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Advances in Vehicular Ad-hoc Networks (VANETs): Challenges and Road-map for Future Development

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Abstract: Recent advances in wireless communication technologies and auto-mobile industry have triggered a significant research interest in the field of vehicular ad-hoc networks (VANETs) over the past few years. A vehicular network consists of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications supported by wireless access technologies such as IEEE 802.11p. This innovation in wireless communication has been envisaged to improve road safety and motor traffic efficiency in near future through the development of intelligent transportation system (ITS). Hence, governments, auto-mobile industries and academia are heavily partnering through several ongoing research projects to establish standards for VANETs. The typical set of VANET application areas, such as vehicle collision warning and traffic information dissemination have made VANET an interesting field of mobile wireless communication. This paper provides an overview on current research state, challenges, potentials of VANETs as well as the ways forward to achieving the long awaited ITS.

Keywords: Vehicle-to-vehicle communication (V2V), vehicle-to-infrastructure (V2I), intelligent transport systems (ITS), IEEE 802.11p, wireless access in vehicular environment (WAVE), IEEE 1609.

1 Introduction

Road accidents have been on an alarming increase despite the introduction of several innovative in-vehicle safety-oriented devices such as anti-locking braking system (ABS), seatbelts, airbags, rear-view cameras, electronic stability control (ESC). Several studies have maintained that 60% of the accidents that occur on motorways could be avoided if warning messages were provided to the drivers just a few seconds prior to moment of crash[1, 2].

The possibility of direct exchange of kinematic data between vehicles over an ad-hoc network environment called vehicle ad-hoc network (VANET) has been widely perceived by governments, car manufacturing industries and academia as a promising concept for future realization of intelligent transportation system (ITS) thereby achieving safety and efficiency in our nearly overcrowded motorways. The VANET is a sub-class of mobile ad-hoc network (MANET), where the mobile nodes are vehicles. When compared with MANET and other cellular systems, inter-vehicle communication (IVC) has four major advantages: broad coverage area, relatively low latency due to direct wireless communication, little or no power issue as well as no service fees.

In the recent years, car manufacturing industries, academia and government agencies have started putting much joint efforts together towards realizing the concept of vehicular communications in a wide scale. Some frameworks are already worked out with the first landmark of standardization processes made by US Federal Communications Communication (FCC) through the allocation of 75 MHz of dedicated short range communication (DSRC) spectrum[3] basically to accommodate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications for safety-related applications. Table 1 shows the DSRC standards designated for use in USA, Japan and Europe[4, 5].

Potentials envisaged in VANETs have led to numerous vehicular communications research with their associated standardization projects in many countries across the world. These projects include DSRC development by Vehicle Safety Communications Consortium (VSCC)[6] (USA), European automotive industry project co-funded by the European Communication Commission (ECC) to foster road safety through the development and demonstration of preventive safety-related applications/technologies called PReVENT project[7, 8] (Europe), Internet intelligent transportation system (ITS) Consortium[9] and Advanced Safety Vehicle project[10] (Japan), Car-2-Car Communications Consortium (C2C-CC)[11], Vehicle Infrastructure Integration (VII) Program[12], Secure Vehicle Communication (SeVeCOM)[13], and Network on Wheels project[14] (Germany). In September 2003, both IEEE and American Society for Testing and Materials (ASTM) Committee E2213-03[15] adopted an amendment of the legacy IEEE wireless local area network (LAN) standard done by an IEEE Task

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Table 1 DSRC standards used in the USA, Japan and Europe

Features	USA ASTM	Japan (Association of radio industries and business)	Europe (European committee for standardization)
Communication	Half-duplex	Half-duplex (OBU) Full duplex (RSU)	Half-duplex
Band	75 MHz	80 MHz	20 MHz
Channels	7	Downlink: 7 Uplink: 7	4
Transmission range	1 000 m	30 m	15–20 m
Data rate	3–27 MBps(downlink/uplink)	1/4 MBps(downlink/uplink)	Downlink: 500 KBps, uplink: 250 KBps
Radio frequency	5.9 GHz	5.8 GHz	5.8 GHz
Channel separation	10 MHz	5 MHz	5 MHz

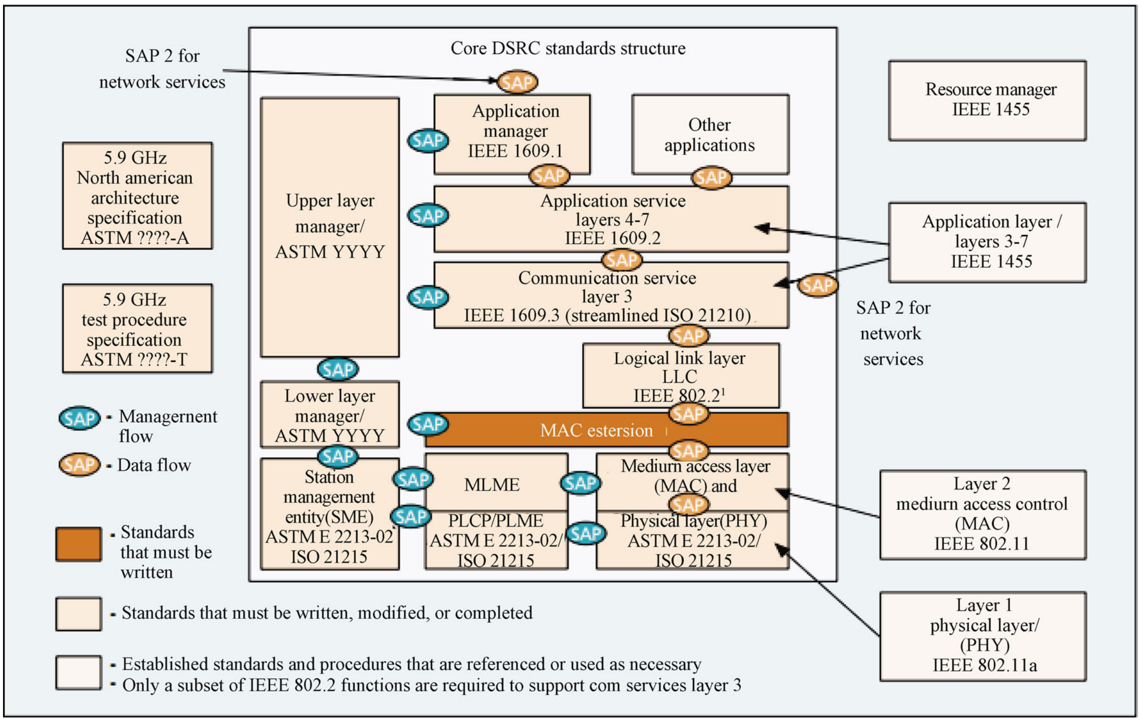

Fig. 1 ASTM endorsed DSRC standards structure

Group (TG). The amendment is denoted by IEEE 802.11p as the platform for wireless access in vehicular environments (WAVE) which will be used to enable wireless communications between moving vehicles within a coverage distance of 1 000 m in a free space (i.e., highway scenario) and 300 m in a non-free space (i.e., urban scenario). Fig. 1 shows the ASTM endorsed DSRC standard structure for DSRC link and data link layer.

The rest of this paper is organized as follows. Section 2 presents a brief overview of VANET. Application of VANET is presented in Section 3, while the current VANET open research challenges and certain ideas on possible solutions are presented in Section 4. Final conclusions of this paper are presented in Section 5.

2 Overview of VANETs

In VANETs, participating vehicles are equipped with a set of wireless sensors and on board units (OBUs) to allow for possibility of wireless communication between the vehicles and their environs. These devices make each vehicle function as packet sender, receiver and router which enable the vehicles send and receive messages to other vehicles or road side units (RSUs) within their reach via wireless medium. These sets of wireless sensors, OBUs or some typical radio interfaces enable vehicles form short-range wireless ad-hoc networks to broadcast kinematic data to vehicular networks or transportation authorities/agencies which process and use the data to foster traffic efficiency and safety on the motorways[16]. VANET-enabled vehicles are fitted with the appropriate hardware which allows for acquisition and processing of location (or position) data such as those from a global positioning system (GPS) or a differential global positioning system (DGPS) receiver[17]. The fixed RSUs are connected to the backbone network and situated at strategic positions across the roads to aid effective, reliable and timely vehicular communications. RSUs are equipped with network devices to support dedicated short-range wireless communication using the IEEE 802.11p radio technology. The possible vehicular communication configurations in intelligent transportation system (ITS) include vehicle-to-vehicle (or inter-vehicle), vehicle-to-infrastructure and routing-based (RB) communication (see Fig. 2).

Vehicles can directly establish communication wirelessly with one another forming V2V communications or with fixed RSUs forming V2I communications. These vehicular communication configurations rely heavily on acquisition of accurate and up-to-date kinematic data of both the vehicles and the surrounding environment with the aid of positioning systems and intelligent wireless communication protocols and access technologies for reliable, efficient and timely information exchange. Considering the network environment of VANETs with unreliable, shared communication medium and limited bandwidth[18], smart cross-layer communication protocols are required to guarantee reliable and efficient delivery of data packets to all vehicles and infrastructures (RSUs) within the vehicles′ radio signal transmission coverage.

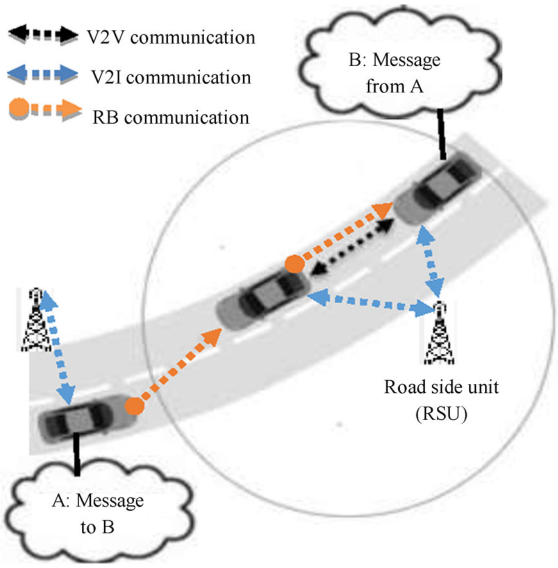

Fig. 2 Possible vehicular communication configurations in intelligent transport systems (ITS)

3 VANET application

The concept of equipping future vehicles with sets of wireless sensors, on-board units, GPS or DGPS receivers and network interfaces presents an ample opportunity to achieve intelligent transportation systems with wireless enabled vehicles capable of sending and receiving kinematic data on the road. VANET is the bedrock upon which vehicles will be able to gather, process and distribute information both for safety-related and non-safety-related purposes on our motorways. Extensive areas of potential VANET applications have been listed and evaluated by several researchers through different projects and consortia. Typically, these applications are classified into either safety-related or non-safety-related applications.

3.1 Safety-related VANET applications

Safety-related VANET applications are classified into three basic categories, namely: driver assistance (co-operative collision avoidance, road navigation and lane changing), alert information (work zone and speed limit alert information) and warning alert (road obstacle, post-crash and other life-threatening traffic condition warning). The vehicular safety communications consortium has listed eight (8) potential safety-related applications[19]: pre-crash sensing, curve speed, lane-change, traffic signal violation, emergency electronic brake light and co-operative forward collision alert, stop sign movement and left turn assistant. Safety-related messages from these applications normally require direct communication owing to their stringent delay requirement. For instance, in the case of a sudden hard breaking or accident, the vehicles following those ones involved in accident as well as those in opposite direction will be sent a notification message.

Major road safety applications are the primary measures taken to reduce (or eliminate) the probability of traffic accidents and loss of life in our motorways[10, 20, 21]. Some of the traffic accidents that occur annually across the world are as a result of intersection, rear-end, head-on and lateral mobile vehicle collisions. The necessary precautionary measures (or traffic warning systems) required for the effective implementation and deployment of this road safety applications with their required use-case, mode of communication, minimum transmission frequency and acceptable latency are summarized in Table 2. These active road safety-related applications offer assistance to drivers through the provision of time-sensitive, life-saving traffic information which enables drivers to avoid collisions with other mobile vehicles on the road. This is achieved through the timely and reliable exchange of safety-related kinematic information amongst vehicles through the V2V communication system as well as amongst vehicles and other road infrastructures through V2I communication, which is processed to predict traffic accidents and collisions. This kinematic information contains the vehicle′s current location, intersection position, speed, acceleration and direction of movement, to create the awareness of the presence of other vehicles on the road. Moreover, most of these life-critical messages in vehicular communications are broadcast-oriented, time-sensitive, life-saving, safety-related messages which must have deep penetration across the entire network and must be reliably delivered to the intended recipients within a short time.

Table 2 Description of selected use-cases and corresponding technical requirements of road safety-related applications

Use-case	Mode of communication	Minimum transmission frequency	Required latency
Intersection collision warning	Periodic message broadcasting	Minimum frequency: 10 Hz	Less than 100 ms
Lane change assistance	Co-operation awareness between vehicles	Minimum frequency: 10 Hz	Less than 100 ms
Overtaking vehicle warning	Broadcast of overtaking state	Minimum frequency: 10 Hz	Less than 100 ms
Head on collision warning	Broadcasting messages	Minimum frequency: 10 Hz	Less than 100 ms
Co-operative forward collision warning	Co-operation awareness between vehicles associated to unicast	Minimum frequency: 10 Hz	Less than 100 ms
Emergency vehicle warning	Periodic permanent message broadcasting	Minimum frequency: 10 Hz	Less than 100 ms
Co-operative merging assistance	Co-operation awareness between vehicles associated to unicast	Minimum frequency: 10 Hz	Less than 100 ms
Collision risk warning	Time limited periodic messages on event	Minimum frequency: 10 Hz	Less than 100 ms

3.2 Non-safety-related VANET applications

The non-safety-related applications of VANETs are also referred to as comfort or commercial applications. Typically, these applications aim to improve traffic efficiency, passenger comfort and commercial platforms in terms of advertisements and electronic toll collection (ETC). These applications include provision of weather information, current traffic and the ability to locate various points of interest (PoI) such as nearest parking lots, gas stations, shopping malls, hotels, fast food restaurants, etc. The owners of these aforementioned businesses can install some stationary gateways to transmit marketing adverts for the mobile customers traveling via the VANET enabled vehicles. The compelling argument in allowing comfort and commercial VANET applications is that of distraction and interference with safety-related applications thereby defeating the aim of improving safety and traffic efficiency in our motorways. Consequently, a possible solution would be achieved by using separate physical network channels for safety and non-safety applications or by applying traffic prioritization where safety-related messages are accorded higher priorities than non-safety-related messages.

4 Open research challenges and possible solutions for vehicular networks

The current key research challenge of VANETs is the lack of central communication co-coordinator associated with all the existing wireless access technologies earmarked for VANET set-up, implementation and deployment. Deploying wireless communication in vehicular environments effectively requires that some intrinsic issues ranging from technical application development and deployment up to economic concerns must be resolved. Though VANET is a form of MANET, its behaviors and characteristics are fundamentally different. Some of the basic VANET research challenges that must be addressed to achieve effective vehicular communication are briefly discussed below.

4.1 Comparison of high-speed wireless communication technologies for vehicular networks

Many high-speed wireless access technologies and standards have been suggested, recommended and considered for use in VANET connectivity by many researchers[17, 19] (see Table 3). Presented below are some of the technologies and air interface protocols capable of supporting high-speed communication in vehicular environments which are currently being considered for VANETs.

4.1.1 Cellular technology – (2 G, 2.5 G,$\cdots$,4 G)

The 2G and 2.5G technologies provide reliable security and wide communication coverage, while 3G and 4G technologies are swiftly taking over offer highly improved communication capacity and bandwidth. In USA, Europe and Japan, many fleet and telematics projects are already using different generations of cellular technology[17]. However, the apparent high cost coupled with its high latency rate and limited bandwidth discourages its possible use as a future communication base for VANETs.

4.1.2 IEEE 802.11p based standards

ASTM and IEEE-adopted amendment is a variation of IEEE 802.11 family meant to support wireless communication in vehicular environment. This air interface protocol is a work-in-progress by IEEE working group that would provide inter-vehicle communication (IVC) and vehicle-to-roadside communication at vehicular speed ranging from 200 to 300 km/h covering communication range of 1 000 m. The medium access control (MAC) and physical (PHY) layers are based on IEEE 802.11a. IEEE 802.11p technology is heavily promoted by vehicle manufacturing industries across the globe especially in USA through VII and VSCC, Japan through Advanced Safety Vehicle project (ASV), Europe through C2C-CC and Germany through SeVeCOM. Due to substantial production volumes, the estimated deployment cost of IEEE 802.11p is predicted to be relatively low when compared with cellular technology. Hence, this nascent technology, also called WAVE has an edge over cellular technologies and fairly more suitable for VANETs.

Table 3 Comparison of high-speed wireless communication technologies for vehicular networks

Indicative wireless features	Communication technologies			
	Wi-Fi	802.11p (WAVE)	Infrared	Cellular
Standards	IEEE	IEEE, ISO, ETSI	ISO	ETSI, 3GPP
Channel bandwidth	1–40 MHz	10 MHz, 20 MHz	N/A (optical carrier)	25 MHz (GSM), 60 MHz (UMTS)
Allocated spectrum	50 MHz @ 2.5 GHz 300 MHz @ 5 GHz	30 MHz (EU) 75 MHz (US)	N/A (optical carrier)	(Operator-dependent)
Frequency band(s)	2.4 GHz, 5.2 GHz	5.86–5.92 GHz	835–1 035 nm	800 MHz, 900 MHz 1 800 MHz, 1 900 MHz
Communication range	< 100 m	$< 1\,000$ m	< 100 m (CALM IR)	< 15 km
Suitability for mobility	Low	High	Medium	High
Bit rate	6–54 Mb/s	3–27 Mb/s	< 1 Mb/s < 2 Mb/s	< 2 Mb/s
Transmission power for mobile node	100 mW	2 W EIRP (EU) 760 mW (US)	12 800 W/Sr pulse peak	380 mW (UMTS) 2 000 mW (GSM)

4.1.3 Unified wireless access

The International Standards Organization–Technical committee (ISO-TC 204 WG16) has performed the most significant unification efforts of the various existing wireless access technologies. The product of the unification process is a vehicular communication standard called the Continuous Air Interface for long and medium range (CALM M5)[19]. CALM M5 combined several related air interface protocols and parameters, building on top of IEEE 802.11p architecture with support for cellular technologies as discussed earlier. These standards combined into a single, uniform standard are expected to provide improved vehicular network performance through increased capacity, flexibility and redundancy in packet transmission and reception.

4.2 Spectrum allocation issues in VANETs

The Federal Communication Commission (FCC) of US allocates a spectrum of 75 MHz at 5.9 GHz (5.850–5.925 GHz) for vehicular communications (V2V and V2I). Most of the ongoing ITS Projects and Consortia (VII and VSC) have already adopted the derivative of IEEE 802.11 family of standards as the best suitable wireless access technology for communication systems using this spectrum[17]. Hence, the new amendment of 802.11 denoted as 802.11p and the unification of various existing wireless access technologies by ISO TC 204 WG16 (i.e., CALM M5[19]) to allow moving vehicles to utilize the officially allocated 75 MHz at 5.9 GHz band as discussed in Section 4.1.3.

In Europe, the distributed short range communication (DSRC) band does not have a continuous spectrum of 75 MHz as is the case in US. However, the C2C-CC of Europe has proposed an approach similar to US approach which allocates two 10 MHz specifically for vehicular safety-related communications at 5.9 GHz (5.875–5.925 GHz). The allocation of this band in Europe provided a sort of global harmonization given that the same band is used in US as a control channel. Use of supplementary spectrum could be supported by this technology for non-safety-related (comfort and commercial) applications in several other bands such as 5 GHz RLAN or 5.8 GHz IRM band[20].

At the moment, 5.9 GHz band is allocated for stationary satellite services and military radar systems. Because a continuous spectrum of the US FCC officially allocated 75 MHz in DSRC band is not available in Europe, the European Commission Car2Car CC has proposed a derivative of the FCC approach. The proposal allocates a 2×10 MHz for primary use of time-sensitive safety applications at 5.9 GHz range (5.875–5.925 GHz) and proposes an additional spectrum at either in the 5 GHz of RLAN band or in the 5.8 GHz IRM band for non-safety (or infotainment) applications. However, the Short Range Device Maintenance Group (SRD/MG) of European Conference of Postal and Telecommunications Administrations (CEPT), and Electronic Communication Commission (ECC) have recommended to place the first proposed 10 MHz control channel in 5.885–5.895 GHz so as to align with the US FCC approach, and place the second proposed 10 Hz channel in the upper part of the Industrial, Scientific and Medical (ISM) band (5.865–5.875 GHz) to provide for radio-location services below 5.85 GHz[19].

4.3 Message broadcasting in vehicular networks

The envisaged VANET applications require transmission, gathering and processing of large volumes of electronic messages/data packets. Message broadcasting has been seen as a potential attractive alternative solution by automotive wireless networking researchers partly as a result of its low-cost and partly due to its support for vast potential volumes of data packets. Hence, several broadcasting techniques and mechanisms have been taken into consideration by many researchers. These techniques include restricted and unrestricted bandwidth digital service solutions as well as satellite broadcasting solution which has already incorporated real time traffic data services[22].

Broadcasting techniques are associated with broadcast storm problem[4]. This problem could be reduced or eliminated by reducing the message broadcast range specifically to the site of interest thereby reducing the unnecessary network overhead. This concept is called location-aware broadcasting. Another approach that has emerged as a promising solution is clustering approach where neighboring mobile vehicles form clusters, manageable groups which limit the message broadcasting range. Several cluster-based VANETs broadcasting protocols have been proposed as can be seen in the case of [23−25].

In order to solve the issues of the broadcast storm problem (redundancy, contention and broadcast packet collisions) which occur due to simultaneous warning message forwarding in VANETs traffic safety applications, Fogue et al.[26] proposed a novel scheme called enhanced message dissemination based on roadmaps (eMDR) protocol which was tested on realistic simulation environments (VANET scenarios based on real city maps). Their proposed eMDR protocol is designed to mitigate the broadcast storm problem in real urban scenarios by increasing the percentage of informed vehicles and by reducing the notification time at the same time. However, eMDR[26] is practically suitable in low vehicle densities and may require enhancement to apply in high vehicle density scenarios, or high market penetration rates.

In what we could refer to as an improvement upon the previous work of [26], Sanguesa et al.[27] proposed two warning message dissemination approaches for adverse vehicle densities which were demonstrated in different urban scenarios. The two proposed message broadcasting solutions in vehicular networks by these authors are called neighbor store and forward (NSF) and nearest junction located (NJL) scheme. While the eMDR scheme proposed by Fogue et al.[26] is practically suitable in low vehicle densities, one of the solutions proposed by Sanguesa et al.[27] (NJL scheme) is specifically designed for very high vehicle densities so as to maximize message delivery effectiveness, something difficult to achieve in adverse vehicle density scenarios. The proposed NJL scheme not only increased the percentage of informed vehicles through message broadcast technique but also reduced the number of messages up to 46.73%[27]. Other similar studies include the further research carried out by Sanguesa et al[28], a real-time adaptive dissemination (RTAD) scheme for VANETs, two distinct protocols in [29], TRAck DEtection (TRADE) and distance defer transmission (DDT) protocols, optimized dissemination of alarm messages (ODAM)[30], smart broadcast algorithm (SBA)[31], contention based dissemination (CBD)[32], time reservation-based relay node selecting algorithm (TRRS) and enhanced TRRS (ETRRS)[33], Urban multi-hop protocol (UMB)[34], BROADCOMM[35], fast broadcast (FB) protocol[36], and REAR[37]. In Table 4, we present a brief comparison of some selected existing message broadcasting solutions in vehicular networks. The following criteria are used in our comparison: the technique used to ensure that there is high percentage of informed vehicles (retransmissions/rebroadcasting), redundancy, latency, delivery rate and memory requirement.

4.4 VANETs ad-hoc routing protocols

Much research has been carried out on the suitability of MANET routing protocols in VANETs as well as several other research surveys[38−41]. Contrarily, the frequent network partitioning (intermittent network connectivity) due

Table 4 A brief comparison of selected message dissemination protocols

Protocol	Retransmissions/ rebroadcasting	Redundancy rate	Latency	Delivery rate	Memory requirement
eMDR[26]	Yes	Low	Low	High	Not mentioned
NSF/NJL[27]	Yes	Low	Low	High	Not mentioned
RTAD[28]	Yes	Low	Low	High	Not mentioned
TRADE[29]	No	High	Medium	Medium	Yes
DDT[29]	No	High	Medium	Medium	Yes
ODAM[30]	No	Medium	Low	Medium	Yes
SBA[31]	Yes	Medium	Low	Medium	Yes
CBD[32]	No	Medium	Low	Medium	Yes
TRRS/ETRRS[33]	No	High (TRRS)/ Lower(ETRRS)	Low	Medium	Yes
UMB[34]	Yes	Medium	High (RTB/CTB)	High	Yes
BROADCOMM[35]	Not mentioned	Low	Low	High	Not mentioned
FB[36]	Yes	Medium	Low	Medium	Yes
REAR[37]	No	Low	Low	Medium	Yes

to extremely dynamic topology and high mobility in VANET render MANET protocols unsuitable for vehicular communications. In a sparse dense network scenario (such as highways), a vehicle will have to adopt the carry-and-forward approach when there are no intermediate vehicle(s) to relay messages to their intended recipients.

Many more existing researches have considered the effectiveness of conventional ad-hoc routing and MANET protocols for VANET environments. Performance analysis and evaluation of several conventional ad-hoc routing solutions such as ad-hoc on-demand distance vector (AODV), dynamic source routing (DSR) and destination-sequenced distance-vector routing (DSDV) protocols for vehicular network scenarios have been presented by Xiong and Li[42]. Xiong and Li[42] inferred that these MANET solutions are not effective in VANET scenarios. The results of their simulation experiments further showed that these traditional MANET protocols lead to increase of routing load over vehicular networks which in turn reduces the overall packet delivery ratio (PDR) and increases network end-to-end delay.

Manvi et al.[43] used a uniform distribution to generate the node movement pattern which they used to carry out performance evaluation of optimized link state routing (OLSR) and AODV protocols. Haemi et al.[44] also compared and evaluated the performance of AODV, DSR and Swarm intelligence based routing protocols. While their simulation results clearly show that Swarm intelligence based routing protocol has certain exciting performance in a vehicular network scenario in terms of throughput, data delivery cost, latency and data delivery ratio, the suitability of AODV and DSR protocols in VANET environment were not guaranteed.

Abedi et al.[45, 46] worked to improve and enhance existing MANET protocol (AODV) in order to make it suitable for vehicular communication systems. Their improved and enhanced routing protocols were called position AODV (PAODV) and direction AODV (DAODV) with improved and enhanced route stability and reduced overall network overhead. Their studies also show that more appropriate routes can be discovered with or without node mobility prediction. They showed that selecting fewer routes would help to mitigate both packet routing overhead on the network and network link breakage as opposed to AODV.

Naumov et al.[47] studied the performance efficiency of AODV and GPRS over highway and urban scenarios using mobility information gathered from a microscopic vehicular traffic simulator based on real-life roadmaps of Switzerland. The results of their study showed that both AODV and general packet radio service (GPRS) demonstrate grave performance limitations in terms of significantly reduced packet delivery ratio due to extremely high mobility of nodes. Table 5 shows the comparative review of evaluated ad-hoc routing protocols designed for vehicular communication

Table 5 Comparative review of existing ad-hoc routing protocols in vanets

Routing protocols	Routing mechanism	Use case	Downsides
GPRS	Unicast	Comparison with other VANET protocols	Low PDR
AODV	Unicast	Performance evaluation in urban scenarios	Low PDR
OLSR	Broadcast	Performance evaluation in urban scenarios	Low PDR
VADD	Unicast	Ensuring packet routing with guaranteed QoS for VANET	Increased end-to-end delay due to incessant varying topology and traffic density
DSR	Unicast	Comparison with other VANET protocols	Low PDR
A-STAR	Unicast	Reliable packet routing in urban scenario	Increased end-to-end delay due to poor packet routing paths
DRG	Geocast	Timely communication over large area	Unsuitable especially for time-critical safety packet transmission in highly dynamic VANET environments
PMB	Unicast	Dissemination of emergency messages	Increased end-to-end delay
BROADCOMM	Broadcast	Dissemination of emergency messages in highways	Only applicable to highway network scenarios
ROVER	Geocast	Transmission reliability and end-to-end QoS	Data traffic type and volume not considered
DV-CAST	Broadcast	Designed for reliability and efficiency of vehicular communication systems	Built on the assumption that vehicles can accurately detect the local connectivity
DOLPHIN	Broadcast	Inter-vehicle communications technology for group cooperative driving in highway scenarios	Overwhelming network loads which leads to high network end-to-end delay
MDDV	Unicast	Efficient and reliable data dissemination	Increased network delay as traffic density varies by time

systems, such as mobility-centric data dissemination algorithm (MDDV)[48], anchor bus street and traffic-aware routing (ABSTAR) protocol[49], vehicle-assisted data delivery (VADD)[50], dedicated omni-purpose inter-vehicle communication linkage protocol for highway automation (DOLPHIN) for inter-vehicle communications system[51], position-based multi-hop broadcast (PMB)[52], robust vehicular routing (ROVER) and distributed robust geocast (DRG) protocols[53], BROADCOMM protocol[35], and distributed vehicular broadcast (DV-CAST)[54].

Hence, where the aforementioned assumptions do not hold in VANET, the carry and forward approach was proposed in [55] for VANETs whereby a moving vehicle continuously carry a data packet until it is forwarded to another vehicle closer to the destination(s) in absence of any direct route.

The challenging issue of packet routing in VANETs could be resolved if the three main categories of VANETs routing algorithm such as geographic, opportunistic and trajectory-based forwarding[17] could be combined with the concept of carry and forward mentioned above to realize an optimum VANET routing solution in order to reduce the end-to-end delay as well as the total number of dropped data packets during routing. Future task could be to carry out extensive experiments and simulations with more refined parameters and extension of existing routing protocols so as to overcome the problems of possible long end-to-end delay and high rate of packet drop during vehicular communications without drastic increment in network overhead.

4.5 Congestion control techniques in inter-vehicle communication

To achieve one of the key aims of VANETs, which is the current and future needs of reducing the number of occurrence of road traffic accidents as well as increasing traffic efficiency and safety on the motorways, cutting-edge research into vehicular safety communication systems must be pursued.

Realizing this feat means solving major technical challenges of congestion control for both periodic and emergency beacon broadcast and ensuring the reliability and scalability of safety messages transmission especially in congested situations. The design and development of efficient IEEE 802.11p-based DSRC wireless access system that will support efficient and reliable congestion control (CC) techniques is required for effective dissemination of time-critical safety messages in vehicular networks. Many studies have been carried out to validate and evaluate the performance of congestion control techniques[45−61]. Several approaches have been employed by researchers for performance evaluation of wireless communication systems such as vehicular wireless communication system with simulation and field test methodology as the two most widely used approaches. Virtually, the performance of all the existing studies on congestion control techniques in vehicular communications[56, 57, 62−64] were validated and evaluated through simulation experiments as opposed to field test which involves high research costs especially with a large number of experimenting vehicles. Most of the recent proposed vehicular network solutions, protocols, schemes and frameworks reviewed in this paper share common approaches and methodologies in their investigations. Each of the works used mobile nodes which are configured according to the specifications of IEEE 802.11p standard, equipped with the GPS receiver and share common IEEE 802.11p CCH. Similarly, in all of the reviewed works, time-sensitive safety messages are accorded higher prioritires over non safety related messages.

The performance parameters used in the reviewed works include message (safety message and beacon) reception rate, channel access delay, percentage of successful message reception (PSMR), channel busy ratio (CBR), percentage of message loss (PML), throughput, level of channel congestion (LCC), packet error ratio (PRR), average transmission delay (ATD), channel busy fraction (CBF), and contention window (CW) size, etc. The propagation loss models used were either Nakagami or TwoRayGround. The findings and results of existing works evaluation contained in Table 5 were summarized as follows.

1) From the review of existing works on congestion control algorithms in vehicular communication systems, one of the most widely used performance parameters is BER. It is also observed that the variation of CW shows little effect on BRR. On the other hand, steep increase in CW size to CWmax leads to a long end-to-end delay[65].

2) The most well-used network simulator in vehicular networks research community is NS-2[57−64] with simulation of urban mobility (SUMO) mobility model which is used to generate trajectories that are fed into the NS-2 simulator to create mobility patterns for nodes movement.

3) It is observed that Nakagami propagation model is well-used compared to other models. Most researchers deployed the Nakagami fading model because of its generality compared to other propagation models like Rayleigh or Rician. Another reason is that Nakagami fading model can represent a wide range of fading situations, even probable conditions which are more severe compared to Rayleigh fading model. Nakagami′s distribution is adjudged more suitable to vehicular networks than Rayleigh or log-normal shadowing model[64, 66].

The review also shows that WAVE-based MAC protocol performs poorly in multiple access coordination as channel load approaches the maximum channel capacity[67].

Several existing works investigated extensively how to improve reliability and efficiency in packet transmission by adjusting vehicle′s transmission frequency or power, but these transmitter-based schemes depend on the vehicle′s wireless radio hardware control and can be difficult to estimate the status of the expected receivers. These challenges were resolved by [68, 69] using the receiver carrier sensing threshold control approach. In their separate studies, the receivers sense the unique control channel (CCH) and adjust their states for the inbound transmissions. The merit of the receiver carrier sensing threshold control approach is that it can be achieved through software as opposed to adjusting vehicle′s transmission frequency or transmission power.

Table 6 shows the review of the performance evaluations of existing works on congestion control algorithms

Table 6 Review of previous works on congestion control techniques in inter-vehicle communication

Algorithms/ schemes	Variation factors	Traffic scenario	Network simulator	Mobility generator	Application type	Propagation loss model	Performance parameters
Message dissemination scheme[26]	Different vehicle densities	Urban	NS-2	SUMO	Safety and periodic message	Real attenuation and visibility model (RAV)[37, 71]	Informed vehicles (%), notification time, delivery rate
Neighbor store and forward (NSF) and nearest junction located (NJL)[27]	Different vehicle densities	Urban	NS-2	CityMob (based on SUMO) message	Warning/safety and periodic	Message RAV	delivery rate
RTAD: real-time adaptive dissemination system[28]	Different vehicle densities	Urban	NS-2	CityMob (based on SUMO)	Safety message	RAV	Informed vehicles (%), notification time, delivery rate
Topology-based visibility scheme[29]	Node densities	Urban	NS-2	SUMO	Warning/safety and periodic message	Obtained directly from experimental data	Packet error rate (PER), packet delivery rate
Dynamic/distributed channel congestion control[56]	Transmission rate, channel load	Highway lanes	Not mentioned	Not mentioned periodic message	Safety and	Nakagami	PSMR, PML, LCC, BRR
Avoiding information congestion[57]	Signal to interference plus noise ratio (SINR)	Highway lanes	Matlab and NS-2	Vanetmobisim	Safety message	TwoRayGround	Throughput, average transmission delay, BER
Scheme for collision avoidance[58]	Hop count, node density	Highway lanes	NS-2 and Matlab	Not mentioned	Safety message	Not mentioned	BER, end-to-end delay
Safety context-ware congestion a control[59]	TX power, packet size, channel	Highway lanes	NS-2	Not mentioned	Safety-critical message	Nakagami	Throughput, packets received
VANET channel congestion control[60]	Packet size, density, channel	Highway lanes	NS-2	SUMO	Safety message	Nakagami	Packet error ratio, BER
Congestion control for DSRC systems[61]	Network density, channel noise	Highway lanes	NS-2	Not mentioned	Safety message	Not mentioned	Channel busy fraction (CBF)
LIMERIC: algorithm for DSRC congestion control[62]	Network density, channel noise	Highway lanes	Matlab and NS-2	Not mentioned	Safety message	Not mentioned	Channel busy fraction (CBF)
Congestion control schemes in VANETs[63]	Node density, TX power	Highway lanes	NS-3 and Matlab	SUMO	Safety and periodic message	Nakagami	Channel busy ratio (CBR)
Beacon congestion control algorithms[64]	TX power, frequency, density	Urban	NS-2	Not mentioned	Safety and periodic message	Nakagami	BER, ERR, (CBR)
Contention window analysis[65]	CW size, TX frequency, density	Highway lanes	OMNeT++	MiXiM framework	Periodic message	Not mentioned	BER, delay, inter-arrival time
Transmit power control for safety-critical messages[68, 70]	TX power, channel	Highway lanes	NS-2	Not mentioned	Safety and periodic message	Nakagami	BER, delay, channel access time

conducted through simulation using various network simulators and road traffic mobility models for vehicular movement pattern generation. However, the performance results obtained with the reviewed congestion control algorithms in Table 4 show that the QoS requirements of safety VANET applications such as high reliability and low latency were not guaranteed by any of the reviewed algorithms. We pinpoint two major shortfalls found in the review of the evaluated works which must be tackled and improved upon in order to realize, develop and deploy vehicular communication systems to reduce the number of road traffic accidents occurrence.

Firstly, virtually most of the studies were conducted on a highway scenario except for the works of [26, 27, 37]. However, urban and highway scenarios differ in features such as their movement patterns (or trajectories). Besides, homogeneous vehicular traffic densities are common in one-dimensional highways as opposed to two-dimensional urban vehicular scenarios[70]. Interestingly, as opposed to most of the works compared in Table 6[26−29, 56−65, 68, 70], the research of [26, 27, 37] carried out a simulation of real city maps with buildings using a modified NS-2 simulator to model the impact of distance and obstacles in signal propagation. The wireless radio propagation model used is the real attenuation and visibility model (RAV)[37, 71], a model which proved to increase the level of realism in VANET simulations using real-life urban roadmaps as scenarios where buildings act as obstacles. This model implements the signal attenuation due to the distance between vehicles based on real data obtained from experiments in different streets of the cities of Valencia and Teruel in Spain. Their studies considered VANETs protocols performance in urban scenarios, as well as different and non-homogeneous vehicular traffic densities in contrast to homogeneous vehicular traffic densities which are common in one-dimensional highway motorways. Additionally, other works that considered the performance of vehicular network protocols in urban scenarios, as well as in a non-homogeneous traffic densities as opposed to homogeneous vehicular traffic density include the reviewed work of [26] (see Table 6). They specifically studied the effectiveness of their two proposed frameworks (i.e., NSF and NJL) in an adverse (or varying) vehicular density scenarios.

Secondly, we recommend the use of network simulators and emulators that tightly combine both network simulation and vehicle traffic mobility simulation such as Veins[72], NCTUNS (EstiNet)[73] and iTETRIS[74]. Studies on congestion control algorithms/schemes should be conducted on these bi-directionally coupled networks and road traffic simulations for improved inter-vehicle communications (IVC) analysis to achieve a more realistic and close to real-life environment for effective VANET simulation.

4.6 Power control and management

Power management in the sense of energy efficiency is not an issue in VANETs as is the case with other evolving wireless technologies such as LTE due to the existence of installed batteries in the vehicles. However, power management in term of transmission (TX) power is a challenging issue that must be resolved to achieve effective vehicular communication. In a dense vehicular network, high TX power could lead to disruption of an ongoing transmission with another transmission at a distant vehicle as a result of interferences. For this reason, reduced TX power should be used in a denser network to achieve reliable and efficient transmission.

Efficient routing could as well be achieved through proper adjustment of the TX power to increase the overall throughput and reduce interference occurrences. So far, very few algorithms have been proposed in this regard. One such algorithm proposed in [75] adjusts the TX power to limit the total number of transmitting neighbors within the maximum and minimum TX thresholds.

4.7 Security, privacy, anonymity and liability

Security is one of the challenges that demands careful attention prior to designing and deployments of VANETs in our motorways. Several potential threats to vehicular communication system exist, ranging from fake (or fraudulent) messages capable of disrupting traffic or even causing danger to driver′s privacy invasion. Frameworks must be worked out to enable vehicles receiving data packets from other vehicles (or network nodes) to be able to establish trust on the entities transmitting the packets while the privacy of the drivers is protected using anonymous node identities. Though, the major challenge of security and privacy in VANET is how to develop a security solution capable of supporting the tradeoff between authentication, liability, and privacy given that every vehicular information (both safety and non-safety related information) must be disclosed to appropriate governmental agencies (transport authority) by the network. However, such security solution must make vehicle identification or tracking impossible especially for non-trusted parties. In line with the above line-of-thought, SeVeCOM, as presented in [76, 77], has provided a security architecture that is used as input for security related European Telecommunications Standards Institute (ETSI)[19] ITS WG5 and ISO CALM standards.

4.8 Reliability and cross-layer approach between transport layer and network layer

The vehicle to vehicle (or inter-vehicle) communication network is associated with the problem of incessant network route break-up leading to erroneous message transmission due to the wireless nature of the VANET environment. This issue gives rise to the challenge of reliability in vehicular communication networks. Several error recovery techniques have been proposed and implemented over the years to achieve reliable transfer of packets in wireless communications with respect to vehicular communication systems. Traditional techniques such as automatic repeat reQuest (ARQ)[78] and forward error correction (FEC)[79] could not yield the desired results in vehicular communication yet. ARQ can only be used to ensure reliability in point-to-point unicast communication. Unlike FEC that works with readily awaiting streams of packets, each vehicle creates packet periodically or automatically in the face of emergency and broadcast to other vehicles. Hence, the issue of broadcast communication reliability remains an open research challenge in the design and deployment of VANET. Consequently, for reliable and efficient vehicular communication networks to be achieved on top of the inherently unreliable wireless network, effective and competent loss packets recovery schemes are required. Designing cross-layer medium access control (MAC) that will span across network (routing) layer and transport layer to support real-time services and multimedia applications can be of immense benefit in vehicular communication networks.

4.9 V2X video delivery

In VANETs, video communication offers a significant contribution to quality of experience (QoE) for both the drivers, passengers and pedestrians on the road. Additionally, video transmission is bit loss tolerant. Hence, the loss of one packet may not affect the experience of users[80]. Therefore, video communication has potential to be of high benefit for traffic management as well as for providing value-added entertainment[81] and advertising services[82]. In vehicular networks, vast literatures exist on the study of transmission technologies for video streaming on both MAC and network layers[83−90]. Several studies on performance of video streaming in IEEE 802.11p vehicular networks have been carried out on MAC layer[91−93]. Over the network layer, Bradai and Ahmed[94] presented a rebroadcast mechanism while Rezende et al.[95] studied the relay node selection algorithm. As more and more vehicles are equipped with wireless communication devices, large number of users expect to be serviced with high QoE in V2X live video content delivery.

Therefore, not only the video delivery approach but also the video source selection scheme should be extensively studied. However, the high mobility and the frequently changing topology of VANET nodes make the selection of video source an impediment to efficient and reliable video delivery. Selection of unsuitable provider may lead to incessant interruptions of communications causing frequent video fragmentation and transmission of invalid video fragments would also lead to unavoidable wastage of valuable communication bandwidth. Chen et al.[96] addressed part of this challenge in their proposed novel video source decision scheme called cluster and dynamic overlay based video delivery over VANETs (CDOV). In their research, they used an on-demand clustering approach where vehicles with the same video requirement/supply and moving features form clusters. Using this approach, an overlay tree will be constructed dynamically inside the cluster based on the relation between supply and demand in which all requesters can find their greedy optimal source easily. Furthermore, the head-RSU communication and the intra-cluster communication are designed for video streaming over this network structure.

Live V2X video delivery over VANETs is an efficient way to improve the applications in both safety and infotainment. However, the characteristics of VANETs such as frequent network disconnection, high mobility of vehicles, dynamic topology, interactive requirements, and limited number of infrastructures pose great challenges for live V2X video delivery in VANETs.

4.10 V2X multi-channel operation

VANETs rely on a multi-channel operational mechanism to support V2X communications. Multiple service channels (SCHs) are assigned in the 5 GHz spectrum for non-safety data transfer, while a CCH is used for broadcasting basic safety messages and service advertisements at regular intervals. Single-radio WAVE devices stay tuned on one radio channel at a time and alternately switch between channels to monitor safety messages and to access information and entertainment services, while dual-radio devices can simultaneously stay tuned on both types of channels. Multi-channel coordination, synchronization, and access are big challenges in VANETs, many design choices are still open challenges in both ETSI and IEEE standardization bodies.

In order to support both safety-related and non-safety applications in vehicular communication networks, IEEE 1609.4 protocol[97] (see Fig. 3) defines a channel switching mechanism to enable a single WAVE radio to operate efficiently on multiple channels. IEEE 1609.4 is a functional extension of IEEE 802.11e MAC[98] to enable multi-channel coordination whose functions include efficient channel routing, data buffers (queues), prioritization, and channel coordination.

Though the availability of multiple channels is beneficial in terms of throughput performance[99], the multi-channel organization in the dynamic vehicular communications environment raises several challenges. In reality, VANET characteristics, such as the heterogeneous nature and requirements of vehicular applications, the absence of central coordination, the unstable, distributed, and frequently changing nature of wireless links (network topology), undeniably challenge the coordination of multi-channel activities. To concurrently support safety and non-safety applications, single-radio devices may periodically and synchronously switch between CCH and SCHs, according to rules defined by the IEEE 1609.4 standard[100], whereas dual-radio devices, as considered by ETSI[101], could have one radio tuned to the CCH and the second radio tunable to one of the available SCHs. WAVE dual-radio devices promise better spectral efficiency but at the expense of a higher level of implementation complexity. However, considering the cross-channel interference issues, the V2X multi-channel operation still has its own challenges that must be adequately resolved.

Although a plethora of researches have been published in the recent years on vehicular networks, very few of them actually addressed the V2X multi-channel operation defined for the frequency spectrum reserved for ITS by the IEEE

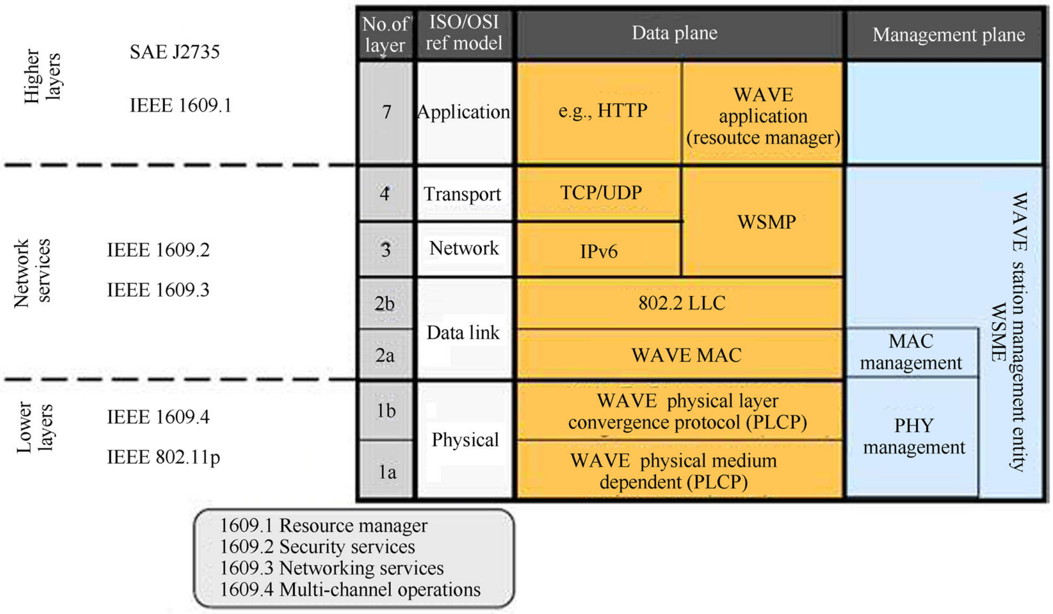

Fig. 3 WAVE protocol stack showing IEEE 1609.4 protocol residing at the lower layer

1609.4 standard. In VANETs, one of the primary issues is medium access control (MAC), which aims to utilize the radio spectrum efficiently, so as to resolve potential contention and collision among vehicles for using the medium since contention reduces the performance of single channel MAC layer. Therefore, multi-channel MAC protocols are useful to provide better quality of services (QoS) because V2X multi-channel interference is a major problem when it comes to channel assignment.

Amongst the few research efforts that have been recorded in this area by different scholars including the studies of [102–109]. Zhang et al.[110] proposed a novel MAC protocol called vehicular MESH network (VMESH) which is a compliant of the WAVE multi-channel operation system and is based on a distributed beaconing scheme. VMESH divides the control channel (CCH) into beacon period (BP) and the safety period (SP). In each Beacon period, all vehicles can transmit a beacon packet which contains information for making dynamic resource reservation on service channels (SCH). The proposed protocol provides contention free access on SCHs to improve the throughput of non-safety applications. This protocol dynamically adjusts the CCH based on density of vehicles to offer supports for safety applications and limits the available share for non-safety applications by the long CCH interval. In line with [111], Mak et al. [112] proposed a centralized MAC protocol called dedicated coordinating access point (DCAP) to enable V2X multi-channel operation for DSRCs. Each DCAP contains a coordinating access point (CAP) and one or more service access points (SAP) to provide non-safety applications in the region. Their proposed protocol divides time into periodic regulated intervals, called the repetition period. The length of repetition period is determined by the maximum tolerable delay of safety messages. Each repetition period is further divided into two distinct sub periods: contention free period (CFP) and contention period (CP). In CFP, DCAP sends a broadcast packet to access the channel and polls each vehicle individually to transmit its safety messages, where remaining vehicles must remain silent. The nodes that are not polled in the CFP will eventually contend the channel in the following CP. This protocol permits vehicles to transmit only one safety message per CFP. DCAP avoids channel interference during the CFP by partitioning the communication range of control channel radio into multiple different radiuses of circular regions with a center at the CAP.

Campolo and Molinaro[105] presented a detailed analytical model validated with an event-driven custom simulation program that closely follows the IEEE 802.11p protocol specifications and implemented in Matlab. Their analytical model was designed for the characterization of the losses of broadcast packets in IEEE 802.11p/WAVE vehicular networks by explicitly accounting for the WAVE channel switching. Even though the WAVE channel switching can have adverse effect on the general network performance, it has not been widely investigated in the literature except this research carried out by [105]. In their work, broadcast packets loss probabilities were derived as a function of contention window (CW) size, number of nodes and WAVE channel errors. The results obtained clearly show that the IEEE 802.11p/WAVE standard fails to guarantee high reliability for packet broadcast transmissions and such is especially true when the sizes of CW of the IEEE 802.11p/WAVE standard are used, as a result of frame collisions synchronization events occurring at the beginning of the CCH interval. Although collisions can be reduced by increasing CWs size, it will be achieved at the detriment of broadcast packet losses due to channel switching at the end of the

CCH interval. In order to solve this challenge, Campolo and Molinaro[105] recommended the use of shorter frames to reduce the impact of broadcast packet losses due to switching and channel induced errors. However, how to improve the reliability of WAVE service advertisements (WSAs) was identified as a critical open research issue that requires further analytical investigation to facilitate wider application and deployment of IEEE 802.11p/WAVE standard.

5 Conclusions

VANET is no longer a remote feasibility, given that heavy investments are already in the pipeline from several sectors including government agencies, auto-mobile industries, navigation safety and public transport authorities. VANET potentials, areas of application and prospects are growing rapidly including several kinds of services with multiple requirements and goals. However, several unique, novel open research challenges ranging from wireless network evolution, reliable message dissemination to event detection are making research in VANETs very attractive.

Many key important topics in vehicular communication are currently under intensive research and discussion. These topical issues include potential modification, refinement, enhancement and implementation of IEEE 802.11p, wireless access in vehicular environment standard (WAVE), allocation of protected frequency band for mobile vehicular safety communication, integration (or unification) of different wireless technologies, congestion control, data security and transport, reliability in V2V communication, etc. The final step would be the harmonization of these promising solutions with other emerging worldwide vehicular communication projects and standards.

Different appropriate governmental agencies are working closely with car manufacturers/industries, such as Mercedes, Toyota, BMW, Fiat, Nissan, Ford, etc. to put prototype of Wi-Fi (IEEE 802.11a/b/g/n) and DSRC (IEEE 802.11p) equipped vehicles and other wireless access technology enabled vehicles on our motorways within the nearest possible future. Besides, the recent technical development, another critical and important phase that will drive this new technology to success is systematic commercial market introduction and public acceptance.

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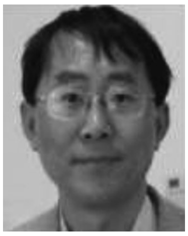

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