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Shielding video streaming against packet losses over VANETs

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Abstract Vehicular ad-hoc networks (VANETs) are being widely adopted in the last few years. This type of network enables the utilization of a large diversity of distributed applications, such as road and traffic alerts, autonomous driving capabilities and video distribution. Video applications can be considered one of the most demanding services because it needs a steady and continuous flow of information. This presents a set of challenges to VANETs considering their scarce network resources due to the vehicle movement and time-varying wireless channels. Considering the above mentioned issues, an adaptive quality of experience (QoE)-driven mechanism is needed to provide live transmission capabilities to video-equipped vehicles. This mechanism has to overcome the challenges to grant a high-quality video transmission without adding any unnecessary network overhead. To this end, a forward error correction (FEC) technique can be adapted to enhance the video distribution, leading to higher QoE for end users. The proposed self-adaptive FEC-based mechanism (SHIELD) uses several video characteristics and specific VANETs details to safeguard real-time video streams against packet losses. One of the main contributions of this work is the combined used of network density, signal-to-noise ratio, packet loss rate, and the vehicle's position. This allows SHIELD to better protect the video sequences and enhance the QoE. In doing that, we are able to improve the user experience, while saving network resources. The advantages and drawbacks of the proposed mechanism are demonstrated through extensive experiments and assessed with QoE metrics, proving that it outperforms both adaptive and non-adaptive mechanisms.

Keywords VANETs · Forward error correction (FEC) · Unequal error protection (UEP) · Fuzzy logic · Quality of experience (QoE)

1 Introduction

The vehicular ad-hoc network (VANET) is considered the core component of intelligent transportation systems (ITS), providing support to many applications, including video services. This type of service is gaining popularity on a daily basis, being currently on high demand [1, 2] due to the popularization of better network and video devices. The adoption of video services can be used as means to provide users with both information and entertainment content.

The endorsement of video-based services can be beneficial to a broad range of situations, such as road safety, driver awareness, traffic status, and infotainment applications. Besides the users' experience, the video quality is also important to allow a better assessment of each situation. For example, it can give police officers, paramedics, and fire fighters an accurate representation of the scene they will attend, thereby reducing the response time. Beyond the traffic related services, a sport venue or a festival could broadcast a live feed to incoming fans caught in a traffic jam. These are only simple examples of a

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limitless number of alternatives to make available rich-format services. These services, however, have to deal with the unreliable wireless connection of the VANETs, which are highly dynamic in nature and strongly prone to packet loss [3, 4]. Because of that, it is imperative to strengthen the video transmissions against losses [5, 6]. This calls for an adaptive mechanism to enhance the video delivery to provide higher Quality of Experience (QoE).

QoE is a set of methods to assess the overall customer's experience level of satisfaction regarding a service. This method is related to, but differs, from the well-studied Quality of Service (QoS). In VANETs there is still a lack of adaptive QoE-driven mechanisms to better support live video transmissions [7–10]. This can be attributed to the challenging combination of the VANETs' dynamic topology and the stringent video requirements. In order to surpass these adversities, a good mechanism has to take into consideration several aspects of the intrinsic network characteristics and video details, being able to correctly identify and protect the most QoE-sensitive data.

Several techniques have been proposed to tackle the VANETs challenges in the last few years. Some of them are trying to solve these issues throughout adaptive routing protocols [11–15]. The results show that a reliable routing protocol has a major influence on improving the video quality. This improvement, however, is restricted to a specific level. After this level, to increase or even sustain the video quality it is crucial to resort to some amount of redundant data, which allows reconstructing the original data set in case of packet losses. A known approach to supply this redundancy is using Forward Error Correction (FEC) techniques. These techniques have been adopted and produced favourable outcomes by enhancing the video quality in live transmissions [16, 17]. However, due to the video requirement of a timely delivery of a considerable amount of data [18], along with the shared wireless channel resources, a self-adaptive FEC-based mechanism is advisable. This mechanism needs to have the capability to operate under unforeseen conditions in order to increase the human perception, while reducing the network overhead.

In order to tackle the above-mentioned issues, this article proposes a self-adaptive FEC-based proactive error recovery mechanism to shield video transmissions over VANETs (SHIELD). One problem frequently found in FEC-based mechanisms is absence of QoE-related details to compute the required amount of redundancy. For this reason, SHIELD is also a QoE-driven mechanism. This means that meaningful video aspects related to the human point-of-view, are not neglected, which leads to the addition of a very specific amount of redundancy.

Another important feature of the proposed mechanism is the use of Unequal Error Protection (UEP). Not all video packets have the same importance to ensure the final video quality [19, 20]. To improve in these issues, SHIELD adopts a Hierarchical Fuzzy System (HFS) [21]. HFS allows adding an accurate amount of video redundancy specifically to the more QoE-sensitive data. This increases the video quality according to the human perception while cutting down on the network overhead.

The SHIELD mechanism was evaluated using real video sequences and actual maps' clippings with the aid of objective QoE metrics. The remainder of this article is organised as described next. Sect. 2 features the related work. Sect. 3 describes the SHIELD mechanism and Sect. 4 its assessment. Conclusions and future work are presented in Sect. 5.

2 Related work

In recent years, several techniques have been proposed to increase the quality of video transmission over VANETs. Some of these proposals rely on routing protocol adaptations, e.g. the QoE-based routing protocol for video streaming over VANETs (QOV) [13]. In QOV, the perceptual quality of the videos is assessed in real-time, at the receivers, using the Pseudo-Subjective Quality Assessment (PSQA) [22] metric. After that, the results are announced to the neighbours throughout `Hello` packets. This allows the routing protocol to choose the best paths to deliver the video sequences. Nevertheless, VANETs are very dynamic networks and because of that, the proposed mechanism would have to update very quickly the PSQA result announcement, overloading the network with `Hello` packets. Another weakness of this proposal is that it does not include any type of error correction (EC). As aforementioned, the video quality can be maintained only up to a certain level without using EC, however, if the network has a high packet loss rate the quality will decrease.

Another proposal is an adaptive multi-objective Medium Access Control (MAC) retransmission limit strategy [23]. At the Road Side Units (RSUs), channel statistics and packet transmission rate are used as input to the optimization framework in order to tune the MAC retransmission limit. This optimization improves the performance of video transmission, leading to better video quality. However, it aims to only minimize the playback freezes and reduce the start-up delay. These are important characteristics, however, QoE metrics should be used to assess the image quality. This evaluation would provide a more comprehensive assessment of the proposed mechanism. Additionally, the authors only took into account the use of RSUs and two-hop communications. It is known that the major advantages of VANETs come from the communication directly between the vehicles, without the need for a fixed infrastructure. This severely restricts the application of the mechanism.

In addition to these mechanisms, several FEC-based methods have also been proposed to enhance the quality of videos in transmissions over VANETs. The Hybrid Video Dissemination Protocol (HIVE) [24] uses a multi-layer strategy to improve the video quality. The HIVE multi-layer strategy is based on the joint use of traffic congestion control scheme, node selection method, and application layer erasure coding technique. This allows higher packet delivery ratio, while keeping latency and packet collisions low. The results show improvement in the Peak signal-to-noise ratio (PSNR) assessment, leading the authors to claim that they improved the QoE for end-users. However, relying in only one metric is not enough to prove that, especially considering that the PSNR results do not correlate well with the human vision system [25]. Another issue is the lack of video characteristics assessment. It is known that these video details have a considerable impact on how resilient a video sequence is against packet loss.

The Blind XOR (BXOR) scheme [26] adopts an adaptive low-overhead XOR technique to enhance the video quality. This mechanism works by blindly setting packets to be retransmitted, relying on the conditional reception probability (CRP). This means that, if there is a probability of not receiving a set of packets, they are tagged to be retransmitted, even if they had not been lost yet. The estimation of the CRP is performed on the server side without feedback from the clients. A drawback of this mechanism is that it heavily relies on the CRP estimation, which may not be accurate. Furthermore, this mechanism also does not take into consideration the video characteristics. As previously mentioned, this detail can have a significant impact on the video quality, especially on determining a precise amount of redundancy.

Another mechanism to improve the video quality over VANETs compares the efficiency of Random Linear Coding (RLC) and XOR-based coding [27]. The benchmark results show that both erasure codes are able to improve the video quality by increasing the number of successfully received packets over error-prone networks. The results also show that XOR-based coding outperforms the RLC scheme. In addition, the proposed mechanism finds the optimal packet block size, which allows adding a more precise amount of redundancy. However, important features are not considered, namely the network status and the video characteristics. These details play a critical role in the optimization of the amount of redundancy required to provide both good video quality and low network overhead.

3 QoE-driven video transmission

On account of the previously mentioned challenges, this work presents and assesses the self-adaptive FEC-based SHIELD mechanism. The importance of this proposal relies on the shortage of QoE-driven mechanisms that are able to combine video characteristics, such as the motion activity, with particular VANETs features. Our mechanism is able to offer videos with higher QoE while, at the same time, downsizing the network overhead footprint. This work improves on our previous mechanism [28]. Key enhancements are disclosed and discussed below.

Additionally, in this work the vehicle-to-vehicle (V2V) communication characteristics are explored to better adjust the proposed mechanism to the actual network conditions. Even though a VANET environment enables roadside infrastructure, the V2V communication was chosen because it is unlikely that such infrastructure will cover all the highways and cities in the near future. Consequently, if the infrastructure is available it can be used, however, the optimizations will only be performed on the communication between the vehicles.

3.1 SHIELD overview

Figure 1 depicts an overview of the proposed mechanism. The first step, is to assess the network conditions (1). In order to do that, different parameters are evaluated in a combined way, namely the network density, SNR, and PLR, as well as the node's position. To calculate the density, first the network area is found through an approximate hull algorithm. After that, the total number of 1-hop nodes is divided by the area, which gives the network density. All these parameters are necessary because none of them by itself is accurate enough to characterize the quality on the network links [29, 30]. The combination of them, however, can provide a very good estimation of the network conditions. Thereafter, using cross-layer techniques, important details about the video characteristics are collected (2). In the video-aware procedure of the mechanism several details are analysed, such as the image resolution, frame type and size, motion vectors, and macroblock configuration. At the end, all the gathered data are fed to the fuzzy inference engine, which will compute a specific amount of redundancy (3).

Provided that the network conditions are not the same at all intermediate nodes, this parameter has to be reassessed at each hop (4). On the other hand, the video characteristics do not change during the transmission. Because of that, they are embedded in each packet header by the server node. This eliminates the need for processor intensive tasks (e.g. deep packet inspection) on each and every packet. The IPv6 optional hop-by-hop header was chosen to store this information [31]. This means that it is always ready to use whenever needed (5,6). Owing to this, the task of adjusting the redundancy amount on each hop is facilitated. The

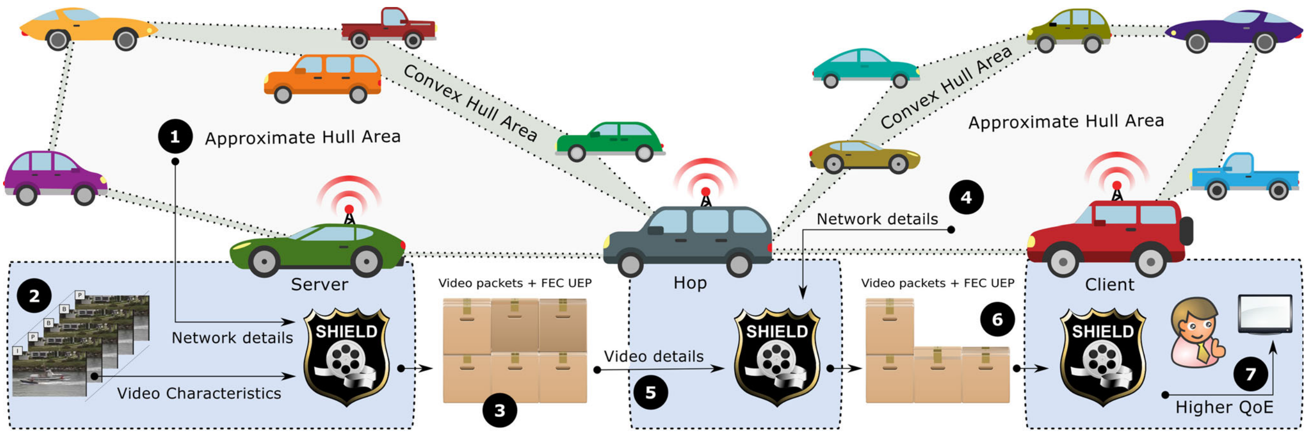

Fig. 1 General view of the SHIELD mechanism

result is a higher video quality, and consequently, superior QoE is perceived by the end-users (7).

3.2 Towards the design of SHIELD

This section describes the manifold procedure and modules that the SHIELD mechanism is composed of. Primarily, to enable the SHIELD real-time capabilities, a knowledge database is needed. This database is created using a hierarchical clustering technique [5] to store video details, which includes several video characteristics and their impact on the QoE. A comprehensive description of this process can be found in [32].

Another important feature to enable the SHIELD real-time capabilities is the use of Fuzzy Logic (FL). This allows building a dynamic and comprehensive scheme, which takes into consideration several network and video characteristics, and still manages to perform in real-time. Nevertheless, in conventional FL systems the rules grow exponentially according to the number of variables. Because of that, it is common to have a rule-explosion situation when handling a lot of variables, making the FL controller very hard to implement. To address this issue, the SHIELD mechanism was designed to use a Hierarchical Fuzzy System (HFS). In HFS, low-dimensional fuzzy systems can be arranged in a hierarchical form, reducing the global number of rules because the system grows linearly.

The combined use of the knowledge database and human expertise enables setting up the fuzzy sets, rules, and hierarchical levels. Once this analysis is finished, the produced data is loaded in the fuzzy inference engine, making it possible to be performed in real-time. This is a very important step in the mechanism because it reduces the number of rules that will be processed in real-time, leading to a more precise and faster mechanism.

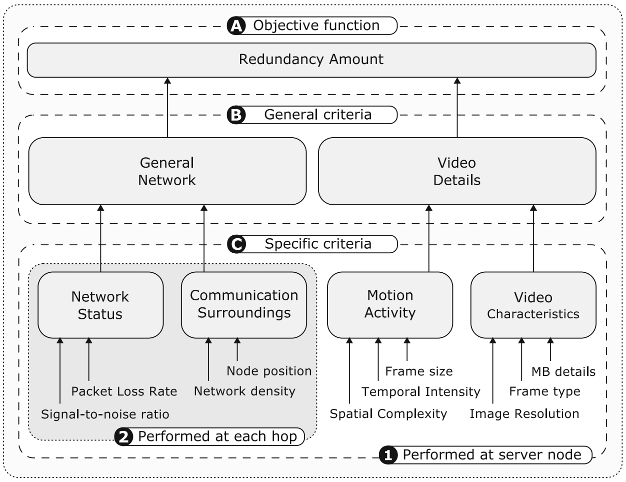

Fig. 2 Hierarchical fuzzy logic structure

Figure 2 depicts the hierarchical levels adopted by SHIELD. There are three layers, namely (A) Objective function, (B) General criteria, and (C) Specific criteria. The output of each low-level layer is used as input to the next layer. The first layer (A) represents the amount of redundancy that our mechanism will add to a specific portion of video data. The main goal is to find the amount of redundancy for a system that, given its constraints, results in less network overhead and better QoE. The second layer (B) encompasses the overall details that the proposed mechanism uses to determine the redundancy amount, namely the network details and the video characteristics. The bottom layer (C) is responsible for handling the input parameters of each feature used by the fuzzy logic inference system. This layer has a subdivision (C)(2), which is performed at each network hop. All the input parameters (C)(1) are only taken into consideration at the server node.

The design of HFS follows the same method as in standard fuzzy logic schemes. This means that several fuzzy components have to be defined, such as sets, rules, membership functions and the inference engine. The fuzzy rules are a group of linguistic control rules, which describe how the system works. The fuzzy sets are a collection of elements that have some degree of membership. This differs from the classical set definition, where an element either belongs or does not belong to a set. The membership functions provide the degrees of truth of each element in the fuzzy set. The inference engine is responsible for the decision-making process, which is based on the fuzzy rules, sets and the input linguistic parameters. This is an offline process and needs to be executed only once. Following this, the resulting data are loaded into the fuzzy inference engine to be used in real-time. A detailed explanation of this process is given below.

3.2.1 The "general network" criteria

The "general network" criteria accounts for the definition of the network conditions. The characterization of a good or bad channel is not an easy task and it cannot rely upon a single metric, especially in wireless networks [29]. With this in mind, the SHIELD mechanism uses four metrics to better establish a network quality indicator. These metrics are divided into two specific criteria, namely "network status" and "communication surroundings". The former is defined by the combined assessment of the SNR and the PLR. The latter is given by the network density and the position of the vehicles. Each one of these metrics is described next.

The SNR is the level of the desired signal against the level of background noise. This is a good indicator for the physical medium, especially for spectrum sensing. While this is true, it cannot be considered a reliable general network quality indicator by itself. This steams from the fact that a strong channel signal will not always produce a good network connection [29]. On the other hand, a very weak signal will yield a low quality network connection. Because of that, to create a more holistic indicator more than one metric has to be used. Another obvious candidate to define the network quality is the PLR. In general, the SNR and PLR have a negative correlation, meaning that when one increases, the other decreases and vice versa. However, they complement each other because the SNR takes into consideration the physical spectrum part of the transmission and the PLR provides a point of view closer to the application layer.

An extensive number of network simulations were carried out to better characterize the impact of different PLRs in the QoE. Video sequences tend to have a natural resiliency to packet loss [33], because of that, several video sequences, with distinct features were used during the experiments. The output of the experiment made evident that it is possible to have a good QoE with packet loss between 0 and 12 %. In most of the cases, an acceptable video quality for end-users was perceived with losses from 5 up to 23 %. However, after a threshold of 19 % the video quality starts to decrease apace, particularly in videos with high resolution and motion intensity. In the experiments with more than 36 % of PLR the QoE reached unbearable levels. Algorithm 1 shows only one of the many fuzzy sets defined in the SHIELD mechanism. In this case, it is the PLR fuzzy set, which was found through the experiments aforementioned.

Algorithm 1: Packet loss rate fuzzy set

```
InputLVar* PLR = new InputLVar("PacketLossRate");
    PLR → addTerm( TriangularTerm("LOW", 0, 12));
    PLR → addTerm( TriangularTerm("MEDIUM", 5, 23));
    PLR → addTerm( TriangularTerm("HIGH", 19, 100));
engine.addInputLVar(PLR);
```

Another component of the "general network" criteria is the "communication surroundings". As aforementioned, it uses the network density and the position of the vehicles to provide more information about the network in which the video sequences are being transmitted. These parameters are updated at each beacon exchange in the routing protocol. The network density is given by the number of nodes, in our case vehicles, divided by the network area. It is important to notice that VANETs are very dynamic networks with a decentralized structure, proving to be a challenge the estimation of the network surface area. To address this issue, the proposed mechanism uses an approximate convex hull algorithm.

A convex hull algorithm is able to find the smallest boundary polygon containing all the points inside of it, using only non-intersecting segments, as showed in Fig. 3a. There are several algorithms to find the convex hull of a given set of points. In our previous work [28] the QuickHull [34] method was used. It uses a divide-and-conquer algorithm with average complexity of $\mathcal{O}(n \log n)$ and at the worst case it could take $\mathcal{O}(n^2)$. However, the proposed mechanism does not need a high precision value for the area, instead, a good approximation is sufficient to provide very good results. Because of this, and to improve the general performance, we use the BFP [35] approximation convex hull algorithm as showed in Fig. 3b.

The BFP algorithm, which runs in $\mathcal{O}(n)$ time, replaces the sort operation by dividing the plane in vertical strips. In each strip, the minimum and maximum points are found and added to the boundary. This algorithm is an approximation because a non-extreme point, in a given strip, can be discarded even if it is on the convex hull boundary. Nevertheless, the point will not be far from the convex hull, resulting in a good approximation of the actual convex hull.

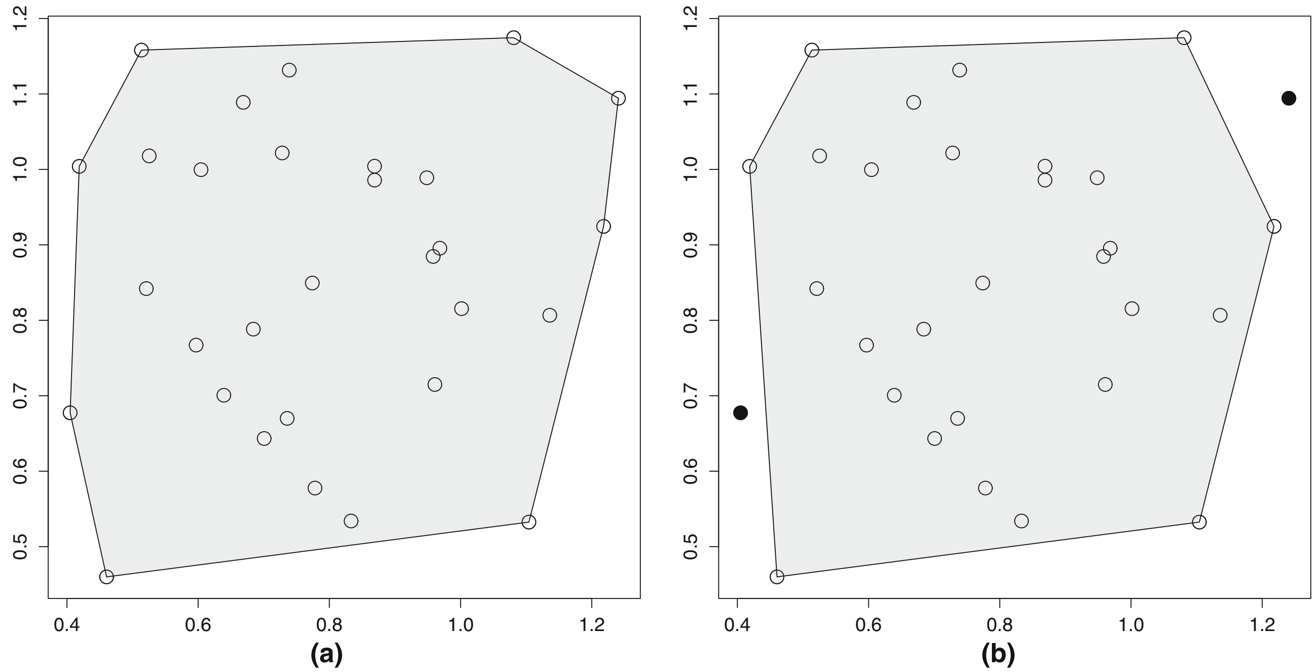

Fig. 3 **a** Convex hull and **b** approximate convex hull

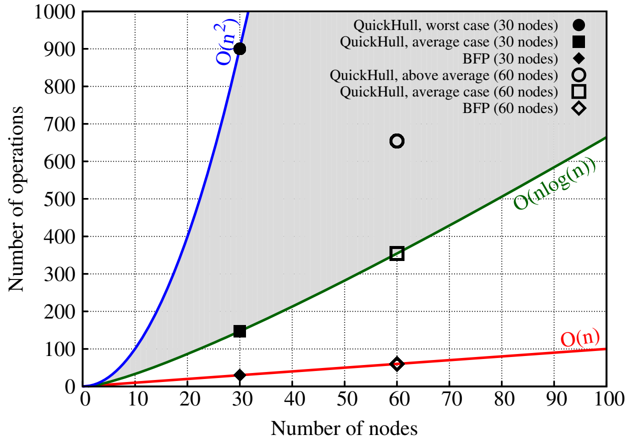

Fig. 4 Complexity of QuickHull and BFP

Figure 4 shows the comparison between the number of nodes and the resulting number of operations in both QuickHull and BFP algorithm. On average, the QuickHull algorithm has fairly good performance, it can degrade however, up to exponential in the worst case. On the contrary, the BFP algorithm has a steady linear performance, providing results more quickly even with small number of nodes.

There is a multitude of advantages to perform fewer operations. First of all, due to the time-sensitive video data it is important that the client node receives the information as soon as possible, thus performing fewer operations allows dispatching the video quickly. In addition, because of the fast time-varying network conditions, the faster this information is made available the more accurate it is. At last, performing a minimum number of operations means less energy consumption as well as more available processor power to perform other tasks.

The node position is the last specific criteria of the "general network" layer. This is a straightforward, but very important information. Because of signal attenuation and radio-frequency interference, nodes further away from each other tend to require a higher amount of redundancy to preserve a good video quality. This information becomes even more valuable used in conjunction with the other input parameters. For example, a much higher amount of redundancy will be required if the network is very dense and the nodes are far apart than if the network was not so heavily populated.

At the end, the "general network" layer is responsible for the integration of the SHIELD mechanism for the VANETs. In this layer, all the network related issues are tackled, allowing the proposed mechanism to be tailored specifically for this type of network. This provides higher performance and better QoE results.

3.2.2 *The "video details" criteria*

Besides the network conditions, the video characteristics are also important to define a precise amount of redundancy. In SHIELD hierarchical fuzzy system the "video details" criteria layer is divided into two specific components, namely “motion activity” and “video characteristics”.

The motion activity parameter is defined by the combined use of temporal intensity and spatial complexity. The temporal intensity in the SHIELD mechanism is given by the motion vector (MV) details. The MV in the video sequences complies with the classical mechanics concept of vector-oriented motion model. All moving objects are described as a simple sequence of small translations on a plane. This was transposed to the Moving Picture Experts Group (MPEG) standard as the movement of macroblocks from one position, in any given frame, to another position, in the next one. Since the MPEG standard allows the use of distinct macroblock sizes, the SHIELD mechanism computes the area of each macroblock and uses the number of pixels that are being moved. This enables a better representation of the intensity of the motion in arbitrary resolutions.

In addition, the Euclidean distance of each MV is also computed, resulting on how far each and every macroblock is being moved. This information gives more precise results than just counting the number of motion vectors. All the input parameters are normalized, allowing the protection of videos with arbitrary resolutions on the fly. Following the same idea as presented before, an exploratory analysis using hierarchical clustering is performed to find the best classes that represent the temporal intensity. After finding the classes, the fuzzy set and the membership function can be defined. Finding the best-fitted membership function is a complex and problem-dependent task [36], being difficult to attain the optimal solution. For this reason, piecewise linear functions are desired. These functions are formed of straight-line sections and because of that, provide efficient computational operations.

As previously mentioned, the spatial complexity is also used to quantify the amount of the motion activity. This parameter represents the difference of the static information that the actual frame has when compared to the one before. One way to compute this value is using the Sum of Absolute Differences (SAD) [37]. This process, however, compares each and every pixel of both frames resulting in a very complex and time-consuming operation. Taking this into consideration, the SHIELD mechanism uses the normalized frame size to the same end. This enables a much faster operation and, on top of that, it also allows the use of arbitrary video resolutions.

The same process used to find the different classes in the temporal intensity is also used to define the clusters here. This means that, once all the frame sizes are normalized, an exploratory analysis is performed to divide the data into the most homogeneous groups. After that, using the linkage distance between the clusters was possible to separate them into five distinct groups, namely “very small”, “small”, “medium”, “large”, and “very large”.

With the definition of the fuzzy sets completed, the fuzzy rules must be designed. As mentioned before, this is an intricate task, which requires a jointly knowledge of the network details, VANETs properties, and video characteristics. Aiming to reduce this complexity during the design phase of the rules, as well as to have a better performance in real-time, the SHIELD mechanism uses HFS. This layered system allows handling fewer input parameters at the same time. At the end, the result is a system with a small number of simple rules, which lead to better performance.

The last step of the offline process is to load all the fuzzy sets and rules in the Fuzzy Logic Controller (FLC). Unlike genetic algorithms or neural networks, the FLC does not require an online training or a period of convergence, making it an appropriate engine for real-time control. This process has to be performed just once, during the system bootstrap period. After that, all the functions can be accessed in real-time. This provides the SHIELD mechanism to ascertain the best-fitted QoE-aware amount of redundancy according to each video sequence that is being transmitted in the VANET environment.

4 Performance evaluation and results

The primary goal of the SHIELD mechanism is to enhance the QoE, while avoiding any unnecessary network overhead. In doing that, it improves the end-users satisfaction and preserves the already scarce wireless resources at the same time.

4.1 Experiment settings

In order to better characterize the performance of the proposed mechanism two very distinct environments were assessed: urban and highway. Each of these surroundings features a variety of unique challenges. In the urban environment, there are buildings and many other structures that will affect the signal propagation. On the other hand, in the highway environment there is much more free space, which facilitates the signal propagation. Besides that, the mobility patterns are also very distinctive. The urban scenario presents a lot of driving options, such as avenues and streets close to each other. On the highway is quite different, as there are no crossroads and just a few exits and entrances. In addition, the speed of the vehicles has very particular properties in each one of these environments. In the urban case, the velocity usually is between 20 km/h and 60 km/h, and it changes frequently due to traffic lights, speed bumps, and crosswalks. Meanwhile, on the highway, the speed variance is very low, staying consistently from 80 km/h to 120 km/h.

Taking account of all such differences, the Network Simulator 3 (NS-3) [38] was used to perform the experiments; both environments were simulated in a variety of situations. Several configurations are shared, such as the wireless and network technology, as well as the video content and parameters. All videos were sent using Evalvid Tool [39] and encoded with H.264, GoP length of 19:2. Additionally, three different resolutions were used, namely 1080p, 720p, and SVGA. For each resolution, 10 videos were chosen to be transmitted [40]. These real video sequences cover different content of commonly viewing material. The videos also have luminance and colour stress, still and cut scenes, as well as distinct motion intensities and several levels of distortions. A multi-flow scenario was adopted. This means that up to 10 videos are transmitted simultaneously[1]. All the receiver nodes are enabled with Frame-Copy error concealment, meaning that each lost frame will be replaced by the last good one.

Another feature that is the same for both environments is the wireless standard adopted: IEEE 802.11p Wireless Access for Vehicular Environments (WAVE) [41]. The communication is Vehicle To Vehicle (V2V), because it does not require a pre-existing infrastructure. Moreover, this type of communication is envisaged as the next generation of connected cars, providing a mesh-network based communication system, where each vehicle is able to both send and receive information. Additionally, the routing protocol Cross-Layer, Weighted, Position-based Routing (CLWPR) [42] was adopted due to its position-based characteristics. This protocol uses mobility details acquired from the nodes to better adapt itself for a particular VANET environment.

The mobility traces for both environments were generated using the Simulation of Urban MObility (SUMO) [43]. This tool uses real map clippings to produce the traces. Several details are taken into consideration, such as routes, roundabouts, driving patterns, and traffic lights. For the urban environment, a clipping of 2 × 2 km of the Manhattan borough (New York City) was used. This environment was simulated with up to 360 vehicles at speeds ranging from 20 and 60 km/h. Despite the name, SUMO can also generate highway traces considering, for example, interchange junctions (entrance and exit ramps) and the number of lanes. To simulate this environment a clipping of 10 km of US Interstate Highway 78 (I-78) was used. The number of vehicles is the same, up to 360, with velocity between 80 and 120 km/h.

Two different propagation models were used to better represent each environment. In the highway scenario, the logDistance propagation model was used [44]. This is because of the open spaces and the reduced number of sources of interference existent in this environment. This leads to easier communication between the nodes. On the other hand, in the urban environment there are plenty of sources generating interference. Because of that, on top of the logDistance model was added the Nakagami-m propagation model. This allows simulating the fast fading characteristics commonly found in this environment [45]. Table 1 summarizes the simulation parameters.

Figure 5 shows the steps involved in the experiment. First of all, the mobile traces are required from the SUMO application (1). After that, SUMO will use real map clippings from the OpenStreetMap (2) to generate the traces. The traces enable a realistic simulation, providing more accurate results. Following this, all the information is loaded in the SHIELD mechanism (3). Next, the proposed mechanism will assess the network conditions (4) and request the video to be transmitted (5). Real video sequences are used in the experiment (6). Afterwards, the SHIELD mechanism optimizes and secures the video transmission against packet loss (7). The next step is to

Table 1 Simulation parameters

Parameters	Value
Display sizes	1920 × 1080, 1280 × 720, and 800 × 600
Frame rate mode	Constant
Frame rate	29.970 fps
GoP	19:2
Codec	H.264
Container	MP4
Wireless technology	IEEE 802.11p (WAVE)
Communication	Vehicle to vehicle (V2V)
Routing protocol	CLWPR
Mobility	SUMO mobility traces
Radio range	250 m
Internet layer	IPv6
Transport layer	UDP
Highway environment	
Propagation model	logDistance
Location	I-78
Map size	10,000 m
Vehicles speed	80–120 km/h (50–75 mph)
Urban environment	
Propagation model	logDistance + Nakagami-m
Location	Manhattan borough(New York City)
Map size	2.000 m × 2.000 m
Vehicles speed	20–60 km/h (12–37 mph)

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[1] Samples of the transmitted videos are available in http://www.youtube.com/channel/UCsB0SdKpCKD2GS6aXzB-FUQ/videos

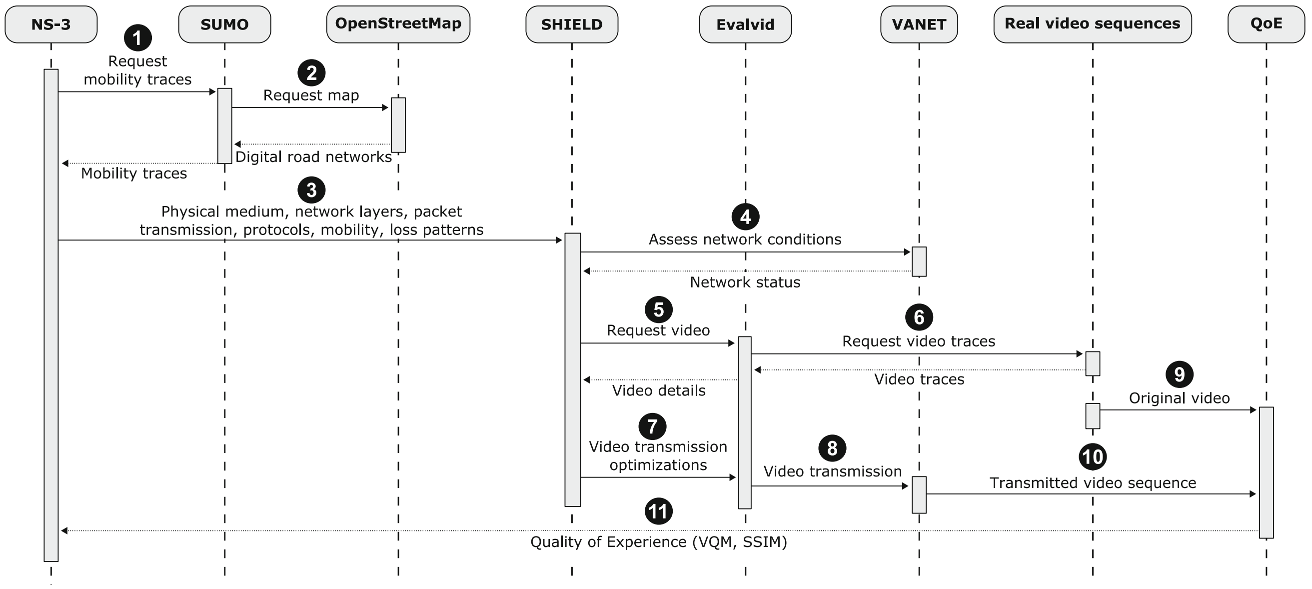


Fig. 5 Steps involved in the experiment

deliver the video sequences to the receiver (8). At the end, the original (9) and the transmitted (10) videos are assessed using objective QoE metrics (11).

Five different scenarios were assessed in both urban and highway environments. The first one is without any type of FEC. The results of this experiment will be used as a baseline for the others. The second scenario is the Video-aware Equal Error Protection FEC (VaEEP) mechanism. In this mechanism I- and P-frames are equally protected with a fixed amount of redundancy. The Video-aware Unequal Error Protection FEC (VaUEP) mechanism is the third scenario. VaUEP takes into consideration the importance of each frame type and protects I- and P-frames with a tailored amount of redundancy. The fourth scenario is using our previous adaptive QoE-driven COntent-awaRe VidEo Transmission opTimisation mEchanism (CORVETTE) [28], which considers several distinct video characteristics as well as the network state. The fifth, and last scenario is the proposed SHIELD mechanism.

4.2 QoE assessments

Objective metrics are desirable to assess the video quality level because they intend to be unbiased. In addition, they are computed through mathematical calculations, and thus, measurable and verifiable. The PSNR is a common objective metric to assess data fidelity. However, it is based on a byte-by-byte comparison disregarding completely what the information actually represents. Additionally, PSNR does not recognize the pixel structure in the image nor the spatial relationship between the pixels, thus, it does not consider the visual importance of each pixel [25, 46].

To increase the results reliability, two objective QoE metrics that mimic the human visual system [47] were employed in order to quantify how impairments are perceived, namely the Structural Similarity Metric (SSIM) [48] and the Video Quality Metric (VQM) [49]. The MSU Video Quality Measurement Tool [50] was used in the experiments. In the SSIM metric, the grade system goes from zero to one, whereas the higher the value, the better the video quality. In the VQM metric, the closer to zero the better quality. Another important difference between these metrics is that VQM tends to be stricter with video impairments. Because of that, it will give worse scores to video sequences with fewer flaws. This will produce a higher difference of the mechanisms results in comparison to the baseline.

Figure 6 shows QoE results of the urban scenario. (a) and (c) depict the SSIM and VQM average, respectively. (b) and (d) show the QoE improvement of each metric in comparison to the base line. In (a), it is possible to notice that the simulation starts with a small amount of vehicles and the QoE results, for all mechanisms, can be considered low. This can be credited to the fact that the network is suffering from connectivity issues, because it is relying on very few and scattered nodes to transmit all the video data. Even in this scenario, the SHIELD mechanism was able to protect the most important parts of the video sequences, producing better results. As showed in (b), this led to an improvement of more than 90 % on the video quality when compared to the baseline (without FEC). The

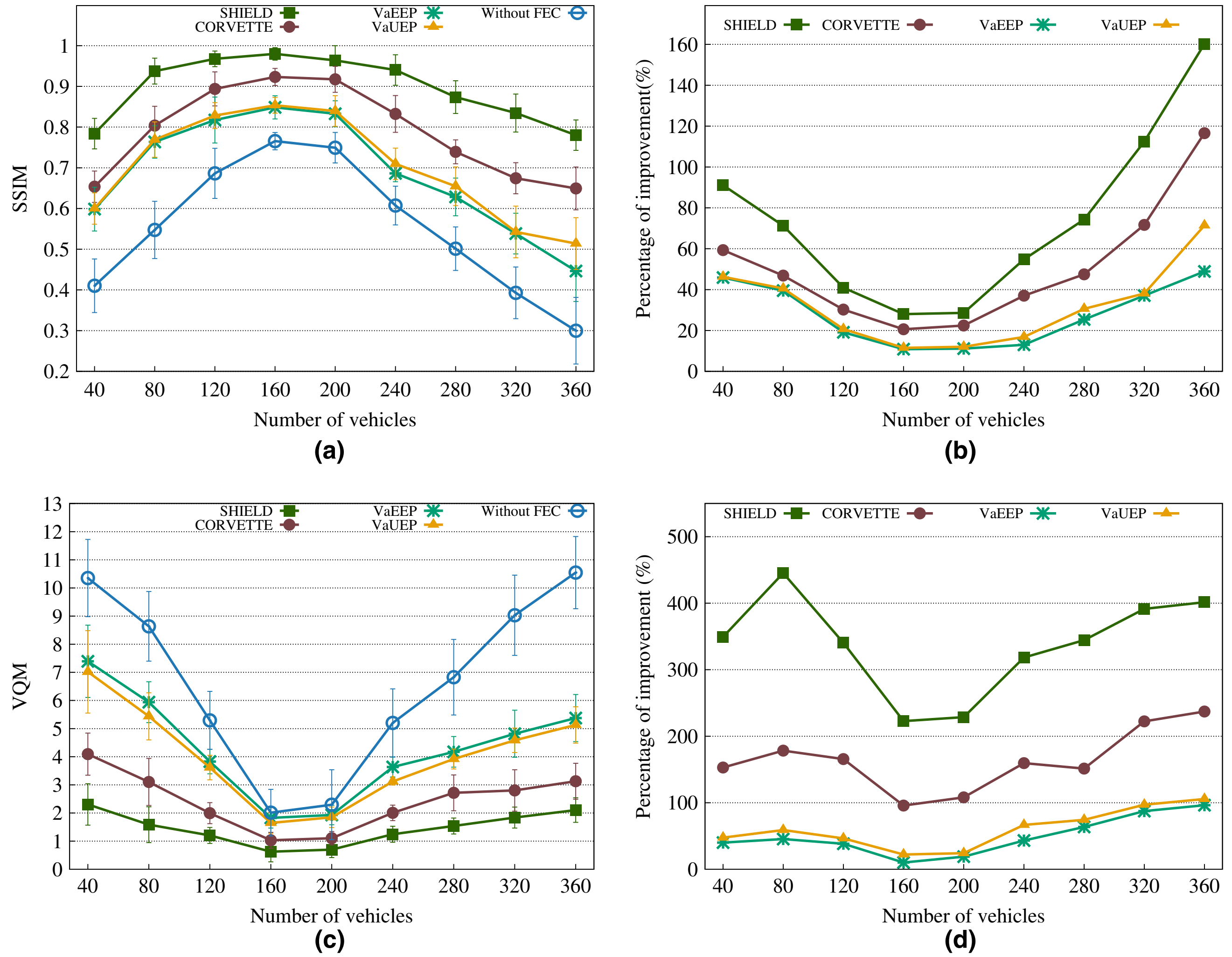


Fig. 6 QoE assessment of the urban environment. **a** Average SSIM. **b** Percentage of SSIM improvement. **c** Average VQM. **d** Percentage of VQM improvement

second best result was the CORVETTE mechanism with 60 % of SSIM improvement.

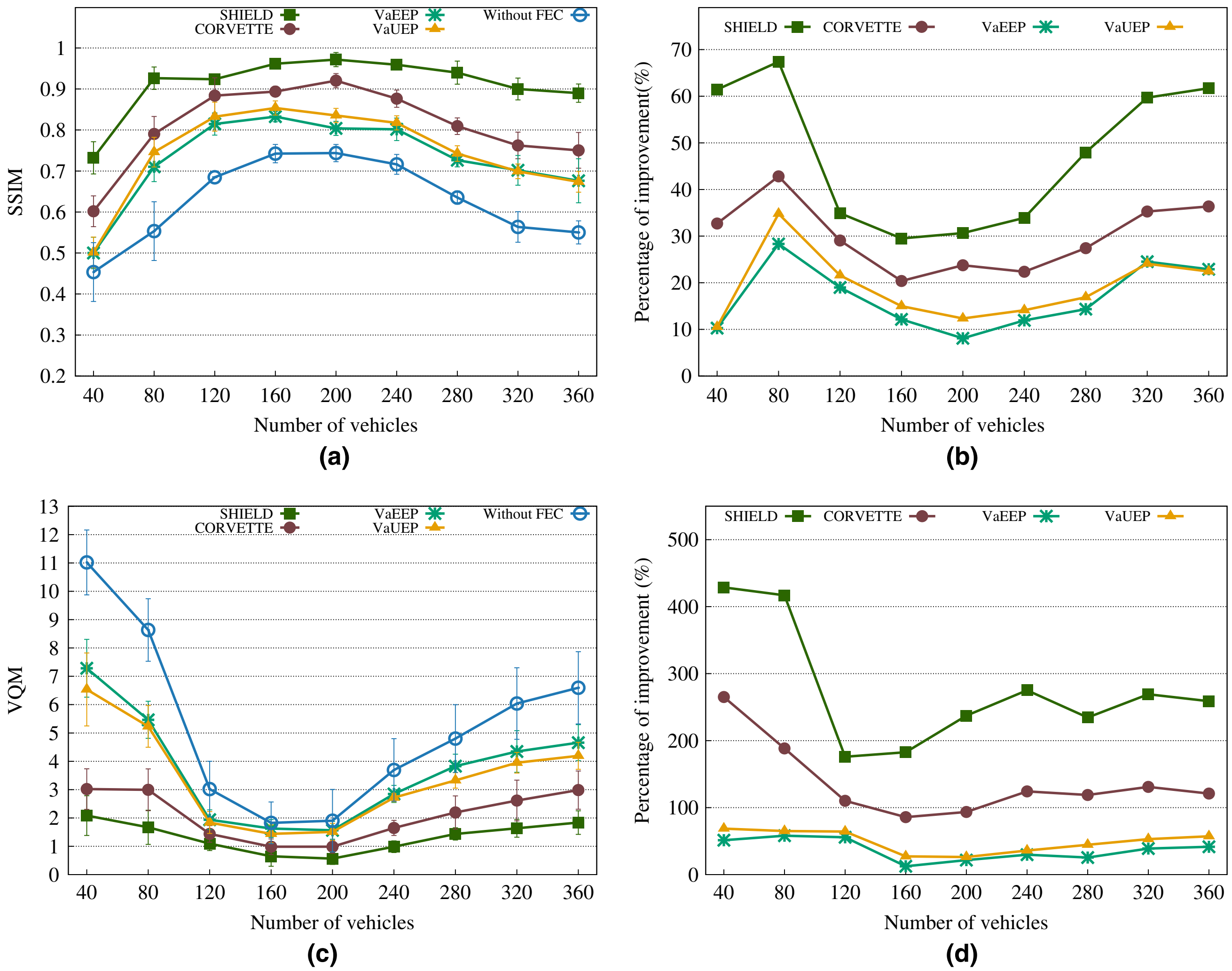
Figure 6a also shows that the best QoE results for all mechanisms are obtained when the network has 160 and 200 vehicles. This number of nodes provides the best coverage of the whole area, while it does not cause excessive interference. Because of the improved network conditions, the baseline also has better results, thus reducing the SSIM improvement perceived by the other mechanisms. This situation is clearly evidenced in Fig. 6b for 160 and 200 vehicles. On the other hand, when the network becomes very dense, e.g., above 280 vehicles, the mechanisms have to face increasingly degraded network connections. Once again, the SHIELD surpassed the other mechanisms, providing up to 160 % higher SSIM scores in comparison to the baseline.

As mentioned before, Fig. 6c shows the VQM average and (d) depicts the percentage of QoE improvement of the mechanisms in comparison to the baseline. Although this metric differs from SSIM, almost the same pattern can be found in (c). At the beginning of the experiment, the network is sparse and the videos have low quality. VQM gives them high scores, which in this case are not good. This is especially true for the baseline, because it does not use any type of FEC-based mechanism to secure the transmissions. The best-case scenario in the VQM scores is the same as in the SSIM results, for 160 and 200 vehicles. This confirms the notion that the videos are transmitted with better quality with this configuration. In the same way as in the SSIM assessment, the VQM scores demonstrate that the SHIELD mechanism outperforms all other mechanisms.

Additionally, Fig. 6d shows a pattern similar to the SSIM results. The highest improvements are accomplished when the network is sparse, between 40 and 120 vehicles, or in a very dense network, above 240 vehicles. On average, the proposed mechanism provided scores 78 % better than the baseline. Additionally, it achieved 66 and 63 % higher marks than VaEEP and VaUEP, respectively, and over 40 % better scores in comparison to the CORVETTE mechanism.

In addition to the urban scenario, a highway environment was also assessed with both SSIM and VQM metrics. Figure 7 shows the QoE assessment, whereas (a) and (c) depict the average SSIM and VQM, respectively. (b) and (d) show the percentage of improvement achieved in each metric by the mechanisms against the baseline. In (a), the first thing to be noticed is that the QoE results are closer to one another in this environment. This happens because the network conditions are not as harsh as in the urban scenario. At first, there are some connectivity issues when the network is sparse, e.g., 40 vehicles. After this threshold, a better video quality is being provided. The best results are evidenced for 120 and 240 vehicles. In (b), it is possible to notice that the highest improvements are reached when connectivity issues affect the network. For example, when the number of deployed vehicles is 40 and 80. In addition, major improvements are also perceived when there is a higher level of interference, such as above 280 vehicles. Here again, the SHIELD mechanism outperforms all its competitors.

As previously mentioned, the average VQM is shown in Fig. 7c and the percentage of VQM improvement by each mechanism is shown in (d). In (c), the results follow the same tendency as the SSIM scores. This means that the VQM results are also closer to one another, especially above 120 vehicles. This is evidenced because the highway environment is not as rough as the urban setting. In (d), it is clear that the highest percentage of improvement is achieved when the nodes are sparse. This means that connectivity issues are afflicting the network, e.g., for 40 and 80 vehicles. After this threshold, the network conditions improve and the enhancements provided by the



(a)

(b)

(c)

(d)

Fig. 7 SSIM assessment of the highway scenario. **a** Average SSIM. **b** Percentage of SSIM improvement. **c** Average VQM. **d** Percentage of VQM improvement mechanisms decrease. Nevertheless, the SHIELD mechanism is able to surpass the competitors.

4.3 Network assessment

In addition to a higher video quality, to reduce the network overhead is also desirable. This is even more critical in wireless networks, where the resources are scarce and unevenly distributed. In our experiments, the network footprint is the size of all video frames transmitted after deducting the original frame size.

Figure 8 shows the network overhead of all mechanisms in both (a) urban and (b) highway environments. The non-adaptive VaEEP and VaUEP schemes yield a constant network footprint in both scenarios, because they do not adapt the amount of redundancy according to the network conditions. As depicted in the graph, these non-adaptive schemes add a considerably larger amount of redundancy. On top of that, the protection is not very efficient because, in the VaEEP case, the protection is added equally to all video data. As highlighted before, not all video packets need the same degree of protection. To tackle this issue VaUEP considers the frame type to add a specific amount of redundancy. This results in less network overhead and, at the same time, improves the video quality.

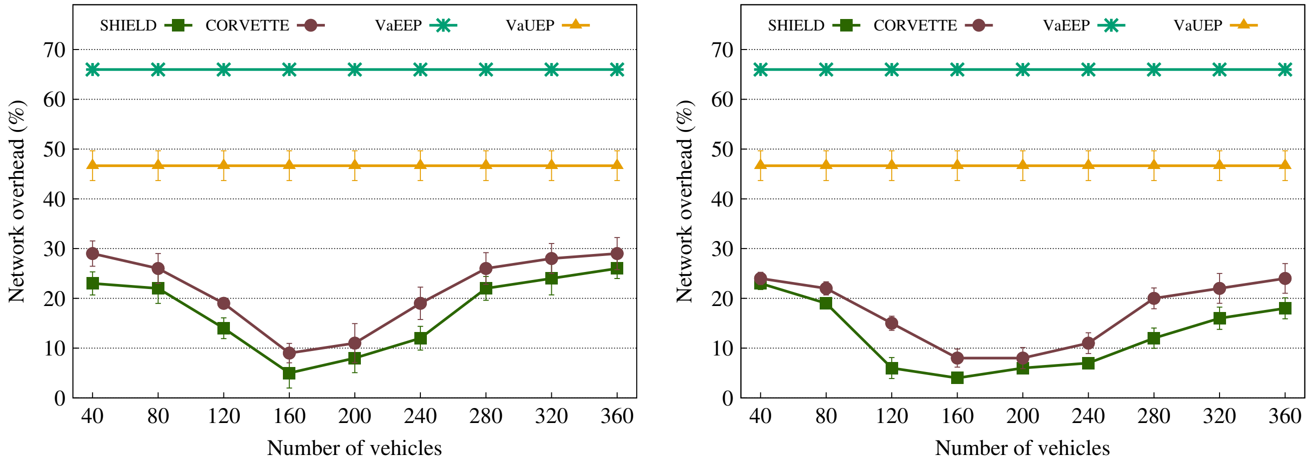
The VaEEP mechanism does not have a standard deviation because it uses a unique and pre-defined amount of redundancy, which is applied equally in all videos. The VaUEP mechanism also has a pre-defined amount of redundancy, but it is not unique. This means that each type of video frame will have a specific amount of redundancy. Additionally, each video frame has a different size, leading to a variation in the amount of redundancy, and thus, a standard deviation is displayed.

The adaptive mechanisms, CORVETTE and SHIELD, were able to produce a lower network overhead, improving the wireless resources usage. In both mechanisms, when the network condition is better the footprint decreases. In the urban environment, this is evidenced when the simulation has 160 vehicles. The SHIELD mechanism produces a network overhead of only 5 %, while CORVETTE is producing 9 %. In the highway environment, the best conditions are experienced between 120 and 240 vehicles. The overhead produced by the SHIELD mechanism was between 4 and 7 %, while CORVETTE is producing between 8 and 15 %.

On average, the SHIELD mechanism added 20 % less overhead in the urban environment and 28 % less in the highway scenario, in comparison to the CORVETTE mechanism. When compared to the VaEEP and VaUEP mechanisms, the SHIELD mechanism produced 73 and 63 % less overhead, respectively in the urban scenario. In the highway scenario, the network overhead downsize was 81 and 73 %, respectively. In the end, the proposed mechanism was able to produce a tailored protection, enabling a higher video quality and lower network overhead.

4.4 Overall results

The overall results demonstrate that the SHIELD mechanism outperforms all its competitors as showed in Table 2. This table summarizes the average SSIM, VQM, and the network footprint. The SHIELD mechanism enables downsizing the network footprint in both urban and highway environment. This stems from the fact that a tailored amount of redundancy, based upon video characteristics and the network conditions, is added to each video



(a)

(b)

Fig. 8 Network footprint. **a** Network overhead of the urban scenario. **b** Network overhead of the highway scenario

Table 2 Average SSIM, VQM, and network footprint

	SHIELD	CORVETTE	VaUEP	VaEEP	Without FEC
Urban environment					
SSIM	0.895	0.787	0.701	0.684	0.551
VQM	1.459	2.441	4.034	4.323	6.688
Overhead	17.333 %	21.778 %	46.660 %	65.984 %	–
Highway environment					
SSIM	0.911	0.809	0.744	0.729	0.627
VQM	1.328	2.095	3.414	3.728	5.281
Overhead	12.333 %	17.112 %	46.660 %	65.984 %	–

sequence. This prevents any unnecessary redundancy. Furthermore, the proposed mechanism also enhanced the quality of the video delivered, thus providing higher QoE for the end-users.

5 Conclusion and future works

Following the recent growth of video transmission over VANETs there is the need for self-adaptive QoE-driven mechanisms to protect the packet delivery against losses. The SHIELD mechanism is able to safeguard the most QoE-sensitive data, which leads to a resilient video transmission. This allows improving the video quality even in networks with high mobility nodes and error-prone tendency. Through an extensive set of experiments, the proposed mechanism demonstrates that it is capable of identifying, with great accuracy, several network and video characteristics. All these details are used to shield the most important data, which in turn, leads to a higher video quality and an efficient use of the wireless resources.

The experimental results show that SHIELD surpasses the adaptive and non-adaptive competitors in both video quality improvement and network overhead downsizing. In terms of video quality, it achieved between 13 and 62 % SSIM improvement in the urban environment and between 12 and 45 % of SSIM improvement in the highway environment. In the VQM assessment, the video quality improvement was between 67 and 358 % in the urban environment and between 57 and 297 % in the highway scenarios. The VQM results are higher because, as explained before, it tends to give worst scores than SSIM as the quality decreases.

In addition to the improved video quality, the proposed mechanism was also able to reduce the network footprint. The overhead downsize in the urban environment is between 20 and 70 % and in the highway scenarios is between 27 and 81 %. This means that it was possible to enhance the video transmission without adding unnecessary redundancy, saving the scarce wireless resources. As future work, other mobility scenarios and environments are going to be assessed, as well as additional video and network parameters.

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