SPECIAL SECTION ON RESOURCE MANAGEMENT IN VEHICULAR AD-HOC NETWORKS: ENERGY MANAGEMENT, COMMUNICATION, PROTOCOL, AND FUTURE APPLICATIONS

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QoS-Aware Video Transmission Over Hybrid Wireless Network for Connected Vehicles

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ABSTRACT Communication between vehicles enables a wide array of applications and services ranging from road safety to traffic management and infotainment. Each application places distinct quality of service (QoS) constraints on the exchange of information. The required performance of the supported services differs considerably in terms of bandwidth, latency, and communication reliability. For example, high-bandwidth applications, such as video streaming, require highly reliable communication. However, the attenuation of the IEEE 802.11p/DSRC communication link, due to static and mobile obstructing objects, degrades the link quality and can compromise the QoS requirements of the supported applications. On the other hand, a dual-interface hybrid architecture may have a failover or backup mechanism and benefit from more reliable alternatives, such as cellular networks for occasionally offloading data transmission by radio access technology (RAT) selection and vertical handover process. Since 4G/Long-Term Evolution (LTE) is generally not free, it is, therefore, highly desirable to minimize the time during which the cellular interface is used and to return to the IEEE 802.11p/DSRC interface. This paper proposes a hybrid communication approach based on 4G/LTE and the IEEE 802.11p technologies to support a V2X video streaming application. The proposed approach includes details on the underlying communication architecture, a procedure for selecting the best RAT, a real test platform complemented by a standard software protocol stack, and finally an extensive performance evaluation of the proposed solution based on field test measurements. The results indicate that the proposed approach significantly improves the overall reliability of communication with respect to packet and frame delivery metrics.

INDEX TERMS V2X communication, dedicated short range communication (DSRC), 4G/LTE, vertical handover, RAT selection algorithm.

I. INTRODUCTION

The introduction of the IEEE 802.11p modification, early 2007, modifies the IEEE 802.11 standard [1] by supporting the wireless local area network in a vehicular environment. The IEEE 802.11p, a synonym of Dedicated Short Range Communication (DSRC) [2], allows direct communication between vehicles (i.e. V2V) and between vehicles and road side units (RSU) (i.e. V2I). V2V and V2I are called V2X communication. DSRC radio technology presents challenges inherent in spectrum availability and fading [3]. Henceforth, efforts to extend the capabilities of the wireless channel are envisaged using different techniques. Some of these techniques are standardized such as the "*Decentralized congestion control*" (DCC) in the ITS-G5. It was designed to maintain network stability, increase throughput and ensure an equitable allocation of resources [4]. Other techniques are investigated in the research community such as the use of directional antennas [5]. Overall, in V2X mode, the communication is carried out on direct links in an ad hoc manner, that is to say, Vehicular Ad hoc Network (VANET).

The various functional and performance requirements posed by VANET applications and services regarding the underlying communication technologies are challenging. With a view to these challenges, the access layer in Intelligent Transportation Systems (ITS) reference architecture is open for multiple radio access technologies. Several promising solutions have been considered such as reuse of available spectrum and VHO algorithms that coordinate RAT selection among multiple networks. However, these solutions encompass a large number of sub-modules with complex methods are expected to have a good potential in the future generation of mobile networks [6].

Earlier in [7]–[9], we validated the feasibility of using 4G/LTE mobile cellular network for providing V2X communication. These studies recommended a hybrid network architecture where vehicular communication is either performed over direct links in an ad hoc fashion using IEEE 802.11p/DSRC interface or alternatively through mobile cellular networks, e.g., 4G/LTE [10] with the infrastructure assistance. While ad hoc communication is more suitable for applications such as active road safety and traffic efficiency which require timely dissemination of warnings and awareness messages, 4G/LTE-based communication is more favorable to bandwidth-greedy applications which require higher throughput and reliable network connection linking vehicles and remote data sources.

Such an architecture not only brings entirely new opportunities for improvement but also challenges of its own. Indeed, combining dual-network terminal that uses 4G/LTE and IEEE 802.11p/DSRC technologies requires *Always Best Connected (ABC)* approach [11], [12]. The ABC approach endorses seamless V2X communication by selecting the best available communication technology via handover mechanism. These decisions are performed based on a number of factors such as link connectivity, wireless channel condition, network load, and application QoS requirements, etc.

In order to gain full advantages of IEEE 802.11p/DSRC communication and 4G/LTE capabilities, a hybrid platform is developed which is capable of providing dual-link V2X communication. The main idea is to exploit the benefits of both systems to enhance the overall data exchange. The software protocol stack that is designed to extend coverage, reduce latency, and improve throughput by carefully steering data between the two interfaces depending on the state and load of the channel is equally important. To this end, an adaptive network RAT selection and VHO algorithm based on the real-time monitoring of the quality of communication is developed. The algorithm aims to transmit data over the best available radio interface in a way that increases the data delivery ratio while maximizing the usage of the DSRC interface in an urban environment. To assess the efficiency of the hybrid system, a video streaming scenario that improves road safety application such as *see-through,Monreal2010,Gomes2012* is implemented and tested. The see-through system helps drivers to safely make overtaking by displaying video of vehicles approaching from the opposite direction. Finally, a testbed setup is developed to perform evaluation using field test results. The results were obtained in various communication environments in the presence of different obstacles like vehicles and buildings. The field test results show that the IEEE 802.11p and 4G/LTE combination is capable of achieving significant performance gains regarding packet delivery ratio (PDR) and Frame Delivery Ratio (FDR) over IEEE 802.11p only interface.

The remainder of this paper is organized as follows. Section 2 describes related work on video streaming and the usage of a hybrid network architecture in a vehicular environment. Section 3 provides an overview of hybrid vehicular network architecture. Followed by the details on the design of QoS-aware Radio Access Technology (RAT) selection and Vertical Handover (VHO) algorithm for steering data traffic over the hybrid vehicular network. Section 4 explains the development of software protocol stack and the testbed setup for implementing the video streaming application between two vehicles. Section 5 discusses the performance results based on field test measurements. The last section concludes the paper and highlights future work.

II. RELATED WORK

The real-time video streaming in the vehicular network has been envisioned and designed to increase road safety and traffic efficiency. Incorporating video streaming in vehicular networks not only enhances existing vehicular networking applications but also spurs a variety of emerging applications such as in-vehicle and traffic condition surveillance, overtaking assistance and multimedia/gaming content delivery among a platoon of vehicles. This section discusses the techniques and solutions for providing video streaming over the vehicular network.

From the application specific perspective, some research efforts were dedicated to the usage of video content delivery to improve road-safety also referred as "*see − through systems*" [13], [14]. These systems are designed to assist drivers in their overtaking maneuver of long vehicles by delivering video of traffic on the opposite lanes. While integrating video lend many promising features to vehicular networks, it brings several challenges such as transmitting video with lower end-to-end delay and better visual quality. To address these stringent performance requirements, Vinel et al. in [15] and [16] used periodic dissemination of Cooperative Awareness Messages (CAM) [17] to estimate the wireless channel condition, and codec channel adaptation is performed accordingly. Belyaev *et al.* in [18], further build on this idea. They exploited automotive radar to detect the oncoming vehicle and use this information for efficient channel resource allocation. In [19], showed further improvement regarding visual quality using heuristic-based power control scheme.

Additionally, there are few studies which provide a practical implementation of video streaming in a vehicular environment. Vinel *et al.* in [20]–[22] describe experimental results regarding expected end-to-end visual depending on the inter-vehicle distance. The real test-bed setup consisted of DSRC [2] enabled platform along with scalable video codec. Similarly, in [23], implements a simple test-bed setup to demonstrate the impact of different channel condition on the video quality. Jiang *et al.* [24] reported the performance of multihop video streaming both in the presence and absence of interference. To account for packet losses, authors proposed enhancements to the application layer by incorporating retransmission and startup caching mechanisms. Patra *et al.* [25] implemented a smartphone based real-time video capturing systems and demonstrated an overtaking assistance application.

There have been several studies conducted to facilitate video streaming in vehicular networks. To this end, various protocols such as clustering [26], routing [27], [28], medium access control (MAC) [29], resource management and power control [19] have been applied to enhance the quality of video transmission between a source and the destination. In [26], a novel user-oriented clustering scheme for video transmission is proposed to improve video transmission performance in terms of throughput and loss. The scheme consists of two algorithms, i.e., cluster formation and cluster head selection which make use of vehicle characteristics and user preference information in grouping vehicles into clusters and selecting an appropriate cluster head among them. Qadri *et al.* [27] reported gains in video quality in the presence of multiple sources transmitting video information. In [28], the Asefi *et al.* proposed application-centric routing protocol to minimize video distortion by considering multiple transmission related parameters such as video packet rate, error probability and transmission time while deciding on the next hop. An adaptive MAC is described in [29] which adjust the retransmission limit based on the channel condition for improved video streaming in vehicular networks.

In [12], Olivera *et. al.* described a network-layer solution to provide continuous communication among vehicles equipped with dual-interface terminals. Based on IP-based reachability information, the proposed mechanism initiate handover process between the WiFi and 3G networking technologies. The main advantage lies in its simplicity and the development of a working prototype. However, the fact that only destination′s connectivity is checked while making the handover decision might defy QoS requirement of an application where despite the IP-based reachability the packet losses are higher than the given QoS threshold. Furthermore, no vehicular networking specific application implementation and its performance evaluation were provided. More recently, [8], [9] proposed QoS-aware RAT selection and VHO algorithm for hybrid vehicular networks. The main focus was to avoid the ping-pong effect by reducing the number of VHOs. The proposed scheme measures network load and congestion and use that information to adapt the application transmission rate. It only decides to switch network if the local load goes beyond the given threshold such that the QoS cannot be met. The paper reported considerable performance improvement regarding reliability and latency while performing a fewer number of handovers.

In the context of video content delivery over hybrid vehicular network architecture, we made the following contributions.

1) We implemented a dual-interface enabled platform to provide V2X communication with several components including IEEE 802.11p/DSRC standard compliant transceiver, 4G/LTE enabling dongles and webcam camera, all connected to a laptop running Linux OS.
2) In order to implement a see-through application scenario, the test-bed setup is complemented with three main software module in addition to the software protocol stack. (1) Video content processing, which further includes video capturing/encoding/decoding, video editing, and GUI-based displaying. (2) Data transmission, including a simple fragmentation and reassembly mechanism. (3) Traffic steering, based on QoS monitoring.
3) We proposed and implemented QoS-aware RAT selection and VHO algorithm to provide continuous video transmission using both technologies. The application QoS requirements are taken into consideration by mean of continuously monitoring the application Packet Loss Rate (PLR) parameter.
4) Finally, we provided extensive performance evaluation using testbed setup. The field test measurements were obtained under various scenarios and networking conditions.

III. QoS-AWARE VIDEO TRANSMISSION PROTOCOL OVER HYBRID VEHICULAR NETWORK

The protocol design follows "*Always Best Connectivity*" [11], [12] concept which states that always-connected in a best possible and transparent way for seamless connectivity in multiple network environment. The large deployment of different radio access networks and their coverage extension give connectivity alternatives to end-users [30]. While there can be several competent communication technologies such as IEEE 802.11p/DSRC, WLAN, 4G/LTE, we leverage, in this study, IEEE 802.11p/DSRC and 4G/LTE technologies as two potential candidates for data transmission in the hybrid vehicular network.

A. HYBRID VEHICULAR NETWORK ARCHITECTURE

In Hybrid Vehicular Network (HVN), vehicles are part of a V2X network with an option of sending data either by using ad hoc communication link as defined by IEEE 802.11p/DSRC standard or by using a cellular network infrastructure such as 4G/LTE. It involves Vertical Handover (VHO) to provide seamless switching between two radio access technologies (RAT). The RAT selection and VHO decisions are made in dual-interface enabled communication unit in every vehicle based on a number of factors such as application QoS requirements, network resources availability and cost, etc.

As Fig. 1 illustrates, within an HVN, the network components communicate in several different ways. The figure shows the information flow among various components. All vehicles send application data either periodically or event-based triggered. Two options are available for communication, either in ad hoc or direct short range links fashion or

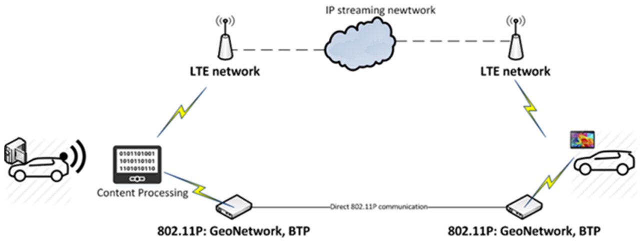


FIGURE 1. Hybrid vehicular networks architecture.

through the infrastructure-assisted cellular network. In the former case, single-hop broadcasting is performed to send warnings and cooperative awareness messages to nearby vehicles based on IEEE 802.11p/DSRC standard. The delay sensitivity of these messages doesn't allow extra time delay for association or authentication processes.

Alternatively, communication over 4G/LTE can be applied to distribute information messages among a large number of users within an extended area. For some applications that require a centralized aggregation point before disseminating data, the infrastructure support is in the form of back-end server within or outside the LTE network which plays a key role of message rendezvous. First, vehicles initiate uplink transport of application data to the back-end server. The application server applies application-specific processing such as filtering or aggregation and forwards the data towards the vehicle within the destination region. The downlink transport of data messages can be performed in one of the several ways. The simplest approach, but less resource efficient, is to send multiple unicast messages to each vehicle located within the destination region. Alternatively, Evolved Multimedia Broadcast Multicast Service (eMBMS) can also be utilized, however at the expense of maintaining multicast groups. Equally possible is to send a unicast message to any of the vehicles in the destination region, which in turn broadcasts to the neighboring vehicles.

B. RADIO ACCESS TECHNOLOGY (RAT) SELECTION AND VERTICAL HANDOVER (VHO)

This sub-section explains a joint QoS-aware RAT selection and vertical handover algorithm. It is assumed that vehicles are equipped with dual-interface enabled communication unit where primary interface is IEEE 802.11p/DSRC-based to provide ad hoc connectivity, and the secondary interface is 3GPP LTE-based cellular connectivity.

During the initialization phase, vehicular applications like video and traffic safety specify their QoS requirements in term of common performance metrics such as latency, bandwidth, packet loss rate (PLR) and communication cost. In the proposed RAT selection technique, the focus is on the minimum packet loss that has not been the focus earlier. The main idea is to constantly monitor and maintain the minimum packet loss termed as *PLR_Threshold* that is critical to achieving certain QoS requirement of each application, and that shall be satisfied by the in-vehicle communication unit between the source and intended destinations. Next, important communication parameters are set such as data transmission rate i.e. the number of packets per second and the time window length T_w over which the radio interface is monitored and assessed. Initially, IEEE 802.11p/DSRC based primary interface is selected as the default access network to send application data over the direct communication link.

Each vehicle continuously assesses the Packet Loss Rate (PLR) over the primary interface. Here, PLR is defined as the ratio between a number of received packets and the actual number of sent packets. The monitoring and assessment of the IEEE 802.11p link keeps on going through a background process which continuously measures the link reliability based on high frequency exchanged packets such as Cooperative Awareness Messages (CAM) [17] for ETSI or Basic Safety Messages (BSM) in DSRC [2] message set dictionary. The resulting metric is named *PLR_DSRC*. The RAT selection procedure checks if the *PLR_DSRC* exceeds a predefined QoS threshold value, i.e., *PLR_Threshold*, as determined by the application requirements. If the *PLR_DSRC* exceeds the QoS threshold *PLR_Threshold*, the switching to the LTE access technology (Secondary interface) is performed. On successful RAT selection, vertical handover is performed and data packets are sent over the selected network technology.

To avoid frequent switching (or the ping-pong effect [8]) between the two networking technologies, the *PLR_DSRC* has to be consistently below the given threshold value *PLR_Threshold*. If this latter goes down for a predefined number of times (default value equal to three assessment times ($n = 3$)), the primary interface is selected. Network conditions are periodically checked and the procedure above is being executed accordingly. Algorithm 1, presents an informal high-level description of the QoS-aware RAT selection procedure using pseudo-code.

The vertical handover process is initiated whenever the packet loss rate of the running application(s) is higher enough than the QoS threshold such that the primary interface is unable to support. The control returns to the primary interface once it is found deem suitable for meeting the application's QoS requirements. Fig. 2 shows the side-by-side flowcharts of the application and Radio Access Technology (RAT) selection execution flows in the event of a VHO, respectively.

1) By default Primary interface (i.e., IEEE 802.11p) is selected.
2) When an application is scheduled to send information, it opens a socket and transmits the information in packets.
3) In case the packet transmission is unsuccessful, or a problem is detected either during the transmission or reception of the packets, generally due to link quality degradation, the application is notified so that it either retransmits the lost packets or ignores the losses and sends the next packet.
4) The Secondary interface (i.e., 3GPP LTE) is selected according to the given network selection policy.

Algorithm 1 QoS-Aware RAT Selection Algorithm

```
$Active\_rat \leftarrow DSRC$ { Set the default primary RAT as active interface}
$Spare\_rat \leftarrow LTE$ { Set the secondary RAT as spare interface}
$T_w$ {Time window over which the radio interface is monitored}
$n \leftarrow 3$ { Number of expired successive time windows before VHO}
while True do
    Exchange video data over the active interface
    Exchange traffic safety data over DSRC
    Update QoS parameters
    if $T_w$ expires then
        if $Active\_rat == DSRC$ & $PLR\_DSRC >= PLR\_Thresh$ then
            $Active\_rat \leftarrow LTE$
            $Spare\_rat \leftarrow DSRC$
        end if
    end if
    if $n * T_w$ expires then
        if $Active\_rat == LTE$ & $PLR\_DSRC < PLR\_Thresh$ then
            $Active\_rat \leftarrow DSRC$
            $Spare\_rat \leftarrow LTE$
        end if
    end if
end while
```

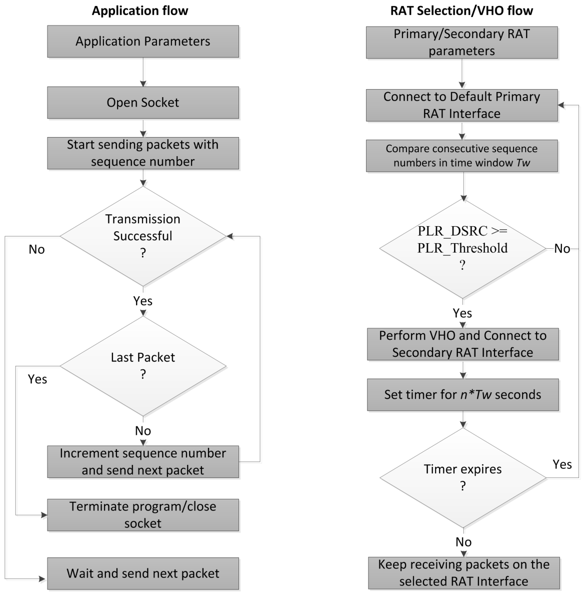


FIGURE 2. Radio Access Technology (RAT) selection and Vertical Handover (VHO) protocol design.

5) Whenever the *PLR_DSRC* is above the application's QoS threshold *PLR_Threshold* (i.e., $PLR\_DSRC >= PLR\_Threshold$) the vertical handover (VHO) is initiated.
6) The connection is transferred to the secondary interface and made active.
7) On successfully completing the handover process, a timer is set that specify the time interval (i.e., $n * T_w$) secondary interface must be used before switching back to the primary interface. As soon as the timer expires and the PLR_DSRC is checked to be lower than the PLR_Threshold, the execution flow goes back and starts monitoring the PLR over the primary interface.

IV. PROTOCOL STACK IMPLEMENTATION AND TESTBED SETUP

We developed a field testbed, to study the behavior of the RAT selection algorithm in real-time. In this section, we describe the protocol stack implementation, the application scenario, hardware utilized and the software module implemented for testbed setup.

A. DESCRIPTION OF PROTOCOL STACK IMPLEMENTATION

This sub-section present the description of the software protocol stack for the hybrid system. The communication stack for IEEE 802.11p wireless system is ETSI TC ITS [17] standard compliant resulting from CopITS [31] research project. The 5.9Ghz bandwidth is enabled using the off-the-shelf Alix3d3 board where the Linux voyage lightweight OS is running after being patched and recompiled to enable 5.9GHz channels. On top of this radio capability, the Basic Transport Protocol/GeoNetwork (BTP/GN) stack is developed to allow applications to exchange packets. The protocol stack supports different transport packet types such as Single-Hop Broadcast (SHB), Geographically Scoped Anycast (GAC), Topologically Scoped Broadcast (TSB), Geographically Scoped Broadcast (GBC), and Geographical Area (GA). Each packet type is identified with the corresponding number, e.g., 0: SHB, 1: GAC, 2: TSB, 3: GBC, 4: GA. The BTP/GN communication stack also offers different modes of data transfer for a multitude of upper facilities (CAM, DENM, SPAT, MAP, etc.) and application components.

Fig. 3 presents the resulting dual-interfaces-enabled protocol stack. The application packets in the streaming (the source vehicle) are passed to BTP/GN layer through the Ethernet interface. Once received by the communication board, the data payload is extracted, and the required headers are added according to transport packet type, occasionally secured, and then sent over the air through the wireless interface. We used the Single-Hop Broadcast (SHB) mode of GeoNetworking layer since no packet forwarding is required. Internally, the BTP/GN/IEEE 802.11p communication layers need standardized headers to route packets from source to relevant receivers. After encapsulating the data payload into BTP/GN PDU, it is transmitted to MAC/PHY layer using the raw socket API to be broadcasted through the 5.9 GHz wireless channel. In the reception side, packets are verified and filtered by the packet type in the MAC header and forwarded up to the BTP/GN layer where packets undergo a security processing

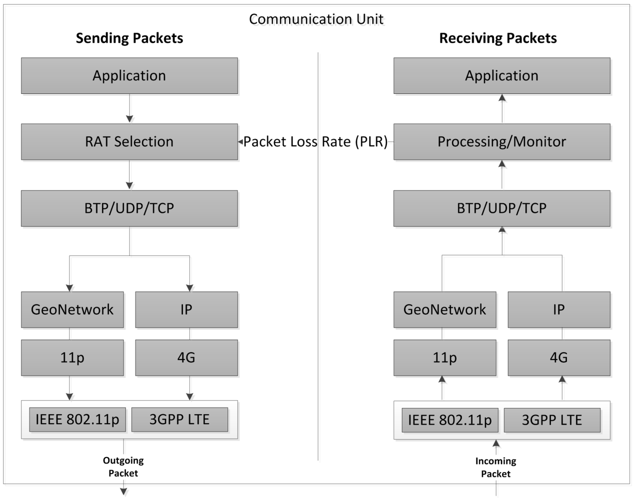


FIGURE 3. **Communication protocol stack with IEEE 802.11p and 3GPP LTE dual radio technologies.**

if required then delivered to the application layer. As for the communication over LTE link, UDP/IP packets are sent.

B. APPLICATION SCENARIO AND TESTBED SETUP

The testbed setup consists of a Peer-to-Peer (P2P) video streaming application between two peers (in our case between two vehicles) using LTE and IEEE 802.11p radio access technologies for data transmission. A typical target scenario is streaming a Dash camera between two vehicles separated by a certain distance with an obstacle in between them. The real-time video streaming will help the drivers to avoid an accident while trying to make an overtake move. To implement the scenario and testbed setup following hardware and software modules were utilized, summarized in Table 1.

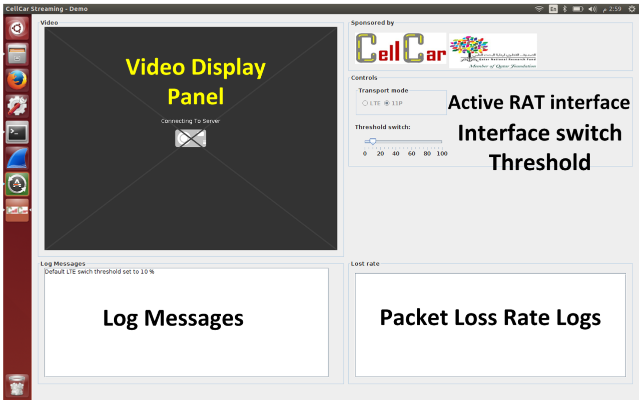
TABLE 1. **Testbed setup: Hardware and software components.**

Component	Description / Characteristics
Cellular connectivity	Two 4G/LTE-enabled USB dongles
ITS-G5 connectivity	Two ETSI TC ITS compliant interfaces
Testing vehicles	VW Tiguan and Toyota Corolla
ITS-G5 Radio	10 Mhz width channel centered at 5.9 GHz
ITS-G5 Tx Power	23dBm
Laptops	Two Dell laptops with Ubuntu 14.04 LTS
Localization	Two NMEA compliant GPS devices
Xuggler[34]	Java library for video encode/decode
Sarxos [35]	Java library to access camera
Javolution [36]	Java library for real-time applications

1) Two ETSI TC ITS standards compliant in-vehicle wireless system, designed and developed by CopITS project [31]. Each wireless system includes one ITS G5 (5.9GHz) communication unit and two 5.9GHz wireless antennas.
2) The CellCar project [32] extends the CopITS prototype with two 4G/LTE USB dongles. The developed hardware platform is tested using 4G/LTE connectivity provided by Mobile Network Operator (MNO) OoredooTM [33].
3) Two Linux-based laptops with webcam camera. The OBU and 4G/LTE dongle are connected to a laptop running latest Ubuntu 14.04 Linux operating system.

The testbed setup is built around three main software modules:

1) Real-time streaming of video content, which further comprises of (1) Video capturing. (2) Video editing and encoding. (3) Video decoding and displaying. This module is responsible for encoding the images from the selected data source (webcam or stored video) within a frequency rate of 25 image frame per seconds (FPS = 25). Next, Transcoding the received image using the H.264 codec [37] is performed before transmitting the raw encoded data. On receiving the encoded images on the receiver side, the image is decoded and displayed on the GUI screen. The GUI illustrated in Fig. 4 is purpose-built with multiple split panes, each for displaying live streaming video, application parameter setting, message log, and communication statistics.



Transport mode
○ LTE ● 11P
Threshold switch:

Default LTE swich threshold set to 10 %

FIGURE 4. **Video streaming application: Multi-pane GUI.**

2) Data transmission, once the image is encoded, the raw data is transmitted using the UDP transport protocol over selected network interface (i.e., either LTE or IEEE 802.11p). There was two limitations with the previous implementation of IEEE 802.11p stack. Firstly, no fragmentation mechanism was implemented. The default Maximum Transmission Unit (MTU) value is set to 1500 bytes, and the GeoNetwork header is about 100 bytes. Therefore, if the payload data is more than 1400 bytes, the data packet will be lost. Secondly, only one UDP was provided, thus preventing us from using standard streaming protocols like RTSP, RTP/RTCP, etc. To circumvent these issues, we have developed a simple fragmentation mechanism. Fig. 5 (a) shows the data packet format to transport streaming raw data.
3) A separate module is implemented for monitoring and steering application packets over the best available interface. The switching logic is totally decoupled from the underlying communication interfaces. For this purpose, the receiving vehicle periodically com-

```
0                   1                   2                   3
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Fragmented | Seq. Number |  Last Frag  |        type          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|       Sequence Number       |            Reserved             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
:                            Data                               :
:                                                               :
|                                                               |
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(a)

```
0                   1                   2                   3
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type     | Loss fraction | Cum Nbr of packet lost         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

(b)

FIGURE 5. Video streaming application: (a) Data packet format. (b) Control packet format

putes the PLR value and sends a control packet to the video streaming vehicle to take the network switching decision. The control packet format is illustrated in Fig. 5 (b).

FIGURE 6. (Top) Table-top testbed setup with hardware components. (Bottom) Vehicles used in the field tests.

Fig. 6 shows the hardware components embedded in each vehicle to realize the testbed setup. The top figure shows the table-top testbed setup with hardware components while the bottom figure illustrates vehicles used to obtain measurements in the field tests.

V. PERFORMANCE EVALUATION

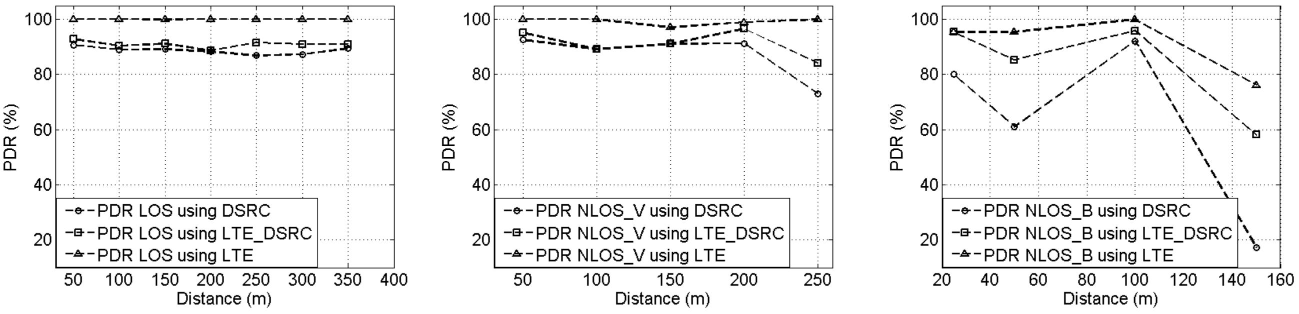
In this section, the link quality and the data transmission reliability are assessed through the field test results. The study was carried out in the real-time urban environment, by taking into account the different type of obstructions that may have a direct impact on the ITS-G5 wireless interface. As discussed in [38] and [39], the vehicles have a non-negligible impact on a wireless communication link in the presence of obstructing objects such as buildings, vehicles, and foliage. For this reason, three different scenarios are considered in the scope of this study. In each scenario, different distances between the vehicles are tested. We did not consider the foliage as obstacles in this study because of less greenery in Doha, Qatar.

1) The free space or line-of-sight (LOS) communication case where data load transmission between vehicles was carried out in an open-space area.
2) The second scenario deals with the presence of vehicles as obstacles between the transmitter-receiver pair (also NLOS_V) which cause an additive signal attenuation in both sparse and dense vehicular networks.
3) In the last investigated scenario, the inter-vehicle communication is performed with buildings as obstacles (also NLOS_B).

A. PACKET DELIVERY RATIO (PDR)

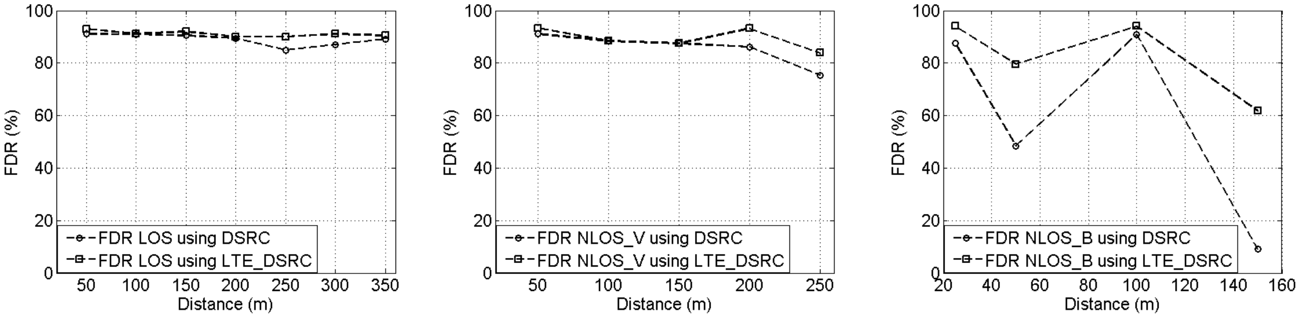
The goal of establishing testbed setup is to assess the quality of communication which can be quantified through the measurement of packet delivery ratio (PDR). In the setup, the video stream is encoded in packets which are transmitted through the selected interface. The encoded frames passed from the application to the lower communication layers are with different sizes. Some packets require fragmentation to be supported over the DSRC interface. Therefore, a fragmentation and reassembling modules were developed and integrated into the setup in conjunction with the RAT selection algorithm. Fig. 7 shows the results of packet delivery ratio in each interface for different types of links over various distances. The packets sent over the 4G/LTE interface present a high success rate, especially in the free-space (i.e., LOS) scenarios. For NLOS_B link type, lower PDR was observed at longer distances between the streaming source and the destination. Nevertheless, the PDR is above 90% in most of the experiments. In the obstructed line-of-sight scenarios caused by vehicles and buildings, the PDR decreases as the distance between transmitter-receiver pair increase. The foremost reason is that signal undergoes attenuation caused by reflection and diffraction due to vehicles and buildings.

The DSRC only interface case presents a lower packet delivery ratio than the LTE one. The impact of the obstacles is quite visible in the quality of the radio link and consequently in PDR. The presence of the vehicle and building obstructions degrade the signal strength and limit the reliable communication range to around 200m and 100m, respectively. The DSRC and LTE combination with the proposed



(a) (b) (c)

FIGURE 7. **Packet delivery ratio in LOS, NLOS_V, and NLOS_B scenarios using different communication schemes. (a) Packet delivery ratio in LOS. (b) Packet delivery ratio in NLOS_V. (c) Packet delivery ratio in NLOS_B.**



(a) (b) (c)

FIGURE 8. **Frame delivery ratio in LOS, NLOS_V, and NLOS_B scenarios using different communication schemes. (a) Packet delivery ratio in LOS. (b) Packet delivery ratio in NLOS_V. (c) Packet delivery ratio in NLOS_B.**

RAT selection algorithm enhances the delivery of transmitted packets as compared with the DSRC only interface. Indeed, with a 10% packet loss threshold defined to trigger a VHO, the joint LTE_DSRC approach maintains a significantly higher delivery ratio (i.e., above 90%) up to 350m distance in the LOS scenarios. As for the NLOS_B scenario, the presence of buildings as obstacles limits the communication range to 150m over which most of the packets are not delivered. The NLOS_V links present the same impact but with lower intensity. A more extended communication range is reached with higher packet delivery ratio.

B. STUDY ON QoS-AWARE VIDEO STREAMING

The DSRC communication technology presents a good relevance especially in the critical safety-related applications where transmission delay is highly critical. For less-critical driver assistance applications and infotainment, DSRC service channels could support a different kind of data streams. A typical video-based application for driver assistance is $See - Through$ which require high data throughput to ensure an acceptable video quality. Since video encoded frames may undergo a fragmentation and reassembling processes, the packet level delivery ratio is not enough to assess the relevance of the technology regarding the video quality. For instance, if a frame of big size is fragmented and broadcasted in different packets, the whole frame will have no meaning to the video codec if one of the packets was lost. Since the first goal of the present approach is assuring an acceptable quality of streaming, we define the frame delivery ratio (FDR) to assess the success of delivering all the sub-frames to the receiving codec. Graphs in Fig. 8 show the frame delivery ratio using DSRC interface and the RAT selection algorithm approach in the three different scenarios according to the link type. The proposed solution enhanced the FDR and kept it above 90% most of the time. As for the LOS scenarios, the results are comparable. In NLOS_V scenarios, FDR decreases considerably as the distance between transmitter-receiver pair increases for the DSRC only interface, while the hybrid approach is capable of maintaining substantially higher FDR, i.e., above 85%. Finally, in NLOS_B scenarios, the FDR for the DSRC only interface dropped sharply, whereas the dual-interface enabled communication case maintains reasonably higher FDR.

C. STUDY ON RELIABLE COMMUNICATION RANGE

The reliable communication range is defined as the maximum distance between a transmitter-receiver pair where the packet delivery ratio (PDR) is above 90%. In vehicular ad-hoc networks, different models are proposed for modeling the radio attenuation between communicating vehicles. Obstacles and

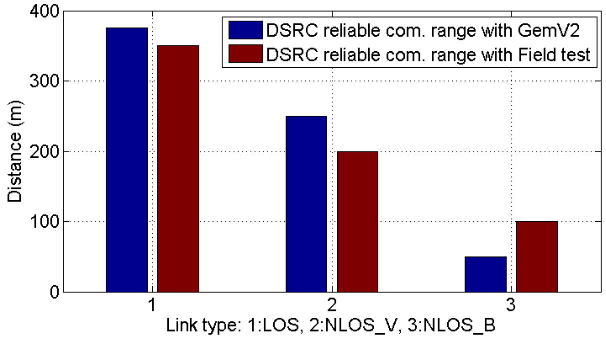


FIGURE 9. Reliable communication range: GemV2 model-based vs. Field test-based results.

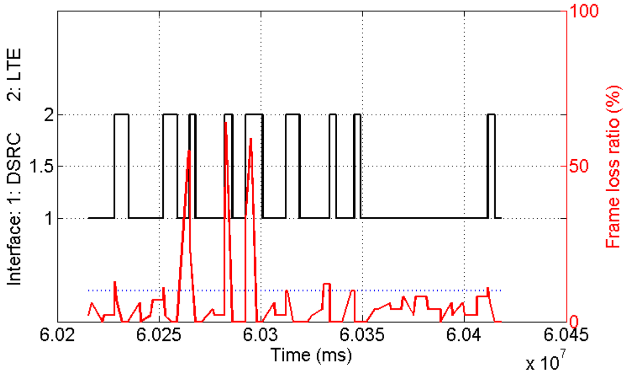


FIGURE 10. RAT selection algorithm output in LOS 300m scenario.

fading are quantified differently in each model. One of the models is the geometry-based model [40] which considers the vehicles and building as 3D object obstacles with measured attenuation parameters. Fig. 9 illustrates the average reliable communication range of DSRC interface both in the GemV2 model and the field measurement results. The results are correlated with some differences due to the different measurement contexts and the width or the number of considered obstacles. In the LOS scenario, the results are comparable.

D. STUDY ON INTERFACE SWITCHING AND ITS-G5 THROUGHPUT

This subsection details the output of an executed LOS scenario with 300m distance between the video streaming transmitter and receiver. The joint RAT selection and VHO algorithm is utilized to ensure higher QoS is achieved (i.e., 10% of Frame Loss Rate). Fig. 10 depicts the interface switching (black line) between the DSRC and LTE radios during the experiment period. The red line depicts the variation of the frame loss ratio (FLR), the ratio between the number of lost frames and the actual number of sent frames, which trigger a VHO whenever a threshold limit is reached (blue line at FLR = 10%). The graph shows the adaptive behavior of the RAT selection and VHO algorithm to ensure better packet delivery while maximizing the time usage of the native DSRC radio interface. Fig. 11 illustrates the DSRC channel throughput during the video streaming, for the same scenario.

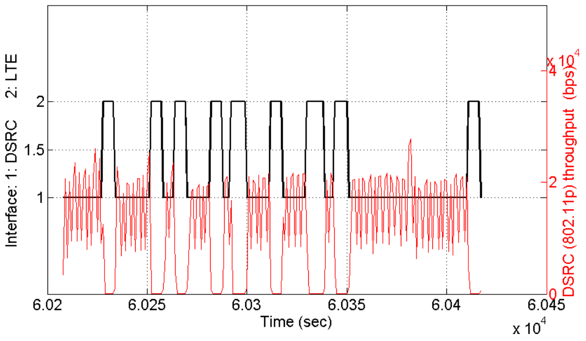


FIGURE 11. DSRC interface throughput and channel switching in LOS 300m scenario.

The interface switching is drawn with a black line and the DSRC channel throughput with a red line. When the LTE interface is inactive, the DSRC interface is monitored with periodic CAM-like packets sent at a frequency of 10Hz, representing a typical road safety application. The maximum usage of the DSRC interface is clear.

VI. CONCLUSION AND FUTURE WORK

This paper presents a hybrid communication scheme in vehicular networks. The architecture is based on dual-interface enabled V2X communication where IEEE 802.11p/DSRC radio technology and 4G/LTE-based cellular connectivity are provided to ensure reliable data exchange and a quality of service for the video streaming application. We followed Always Best Connectivity (ABC) approach by offloading data transmission to the 4G/LTE radio interface whenever the link quality of IEEE 802.11p/DSRC interface is degraded. Extensive measurement-based studies were carried out using a testbed setup along with the software protocol stack. The field results were gathered under various networking conditions and in the presence of different types of obstructing objects (LOS, NLOS_V, and NLOS_B). The testbed measured the performance gained by using an adaptive interface switching regarding packet-level and frame-level delivery ratios. The results show the feasibility of the proposed approach and significant improvements regarding communication reliability. The reliable communication range could also be extended as well. The seamless network switching, achieved through the QoS-aware RAT selection and VHO algorithm, allows the vehicles' passengers to watch a smooth video streaming without crashes or interruptions. The proposed approach reports an efficient trade-off between the usage of the IEEE 802.11p/DSRC interface on the one hand, and ensuring a better quality of service of the video streaming on the other hand.

In future work, we will look into developing a link quality estimator that could predict the link reliability in the near future based on the vehicle's kinematics and the evolving networking conditions. Such an estimator could avoid the loss of some packets before switching to 4G/LTE interface or an earlier switch back to IEEE 802.11p/DSRC interface when the link quality estimation is assessed favorably.

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