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Enabling DSRC and C-V2X Integrated Hybrid Vehicular Networks: Architecture and Protocol

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ABSTRACT Emerging Vehicle-to-Everything (V2X) applications such as Advanced Driver Assistance Systems (ADAS) and Connected and Autonomous Driving (CAD) requires an excessive amount of data by vehicular sensors, collected, processed, and exchanged in real-time. A heterogeneous wireless network is envisioned where multiple Radio Access Technologies (RATs) can coexist to cater for these and other future applications. The primary challenge in such systems is the Radio Resource Management (RRM) strategy and the RAT selection algorithm. In this article, a Hybrid Vehicular Network (HVN) architecture and protocol stack is proposed, which combines Dedicated Short-Range Communication (DSRC) technology-enabled ad hoc network and infrastructure-based Cellular V2X (C-V2X) technologies. To this end, we address the design and performance evaluation of a distributed RRM entity that manages and coordinates Radio Resources (RR) in both RATs. Central to distributed RRM are adaptive RAT selection and Vertical Handover (VHO) algorithms supported by two procedures. (1) Measurement of Quality of Service (QoS) parameters and associated criteria to select the suitable RAT according to the network conditions. (2) Dynamic communication management (DCM) via implementing RR-QoS negotiation. The simulation results show the effectiveness of the proposed architecture and protocol suite under various parameter settings and performance metrics such as the number of VHOs, packet delivery ratio, and throughput, and latency.

INDEX TERMS C-V2X, DSRC, hybrid vehicular networks, IEEE 802.11p, LTE, RAT selection, vertical handover (VHO).

I. INTRODUCTION

The emerging vehicular networking applications and use cases demand stringent Quality of Service (QoS) requirements in terms of latency, data rate, reliability, and communication range. These performance requirements are hard to meet by a single communication technology [1]. Several Radio Access Technologies (RATs) exist for vehicular networking but predominantly include two RATs. (1) The Dedicated Short-Range Communication (DSRC) technology that allows short-range, un-coordinated communication among vehicles and between vehicles and Roadside Units (RSUs), thus establishing Vehicular Ad Hoc Networks (VANETs). (2) The Cellular Vehicle-to-Everything (C-V2X) [2] technology is wildly considered as a feasible alternative for providing vehicular communications because it offers superior performances in terms of throughput and lower latencies. Moreover, simplified network architecture and advanced algorithms for resource management resulted in lower cost and higher performance efficiency. Combing these two competitive standards bring immense opportunities as well as challenges to provide seamless connectivity that could not only enhance existing applications but also spur an array of new applications and services. However, a multi-RAT environment not only necessitates well-defined network architecture but also signify the need for new protocols and algorithms at each layer of the protocol stack.

In the literature, two alternatives have been discussed to combine DSRC and C-V2X using a dual-interface enabled V2X communication system. The first alternative requires

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frequency sharing between the two competing technologies [3]. To reap the benefits such as interoperability between two incompatible RATs requires permitting both to coexist in the 5.85-5.925 GHz frequency range. Considering that such a proposal is at early stages, exclusive access of ITS band for vehicular safety applications, and potential negative impact of adjacent channel operation, such coexistence often leads to performance degradation [4]. The second alternative seamlessly switches between the two access technologies based on the coupling of the QoS requirement and RAT selection strategy. A DSRC-enabled direct, ad hoc communication link can be used between nearby vehicles to exchange time-critical messages. The C-V2X might be used simultaneously with DSRC to increase the reliability in cases where DSRC-enabled links fail [5]. Similarly, C-V2X can be applied effectively to distribute application data among many users within an extended area as an alternate or backup system [6]. Moreover, applications that require full internet access with higher data rates, C-V2X, can be applied as the preferred RAT. But these advantages come with the challenges of its own, for example, how to assign a particular vehicular user to the most suitable radio access network, i.e., RAT selection while lowering the signaling cost of performing Vertical Handover (VHO)? Moreover, it is also essential to efficiently manage and utilize the Radio Resources (RR) within each RAT, to provide applications with the required level of QoS.

In heterogeneous wireless networks, Radio Resource Management (RRM) functions such as RAT selection and VHO have been an active research topic. In the context of dual-interface enabled vehicular networks, extensive work is available on combining and Wireless Local Area Network (WLAN) and Wireless Wide Area Network (WWAN). For example, Olivera *et al.* in [7] implemented a prototype using IEEE 802.11b/g for the primary interface while 3G as the secondary interface. Similarly, bulk of research on RAT selection and VHO such as [8]–[11] and [12] proposed the integration of IEEE 802.11 based WLAN and CDMA2000, UMTS, WiMAX, or 3G/4G based WWANs. Generally, the RRM functionalities are implemented in infrastructure nodes only, i.e., integrated into the Access Point (AP), Base Station Controller (BSC), Radio Network Controller (RNC), or Evolved Node B (eNodeB). However, due to the distributed nature of vehicular networks, this approach often leads to scalability issues as the number of connections between the vehicles and RRM entities is increased [13]. The coexistence of multi-RAT and the dual-interface support is critical to the successful implementation of the hybrid communication systems herein, referred to as Hybrid Vehicular Network (HVN), which brings together the DSRC and C-V2X that operate in ad hoc and infrastructure modes, respectively. The HVN requires a distributed implementation of ad hoc domain RRM in each vehicle, which is functionally equivalent to the RRM in infrastructure-based networks. Moreover, enhanced network architecture with new protocols to support dynamic communication and resource management over HVN are highly sought-after.

In this article, a generic framework called *CellCar* is presented along with enhanced architecture and protocols for dynamic RAT selection and communication management in DSRC and the C-V2X integrated HVN. For the rest of the discussion, we will refer to current standards IEEE 802.11p [14] and the Long Term Evolution (LTE) [15] (LTE, LTE-V2x, and C-V2X are used interchangeably) for ad hoc and cellular communication technologies, respectively. However, the framework is not limited to these technologies, other *evolutionary* alternatives such as 802.11bd and un-supervised PC5 interface (via C-V2X sidelink Mode 4) operating and sharing the spectrum in the same 5.9 GHz frequency band could also be considered. Similarly, the 5G NR (New Radio) or the Uu interface could also allow vehicles to use the mobile cellular network for V2X communications. Because of the interoperability, coexistence, and backward compatibility requirements of these future standards [16], for the large part, the concepts presented in this article remain valid from the practical perspective.

Instead of considering DSRC and C-V2X technologies as competitors, a merger to create a hybrid network leverages the best of both. Based on the LTE Device-to-Device (D2D) platform [17], [18], the Direct communication over the PC5 interface and network communication over Uu interface and its coexistence with DSRC would result in reduced cost, improved reliability, and lower complexity. The HVN could also take advantage of reusing the already established upper layers, such as application, security, and transport layers of the protocol stack. Moreover, RSUs with DSRC and PC5 interfaces and 4G/5G small cells with the Uu interface further reduce the cost of infrastructure deployment. Finally, the coexistence of both technologies promises to meet the challenging performance requirements posed by emerging applications and use cases.

Since in DSRC, the channel access is distributed, i.e., without centralized coordination, the proposed solution translates resource management in the ad hoc domain, i.e., *Primary RRM* into efficient radio access. The efficiency in radio access is achieved by employing congestion control based on locally available measurements. To this end, a *beaconing rate adaptation* technique is employed to adapt the traffic over the shared radio channel according to the application QoS requirements. Similarly, resource management in the LTE network is controlled by *Secondary RRM* through preemption-based admission control. To provide coordination between Primary and Secondary RRMs, we introduce *CellCar Radio Resource Management (CRRM)*, which allows communication systems in individual vehicles instead of the network to make the RAT selection and VHO decisions. Central to the proposed framework is an adaptive *RAT selection and VHO algorithm*. The RAT selection algorithm selects the most suitable technology while seamlessly maintaining the connectivity via VHO. The proposed algorithm relies on criteria based on application QoS requirements, channel condition, and network load at the DSRC and LTE networks. An *Application Profiler* automatically derives the QoS requirements of an application, and initial RAT selection is performed according to the type, priority, and the traffic of the application it carries. Finally, we include details of *Dynamic Communication Management (DCM)* via implementing *RR-QoS negotiation algorithm*. The main focus of the simulation-based study is two-fold. Firstly, to provide a quantitative assessment of combining two different RATs and its potential to cater to a diverse set of QoS requirements under several parameter settings. Secondly, to show that the hybrid approach and the signaling procedures can deliver more data reliably, with lower latencies while avoiding unnecessary switching between the two RATs.

The rest of the paper is organized as follows. Section II provides an overview of the related work. The details of the proposed architecture and protocol stack are given in Section III. Section IV presents the criteria used for RAT selection in both DSRC and LTE networks. Section V provides details of the proposed RAT selection and VHO algorithms, followed by the DCM scheme in Section VI. Section VII describes the simulation scenario and performance evaluation. Finally, the paper is concluded in Section VIII.

II. RELATED WORK

In recent years, the use of multi-technology enabled vehicular communication has gained widespread attention. Central to this concept are the two fundamental assumptions. (1) The communication subsystem on all or a subset of vehicles is equipped with several RATs. (2) The communication subsystem is capable of selecting and switching among different RATs by performing VHO.

Most of the research in the Heterogeneous Vehicular Network (HetVNet) [19] focused on utilizing different technologies such as Wi-Fi, WiMAX, UMTS, and 3G/4G as a standby alternative for data offloading. Such architecture usually follows Always-Best-Connectivity (ABC) [7] paradigm where the *always-on* and *seamless connectivity* is provided by consistently selecting the best RAT. Primarily, the alternative technologies act as a backup with the RAT selection algorithm is at the center of the ABC concept involving VHO. The Media Independent Handover (MIH) protocol [20] by IEEE 802.21 Working Group and Communication Access for Land Mobile (CALM) [21] is the leading standardization efforts that can be applied in a vehicular networking environment to provide optimized handover mechanism between various network technologies. There also exist several lightweight approaches as an alternative to complex standards such as MIH and CALM that consist of a considerable number of modules. For example, Olivera *et al.* in [7] developed a simple, transparent, and application-level handover mechanism for vehicular communications. The scheme mainly utilized Internet Protocol (IP) reachability information to switch between IEEE 802.11p and 3G interfaces. Similarly, Marquez-Barja *et al.* [22] proposed a VHO mechanism based on the IEEE 802.21 standard. The criteria for selecting the wireless access network considers many factors such as user preferences, price-performance based metric, and location with map layout and route itinerary information.

Initially, researchers proposed the idea of utilizing co-located hotspots or WLAN and WWAN technologies together. These studies mainly differ in two aspects, in their choice of WWAN technology and the switching mechanism, i.e., RAT selection algorithm. Hasib and Fapojuwo [8] proposed an algorithm that alternated between IEEE 802.11 and CDMA2000 network based on the service type, location, and congestion-level information. Similarly, the scheme proposed by Vegni *et al.* in [9] considered QoS parameters like channel resource utilization and latency to switch between Wi-Fi and UMTS network. In [10], Shafiee *et al.* exploited vehicular mobility profile and network characteristics to perform VHO between WLAN APs and CDMA2000 1x-EV networks. In their follow-up work, [11] assumed ad hoc communications over WLAN and WiMAX technologies. It proposed a hybrid routing protocol combining both location-based routing over WLAN-based links and topology-based paths over the WiMAX network.

Similarly, the rationale behind WiFi-3G integration given in [12] is that the data delivery process must take into account 3G budget constraints while achieving a good trade-off between delay and delivery success rate. Accordingly, Zhao *et al.* work rely on the estimated packet delivery probabilities over the ad hoc network. Only those packets are delivered through the 3G network interface with lower expectations, whereas all other packets are transported via multi-hop transmissions using Epidemic routing.

In our previous work, we suggested combining a VANET and 4G/LTE cellular networks. For such scenarios, the distinguishing factor for the VHO decision algorithm is the use of ad hoc mode rather than the traditional infrastructure model. Authors in [23]–[25] proposed and implemented a hybrid vehicular network architecture by combining IEEE 802.11p standard and 4G/LTE. The QoS-aware RAT selection and VHO algorithms took into account network load and application's requirements before switching and steering traffic between the alternative technologies while reducing the number of VHOs performed. Mir *et al.* considered 4G/LTE to provide infrastructure-assistance [6], [26] by steering control packets containing in-network status information over the mobile cellular network and data packet over the ad hoc network. The status information is collected at a centralized remote server, which subsequently utilizes it to decide on power adaptation and hybrid routing protocol.

In some approaches, instead of all vehicles, only a few static or mobile gateway or cluster-head vehicles are required to be equipped with dual-interface enabled communication systems. All other vehicles opportunistically offload vehicular data to nearby gateways or cluster-head vehicles using ad hoc networks. The gateways act as the first hop from the source vehicle and last hop towards the final destination vehicle. Typically, the system follows multi-tiered hierarchical architecture [5] in which gateways or cluster-heads collect and send aggregated data one level up in the hierarchical organization. Central to this approach is the selection of the cluster-heads or gateways. In the context of heterogeneous networks, the cellular network infrastructure is used mainly in two ways. In the first approach, proposed in [27], the base station or a remote server assists in creating and maintaining the cluster organization (or clustering) in a centralized fashion. The second approach assumes that the grouping is already in place and refers to selecting an optimal number of mobile gateways [28] in a distributed manner. The mobile gateways act as the relaying element between the vehicles and the cellular network infrastructure. To this end, several gateway or cluster-head selection algorithms have been proposed that mainly differ in their choice of selection criteria. Abderrahim *et al.* in [29] utilized speed, Received Signal Strength (RSS), and link stability information for gateway selection in a VANET-UMTS (3G) integrated vehicular network.

Similarly, Rajarajan *et al.* in [30] proposed a multi-criteria gateway selection algorithm in a VANET-LTE enabled vehicular network by considering the DSRC transmission rate, LTE channel quality, and relative distance metrics. Finally, in [31], [32], Zhioua *et al.* used QoS traffic classes and link connectivity information for electing the gateway vehicle. More recently, Ion *et al.* proposed a timer-based cluster-head selection algorithm, where the timer value depends on the number of neighbors and LTE channel quality [33].

Compared with the related work, the main contributions and novelties of this article are given below.

1) Unlike most of the earlier work where the RRM functionalities are implemented in their respective infrastructure nodes only, we proposed a two-tiered RRM strategy. The distributed CRRM module at the upper-tier manages the Primary RRM, i.e., DSRC RAT, and provides coordination with radio resource allocation at the lower-tier in the Secondary RRM, i.e., C-V2X RAT.
2) An adaptive RAT selection algorithm that takes in to account QoS metrics such as channel occupancy level in the Primary RAT and network load in the Secondary RAT. To select the most appropriate RAT according to network conditions, it also includes a network-assisted, but the vehicle-initiated VHO mechanism, which ensures seamless connectivity in the best possible way.
3) A dynamic communication management module performs QoS negotiation of critical communication parameters against the application's QoS requirements to reduce unnecessary switching between RATs significantly. Towards this end, the DCM module implements beaconing rate adaptation and admission control in the Primary RRM and the Secondary RRM.
4) A suite of protocols was developed and tested that allows a unified communication system by interweaving CRRM, RAT selection with VHO, and DCM algorithms. The CellCar framework provides performance improvements in a heterogeneous vehicular networking environment using DSRC and C-V2X technologies.

III. SYSTEM ARCHITECTURE AND PROTOCOL STACK

A. COMPONENTS OF THE PROPOSED ARCHITECTURE

This section provides details on the dual-interface enabled V2X communication system architecture and protocol stack. A CS can perform V2X communication based on two established links. The DSRC-enabled direct link to exchange the time-critical messages between nearby vehicles. Based on IEEE 802.11p, the direct link uses radio resources at the 5.9 GHz frequency band. Alternatively, use the LTE link, where messages are exchanged reliably over the more extensive range by passing through the cellular infrastructure. The 4th Generation (4G) mobile radio system LTE offers a highly flexible network located in the 800 MHz, 1800 MHz, and 2600 MHz band with a channel width between 1.4 and 20 MHz.

1) **CellCar Station (CS):** is a vehicle running CellCar. It comprises an application unit (CCApp) where the messages are generated and passed to an onboard unit (OBU). The OBU is connected to dual-interface radio transceivers embedded with DSRC and C-V2X RATs. The CellCar system supports the Global Positioning System (GPS) component for providing location information. The OBU also implements optimized protocol architecture design as suggested by relevant standardization bodies, e.g., Wireless Access in Vehicular Environment (WAVE), Communication Access for Land Mobile (CALM) [21], Car-2-Car Communication Consortium (C2C-CC) [34]. The optimization is achieved by integrating new methods, protocols, and services in the *data plane* layers and the associated *management plane* of the protocol stack.
2) **CellCar Information Center (CIC):** is a central entity that runs several back-end services such as location management. The CIC is also responsible for sending application data from one CS to one or several CS in a specific geographical Area of Interest (AOI).
3) **CellCar Application (CCApp):** comprises all the application types and defines the format of application-level data messages exchanged among CSs and between CS and CIC. As given in the ETSI TC ITS [35] standard, CCApp can generate one of the two types of messages. (1) Cooperative Awareness Message (CAM) that are generated periodically and (2) Distributed Environmental Notification Message DENM) that are triggered due to the occurrence of an Event of Interest (EOI). Intelligent mechanisms facilitate the handling of application data at the CIC. It includes selecting the destination geographical areas that require messages to carry the destination area (i.e., message type GA).
4) **DSRC-enabled Ad hoc Network:** In the DSRC-enabled network, the CAM/DENM are exchanged in a distributed fashion using single-hop broadcasts

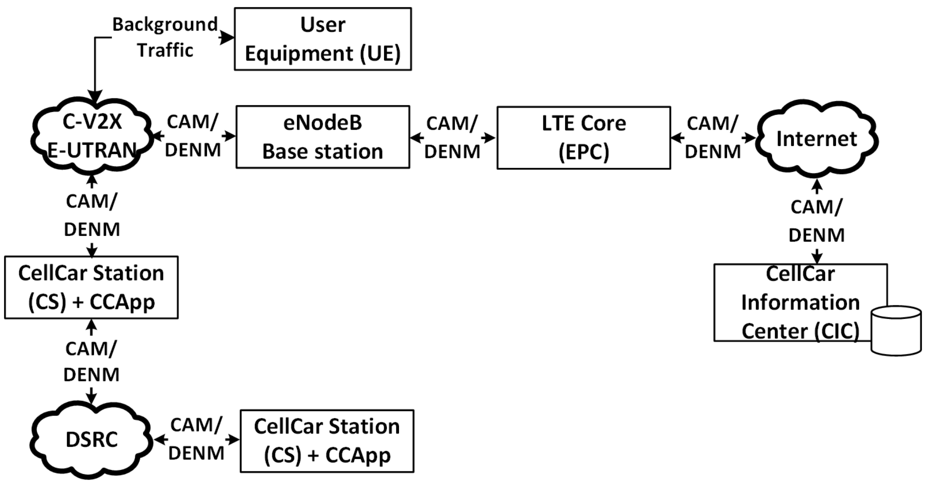

FIGURE 1. CellCar system architecture with five major components, CellCar Application (CCApp), CellCar Station (CS), CellCar Information Center (CIC), ad hoc and mobile cellular networks.

from each CS to its immediate neighborhood. Alternatively, position-based multi-hop communication is performed to reach more distant destination CSs within the AOI disseminating through specific geographical forwarding region. The GeoNetworking [36] carries out the latter technique layer, which performs position-based geographical forwarding of the messages. From the protocol architecture perspective, two configurations exist. A simple transport protocol stacked over the GeoNetworking layer, which transmits messages using short-range wireless communication standard for vehicular networks. Alternatively, messages can be carried by the GeoNetworking layer with Transport Control Protocol (TCP)/IP or User Datagram Protocol (UDP)/IP application on top.

5) **Mobile Cellular Network:** The cellular network architecture comprises a radio access network (E-UTRAN), which takes care of all radio control and management functionalities and interaction between the User Equipment (UE) and Evolved NodeB (eNodeB). The eNodeB is directly connected with the Evolved Packet Core (EPC), which supports mobility management, QoS handling, and interoperability with legacy 3GPP and Non-3GPP access technologies. LTE support IP-based data transmission; therefore, messages can be encapsulated and transported as an IP packet payload with TCP/IP or UDP/IP applications running directly on top of the wireless access network. As another option is to run applications on top of the GeoNetworking layer that, in turn, utilizes the IP protocol to transmit the datagrams. In the latter case, the dissemination of application data over a cellular network requires the presence of CIC like centralized entity. The CIS server receives data transmitted by the CSs and further relays it towards the destination CSs within the AOI.

As Fig. 1 shows, CSs can communicate with other CSs either directly through DSRC based ad hoc communication or via infrastructure-assistance in the form of CIC. The CIC is either interconnected to a network element within eNodeB or EPC or accessible through the Internet. From the data dissemination perspective, CS sends the vehicle's movement and application data to the CIC server(s) and immediate neighboring CSs. The CIC's back-end server implements services such as storage and management of location information and forwarding and aggregation of messages. Furthermore, LTE supports both CS and UE background traffic.

B. PROTOCOL STACK DESIGN

The protocol design is based on a convergent architecture, which includes an optimized dual-protocol stack combining DSRC and GeoNetworking. The protocol stack comprises an application, facilities, transport and networking, and access layers. A WAVE Management Entity (WME) manages the upper and the lower layers of the protocol stack, which constitutes the *management plane*. Simultaneously, the layers that operate on the messages themselves are known as the *data plane*. Fig. 2 shows the detailed protocol architecture design. The WME registers priority, data rate, and power for different applications.

1) **Application Layer:** The proposed protocol design architecture supports four types of vehicular applications, i.e., active road-safety, Enhanced-V2X (e-V2X) [37], traffic efficiency, and infotainment. The application layer assigns each application a unique application identifier. Applications are classified according to four basic types, and corresponding priorities and initial RAT preferences are determined. Finally, their functional and QoS requirements are registered in several communication performance metrics, such as the beaconing rate.
2) **Facilities Layer:** supports application, information, and communication functionalities. Among others, the essential supported features are providing location information, Local Dynamic Map (LDM), and

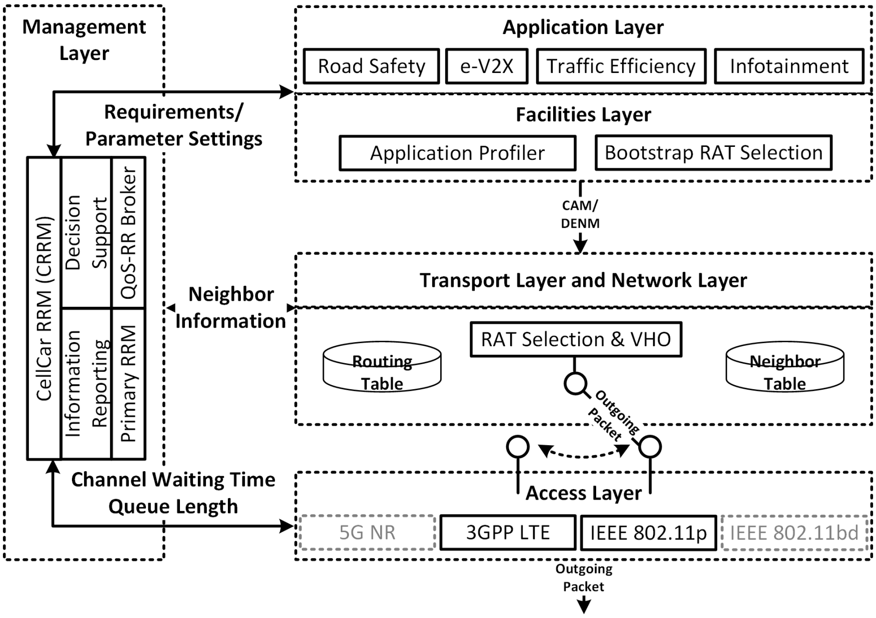

FIGURE 2. Protocol stack design for the CellCar system.

CAM/DENM management. Additionally, build on top of existing functionalities, in the proposed framework, the facilities layer contains support for Application Profiler and Bootstrap RAT Selection. More details are given in Section V.

3) **Transport and Network Layers:** The communications among CS is performed in the DSRC access network over *Primary RAT* interface. The position-based forwarding strategy or GeoNetworking is employed for application data dissemination. Whereas transmission between CS and CIC server via the Internet is carried out in LTE access networks using *Secondary RAT* interface. Two alternatives exist, first end-to-end with application data encapsulated in the IP packet payload and IP over GeoNetworking. The networking protocol is connected to a simple, dedicated transport protocol for vehicular communication or the TCP or UDP. The networking layer also maintains the neighbor and routing tables containing locations of the direct neighboring CS.

4) **Access Layer:** is responsible for the Physical and Data Link Layers of each communication interface. The access layer monitors the communication interface and provides information on several status indicators, such as busy channel rate, RSS, and frame transmission statistics. Moreover, the access layer is also capable of manipulating the parameters of the specific communication interface. In the context of the hybrid vehicular network, the connectivity for CS is provided by two access networks technologies, including DSRC based system and LTE network, also Primary RAT interface and Secondary RAT interface, respectively.

5) **Management Layer:** Generally, the management layer manages different aspects of the service advertisement, communication service, and networking management. The two functionalities that the proposed framework extends significantly are the congestion control and the mapping of application data flows on the available communication interfaces. The *CellCar Radio Resource Management (CRRM)* primarily describes the component that implements effective communication and resource management in a multi-technology vehicular network.

   Central to the multi-technology enabled CS is the CRRM, which follows a two-tiered model where an individual RMM manages each access network, i.e., Primary RAT and Secondary RAT interfaces are controlled by *Primary RRM* and *Secondary RRM*, respectively. The CRRM not only coordinates with each RRM but also communicates with other CRRM entities. Each RRM is responsible for implementing strategies like power control, packet scheduling, congestion control, admission control, and handover control, etc. for their respective access networks. Due to higher interaction between CRRM and RRMs and dynamic RRM handling, CRRM is implemented in a distributed manner. Therefore, RAT selection, VHO, and DCM for the Primary RAT are left for the CS to handle and not to a centralized entity. One of the benefits of moving CRRM functions to the CS is that all necessary measurements, such as Channel Waiting Time (CWT), Queue Length (QL), originate at the CS terminal. Moreover, the CS also contains the application interface, which provides information on

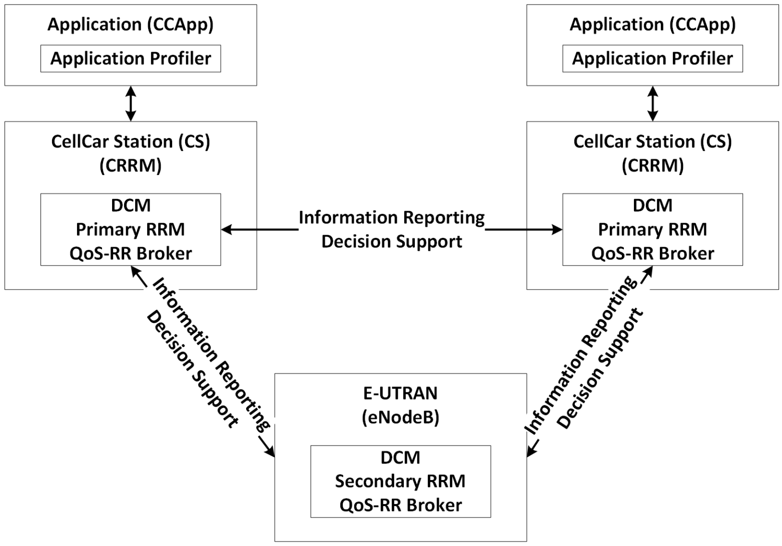

FIGURE 3. Two-tiered topology for the CellCar Radio Resource Management (CRRM) entity.

the application's QoS requirements. Fig. 3 shows the high-level abstraction for the CRRM and its two-tiered topology.

From the functional perspective, the coordination between CRRMs and individual RRMs is carried out by mean of *information reporting* and *decision support* functions [13]. (1) Information Reporting: The information reporting sub-module is responsible for monitoring and exchanging local measurements and QoS information associated with both Primary RRM and Secondary RRM and among CRRM entities. The sharing of information can be done either periodically or as the result of a particular condition. (2) Decision Support: The shared information is acted upon and conveyed by the decision support sub-module where RRMs make decisions regarding radio resource utilization either independently or as per instructed by the CRRM, which work in close interaction with other CRRM entities.

IV. SELECTION CRITERIA FOR DSRC AND LTE NETWORKS

The proposed RAT selection and VHO algorithms utilize in-network information such as channel occupancy level and cellular network load, monitored and coordinated by the Primary RRM and Secondary RRM entities. In the former case, the Primary RRM only observes the local (one-hop) neighborhood area, whereas the Secondary RRM coordinates available resources at the single macro-cell site. To this end, the critical parameters considered for both the RAT selection and VHO algorithms are given in the following section.

A. CHANNEL OCCUPANCY AS DSRC SELECTION CRITERIA

In this article, the *Channel Waiting Time (CWT)* and *Queue Length (QL)* are considered to measure the congestion in terms of *Channel Occupancy Level (COL)* in the vehicular ad hoc network. The COL estimates based on the CWT, and QL is obtained from the Access layer [38].

1) CALCULATING CHANNEL WAITING TIME (CWT)

The frequency channel layout of a 5.9 GHz DSRC consists of seven channels, each with the bandwidth of 10 MHz. One channel is reserved as a control channel (CCH), four channels are allocated as service channels (SCHs), and two are for future use. The road-safety and control messages are transmitted over CCH. In contrast, SCHs carries messages for traffic efficiency and infotainment applications during the fixed CCH Interval (CCHI) and SCH Interval (SCHI), respectively. The DSRC standard utilizes Enhanced Distributed Channel Access (EDCA) [39] method to enable QoS for packet transmission. EDCA uses four queues to differentiate among the different levels of priorities, also called *Access Categories (AC)*. Each AC, in turn, is dedicated to another type of data traffic. For example, we assume that the higher priority queue, i.e., AC0 relates to road-safety applications and AC1 concerns with the Enhanced-V2X (e-V2X) [37] use cases such as teleoperated remote automated driving with stringent latency requirements. Whereas the other two access categories AC2 and AC3, hold traffic for delay-tolerant traffic efficiency and comfort applications. In EDCA, the priority is established by implementing several delay parameters such as Arbitration Inter Frame Space Number (AIFSN) and Contention Window (CW) with the basic principle, which states that the smaller these parameter values higher the priority, thus earlier the chances of transmissions. For further information on delay parameters and their values corresponding to each AC, refer [39]. Consider the following parameter settings.

- Maximum CCHI and SCHI: $T_{max} = 50$ ms.
- Number of queues: q = 4.

- Medium busy time of m^{th} message at the i^{th} queue as indicated by the Channel Clear Assessment CCA) module: T_m^i where i ∈ 0, 1, 2, 3.
- aSlotTime = 32 μs.
- Short Inter-Frame Space (SIFS) = 13 μs.

The following equation gives the mean back-off duration.

$$T_{backoff}^i = 0.5 \times aCW_{min}^i \times aSlotTime \tag{1}$$

The AIFS duration for the i^{th} queue with corresponding Arbitration Inter Frame Space Number (AIFSN) is given as follows.

$$T_{AIFS}^i = SIFS + AIFSN^i \times aSlotTime \tag{2}$$

Then, the average waiting time for m^{th} messages at the i^{th} queue is given as follows.

$$T^i = (\frac{\sum_1^m T_m^i}{m}) + T_{AIFS}^i + T_{backoff}^i \tag{3}$$

Finally, the CWT is defined as the ratio between the average duration in time the channels were found busy and the maximum interval duration. CWT is calculated using the following equation and normalized to a value between 0 and 1, i.e., CWT ∈ [0, 1].

$$CWT = (\frac{\sum_{i=0}^{q-1} T^i}{T_{max}}) \tag{4}$$

2) CALCULATING QUEUE LENGTH (QL)

QL is the degree with which queues are occupied. Consider the following parameter settings.

- Maximum Capacity of all the queues: $Q_{max} = 50$.
- Number of neighbors: n.
- Number of messages received from the j^{th} neighboring CS: R_j where j ∈ 0, 1, 2, ... n−1.
- Number of messages sent by the current CS k: S_k.

It is assumed that each queue service the transmission and reception packets, and the system is not full-duplex. The rationale behind counting the number of packets received and sent is to signify the congestion level of the CS itself and the resources occupied by the other neighboring CS. The current size of the i^{th} queue at the k^{th} CS is based on the following equation.

$$Q_k^i = \sum_{j=0}^{n-1} R_j^i + S_k^i \tag{5}$$

Finally, QL is given as the ratio between the total queue size and maximum queuing capacity using the following equation and normalized to a value between 0 and 1, i.e., QL ∈ [0, 1].

$$QL = (\frac{\sum_{i=0}^{q-1} Q_k^i}{Q_{max}}) \tag{6}$$

3) CALCULATING CHANNEL OCCUPANCY LEVEL (COL)

COL is used as the criteria for selecting DSRC-enabled interface. It is calculated by combining the values of CWT and QL as follows:

$$COL = (\alpha) \times CWT + (1 - \alpha) \times QL \tag{7}$$

where α is a weighting factor i.e., $\alpha \in$ [0,1]. The parameter α is close to 1 if the CWT is more important and close to 0 when the QL is more important. More formally expressed in the following equation.

$$COL = \begin{cases} CWT, & \text{if } \alpha = 1 \\ (\alpha) \times CWT + (1 - \alpha) \times QL, & \text{if } 0 < \alpha < 1 \\ QL, & \text{if } \alpha = 0 \end{cases} \tag{8}$$

B. NETWORK LOAD AS LTE SELECTION CRITERIA

The basis for the selection of Secondary RAT is the knowledge about the cellular network load. As suggested in [24] and [40], the cellular LTE network load is primarily measured in terms of the number of free Physical Resource Blocks (PRBs) that are available to schedule. Fewer PRB available indicates a higher load in the connected cell and vice versa. Each CS gets the feedback regarding the LTE network load using LTE Load Indication (LLI) [24]. The 3-bit LLI value indicates eight different load states in both uplink and downlink for a particular LTE cell. The LLI can be received on the Physical Downlink Shared Channel (PDSCH).

The Call Admission Control (CAC) is one of the RRM functions in the LTE Evolved Packet System (EPS) to control and maintain the QoS of the admitted traffic flows at the bearer level. In this article, we utilized the CAC model given in [40], which rely on the partial and full preemption of application session based on the priority. Consider the following parameter settings.

- Total load contribution over a given time window: $L_{current}$.
- Requested resources in Physical Radio Block (PRB) to achieve bit rate b: $L_{new}(b)$.
- Total capacity of a single-macro LTE cell: C.
- Total resources needed to preempt for admitting new session: $\triangle \rho$.

Then, the criteria for admission control and resource allocation $PRB(b)$ of a new session with load $L_{new}(b)$ is given as follows:

$$L_{new}(b) = \begin{cases} PRB(b), & \text{if } L_{new}(b) \le C - L_{current} \\ PRB(b), & \text{if } L_{new}(b) \le C - (L_{current} - \triangle \rho) \\ 0, & otherwise \end{cases} \tag{9}$$

The first condition checks if sufficient resources are available for allocation with the required data rate. The second condition describes the scenario where needed resources are only made possible by either partially or fully preempt the lower priority application session. Finally, the last term represents the situation where no resources are available for allocation.

V. PROPOSED RAT SELECTION AND VHO ALGORITHMS

The proposed protocol suite mainly consists of three algorithms (1) RAT selection, (2) VHO, and (3) DCM. The overall objective is to ensure seamless connectivity and improve performance while minimizing the number of handovers and associated latency and loss of data throughput. When a new application flow is originated, a bootstrap RAT selection procedure is performed, which selects an initial RAT based on the application type. For the adaptive RAT selection, the respective RRM entities are checked whether the application flow can be accommodated as permissible by its QoS requirements. If the measured channel occupancy level and the network load is within the pre-specified threshold value, the flow is directed to the Primary RAT and Secondary RAT, respectively. The VHO algorithm initiates the DCM procedure before making the handover decision to avoid unnecessary handover between RATs. The DCM applies beaconing rate adaptation and admission control techniques using the Primary QoS-RR Broker and Secondary QoS-RR Broker, respectively. The traffic is carried over the selected RAT until it is inevitable, and the VHO is performed.

A. APPLICATION PROFILER AND THE RAT SELECTION ALGORITHM

Application profiler supports automatic derivation, storage, and setting of application's QoS requirements. The Application and Facilities layers define the QoS requirements on a per-application traffic flow basis. The first step in the provisioning of an application traffic flow is to specify its QoS requirements in terms of its beaconing rate. Initially, the Application layer assigns a unique identifier. It classifies application into one of the four application types, i.e., (1) Active Road Safety, (2) e-V2X, (3) Traffic Efficiency, and (4) Infotainment along with different priorities and traffic classes. For each application traffic flow, the Application Profiler in the Facilities layer manages the following QoS and system-level parameters. Table 1 summarizes the application types and initial parameter settings [37], [41], [42].

TABLE 1. Applications and traffic types with initial parameter settings [37], [41], [42].

Application type	Preferred RAT	Beaconing Rate	QCI	Priority
Road safety	Primary	1-10	75	2.5 (GBR)
Traffic efficiency	Primary	1-10	79	6.5 (Non-GBR)
Infotainment	Primary	1-2	79	6.5 (Non-GBR)
e-V2X	Secondary	2-50	84	2.4 (GBR)
Voice	Secondary	0.1-10	1/7	2/7
Live Streaming	Secondary	0.1-10	2/7	4/7
Interactive	Secondary	0.1-10	3/7	3/7
Best effort	Secondary	0.1-10	6/8	6/8

- Application Identifier and type.
- Priority and traffic class, since application flows can take any of the Primary or Secondary RAT interfaces for communication, for priority assignment LTE convention are followed along with QoS Class Indicator (QCI) both in Guaranteed Bit Rate (GBR) and Non-Guaranteed Bit Rate (Non-GBR).
- Preferred or default RAT.
- QoS parameter in terms of beaconing rate, i.e., the number of beacons transmitted per second. The value varies between 1-10 packets per second, with some applications require a maximum of up to 50. The application profiler maintains three values for each application flow i.e., *minimum*, *maximum* and *tolerance*.

The application layer initiates data transmission via default RAT, selected according to the *Bootstrap RAT selection* strategy. Based on the application requirements, the Application Profiler checks the following rules to decide an appropriate access network:

1) If the initial RAT selection preference is given based on application type and traffic, the Secondary RAT interface for the streaming and Primary RAT interface if the application is of active road safety or traffic efficiency type.
2) Else if the Application Profiler checks whether the destination can be reached directly by finding an entry in the local neighbor or routing tables. Given it is true, the Primary RAT interface is selected.
3) Finally, the flow control is transferred to the CRRM, which initiates the RAT selection and DCM procedures by sending the *QoS Request message* either to the Primary RRM or Secondary RRM.
4) If the Primary RRM receives the *QoS Request message* from the CRRM, it first checks whether the application QoS requirements can be supported by the Primary RAT interface.
   a) Primary RRM monitors different local measurements such as CWT and QL, to determine Channel Occupation Level (COL), as described in Section IV. The Primary RRM considers maximum channel occupancy, which in practice can be determined by either T_{max} or Q_{max}. The fixed threshold limit ratio over the maximum channel occupancy $\beta \in [0,1]$ is used to calculate the effective COL i.e., $\omega = \beta \times T_{max}$ or $= \beta \times Q_{max}$. If the COL is well under the given threshold limit ω, i.e., $COL < \omega$, the CRRM is notified with a *QoS Reply Grant message*. The Primary RAT interface is selected, and the data dissemination over the selected interface is carried out.
   b) Else, if the estimated COL value exceeds specified threshold limit value ω, i.e., $COL > \omega$, the CRRM is notified with a *QoS Reply Decline message* indicating the current channel condition is saturated that could lead to performance degradation.
   c) The Primary RRM initiates the DCM via the Primary QoS-RR Broker procedure, as given in Section VI.
5) If the Secondary RRM receives the *QoS Request message* from the CRRM, then the following steps are performed.

a) Based on the application's QoS requirements given by the application profiler, the Secondary RRM maps application traffic flow to one of the traffic classes of the selected E-UTRAN.
b) The Secondary RRM located at the eNodeB measures the load contribution in terms of minimum or guaranteed bit data rate based on the traffic class. If the resources are enough to satisfy the application requirements, the CRRM is notified to select the Secondary RAT interface with a *QoS Reply Grant message*. The data is then forwarded over the selected interface. Else, if the measured load exceeds the capacity, i.e., LTE doesn't have enough resources, a *QoS Reply Decline message* is sent to the CRRM.
c) Subsequently, the Secondary RRM initiates the DCM through the Secondary QoS-RR Broker procedure, as described in Section VI.

B. VHO DECISION ALGORITHM

The VHO decision includes two aspects, i.e., VHO signaling and VHO algorithm. The VHO is terminal initiated and consists of the following steps.

6) From Primary RAT interface to Secondary RAT interface.
    a) A CS using the Primary RAT interface monitors the channel occupation level (COL). If the COL values reach a certain threshold limit, the Primary RRM tries to reduce the channel occupancy level by performing the Primary QoS-RR Broker process.
    b) If the Primary CRRM decides that VHO is inevitable for an application to function, it sends a request to the CRRM for handover initiation to the Secondary RRM.
    c) The CRRM sends the handover preparation request to the Secondary RRM and queries the availability of resources for the given application.
    d) Upon successful allocation of required resources, a VHO from DSRC to LTE is performed.
7) From Secondary RAT interface to Primary RAT interface.
    a) The Secondary RRM periodically reviews all the sessions within the single macro-cell area to evaluate the offered traffic load.
    b) If a request for a new session arrives from a vehicular user, then the Secondary RRM performs the Secondary QoS-RR Broker process by matching the requirements of the new traffic class with the available radio resources. It tries to reach an agreement with other sessions to accommodate the new application session by preempting lower priority sessions so that the overall load stays well below the total capacity.
    c) On successfully acquiring the required resources by the Secondary RRM, the resources are reserved, and the application flow continues to disseminate data using the Secondary RAT interface.
    d) Else, for the preempted application sessions, the CRRM is notified, and a VHO is performed from LTE cellular network to DSRC.

If switching to the Primary RAT and Secondary RAT interfaces are declined, the CRRM waits for an arbitrary length of time and re-initiates the RAT selection procedure. Fig. 4 shows the signaling processes to coordinate among different elements of the proposed architecture for an efficient RAT selection, VHO, and DCM.

VI. DYNAMIC COMMUNICATION MANAGEMENT (DCM)

While adaptive load threshold criteria based RAT selection decision results in an efficient solution, the parameter values keep going up and down, resulting in the ping-pong effect [13], i.e., frequent VHO between the Primary and Secondary RATs. The Primary and Secondary RRM entities avoid unnecessary vertical handovers by applying dynamic communication management via implementing QoS-RR Broker procedures in their respective access networks. In an attempt to reduce the channel load and thus a potential handover, the Primary QoS-RR Broker assigns an effective beaconing rate between the minimum and maximum beaconing rates as permissible by the application's QoS requirements. Similarly, the Secondary QoS-RR Broker gradually preempts low priority sessions to accommodate increasing load demand while avoiding handover to the Primary RAT.

A. PRIMARY QoS-RR BROKER

Most of the applications in the vehicular network domain rely on detailed data obtained both from local sensors and neighboring CSs by transmitting beacons or heartbeat messages. The data provide drivers or autonomous systems an extensive field of view on the driving environment. The reliability and accuracy of vehicular applications depend on real-time beacon transmission and processing to allow the driver to react to any potentially hazardous situation appropriately within a critical time window. Higher beaconing rates, i.e., many beacons per second, can saturate the channel, causing traffic congestion, higher latency, and lower throughput [1]. On the other hand, lower beaconing rates can severely impact the accuracy of the application. Therefore, the beaconing rate can be utilized as a numerical QoS metric [43] for the proposed system. Moreover, different applications involve different beaconing rates; for example, pre-crash road safety application requires a beaconing rate of 50 beacons/sec. In contrast, community service applications can operate with as low as one beacon/sec. [5], [44]. Therefore, instead of assigning an optimal beaconing rate to all the CSs, different beaconing rates are assigned depending on the application QoS requirements, time-dependent vehicle kinetics, and the surrounding environment.

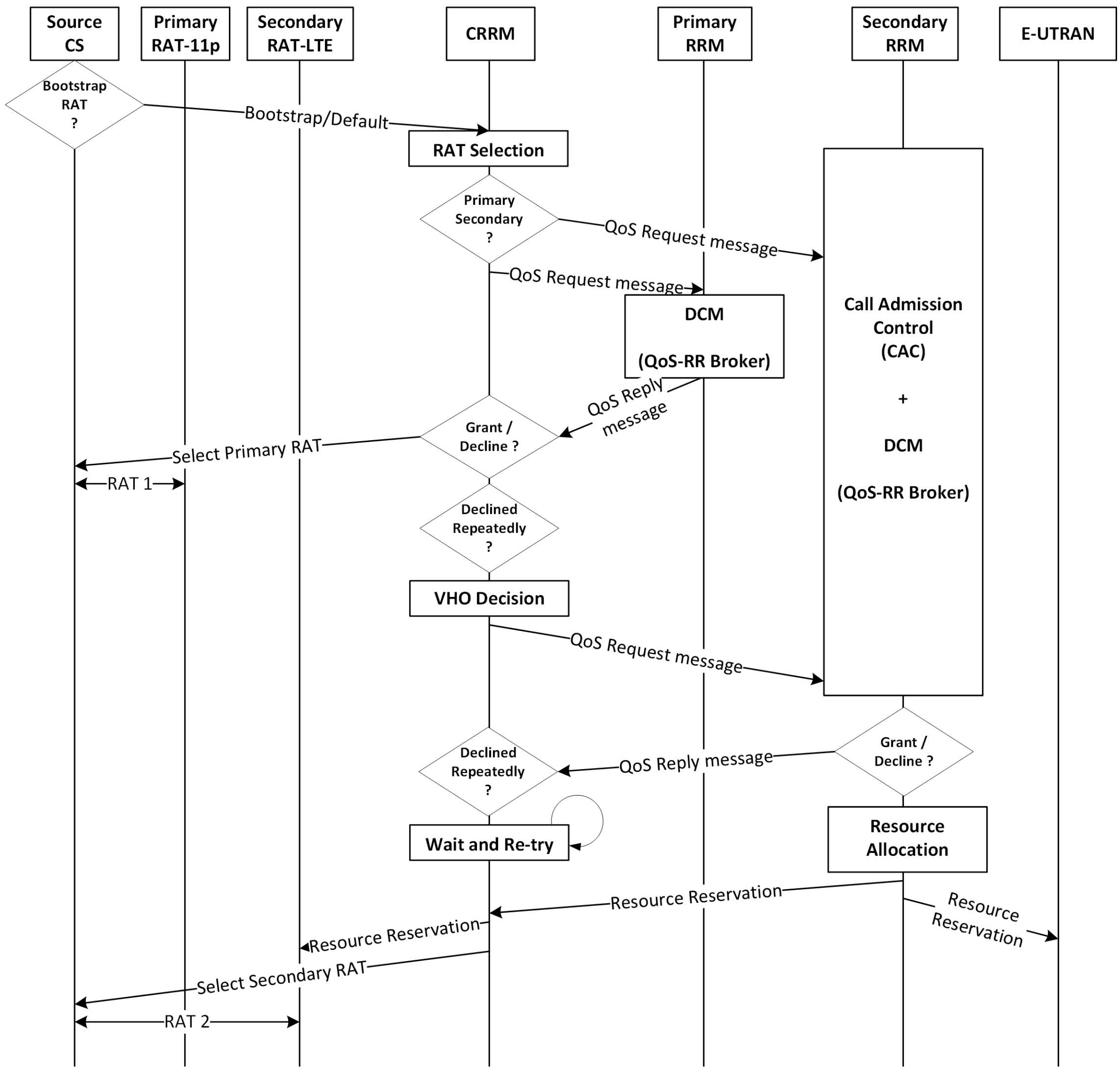

FIGURE 4. Signaling procedures for RAT selection, Vertical Handover (VHO), and Dynamic Communication Management (DCM).

In vehicular ad hoc networks, access to the wireless medium is uncoordinated; therefore, the radio resources are managed and utilized in a distributed manner. In this article, it is assumed that each CS operating the Primary RAT interface adapts the beaconing rate within a range between BR_{min} and BR_{max}. The Primary RRM negotiates a lower beaconing rate for the applications. The adaptation mechanism gradually decreases the beaconing rate in multiple steps permissible by application QoS requirements and channel conditions. The selected value is then updated and stored in the data structure maintained by the application profiler. The CSs coordinate via Information Reporting and Decision Support functions by sending and receiving QoS Request and QoS Decline control messages. The interval adaptation procedure can be initiated by periodically monitor the value of COL or triggered as the result of receiving a QoS Request message from one of the neighboring CS CRRM.

The proposed beaconing rate adaptation algorithm relies on the following parameters.

- A CS can select a beaconing rate given by $BR_{current}$ between BR_{min} and BR_{max}, i.e., $BR_{min} \leq BR_{current} \leq BR_{max}$. Initially, the current beaconing rate, is set to BR_{max}.
- Beaconing rate tolerance $BR_{tolerance}$ given as the percentage of the BR_{max}. It is defined as the maximum tolerable reduction in beaconing rate by an application based on its QoS requirements in order to ensure the required accuracy of the application.
- Beaconing rate reduction factor BR_{factor} is defined as the percentage decrease in current beaconing rate.
- $T_{initial}$ is a timer which defines the minimum time period that an application must operate at BR_{max}.
- T_{reduce} is a timer which defines the maximum time duration an application can operate at the reduced beaconing rate.

The following are the steps of the beaconing rate adaption algorithm. Fig. 5 shows the flowchart diagram of the beaconing rate adaptation mechanism.

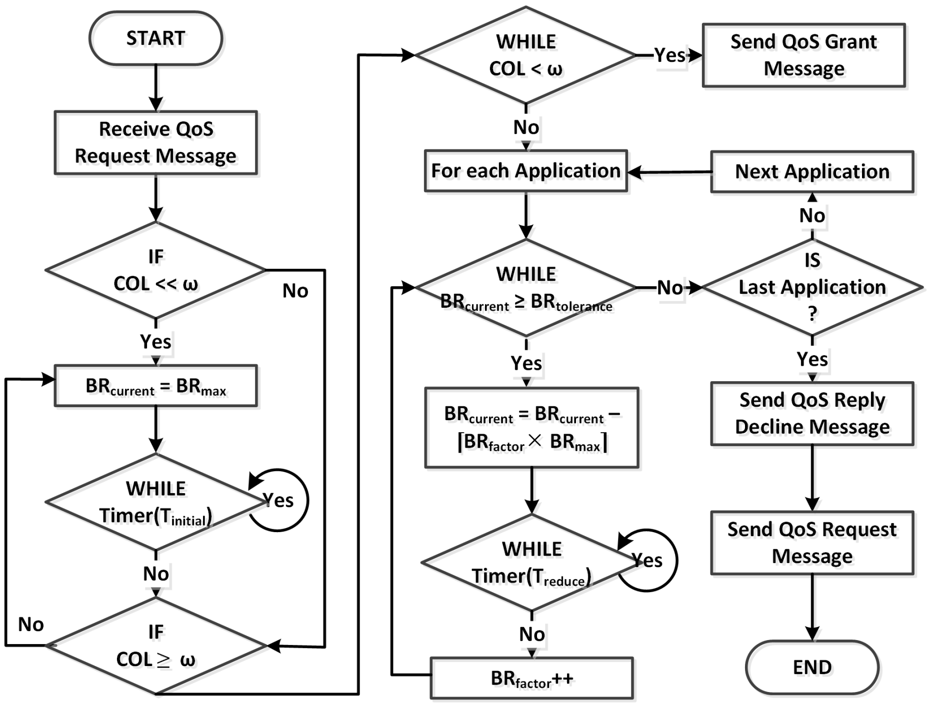

FIGURE 5. Flowchart diagram of the beaconing rate adaptation algorithm.

1) During the uncongested scenarios i.e., $COL \ll \omega$, the applications operate at BR_{max} for minimum $T_{initial}$ interval.
2) As the congestion level exceeds the given threshold value, i.e., $COL \geq \omega$, the Primary QoS-RR Broker repeatedly applies the following steps for each application flows currently originating from the CS.
3) Gradually decrease the beaconing rate by the given BR_{factor} parameter until the beaconing rate cannot be reduced further, i.e., parameter $BR_{tolerance}$ is reached. The proposed mechanism calculates the $BR_{current}$ given as:

$$BR_{current} = \lceil BR_{current} - (BR_{factor}\% \times BR_{max}) \rceil \quad (10)$$

4) Start a timer T_{reduce} and transmit using the current beaconing rate of $BR_{current}$.
5) The steps mentioned above are repeated for each application until the COL value becomes lower than the specified threshold limit, i.e., $COL < \omega$.
6) The value of the current beaconing rate of $BR_{current}$ is determined based on the following criteria.

$$BR_{current} = \begin{cases} BR_{max}, \text{ if } COL \ll \omega \\ \lceil BR_{current} - (BR_{factor}\% \times BR_{max}) \rceil, \\ \text{if } COL \geq \omega \\ BR_{tolerance}, \, otherwise \end{cases} \quad (11)$$

B. SECONDARY RR-QoS BROKER

The Secondary RR-QoS Broker facilitates the negotiation between the applications QoS requirements and the available resources. On selecting the Secondary RAT interface, the Secondary RRM maps the application traffic to one of the traffic classes of the cellular network.

1) To accommodate requested bandwidth, the Secondary RR-QoS Broker utilizes CAC functionalities to control the LTE EPS bearers to maintain the QoS of the admitted bearers.
2) On finding that the load contributed can't be accommodated, the CAC applies preemption of low priority session by initiating a two-step negotiation process based on the criteria described in Section IV.
    a) Firstly, partially preempt the resources with the lowest priority traffic class to their minimum data rate requirements.
    b) Secondly, if the above step fails, entirely preempt the lowest priority traffic.
3) If the EPS bearer setup request by the Secondary RRM is accepted, the required bandwidth is allocated, and the CRRM is notified subsequently.
4) The CRRM registers with the cellular network and starts the VHO signaling for data communication.

VII. PERFORMANCE EVALUATION

This section describes a simulation-based study of the proposed scheme. The main focus is to evaluate the impact of hybrid architecture and distributed radio resource management on the performance of the DSRC based vehicular ad hoc network. The performance is assessed in terms of vital communication and networking metrics such as the number of VHOs performed, throughput, Packet Delivery Ratio (PDR), and latency. Mainly two simulation studies are conducted.

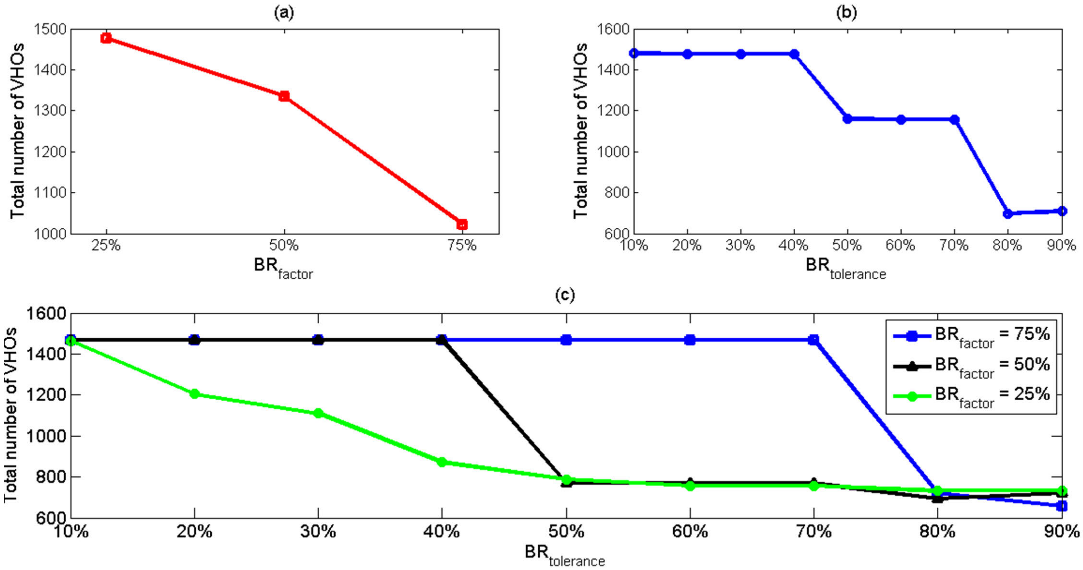

FIGURE 6. Impact of parameters: (a) BR_{factor}, (b) $BR_{tolerance}$ and (c) Combined BR_{factor} and $BR_{tolerance}$ on Number of VHOs.

TABLE 2. Simulation parameters and values.

Parameters	Values
Road length	5 km
Lane width	5 m
Number of lanes	3
Number of vehicles	150
Minimum speed	50 km/h
Maximum speed	120 km/h
Simulation time	300 s
DSRC communication range	250 m
DSRC Data rate	6 Mbps
α	0.5
Threshold limit ratio β	80%
Beaconing rate	1 to 20 beacons/s
Number of LTE cells (eNodeB)	1
LTE bandwidth (Uplink/Downlink)	50 Mbps/50 Mbps
LTE time slot	1 ms
LTE resource blocks	6
LTE total number of subcarriers	72 (12 x 6 resource blocks)

1) Study the impact of different parameters on the performance.
2) A comparative study with several simulation scenarios such as periodic RAT switching, DSRC only, proposed hybrid approach and proposed a hybrid approach with DCM.

A. SIMULATION ENVIRONMENT

The proposed protocol performance is validated through extensive simulations using the Matlab tool. The simulation environment represents a typical highway scenario of a 5 km road strip. The highway layout consists of three lanes on both sides, where each lane is 5 m wide. A total of 150 vehicles participated in the simulation, each traveling with a varying speed between 50 km/h to 120 km/h. The ad hoc network part is simulated using the DSRC compliant standard with an application, EDCA-based MAC, and PHY layers. The application layer is responsible for generating CAM/DENM messages at a different beaconing rate ranging between 1 beacon/sec. to 20 beacons/sec. The maximum beaconing rate is set to 20 beacons/sec. because some of the advanced V2X applications pre-crash warning require the rate of up to 50 beacons/sec. [42], [44]. Each CS periodically transmits beacons of 250 bytes size using a single-hop broadcast. The ad hoc interface operated at 5.9 GHz frequency with a 6 Mbps data rate. The maximum communication range is set to 250 m. A two-ray ground reflection model is included in the PHY layer. Generally, the highway scenario has fewer obstructions, and most vehicles have a Line-of-Sight (LOS) link among them for longer durations [45].

For modeling cellular networks, we used a simplified setup with a single cell, i.e., the radio access network, which constitutes only one eNodeB. The focus is on modeling the uplink or Uu radio interface between the vehicle and radio access network (RAN). All CS communicates through LTE broadcast on the downlink and unicast in the uplink using the Secondary RAT interface. We used the Friis channel model for cellular communication. The simplified channel models provided a reasonable abstraction level at the PHY layer and a better trade-off between the simulation complexity and details. Table 2 summarizes the stimulation parameter settings for both DSRC and cellular technologies. The results obtained were averaged over ten different simulation runs.

B. SIMULATION RESULTS

1) STUDY THE IMPACT OF PARAMETERS ON PERFORMANCE

Fig. 6 represents the relationship between two critical parameters, i.e., $BR_{tolerance}$ and BR_{factor}. Fig. 6 (a) shows that the number of VHO decreases as the BR_{factor} parameter value

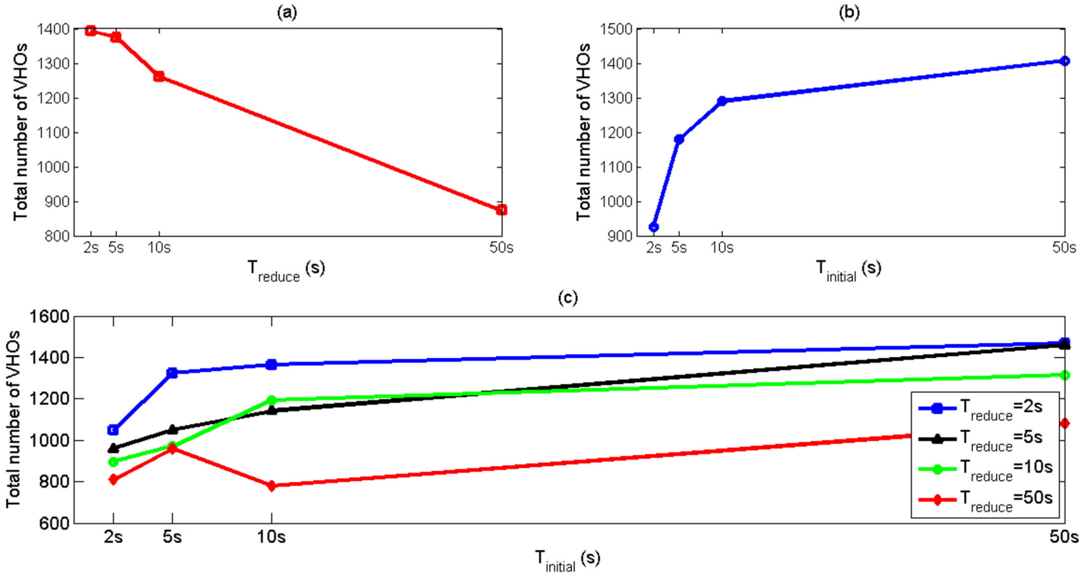

FIGURE 7. Impact of parameters: (a) T_{reduce}, (b) $T_{initial}$ and (c) Combined T_{reduce} and $T_{initial}$ on Number of VHOs.

increases, as long as the maximum tolerable reduction is high. In such applications, a higher BR_{factor} values impact the number of VHOs, which drops considerably. Scenarios where the maximum tolerable reduction $BR_{tolerance}$ is negligibly low results in a higher number of VHOs. These scenarios mostly arise in applications like pre-crash sensing, remote automated driving, which are more sensitive to reducing the beaconing rate. For applications less acceptable to the decrease in beaconing rate, even decreasing the beaconing rate by 25% results in a high number of VHOs. The obtained results are mainly because the parameter $BR_{tolerance}$ threshold is attained very quickly in the first couple of iterations that wouldn't allow the beaconing adaptation mechanism to be fully applied. These applications tend to switch more often to maintain the pre-specified QoS requirements, thus causing a higher number of VHOs. Fig. 6 (b) shows that the higher the applications can tolerate the reduction in its beaconing rate requirements, the lower the number of VHOs it performed. The higher $BR_{tolerance}$ threshold value allows applications to operate at lower beaconing rates without sacrificing their QoS requirements, which translates into lower network load and, therefore, fewer VHOs. Fig. 6 (c) shows the combined impact of $BR_{tolerance}$ threshold and BR_{factor} parameters on the number of VHOs. Unless the application is more flexible towards reduced beaconing rate, i.e., $BR_{tolerance}$ value considerably more significant than BR_{factor}, the impact of higher BR_{factor} values on the number of VHOs performed remains less signification. There is a sharp decline in the number of VHOs as soon as the $BR_{tolerance}$ threshold values exceed the BR_{factor} values.

Fig. 7 shows the impact of two timer values on the number of VHOs, i.e., T_{reduce} and $T_{initial}$. Fig. 7 (a) illustrates that the longer an application operates with reduced beaconing rate, i.e., higher T_{reduce}, the lower the number of VHOs. For applications that are less sensitive to lower beaconing rates, there are lesser chances of channel occupancy to grow beyond the given threshold limit, therefore resulting in fewer VHOs. Fig. 7 (b) shows that the longer an application maintains the initial beaconing rate, i.e., $T_{initial}$ duration, the higher the number of VHOs. Since the applications operate at the initial beaconing rate for an extended period, it results in considerable higher channel occupancy. The beaconing rate adaptation mechanism intervenes more often and quickly reaches the threshold limits, thus causing frequent VHOs. Fig. 7 (c) shows, as the $T_{initial}$ increases, for all the T_{reduce} durations the number of VHOs increases. Regardless of the duration, an application operates at a lower beaconing rate. If it requires to keep the higher beaconing rate longer, this will increase the channel occupancy to the level where VHO cannot be avoided.

Similarly, as the timer T_{reduce} value increases, for all the values of timer $T_{initial}$, the number of VHO decreases. Shorter an application can tolerate staying at the original beaconing rate, fewer the chances that the channel occupancy to increase beyond the specified threshold limit. Therefore, fewer numbers of VHOs are required to satisfy the application's QoS requirements.

Fig. 8 (a), (b) and (c) quantifies the impact of $BR_{tolerance}$ and BR_{factor} parameters on the throughput. Situations where a selected RAT could not further support the transmission often results in switching to the other access technology. The higher throughput is obtained by steering traffic between interfaces whenever necessary, therefore attaining better reliability. It is noteworthy the contribution of each access technology towards achievable throughput. The fewer number of VHOs can easily be translated into more traffic over

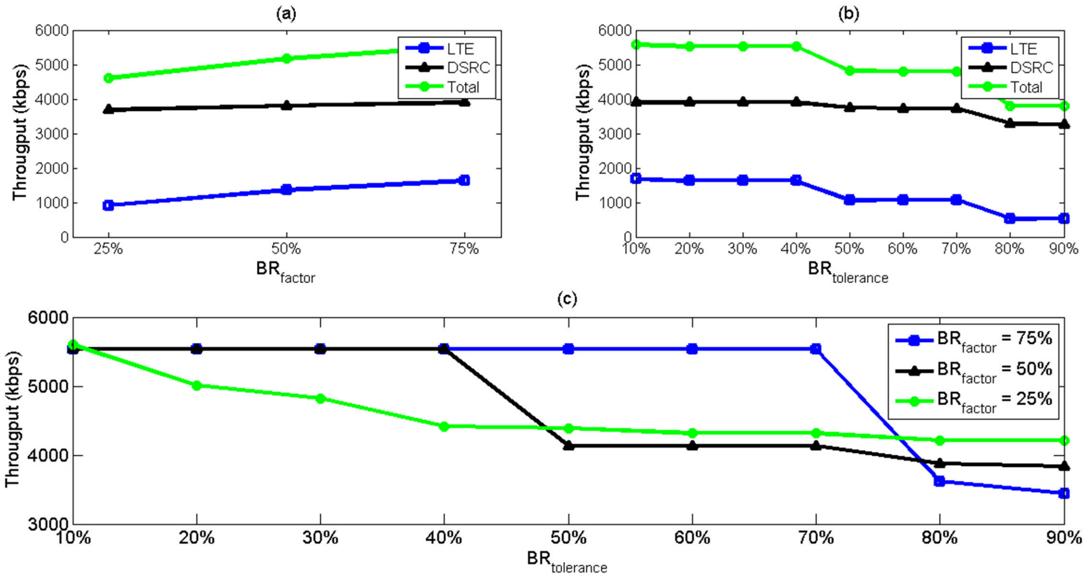

FIGURE 8. Impact of parameters: (a) BR_{factor}, (b) $BR_{tolerance}$ and (c) Combined BR_{factor} and $BR_{tolerance}$ on Throughput (kbps).

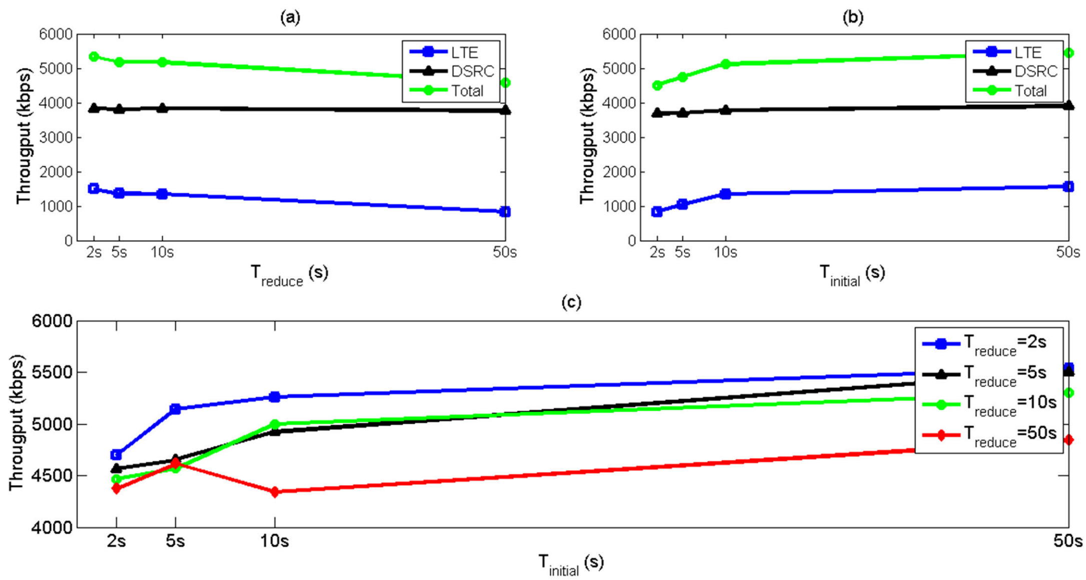

FIGURE 9. Impact of parameters: (a) T_{reduce}, (b) $T_{initial}$ and (c) Combined T_{reduce} and $T_{initial}$ on Throughput (kbps).

the DSRC interface. Conversely, a higher number of VHOs resulted in more traffic pass through the LTE interface. As the values of BR_{factor} and $BR_{tolerance}$ increases, there were fewer VHOs, which causes most of the traffic to go over the direct DSRC enabled links. The throughput decreases slightly as the $BR_{tolerance}$ threshold increases. Despite that the combined impact of $BR_{tolerance}$ and BR_{factor} result in lower throughput, the achieved reliability of over 92% satisfies the reliability requirements for most vehicular networking applications.

Fig. 9 (a), (b) and (c) quantifies the impact of T_{reduce} and $T_{initial}$ parameters on throughput. The higher values of T_{reduce} results in a fewer number of VHOs, which results in more traffic to go through over the Primary RAT interface. As the value of $T_{initial}$ increases, there was a higher number of VHOs, thus more traffic over the Secondary RAT interface resulting in higher reliability. The combined impact of T_{reduce} and $T_{initial}$ shows that the proposed scheme can attain better reliability and throughput if the applications operate at lower beaconing rates for longer durations.

Fig. 10 (a), (b) and (c) quantifies the impact of BR_{factor} and $BR_{tolerance}$ parameters on the latency. As the values of BR_{factor} increases, the lower number of VHOs causes vehicles to transmit more data over the Primary RAT interface. Although direct communications using the Primary RAT interface are

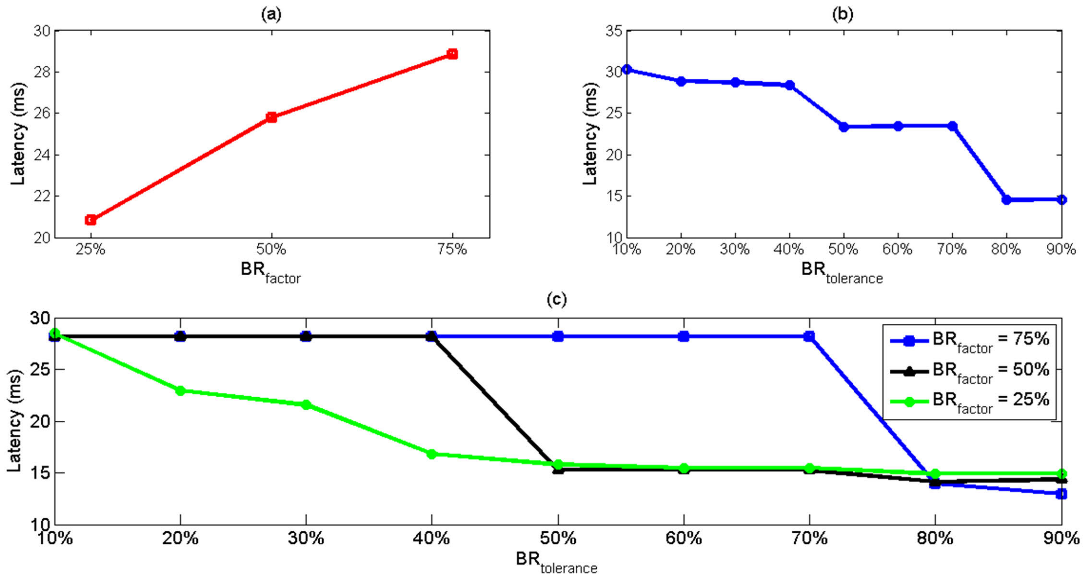

FIGURE 10. Impact of parameters: (a) BR_{factor}, (b) $BR_{tolerance}$ and (c) Combined BR_{factor} and $BR_{tolerance}$ on latency.

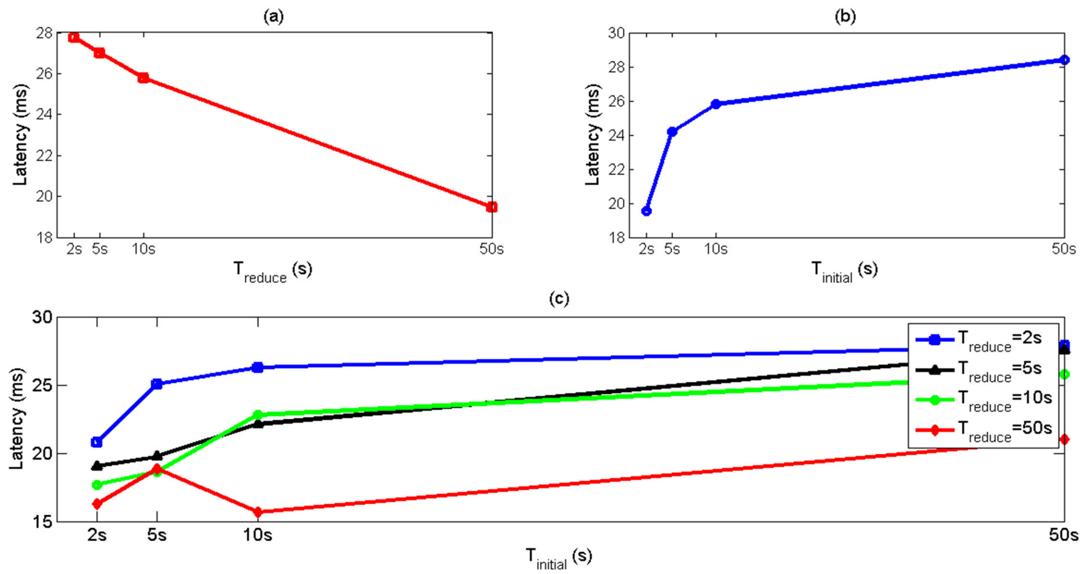

FIGURE 11. Impact of parameters: (a) T_{reduce}, (b) $T_{initial}$ and (c) Combined T_{reduce} and $T_{initial}$ on latency.

generally faster, the latency increases due to the delays caused by the presence of hidden nodes, contention, and retransmissions, as shown in Fig. 10 (a). Additionally, the RAT selection and switching latency caused by the network selection delay is also considerable. The beaconing rate adaptation and DCM mechanisms can effectively reduce the latency if the application QoS requirements permit to operate at lower beaconing rates. Fig. 10 (b) and (c) show that the increase in the value of $BR_{tolerance}$ causes the delay to decrease on average by 11%. Fig. 11 (a), (b) and (c) quantifies the impact of T_{reduce} and $T_{initial}$ parameters on the latency. The higher values of T_{reduce} results in longer duration vehicles need to operate in reduced beaconing rates, which results in lower latency. The increase in the value of $T_{initial}$ results in higher latency. The proposed scheme can reduce the latency; however, if the applications demand longer $T_{initial}$ durations, then the latency increases.

2) COMPARATIVE STUDY AMONG DIFFERENT APPROACHES

Fig. 12 shows the comparison among different schemes, including (1) periodic RAT selection and VHO, where the vehicles switch every pre-specified length of time, (2) DSRC only, (3) proposed hybrid scheme, and (4) proposed hybrid scheme with DCM. For these simulations, the average values of major simulation parameters are selected. The values set for the parameters BR_{factor}, $BR_{tolerance}$, T_{reduce}, and $T_{initial}$ are 50%, 75%, 10 sec., and 10 sec., respectively.

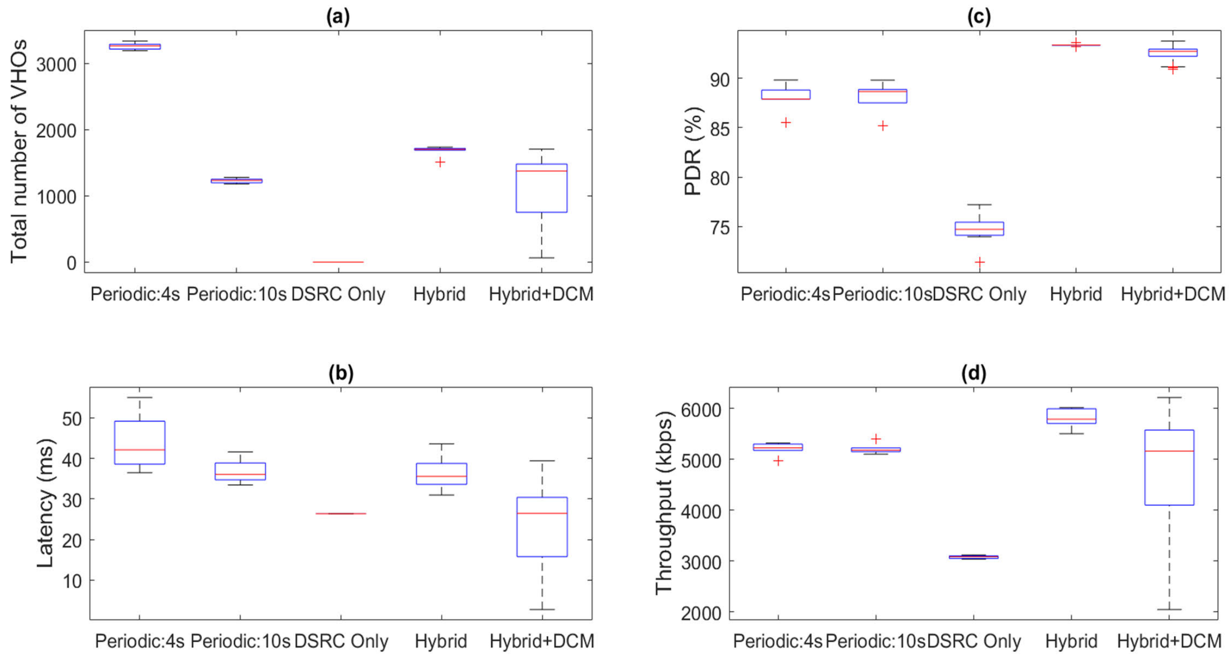

FIGURE 12. Comparison among different approaches, (1) Periodic VHO, (2) DSRC only, (3) Proposed Hybrid, and (4) Proposed Hybrid with DCM: (a) Number of VHOs. (b) Latency (ms). (c) Packet Delivery Ratio (%). (d) Throughput (kbps).

Fig. 12 (a) shows the number of VHOs performed by each scheme. For the periodic switching between the two access technologies, a higher number of VHOs are reported for the lower periodicity interval. The number of VHOs in the simple hybrid schemes is quite comparable with the periodic scheme with the switching interval set to 10s. The graph illustrates the minimum, median, and maximum number of VHOs for the proposed hybrid scheme with DCM. The minimum number of VHOs is significantly lower than any other approach, signifying less reliance on the LTE interface while reducing VHO cost in terms of latency and the corresponding loss in data throughput. As shown in Fig. 12 (b), the DSRC only approach results in considerable delays. Despite the direct communication links among the vehicles, the excessive amount of traffic through a single wireless interface often resulted in a severe congestion scenario, and therefore latency increases. The RAT selection and VHO schemes incur latency, which is caused by the network discovery and selection delays and processing latency to reach the switching decision. Switching RAT intelligently when it is barely necessary, the hybrid approach with the DCM scheme resulted in a lower delay.

In the simple hybrid approach, the higher number of VHOs resulted contributed towards a higher latency cost. For the periodic switching schemes, a higher number of VHOs resulted in considerably higher latency. Fig. 12 (c) compares performance in terms of PDR. The PDR for the periodic switching approach varies between 80% to 90%, whereas the PDR for the hybrid approaches are quite comparable and reaches around 95%. The DSRC only approach suffers from severe reliability issues, especially in high load scenarios. Fig. 12 (d) compares different approaches in terms of throughput. Hybrid approaches attain comparable throughput. However, the amount of data transferred through each access technology differs. As for the periodic switching, both interfaces transferred an equal amount of data. The hybrid-only approach performed well, however, at the cost of significantly higher delays with more data transferred over the LTE interface. In the proposed hybrid schemes, the DSRC interface delivers most of the data, whereas the use of the LTE interface is reasonably lower than all other schemes. For DSRC lower PDR, is translated in lower throughput attained.

VIII. CONCLUSION

This article proposed architecture and a suite of protocol for DSRC and C-V2X integrated hybrid vehicular networks. We address the problem of RAT selection, VHO, and data dissemination in a highway environment. The protocol suite includes an enhanced network protocol stack, an adaptive RAT selection, and VHO algorithm and dynamic communication management (DCM) algorithms. The main features of the proposed solution are: (1) A distributed, two-tiered CellCar Radio Resource Management (CRRM) module that manages the radio resources in the Primary RAT, i.e., DSRC and provides coordination with the Secondary RAT, i.e., LTE. (2) An adaptive RAT selection algorithm that takes in to account QoS metrics such as COL in Primary RAT and network load in Secondary RAT to select the most appropriate RAT according to network conditions. (3) An efficient VHO mechanism. (4) DCM via QoS negotiation by separately implementing beaconing rate adaptation and admission control in Primary RRM and Secondary RRM, respectively. The effectiveness of the proposed architecture and protocols is evaluated using extensive simulation-based studies. In particular, several simulations were conducted with different parameter settings to get insight into the overall performance of the vehicular network in terms of the number of VHOs performed, delay, PDR, and throughput. Furthermore, a comparative study is also included, which concludes that employing a hybrid approach results in a fewer number of VHOs, higher reliability, and lower delays.

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