17), we obtain the solution for the optimal probability of sending (I+P) frames through the best forwarding node, that produces a Nash equilibrium in the utility function U_i and will be named as the *best response of the game*. Therefore, using p_i^* as the probability of sending I+P frames through the best forwarding node will produces the most favorable outcome for player i, taking the other players' strategies as given.

$$p_i^* = \frac{\phi_{B,i} \cdot \hat{n}_{B,i} + \phi_{M,i} \cdot (2 - \hat{n}_{M,i})}{2\left(\phi_{B,i} + \phi_{M,i}\right)}, \quad 1 \le i \le N \tag{18}$$

This way, each vehicle i will continuously update its best response p_i^* using Eq. (18). To compute p_i^*, the vehicle needs to know the number of I+P frames sent ($n_{sB,i}$ and $n_{sM,i}$), and the number of I+P frames received at destination ($n_{rB,i}$ and $n_{rM,i}$), see Table 1. That is, the vehicle i currently holding the packet will compute p_i^* using the number of I+P video frames received (at the RSU) through the best ($n_{rB,i}$) and the medium-quality ($n_{rM,i}$) nodes, see Algorithm 1 and Table 1. Besides, since the vehicle itself already knows the number of I+P video frames sent through the best ($n_{sB,i}$) and the medium-quality ($n_{sM,i}$) nodes, then the vehicle will be able to easily compute $n_{s,i}$. Therefore, what must be reported to each vehicle is the number of messages received at destination (at the RSU), i.e. $n_{rB,i}$ and $n_{rM,i}$. To implement this reporting scheme, there are several alternatives. The one we have implemented is simple and has proven to be effective.

In next Section 6.3 we show the details of the feedback scheme implemented in our framework. The RSU uses this feedback scheme to inform each vehicle i of the number of packets received from that vehicle, i.e. $n_{rB,i}$ and $n_{rM,i}$. Then, in Section 6.4 we explain how the vehicle computes the benefits associated to the use of the best-quality and the medium-quality forwarding nodes.

6.3. Feedback scheme implemented in our framework

As we discussed in the previous section, the RSU has to somehow inform each source vehicle i about the number of packets successfully received from that vehicle i. The challenge here is that in a vehicular network the topology changes so dynamically, that implementing a feedback/acknowledgment system that goes back in the reverse path of frame transmission is extremely difficult due to frequent topology changes. There are some proposals in the literature to address the problem of sending information to a requesting vehicle in motion. For instance, the work CMGR (Connectivity-aware Minimum-delay Geographic Routing with vehicle tracking in VANETs) [36] proposes a vehicle tracking mechanism based on a junction-sequence scheme used to forward feedback messages to get a requesting vehicle in motion. In CMGR, vehicles associate themselves to their closest junction in the city. When vehicles move, they leave a track of their movement in their junction, so the feedback packet has a clue of where the vehicle went. This type of complex framework could be appropriate for services that need large packets, for instance for infotainment services where passengers access video-streaming services. Nevertheless, in our case we just need to send back a small text message to the source vehicles informing of the amount of packets successfully received in the RSU from each vehicle.

Alternatively, in our considered scenario we have implemented a simpler scheme where the RSU periodically (e.g., every T_f = 30 s) disseminates the number of received I+P video frames from each source vehicle i during the last time window of T_f = 30 s To disseminate the feedback information from the RSU to the vehicles around (approximately within an area of 1 km^2) we have used our proposal named "Game-Theoretical Design of an Adaptive Distributed Dissemination (ADD) Protocol for VANETs" [37], which has shown to be very efficient. Basically, the main goal of ADD is to disseminate messages to all vehicles inside the region of interest (ROI) independently of the road traffic condition, being able to cope with the broadcast storm and intermittently connected network problems. ADD is able to respond to environmental changes, adapting its relaying operation based on a game-theoretical scheme able to face the frequent topology changes inherent in vehicular networks. In a nutshell, ADD tries to avoid redundant retransmissions of messages previously broadcast. Besides, the ADD game-theoretical dissemination scheme is based on the classical Volunteer's Dilemma [35] game: ADD computes a defection probability for vehicles that defect rebroadcasting the message, as a function of the cost of volunteering broadcasting the message, the benefit earned by that vehicle when at least one vehicle volunteers, and the average defection probability of all the other players. Additionally, in our previous work [37] we included a performance evaluation of the broadcast overhead of ADD under diverse vehicles' densities from 20 to 300 vehicles/km^2. ADD strongly decreases the number of messages exchanged providing better results than other similar schemes, showing around 50% less overhead while achieving very high packet delivery ratio close to 100% and low average packet delay below 100 ms, see [37]. With our dissemination mechanism the number of messages decreases after a few seconds because when informed vehicles receive a beacon from an uniformed vehicle, they use a mechanism to coordinate the rebroadcast of the message and thus avoid redundant retransmissions.

Note that this feedback corresponds to a small text file and a light data stream. To get an idea, in our considered scenario, the feedback files have a size of around 10 kB and a rate of 20 kbps. Then, vehicles filter out that message sent by the RSU and read their corresponding new feedback reporting information, i.e. the new $n_{rB,i}^{new\_sample}$ and $n_{rM,i}^{new\_sample}$ values, see Eqs. (19) and (20), respectively. To track historical values and smooth out any isolated spiky samples, we apply an exponential weighted moving average (EWMA) filter to weight the historical values ($n_{rB,i}^{previous}$ and $n_{rM,i}^{previous}$), along with the new sample value ($n_{rB,i}^{new\_sample}$ and $n_{rM,i}^{new\_sample}$), using a weight α_E. Finally, the new updated values for the number of (I+P) frames received (at destination) from player i through its best-quality node ($n_{rB,i}$) and through its medium-quality node ($n_{rM,i}$) will be updated using Eqs. (19) and (20), respectively:

$$n_{rB,i} \longleftarrow n_{rB,i}^{updated} = \alpha_E \cdot n_{rB,i}^{previous} + (1 - \alpha_E) \cdot n_{rB,i}^{new\_sample} \tag{19}$$

$$n_{rM,i} \longleftarrow n_{rM,i}^{updated} = \alpha_E \cdot n_{rM,i}^{previous} + (1 - \alpha_E) \cdot n_{rM,i}^{new\_sample} \tag{20}$$

We carried out a large amount of representative simulations in urban scenarios and we found T_f=30 s and α_E = 0.75 be good values for the feedback period and the historical weight, respectively.

6.3.1. Discussion about the interaction between the feedback mechanism and the forwarding decision scheme

Notice that with our proposal of a game-theoretical forwarding algorithm for VANETs, vehicles should only use local information to fulfill the infrastructureless basis inherent of ad hoc networks. That is, the vehicle i currently holding the packet to be forwarded counts only on local information gathered from its current neighbors, i.e. those vehicles located within its transmission range. This local information is gathered through a periodic beaconing process (1 beacon per second) with which the vehicle gathers five metrics from its neighborhood: distance to destination, vehicle's trajectory, vehicles' density, available bandwidth and MAC layer losses, see Section 5.2. Using those metrics, the vehicle i computes a multimetric score for each candidate node as it is explained in Section 4.

Since in vehicular networks vehicles cannot count on any end-to-end forwarding path, neither on a global knowledge of the whole network topology, vehicles only count on local information (gathered within their transmission range) to take their forwarding decisions. The main reason is the potentially high nodes' velocity and thus variable network topology.

The goal of our proposed feedback scheme is to inform the source/ forwarding vehicles about the number of I+P video frames successfully received at destination (i.e., the RSU) that each vehicle i sent through its best neighbor node (in that moment), i.e. $n_{rB,i}$; and also about the number of I+P video frames successfully received at destination that each vehicle i sent through its medium-quality neighbor node (in that moment), i.e. $n_{rM,i}$. Notice that when the feedback message disseminated from the RSU arrives to the intended vehicles, they probably might have other neighboring nodes. Actually, the list of neighbors is updated once per second, see Section 4, whereas the feedback from RSU to vehicles is disseminated every $T_f = 30$ s in our case. We chose that value to keep a good trade-off between low overhead and enough frequent feedback updating. Notice that the new neighboring nodes (when a new feedback from the RSU arrives) also will be arranged according to the multimetric score explained in Section 4. Those candidate forwarding nodes will be classified as the best-quality node, the medium-quality node and the worse node (since our scheme considers up to three next hop forwarding nodes, see Section 5.2) in that moment. And that is precisely what do we need, to have arranged up to three next-hop neighboring vehicles to forward the video frames. Notice that we do not require to use the same forwarding nodes than in the previous period, which would be almost impossible in a so potentially dynamic kind of network. It is not necessary in our algorithm, we just need to have arranged the (up to) three best candidate nodes in that moment to perform our game theory based forwarding algorithm.

Finally, according to Algorithm 1 (see Section 7.4) our next hop forwarding scheme computes the probability p_i^* to send I+P video frames through the best-quality node, which maximizes the utility function U_i expressed in Eq. (13). That is, we apply our game theoretical proposal to calculate the best response probability p_i^* for the vehicle i currently holding the packet, that maximizes its utility function U_i. Notice that in this way we are designing which is the best strategy (the probability p_i^* to send I+P video frames through the best-quality node) for the vehicle to forward the current packet for the current set of neighbors in that moment. It happens the same for any set of neighbors, we only require that the node arranges its neighbors as the best-quality node, the medium-quality node and the worst-quality node (we use up to three forwarding nodes). Recall that only the two best nodes are used at stake to forward I+P video frames, while B video frames are always sent through the third quality node, see Section 5.2). As a result, our proposed game-theoretical forwarding scheme included in our G-3MRP routing protocol for VANETs, is able to balance the load of the video-reporting messages among the two best (classified in that moment) forwarding nodes at each hop, instead of always choosing the best (classified in that moment) forwarding node. According to our simulation results, our strategy makes video packets to be delivered at destination earlier and with a higher probability, see Section 8).

6.4. Computation of the nodes' benefits

We have designed the benefits $\phi_{B,i}$ and $\phi_{M,i}$ regarding the node currently holding a packet associated to a given video-reporting transmission from a vehicle i towards the closest RSU. The benefits $\phi_{B,i}$ and $\phi_{M,i}$ associated to the use of the best-quality (B) node or the medium-quality (M) node, respectively, are designed to be proportional to the multimedia score obtained by G-3MRP. These multimedia scores, $S_{B,i}$ and $S_{M,i}$, regarding each available next forwarding node (B and M) are computed with Eq. (1). Since the multimetric score considers five metrics (distance to destination, vehicle's trajectory, vehicles' density, available bandwidth and MAC layer losses) it can be considered as a local measure of the global QoS.

Accordingly, we define the following equations to compute the benefits associated to the use of the best-quality node (B) and the medium-quality node (M), $\phi_{B,i}$ and $\phi_{M,i}$, respectively:

$$\phi_{B,i} = k_{B,i} \cdot S_{B,i} \tag{21}$$

$$\phi_{M,i} = k_{M,i} \cdot S_{M,i} \tag{22}$$

where $k_{B,i}$ and $k_{M,i}$ are constants for each vehicle i, $k_{M,i} \in \mathbb{R}_{>0}$ and $k_{B,i} \in \mathbb{R}$. $S_{B,i}$ and $S_{M,i}$ are the multimetric score values measured in the highest-quality node (B) and the medium-quality node (M), respectively. $S_{B,i}$ and $S_{M,i}$ are computed with Eq. (1). The benefits $\phi_{B,i}$ and $\phi_{M,i}$ associated to the use of the best-quality (B) node and the medium-quality (M) node, respectively, are designed to be proportional to the multimedia score obtained by G-3MRP using the $k_{B,i}$ and $k_{M,i}$ parameters. This means that if the value of $k_{B,i}$ or $k_{M,i}$ increases positively, the benefits of using this best/medium node will be increased. However, the negative sign of $k_{B,i}$ for example is a clear indication that the benefits of using aggressively this best node can be seen affected shortly and most likely this best node in particular will no longer be the best during the next round of nodes' classification.

Thus, in our feedback mechanism we need to inform vehicles about which type of neighboring node (best one, medium-quality one) was used to forward the I+P video frames that successfully arrived to destination. This way, the vehicle can adjust its forwarding strategy using our game-theoretical forwarding scheme. Notice that other more complex alternative schemes could use information gathered from more than 1-hop, for instance keeping track of how many I+P video frames where successfully delivered at destination through the best and the medium quality nodes in the first 3 or 4 forwarding hops.

Next, using Eqs. (21) and (22) in Eq. (18) we get the following expression for the best response probability, p_i^*:

$$p_i^* = \frac{k_{B,i} \cdot S_{B,i} \cdot \hat{n}_{B,i} + \left(k_{M,i} \cdot S_{M,i}\right) \cdot \left(2 - \hat{n}_{M,i}\right)}{2 \cdot \left(k_{B,i} \cdot S_{B,i} + k_{M,i} \cdot S_{M,i}\right)}, \quad 1 \le i \le N \tag{23}$$

For the sake of simplicity, $\frac{k_{B,i}}{k_{M,i}}$ will be renamed as $k^i_{B/M}$. The whole Eq. (23) can be divided by $k_{M,i}$ as $k_{M,i}$ is different from zero. After substituting, we obtain the Nash Equilibrium strategy for vehicle i as follows:

$$p_i^*(k^i_{B/M}) = \frac{k^i_{B/M} \cdot S_{B,i} \cdot \hat{n}_{B,i} + S_{M,i} \cdot \left(2 - \hat{n}_{M,i}\right)}{2 \cdot \left(k^i_{B/M} \cdot S_{B,i} + S_{M,i}\right)}, \quad 1 \le i \le N \tag{24}$$

where:

- $S_{B,i}$: Multimetric score value measured in the highest-quality node (B), see Eq. (1).
- $S_{M,i}$: Multimetric score value measured in the medium-quality node (M), see Eq. (1).
- $\hat{n}_{B,i}$ and $\hat{n}_{M,i}$: Variables defined in Eq. (16), which depend on the I+P frame received (at destination) from player i through the best-quality node and the medium-quality node, respectively.

We have designed U_i in Eq. (13) to be a concave function in a way that we will only have one p_i^* value where U_i is on its maximum value. Because of that, $\frac{\partial^2 U_i}{\partial^2 p_i}$ must be less than zero. Therefore, if we derive Eq. (17) we get:

$$\frac{\partial^2 U_i}{\partial^2 p_i} = -2 \cdot \left(\phi_{B,i} + \phi_{M,i}\right) \tag{25}$$

Since we need that $\frac{\partial^2 U_i}{\partial^2 p_i} < 0$,

$$\phi_{B,i} + \phi_{M,i} > 0; \quad \forall \phi_{M,i} \in \mathbb{R}_{>0} \quad \textit{and} \quad \phi_{B,i} \in \mathbb{R} \tag{26}$$

To sum up, any vehicle (player) i decides to send its (I+P) frames through the best-quality forwarding node with the probability p_i^*, see Eq. (24), and its own benefit will be maximized. Since all vehicles play the same forwarding game, the whole benefit of the vehicular network will improve as a consequence.

We would like to highlight the fact that the periodical feedback disseminated from the RSU, which consists in the new updated values for ($n_{rB,i}$) and ($n_{rM,i}$) for each vehicle i, is used to update the best response probability (p_i^*) with which vehicle i will balance the load (I+P video frame packets) between the best-quality and the medium-quality neighboring forwarding candidates at that moment. That is, vehicle i updates its probability to send I+P video frames through the best-quality candidate with probability p_i^*, and through the medium-quality candidate with probability 1-p_i^*. This is done periodically for the new set of neighboring nodes within transmission range of vehicle i, set that updates continuously throughout time. For our proposal, the only requirement is that vehicle i must arrange its neighboring vehicles and select the three best nodes, according to our game-theoretical forwarding algorithm explained in Section 5.2. Thus, what is updated throughout time is the strategy (i.e., p_i^*) of vehicle i to balance its I+P video frames between the two best candidate nodes at that moment, which are at stake for our game-theoretical forwarding algorithm.

Notice that in our proposal we consider that sender vehicles are either source vehicles or forwarding vehicles. That is, when we talk about the vehicle i that sends I+P video frames with probability p_i^* through the best-quality neighbor node, we refer either to the first source vehicle or to any intermediate forwarding vehicle. Therefore, the RSU will inform all of them with the periodic feedback messages disseminated, using the feedback mechanism ADD explained in Section 6.3.

All values needed to compute p_i^*, except $k^i_{B/M}$, can be obtained during normal network operation from the local information provided by the hello messages. This way, vehicles will update the probability p_i^* from the current QoS parameters carried in the last received hello message packets from the vehicles in the neighborhood ($S_{B,i}$, $S_{M,i}$), and from the feedback periodically disseminated by the RSU ($\hat{n}_{B,i}$, $\hat{n}_{M,i}$)). Thus, $k^i_{B/M}$ is the single pending parameter to be obtained in Eq. (24). In the next section, we will give a method to calculate analytically this parameter.

7. Computation of $k^i_{B/M}$

Calculating the value of $k^i_{B/M}$ will lead to obtain the value of p_i^* using Eq. (24). These conditions will be taken into consideration when computing the value of $k^i_{B/M}$:

(i) $0 \le p_i \le 1$;
(ii) U_i is a concave function.

Below, we will study separately those three conditions.

7.1. Condition 1: $p_i \ge 0$

Combining Eq. (18) with $p_i \ge 0$, we get that:

$$\frac{k^i_{B/M}\cdot S_{B,i}\cdot \hat{n}_{B,i} + S_{M,i}\cdot\left(2-\hat{n}_{M,i}\right)}{2\cdot\left(k^i_{B/M}\cdot S_{B,i}+S_{M,i}\right)} \ge 0 \tag{27}$$

The denominator $2\cdot\left(k^i_{B/M}\cdot S_{B,i}+S_{M,i}\right)$ will be greater than zero if Eq. (26) is fulfilled and $k_{M,i} > 0$.

Thus, we need:

$$k^i_{B/M}\cdot S_{B,i}\cdot \hat{n}_{B,i} + S_{M,i}\cdot\left(2-\hat{n}_{M,i}\right) \ge 0 \tag{28}$$

Next, we multiply the whole In Eq. (28) by $\frac{1}{S_{B,i}\cdot\hat{n}_{B,i}}$ ($\forall\ S_{B,i}$, $\hat{n}_{B,i} \in \mathbb{R}^+$):

$$k^i_{B/M} \ge \frac{S_{M,i}\cdot\left(\hat{n}_{M,i}-2\right)}{S_{B,i}\cdot\hat{n}_{B,i}} \tag{29}$$

7.2. Condition 2: $p_i \le 1$

Combining Eq. (18) with $p_i \le 1$ leads to:

$$\frac{k^i_{B/M}\cdot S_{B,i}\cdot \hat{n}_{B,i} + S_{M,i}\cdot\left(2-\hat{n}_{M,i}\right)}{2\cdot\left(k^i_{B/M}\cdot S_{B,i}+S_{M,i}\right)} \le 1 \tag{30}$$

Looking at Eq. (26), we can write:

$$k^i_{B/M}\cdot S_{B,i}\cdot \hat{n}_{B,i} + S_{M,i}\cdot\left(2-\hat{n}_{M,i}\right) \le 2\cdot\left(k^i_{B/M}\cdot S_{B,i}+S_{M,i}\right) \tag{31}$$

and solving Eq. (31), we reach to:

$$k^i_{B/M}\cdot S_{B,i}\cdot\left(2-\hat{n}_{B,i}\right) \ge -S_{M,i}\cdot\hat{n}_{M,i} \tag{32}$$

Before we continue we will find out which is the sign of the expression $\left(2-\hat{n}_{B,i}\right)$. We can see $\hat{n}_{B,i}$ defined in Eq. (16) as the relation between the number of I+P frames received in the best-quality forwarding node (n_{rB}) and the total number of I+P frames sent ($n_{s,i}$).

$$0 \le \hat{n}_{B,i} = \frac{n_{rB}}{n_{s,i}} \le 1 \tag{33}$$

Therefore,

$$1 \le 2-\hat{n}_{B,i} \le 2 \tag{34}$$

Finally, the second inequation to be fulfilled by $k^i_{B/M}$ is:

$$k^i_{B/M} \ge \frac{S_{M,i}\cdot\hat{n}_{M,i}}{S_{B,i}\cdot\left(\hat{n}_{B,i}-2\right)} \tag{35}$$

7.3. Condition 3: Concave function U_i

For U_i to be a concave function, Eq. (26) must be fulfilled such that:

$$\phi_{B,i}+\phi_{M,i} = k_{B,i}\cdot S_{B,i} + k_{M,i}\cdot S_{M,i} > 0 \tag{36}$$

If the whole inequation is multiplied by $\frac{1}{k_{M,i}}$ ($\forall\ k_{M,i} \in \mathbb{R}^+$) and renamed $\frac{k_{B,i}}{k_{M,i}}$ by $k^i_{B/M}$, we get:

$$k^i_{B/M}\cdot S_{B,i} > -S_{M,i} \tag{37}$$

Eventually, we achieve the desired Eq. (38) as the third condition to be fulfilled by $k^i_{B/M}$:

$$k^i_{B/M} > \frac{-S_{M,i}}{S_{B,i}} \tag{38}$$

7.4. The three desired inequations to be satisfied by $k^i_{B/M}$

As a starting point, let us rewrite the three desired inequations to be satisfied by $k^i_{B/M}$: Eqs. (38), (29) and (35). In addition, the thresholds of the three inequations will be renamed as α_0, α_1 and α_2, respectively.

$$\begin{aligned} k^i_{B/M} &> \frac{-S_{M,i}}{S_{B,i}} = \alpha_0 \\ k^i_{B/M} &\ge \frac{S_{M,i}\cdot\left(\hat{n}_{M,i}-2\right)}{S_{B,i}\cdot\hat{n}_{B,i}} = \alpha_1 \\ k^i_{B/M} &\ge \frac{S_{M,i}\cdot\hat{n}_{M,i}}{S_{B,i}\cdot\left(\hat{n}_{B,i}-2\right)} = \alpha_2 \end{aligned} \tag{39}$$

Our goal is to find a value for $k^i_{B/M}$ that could satisfy the three inequations. The range of solutions for $k^i_{B/M}$ is $]K^i_{B/M}, +\infty)$, being $K^i_{B/M}$ the maximum value among α_0, α_1 and α_2.

$$K^i_{B/M} = max(\alpha_0, \alpha_1, \alpha_2) \tag{40}$$

The best response probability $p_i^*(k^i_{B/M})$ of sending (I+P) frames through the best-quality forwarding vehicle as a function of $k^i_{B/M}$ is depicted in Fig. 5. Using Eq. (24), we are able to compute the limit of $p_i^*(k^i_{B/M})$ when $k^i_{B/M} \to \infty$ (horizontal asymptote) and it has the following value:

$$\lim_{k^i_{B/M}\to\infty} p_i^*(k^i_{B/M}) = \frac{\hat{n}_{B,i}}{2} \tag{41}$$

The vertical asymptote of Fig. 5 occurs at a given $k^i_{B/M}$ value that makes the denominator of Eq. (24) equals zero, i.e. $k^i_{B/M} = \frac{-S_{M,i}}{S_{B,i}} = \alpha_0$, see Eq. (39).

A value for $k^i_{B/M}$ in the range $]k^i_{B/M}, +\infty)$ that makes the $p_i^*(k^i_{B/M})$ change softly throughout time is a must to be found. This will assure

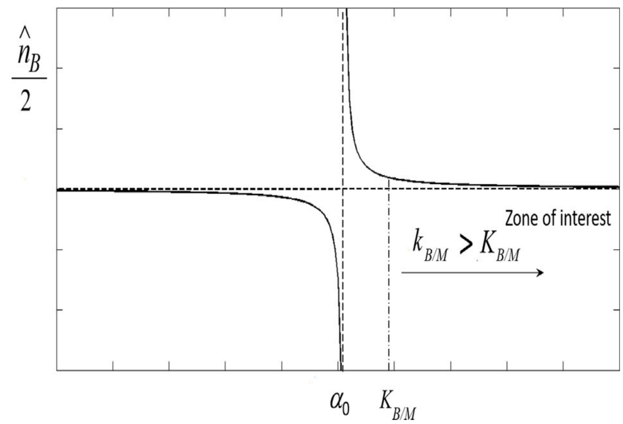


Fig. 5. Best response probability $p_i^*(k^i_{B/M})$ of sending (I+P) frames through the best-quality forwarding node as a function of $k^i_{B/M}$, see Eq. (24).

that the transition in the selection between the best-quality and the medium-quality nodes will be smooth and therefore producing a more stable system. To do so, we compute the first derivative $\frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}}$, that represents the slope value of each $k^i_{B/M} > K^i_{B/M}$ that covers the zone of interest depicted in Fig. 5.

$$\frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}} = \frac{\hat{n}_{B,i} \cdot S_{B,i} \cdot \left(2 \cdot k^i_{B/M} \cdot S_{B,i} + 2 \cdot S_{M,i}\right)}{4 \cdot \left(k^i_{B/M} \cdot S_{B,i} + S_{M,i}\right)^2} - \\ - \frac{2 \cdot S_{B,i} \cdot \left(\cdot k^i_{B/M} \cdot S_{B,i} \cdot \hat{n}_{B,i} + \cdot S_{M,i} \cdot (2 - \hat{n}_{M,i})\right)}{4 \cdot \left(k^i_{B/M} \cdot S_{B,i} + S_{M,i}\right)^2} \tag{42}$$

After simplifying that equation, we obtain:

$$\frac{\partial p_i^*}{\partial k^i_{B/M}} = \frac{S_{B,i} \cdot S_{M,i} \cdot (\hat{n}_{B,i} + \hat{n}_{M,i} - 2)}{2 \cdot \left(k^i_{B/M} \cdot S_{B,i} + S_{M,i}\right)^2} \tag{43}$$

Now, we isolate $k^i_{B/M}$ in terms of $\frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}}$ and we get the following expression:

$$k^i_{B/M} = \frac{\pm \sqrt{\frac{S_{B,i} \cdot S_{M,i} \cdot (\hat{n}_{B,i} + \hat{n}_{M,i} - 2)}{2 \cdot \frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}}}} - S_{M,i}}{S_{B,i}} \tag{44}$$

In Eq. (44) we have that $(\hat{n}_{B,i} + \hat{n}_{M,i} - 2) \leq 0$, since $\hat{n}_{B,i} = \frac{n_{rB}}{n_{s,i}} \leq 1$ and $\hat{n}_{M,i} = \frac{n_{rM}}{n_{s,i}} \leq 1$ according to Eq. (16). Therefore, we need that $\frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}} \leq 0$ to compute a proper $k^i_{B/M}$ value in Eq. (44).

To sum up, the parameters of Eq. (44), represented in Fig. 5, that can be calculated during operation time from the values obtained in the periodically interchanged hello message packets received (by default once per second) from the neighboring vehicles, are:

- The number of I+P frames received at destination that went through the best-quality forwarding node (n_{rB}); and the number of I+P frames sent through that best-quality forwarding node ($n_{sB,i}$), which allow us to compute $\hat{n}_{B,i} = \frac{n_{rB}}{n_{s,i}}$, see Eq. (16).
- The number of I+P frames received at destination that went through the medium-quality forwarding node (n_{rM}); and the number of I+P frames sent through that medium-quality forwarding node ($n_{sM,i}$), which allow us to compute $\hat{n}_{M,i} = \frac{n_{rM}}{n_{s,i}}$, see Eq. (16).
- The global multimetric scores of the best-quality forwarding node ($S_{B,i}$) and of the medium-quality forwarding node ($S_{M,i}$), computed with the G-3MRP routing protocol using Eq. (1).

Eq. (44) shows that the only variable that is not defined yet is $\frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}}$. To obtain a proper value for $\frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}}$, we executed a high number of simulations with different network conditions producing different values of $\frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}}$. Results of the above mentioned simulations noticed us that with a value of $\frac{\partial p_i^*(k^i_{B/M})}{\partial k^i_{B/M}} = -0.655$ we can guarantee a soft variation of p_i^* throughout time.

Finally, from Eq. (44), we see that we have two possible values for $k^i_{B/M}$, one of them is higher than $K^i_{B/M}$ and the other one is lower than $K^i_{B/M}$, so we take the one which belongs to the range $]K^i_{B/M}, +\infty)$, see Eq. (39).

To conclude with, Algorithm 1 summarizes the methodology to compute the best response probability p_i^* for vehicle i to send its I+P frames through the best-quality forwarding node. The vehicle i currently in charge of forwarding a packet, updates the multimetric values from periodically received hello messages from the neighboring vehicles in transmission range (see Line 1 in Alg. 1). Then, vehicle i computes all the parameters needed to derive the probability p_i^* to send I+P frames through the best-quality node seeking to maximize its own utility function U_i (see Lines 2 and 3 in Alg. 1). Finally, vehicle i will send its I+P video frames through the medium-quality forwarding node with a probability 1-p_i^* (see Line 4 in Algorithm 1).

8. Performance evaluation of G-3MRP in an urban scenario

In this section, we first depict a case study of an urban scenario where a vehicle involved in a traffic accident transmits a video-reporting message to the closest emergency unit. The goal is to alert other citizens around and also the emergencies services (e.g., 112 or 911). We claim that by means of a light video clip citizens and authorities can rapidly assess the seriousness of the accident. Simulations are done using the NS-2 [38] simulator.

8.1. A case study in a smart city

In this paper, we focus on a smart city scenario where emergency prevention and response are key issues. In this urban scenario we assume that in a given moment an accident happened: a crashed vehicle automatically shoots a short video-reporting message regarding the traffic accident and sends it through the VANET towards the nearest emergency unit (e.g., police, ambulance, hospital). Authorities will respond upon receiving the video and will take proper actions. As explained before, with a video-reporting message the emergency can

Algorithm 1 Calculation of p_i^*, the best response probability for the vehicle i currently holding the packet, that maximizes its utility function U_i.

1. Obtain updated QoS values from periodically received hello messages (by default once per second) from each vehicle within transmission range.
2. Obtain the values of ($S_{B,i}$, $S_{M,i}$, $\hat{n}_{B,i}$, $\hat{n}_{M,i}$) using Eqs. (1) and (16).
3. Compute the $k^i_{B/M}$ parameter designed that fulfills the requirements:
$$k^i_{B/M} = \frac{\pm\sqrt{\frac{S_{M,i}\cdot S_{B,i}\cdot\left(\hat{n}_{B,i}+\hat{n}_{M,i}-2\right)}{2\cdot(-0.655)}}-S_{M,i}}{S_{B,i}}$$, see Eq. (44).
4. Calculate the probability p_i^* to send I+P video frames through the best-quality node, which maximizes the utility function U_i expressed in Eq. (13):
$$p_i^*(k^i_{B/M}) = \frac{k^i_{B/M}\cdot S_{B,i}\cdot\hat{n}_{B,i}+S_{M,i}\cdot\left(2-\hat{n}_{M,i}\right)}{2\cdot\left(k^i_{B/M}\cdot S_{B,i}+S_{M,i}\right)}, \quad 1\le i\le N,$$ see Eq. (24).

be evaluated much better than with only a simple text. Sending also a video-reporting message, it would be easier to ensure an accurate interpretation of the situation and the accident could be treated with the adequate level of seriousness. The smart witness vehicle sends a multimedia message which includes different information regarding the incident, e.g., the GPS location, a voice message, a short video of the incident. A suitable smart-emergencies application in the vehicle sends the multimedia message to the smart (e.g, 112 or 911) emergency center, who manages proper actions for that incident. For instance, ambulances and paramedical will be sent there, traffic lights will turn to red around the accident, a green wave of traffic lights will help the ambulances get there sooner, the nearest hospital is warned, the doctors wait for the injuries, citizens around the incident will be warned through the dissemination of a warning message, etc. A video of the incident facilitates a preliminary evaluation of the wounded people as well as helps to better determine the requirements needed to manage the dangerous situation. Our purpose in this paper is to design a game-theoretical geographical routing protocol suitable to transmit video-reporting messages over VANETs in smart city scenarios. In the next section, a detailed performance evaluation of our proposal in a case-study VANET scenario is presented.

8.2. Simulation results

In this subsection we present a performance evaluation of our proposal in a urban scenario using the NS-2 [38] simulation framework. We analyze the performance of G-3MRP that includes the multi-user game-theoretical forwarding approach described in Section 6. Video flows regarding a traffic accident are transmitted from two crashed vehicles to two road side units RSU_1 and RSU_2 (see Fig. 6), respectively. RSU_1 is the Ana Torres Institute (a surgery clinic) and RSU_2 is the Hospital Clinic of Barcelona, which represent two emergency units where vehicles will send their multimedia reporting messages upon the event of traffic accidents [39]. Each crashed vehicle will send its multimedia reporting message to the closest RSU. We have carried out ten simulations per point with independent seeds to include 90% confidence intervals (CI) in the figures, computed from statistically independent results.

We consider two vehicles' densities: 50 vehicles/km^2 (scenario 1) and 100 vehicles/km^2 (scenario 2). In the simulations, we use a real city area obtained from the Eixample district of Barcelona, Spain (see Fig. 6). To simulate a realistic scenario, we have used the CityMob for Roadmaps (C4R) [40] simulator to obtain a realistic mobility model. C4R is a mobility generator that uses the simulation of urban mobility (SUMO) engine [41]. Besides, C4R imports maps directly from OpenStreetMap [8] and generates NS-2 compatible files to specify the mobility model for the vehicles through the city. Besides, our G-3MRP proposal includes the REVsim [4] tool described in Section 3 to detect obstacles in the line of sight between vehicles, and therefore the forwarding algorithm is building-aware.

Fig. 6 shows the simulation scenario, where we can see an example with two (green) vehicles that use the same (yellow) intermediate forwarding node. Both close green vehicles have arranged their neighbors and it happened that the same yellow neighbor was their best next forwarding node. However, this node used by both green *players* would get overloaded and soon cease to be the best choice. Additionally, even if there was only one video source vehicle, normally it would always try to choose its best-quality candidate to forward the video frames, and soon that forwarding vehicle would cease to be the best choice. Alternatively, using our game-theoretical proposal vehicles consider their two best next forwarding candidates at stake. They choose the best candidate with probability p_i^*, see Eq. (24), and the medium-quality candidate (see dotted lines in Fig. 6) with probability 1-p_i^*, which balances the load and improves the over whole network performance. Of course, in general cases there could be several common forwarding nodes, but for the sake of clarity in the image, we only show one common forwarding node to clearly highlight what is happening.

Notice that Fig. 6 shows a general case in which a forwarding vehicle could be forwarding video frames from diverse source vehicles. Nonetheless, what really matters for our proposal is that the vehicle i under consideration will have a flow of I+P video frames (belonging to one or more source vehicles) to be forwarded doing load balancing between two candidates nodes at stake: the best-quality neighbor vehicle and the medium-quality neighbor vehicle, see Section 5.2. Then, the vehicle i will distribute the I+P video flows (belonging to any source) through its best candidate neighboring vehicle with probability p_i^* and through the medium-quality neighboring vehicle with probability 1-p_i^*, see Section 5.2. That is, our proposal is intended to for load balancing instead of for managing competing video sources.

The basic simulation settings of the VANET scenario are shown in Table 2. The scenario used to test the proposal consists of a set of 50 or 100 vehicles/km^2 distributed in a urban scenario of 1700 m × 580 m, see Fig. 6. The transmission range of the nodes is 250 m. The average speed of the vehicles is 50 km/h while the maximum speed is 120 km/h. Vehicle speeds in the city are characterized by a Gaussian function with parameters μ = 50 km/h and σ = 23.33 km/h. Thus, 68% of the values are included in the interval [27 km/h, 73 km/h], and 27% of the values are included in the intervals [0 km/h, 27 km/h] or [73 km/h, 110 km/h]. This way, most of the common vehicle speeds in a general city can be represented using a Gaussian function with those parameters. The radio propagation model is Nakagami [42] and the MAC specification is IEEE 802.11p [43]. There are N = 2 crashed vehicles that send video-reporting message to the closest road side unit (RSU). The next-hop forwarding node selected by the G-3MRP routing protocol at each vehicle currently holding a packet that needs to be forwarded, was described in Section 5. Each source decides the next-hop forwarding node towards destination for each packet in accordance with the designed game-theoretical forwarding algorithm explained in Section 5.2 and shown in Figs. 3 and 4.

Fig. 7(a) shows the average percentage of packet losses for N = 2 vehicles when using the novel game-theoretical forwarding scheme in our G-3MRP routing protocol, compared to our former multimedia multimetric map-aware routing protocol (3MRP) [7]. For the sake of having a basic reference of the results, we also include the performance of GPSR [13], since it is a well-known geographic unicast protocol designed for VANETs. GPSR uses the shortest distance to destination

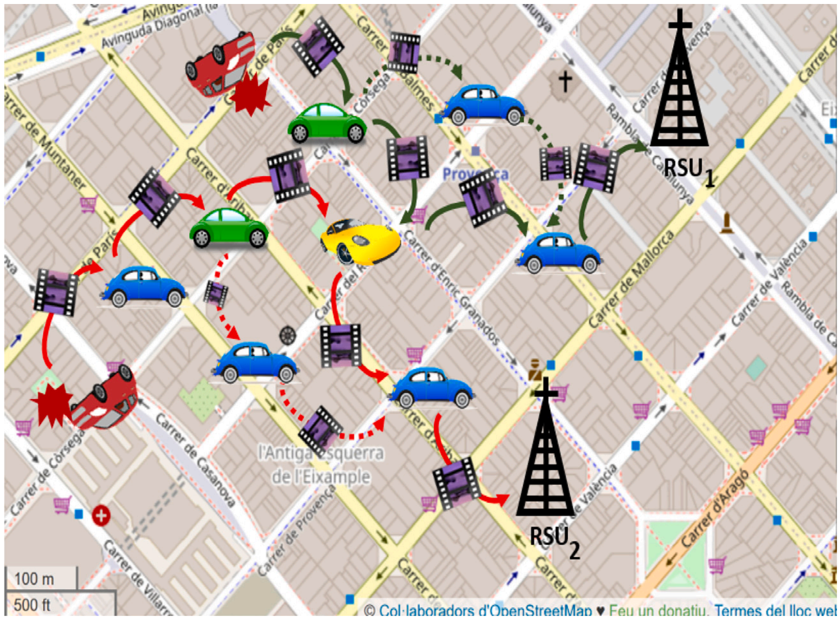


Fig. 6. Simulation scenario of the Eixample district of Barcelona, Spain. There are two crashed vehicles ($N = 2$ vehicles) which automatically send video-reporting messages through the VANET to the closest road side unit (RSU). There are two emergency units: RSU_1 (Ana Torres surgery clinic) and RSU_2 (Hospital Clinic of Barcelona). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

as single metric considered to forward packets without any other topological information. We can see how including the game-theoretical forwarding scheme (G-3MRP) compared to or former proposal without the game-theoretical proposal (3MRP), the average video packet losses are reduced from 53% to 45% for the low vehicles' density scenario, and from 37% to 28% in the high vehicles' density scenario. The optimal selection of nodes based on a probability value (i.e., p_i^* in Eq. (24)) that smartly balances the load among the two nodes at stake depending on the current state of the neighboring nodes of the current node holding the packet, produces a significant decrease in the average packet losses, as it can be seen in Fig. 7(a). Note that the inclusion of a multimetric forwarding scheme (in either 3MRP and G-3MRP) shows a significant improvement over the basic GPSR, which only uses the basic metric of the distance to destination to make forwarding decisions. Also, notice that for the three routing protocols, the average percentage of packet losses is lower for 100 vehicles/km2 than for a sparse configuration of 50 vehicles/km2. The reason is that the network connectivity is better for the 100 vehicles/km^2 topology than for the sparse one.

Fig. 7(b) depicts the average end-to-end packet delay. We can see that G-3MRP slightly reduces the end-to-end packet delay compared to 3MRP, for both scenarios of 50 vehicles/km^2 and 100 vehicles/km^2. The adoption of the game-theoretical routing scheme where the load is balanced between the two best possible forwarding nodes, makes video packets to be delivered earlier to destination. Nevertheless, notice that both multimetric routing protocols (3MRP and G-3MRP) produce higher average end-to-end packet delays compared to GPSR. The reason is that more packets arrived at their destination with 3MRP and G-3MRP, some of them went through a higher number of intermediate hops and consequently took longer to reach their destination. Note, however, that this is a slight increase in the end-to-end delay of around 0.15 s for N=50 vehicles/km^2 and 0.3 s for N=100 vehicles/km^2, which is worth it compared to the noticeable decrease in the percentage of packet losses.

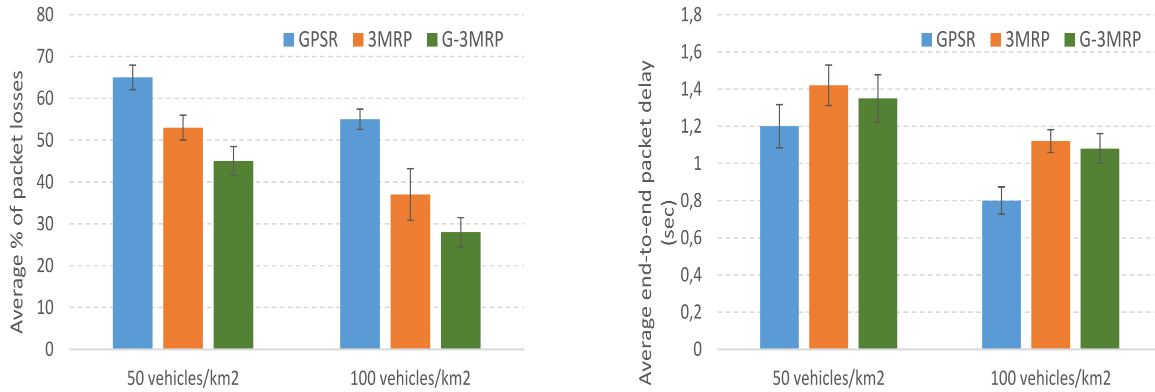
Finally, Fig. 8 depicts the peak signal-to-noise ratio (PSNR) to assess the video quality of the received video flow. We can see that G-3MRP improves the PSNR in around 1 dB compared to 3MRP, and in around 2–3 dB compared to GPSR, in both scenarios with low and high vehicles' densities. The reason is that G-3MRP is able to balance the load of the video-reporting messages among the two best forwarding nodes at each hop, instead of just choosing the best forwarding node (as it is done in 3MRP). That is, G-3MRP is able to select better than 3MRP the next hop forwarding nodes. Results of this performance evaluation show clear benefits after including our game-theoretical forwarding approach in our former multimedia multimetric routing protocol for VANETs (3MRP) .

Table 2
Simulation settings of the VANET scenario.

Map zone	Eixample district of Barcelona, Spain
Area	1700 m × 580 m
Density of vehicles	50 vehicles/km^2 (scenario 1) and 100 vehicles/km^2 (scenario 2)
Transmission range	250 m
Average vehicle speed	50 km/h
Maximum vehicle speed	120 km/h
Vehicles speed function	Gaussian function, μ = 50 km/h, σ = 23.33 km/h
Mobility generator	SUMO [41]/C4R [40]
MAC specification	IEEE 802.11p [43]
Radio propagation model	Nakagami [42]
Nominal bandwidth	11 Mbps
Simulation time	300 s
Routing protocol	3MRP [7], G-3MRP
Number of video sources	2
Video encoding	MPEG-2 VBR
Video bit rate	150 Kbps
Video sequence sent	Video reporting traffic accident [39]
Transport protocol	RTP/UDP
Maximum packet size	1500 Bytes
Weighting values in Eq. (1)	Dynamic self-configured weights (DSW), see Section 4.1
Queue sizes	50 packets

8.2.1. Evaluation of the improvement in the utility function

In this section we will compute the gain of our game-theoretical forwarding scheme included in our novel routing protocol G-3MRP. Let us define U_{G_i} as the utility function for player i when the game-theoretical routing scheme G-3MRP is used; let U_{NG_i} be the utility function when it is not used, i.e. when the routing scheme is 3MRP. Both utility function values will be computed using Eq. (13). G_i, 0 ≤



(a) (b)

Fig. 7. Each vehicle sends a video-reporting message regarding an accident towards the closest RSU. (a) Average percentage of packet losses for $N = 2$ sending vehicles. (b) Average end-to-end packet delay for $N = 2$ sending vehicles.

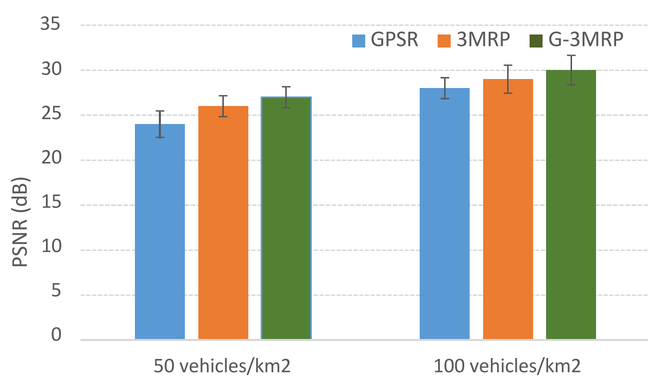


Fig. 8. Peak Signal to Noise Ratio (PSNR) for $N = 2$ vehicles, each sends a video-reporting message regarding an accident towards the closest RSU.

$G_i \leq 1$, is the gain obtained for player i by using G-3MRP with respect to not using it, i.e. with respect to using 3MRP.

$$G_i = \frac{U_{G_i} - U_{NG_i}}{U_{G_i}} = \frac{U_{p_i=p_i^*} - U_{p_i=1}}{U_{p_i=p_i^*}}, 0 \leq G_i \leq 1 \tag{45}$$

Notice that G-3MRP with $p_i = 1$ equals 3MRP, i.e. 3MRP is equivalent to G-3MRP when no game-theoretical forwarding algorithm is used and video frames are always forwarded through the best-quality neighboring node. Using Eq. (13) in Eq. (45) we obtain the gain G_i obtained for player i by using G-3MRP with respect to using 3MRP:

$$G_i = \frac{U_{G_i} - U_{NG_i}}{U_{G_i}}$$
$$= 1 - \frac{\left(\frac{n_{rB,i} - n_{s,i}\cdot 1}{n_{s,i}\cdot 1}\right)\cdot \phi_{B,i} \cdot 1}{\left(\frac{n_{rB,i} - n_{s,i}\cdot p_i^*}{n_{s,i}\cdot p_i^*}\right)\cdot \phi_{B,i} \cdot (p_i^*)^2 + \left(\frac{n_{rM,i} - n_{s,i}\cdot (1-p_i^*)}{n_{s,i}\cdot (1-p_i^*)}\right)\cdot \phi_{M,i} \cdot (1-p_i^*)^2} \tag{46}$$

In the next section we will show a numerical example to assess the gain G_i obtained for player i by using G-3MRP with respect to using 3MRP, using Eq. (46).

8.2.2. A numerical example

In this section we show a numerical example to calculate the gain obtained with our proposal G-3MRP with respect of using 3MRP, for $N = 2$ vehicles using Eq. (46). To assess that gain we need to compute G_1 and G_2 for both vehicles. To do that, from a large number of representative simulations we obtain a set of average values for the variables needed to compute Eq. (46). The obtained values are shown in Table 3 and explained in the following:

Table 3
Simulation output values for $N = 2$ vehicles which send each a video-reporting message towards the closest RSU.

veh.1, veh.2	Measure	Description
$\hat{n}_{B,1}$, $\hat{n}_{B,2}$	(0.65, 0.61)	% of I+P video frames delivered if selecting always best-quality nodes, see Eq. (16)
$\hat{n}_{M,1}$, $\hat{n}_{M,2}$	(0.44, 0.49)	% of I+P video frames delivered if selecting always medium-quality nodes, see Eq. (16)
$S_{B,1}$, $S_{B,2}$	(0.88, 0.83)	Average multimetric score measured for highest-quality nodes, see Eq. (1)
$S_{M,1}$, $S_{M,2}$	(0.74, 0.7)	Average multimetric score measured for medium-quality nodes, see Eq. (1)

- In the first line of Table 3, $\hat{n}_{B,1} = 0.65$ represents that a 65% of I+P video frames sent from vehicle i=1 were successfully delivered at destination (closest RSU), see Eq. (16), when the strategy of the intermediate forwarding nodes is to select always the best-quality forwarding node (B). For vehicle i=2, the percentage was $\hat{n}_{B,2} = 0.61$.
- When the strategy of the intermediate forwarding nodes is to select always the medium-quality forwarding node (M), the percentage of I+P video frames successfully delivered at destination is $\hat{n}_{M,1} = 0.44$ for vehicle $i = 1$ and $\hat{n}_{M,2} = 0.49$ for vehicle $i = 2$, see line 2 in Table 3.
- In the same way, $S_{B,i}$ represents the average multimetric score regarding the forwarding nodes involved in the video-reporting packets sent from vehicle i when the strategy is to select always the best-quality forwarding node as next hop towards destination, see Eq. (1).
- Finally, $S_{M,i}$ is the average multimetric score regarding the forwarding nodes involved in the video-reporting packets sent from vehicle i when the strategy is to select always the medium-quality forwarding node, see Eq. (1).

We calculate the variables $k^1_{B/M}$ and $k^2_{B/M}$ for vehicles 1 and 2 using Eq. (44) and the simulation output values shown in Table 3. Results are shown in Table 4.

Table 4
Best response probabilities p_i^* for $N = 2$ vehicles.

veh.1, veh.2	Calculation	Description
$k^1_{B/M}$, $k^2_{B/M}$	(−0.0766, −0.0822)	Configuration parameter described in Eq. (44)
p_1^*, p_2^*	(0.8256, 0.8036)	Best response probability, see Eq. (24)

After that, we simplify $\left(\frac{n_{rB,i}-n_{sB,i}}{n_{sB,i}}\right)$ and $\left(\frac{n_{rM,i}-n_{sM,i}}{n_{sM,i}}\right)$ as it is done in Eqs. (47) and (48) to be easily calculated later using Tables 3 and 4.

$$\left(\frac{n_{rB,i}-n_{sB,i}}{n_{sB,i}}\right) = \frac{n_{rB,i}-n_{s,i}\cdot p_i^*}{n_{s,i}\cdot p_i^*} = \frac{\hat{n}_{B,i}}{p_i^*} - 1 \tag{47}$$

$$\left(\frac{n_{rM,i}-n_{sM,i}}{n_{sM,i}}\right) = \frac{n_{rM,i}-n_{s,i}\cdot (1-p_i^*)}{n_{s,i}\cdot (1-p_i^*)} = \frac{\hat{n}_{M,i}}{(1-p_i^*)} - 1 \tag{48}$$

We calculate $\phi_{B,i}$ and $\phi_{M,i}$ for player i using Eqs. (21) and (22), respectively, so they can be substituted in Eq. (13).

$$\phi_{B,1} = k_{B,1}\cdot S_{B,1} = k^1_{B/M}\cdot k_{M,1}\cdot S_{B,1} = -0.0674\cdot k_{M,1} \tag{49}$$

$$\phi_{B,2} = k_{B,2}\cdot S_{B,2} = k^2_{B/M}\cdot k_{M,2}\cdot S_{B,2} = -0.0682\cdot k_{M,2} \tag{50}$$

$$\phi_{M,1} = k_{M,1}\cdot S_{M,1} = 0.74\cdot k_{M,1} \tag{51}$$

$$\phi_{M,2} = k_{M,2}\cdot S_{M,2} = 0.7\cdot k_{M,2} \tag{52}$$

Finally, substituting Eqs. (47) to (52) in Eq. (46), we obtain that $G_1 \approx 0.46$ and $G_2 \approx 0.48$. These values mean that for vehicle $i = 1$ the gain is 46% higher using the game-theoretical proposal G-3MRP instead of using 3MRP. In the same way, for vehicle $i = 2$ the gain is 48%. These numerical results corroborate the benefits shown by G-3MRP in the performance evaluation carried out in Section 8.

9. Conclusions and future work

In this paper, we have designed a new multimetric routing protocol for VANETs named *game-theoretical multimedia multimetric map-aware routing protocol* (G-3MRP) to transmit video-reporting messages in smart cities. The geographical routing protocol is based on a game-theoretical forwarding algorithm for *N players* (i.e., vehicles in our case). Our framework could be used in smart cities where prevention and fast management of accidents is an important goal. We understand that including a short and light video message in the incident report, the level of seriousness of an accident could be much better evaluated by the authorities allowing a fast warning of the incident to emergency units, which potentially could save lives.

The users of the framework could be any vehicle that could participate in the VANET by transmitting a video-reporting message to the competent authorities. In this way, other vehicles would be easily warned of any situation in the city, which would improve road safety in smart cities.

Our game-theoretical forwarding algorithm depends on a probability p of sending the most important video frames (i.e., I+P frames) through the best forwarding node available within transmission range of the vehicle currently holding the packet. This probability p varies depending on some local characteristics of the vehicular network. In our case, we use five metrics to assess the candidate next-hop forwarding nodes: distance to destination, vehicle's trajectory, vehicles' density, available bandwidth, MAC losses. In our proposal, instead of sending the I+P video frames always through the best forwarding node in the neighborhood, vehicles play a strategic forwarding game where those frames will be sent through one of the two best available next-hop vehicles according to a certain probability p_i^*, i.e. the best response probability computed in the game-theoretical forwarding algorithm.

Simulation results in a generic VANET scenario show the benefits of our proposal G-3MRP, which outperforms the case of non using our game-theoretical routing scheme. In terms of packets losses, average end-to-end packet delay and PSNR, results notably improve due to the new way of selecting the next forwarding node based on probability p_i^*. Our proposal makes the vehicular network more efficient, as well as it achieves a higher degree of satisfaction of the end users (emergency units in our case) who receive more (I+P) frames with a lower average end-to-end delay. This definitively will improve the quality of experience regarding the video perceived by the end user.

As future work, we will design, implement and evaluate a machine learning-based forwarding approach to send video-reporting messages over vehicular networks in urban scenarios. Additionally, we will investigate how to combine both machine learning-based and game-theoretical strategies to further improve the vehicular network performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Spanish Government under research project "Enhancing Communication Protocols with Machine Learning while Protecting Sensitive Data (COMPROMISE)" PID2020-113795RB-C31, funded by MCIN/AEI/10.13039/501100011033. Ahmad M. Mezher holds a McCain Postdoctoral Fellowship in Innovation with the Electrical and Computer Engineering department at the University of New Brunswick (UNB), Canada.

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