VANET Architecture Analysis and Protocols

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ABSTRACT
This paper provides an overview study and analysis of the communication environment and architecture for vehicular ad-hoc network (VANET). First, the architecture and recent development [12][13][14] in the PHY/MAC layer from two different standards (DSRC 802.11bd, C-V2X NR-V2X)has been discussed. Thenthe observation of the trends of similar technology selection is discussion in detail by comparing the most recent evolution of these two standards. On network and application layer, the characteristics of ad-hoc routing protocols [3][20] are introduced, analyzed and compared to the application environment of VANET. Majority of these routing protocols can be categorized into three classes: table-driven, on-demand and location-based. However,considering the nature of VANET, only on-demand and location-based routing strategies are considered due to their nature on on-demand and positioning enhancement. From all the analysis, this paper at the end provides a vision for the horizontal convergence of different technology and vertical convergence of network layer protocol stack co-design in the VANET architecture. The possibility of incorporating artificial intelligence into routing strategies in application layer is also explored and discussed. This paper also introduced some optimization methods such as broadcast storm mitigation [4] techniques as an example of network layer protocol stack co-design, and considered as part of the optimal solution to the futureVANET architecture in a holistic view.

General Terms
Ad-hoc vehicular network (VANET), V2X, artificial intelligence, communications, computer networks

Keywords
VANET, DSRC, V2X, AODV, Sidelink, Broadcast Storm, RoutingProtocol, Cross Layer Optimization, PHY/MAC, Technology Convergence, Network Layers, Convergence

1. INTRODUCTION
Vehicular Ad-hoc Network (VANET) is a special category of Ad-hoc network consisting of moving vehicle nodes in various scenarios such as high way or urban area. VANET is the core part of Intelligent Transportation System (ITS) and originally characterized by Dedicated Short Range Communication (DSRC) 802.1p and later on LTE-V2X PC5 interface Mode 4 [12]. Different from general categories of Mobile Ad-hoc Networks (MANET), the high relative speed and dynamic topology change in VANET results in the request of dedicated and coherent design at all levels (i.e.,necessary modification of existing systems so as to maximize the reliability and resilience) of communication architecture regarding its special application requirements.

1.1 VANET Applications
As part of Intelligent Transportation System, Vehicular Ad hoc network plays an essential role on important roadside applications including:

1.1.1 Safety Message Dissemination
Critical messages such as lane changing and accident notification are required to be reliably delivered (desired packet delivery ratio is required) to vehicles inside zone of interest within a maximum allowed time period.

1.1.2 Route Planning and Detour
Real time road service information can be broadcast and used by vehicles to avoid congestion and forming congestion. The information can be used by software to implement route planning to save travel time.

1.1.3 Intelligent Traffic Light and Road Crossing
Intelligent roadside applications utilizing available broadcast information from VANET to help improve real time traffic light control and interaction with pedestrians.

1.1.4 Infotainment Extension
With the help of roadside unit, wide area network access through VANET allow users aboard to extend network connection ability and connect to online services such as vocal online search for necessary information.

There have been extensive researches on VANET regarding infrastructure design for channel modeling optimization through probabilistic analysis and routing protocols. The goal of these researches is to minimize the packet error rate, delay and unnecessary packet dissemination redundancy (increase the packet delivery ratio defined as the ratio of successful received packets to total transmitted packets), and increase the reliability and speed of establishing the optimal routing path between any pair of source and destination reachable to each other in an ad hoc manner. The structure of infrastructure should also be designed according to metrics including packet delay, packet loss and error rate.

1.2 VANET Network Layers
When designing VANET architecture, the most fundamental layers are PHY and MAC layers in the 7-layer OSI model, which together define the basic channel access methods and medium sharing mechanism due to the fact that ad hoc wireless network is a shared medium network. The standard documented as 802.11p for DSRC defines PHY and MAC architectures which is based on and a slightly modified version of the PHY and MAC layers of 802.11 standards. The routing protocol in network layer is not defined in this standard and many suitable routing algorithms have been proposed, compared and improved. Comparatively, 3GPP standards defined LTE-V2X sidelink mode 3 and mode 4 as vehicular communication methods, among which mode 4 is for vehicle to vehicle (V2V) communication without involving the coordination of cell tower.

At network layer, asuitable routing protocol needs to consider important factors such as: route established speed, bandwidth cost, bandwidth utilization, resilience capability to link failure. routing overhead, link recovery speed and route maintenance.Among the many proposed routing protocols, some are presented as modifications to existing ones belonging to the category unfavored by some key requirements. For example, proactive (table-driven) [3] based routing protocols suffer from considerable amount of data transmission for route maintenance and slow response to topology update due to the larger overhead (low bandwidth efficiency)compared to reactive and position-based protocols.

However, a standard routing protocol is needed in order to allow future VANET products such as various On-board Unit (OBU) are able to communicate with each other using common functions. Future such products need to be certified under regulations to ensure they are well compatible with the same class of products before putting them onto the market, because on road side there will be a variety of OBU from different manufactures and a slightly non-standard implementation could cause problem in the ad hoc network and degrade the default performance of VANET and even severe safety issues.

This paper intends to provide an overview on proposed VANET architecture by integrating the challenges and potential issues faced by VANET communication environment and discuss some possible solutions with analysis to alleviate these issues. The rest sections of the paper are organized as follows: 2. communication scenarios for VANET; 3. Discussion of PHY/MAC layers of VANET; 4. Discussion of VANET routing protocol; 5.A Demand for Convergence of Network Layers and Different Technologies for Optimization and Adaptive Operation Modes for VANET; 6. Conclusion; 7. Reference.

2. COMMUNICATION SCENARIOS

VANET is a shared medium network due to the ad hoc network connection. The number of new nodes joining the network can grow up to a large number depending on the traffic density of the road side scenario, and only limited number of channels are allocated for communication, and therefore shared medium mechanism is required. Under the high relative movement and topology change communication can be greatly affected by Doppler spread under high relative vehicle speed, and 5.9GHz band frequency [9]for DSRC transmission can be easily block and scattered among high dense obstacles environment which is the case in urban area. Therefore, discerning distinct application scenarios of VANET is important to design appropriate operational mechanism in order to achieve the best performance and reliability for various situations. Highway and urban road side scenarios are quite different in nature, they will be discussed separately. The purpose of this section is to identify the specific requirements for designing PHY/MAC layer architecture and routing protocol capable of different operational modes under distinct VANET scenarios.

2.1 Highway Scenario (Approaching or Non-Approaching)

The behavior of vehicles on highway can be mainly characterized as low relative speed (except for the opposite highway lanes) and occasionally high density due to congestion or accidents, and the topology is dynamically changing due to passing and lane merging which are quite often on the highway. According to DSRC standard the communication range of VANET node is less than 1 kilometers, if the relative speed on the same highway direction is within the range of 0 ~ 30 mph (90mph – 60 mph), and then a vehicle node would stay within the transmission range of another node at least for 2.5 minutes which is a quite long enough period for a well performed routing algorithm to establish a route. However, if considering more vehicle nodes, it turns out the topology change and link breakage would occur more frequently. The worst case would be considering the opposite lanes: vehicles on opposite highway directions have very high relative speed about 130 mph which causes an active link period only for about 15 seconds, and some packets broadcast will be carried by those passing vehicles on the opposite lane and rebroadcast to a far unrelated zone due to the route request message broadcast. This phenomenon would greatly increase the burden of packet processing due to unrelated packets. These unrelated packets cause other prior packets to be delayed.

Ad hoc routing protocol will assign a packet with a finite time-to-live period (TTL) and compare it with the hop count and decide to discard the packet if hop count exceeds the TTL/max hop count. However, as the number of vehicle nodes increased on the highway, these unnecessary received packets would cause extra packet delay and packet collision. It is better to confine the broadcast region only on one side of the highway where the broadcast node is currently stay. This mechanism may be achieved by evaluating the Doppler frequency shift and comparing it with a threshold value to determine if the packet is from the opposite lane. The Doppler shift may be obtained by the channel information contained in the packet or OFDM PHY layer sync words, or through pilot carrier evaluation. By filtering out the broadcast packets from the opposite lane the utilization rate of on-board processing unit can be increased.

2.2 Urban Scenario (Low Relative Velocity and Dense Area)

In populated urban scenario, the movement of vehicle nodes doesn't often have high relative speed, therefore the average link active time is much longer than the case on the highway, thus the link breakage between VANET nodes is less frequent. Routing protocols sensitive to high dynamic movement scenario would work better on the highway.

However urban area usually consists of a variety of obstacles of different materials such as dense tall buildings (concrete) and metal components. The transmitted signals are severely blocked and scattered, and this is more prominent for high frequency signals such as 5.9GHz band wave. In this scenario, one difference regarding deployment of road side unit (RSU) compared to that of highway is the obstacles would block the signal and cause RSSI below the minimum threshold. As a result, broadcast signal may be constrained to a path along the clearance among buildings. This nature matches that of ad hoc routing protocols such as distance vector routing. The obstacles do not affect topology discovery process of such protocols due to distance vector routing working with received signal strength.

Some vehicle to vehicle (V2V) routing protocols may not perform well in urban scenario such as location aided routing (LAR) protocol. For example,greedy based routing algorithms such as Greedy Perimeter Stateless Routing (GPSR) [6], the route request process is based on position information of all neighbors to build the topology, and uses shortest path principle for each hop to find the closest node towards the destination. This is not an ad-hoc based routing protocol and would fail if no information regarding obstacles on the way to the next hop is provided. For location aided routing protocol, GPS or other positioning techniques are required to provide accurate position data in order for the routing mechanism to operate in local range and usually requires high precision clock. The dense building area would frequently result in below the minimum RSSI GPS signal strength. Here it is clear the useful information for determining the proper routing operation mode come from other network layers (PHY and MAC), which is further discussed in details in Section V as part of coherent solutions for an optimal VANET architecture.

As a result, applying different routing mechanisms and communication architectures under suitable scenarios is essential to the stability and reliability of VANET environment.

3. DISCUSSION of PHY/MAC LAYERS of VANET

3.1 DSRC 802.11p& 802.11bd

3.1.1 DSRC 802.11p

The DSRC standard of wireless access in vehicular environment has been merged to 802.11p standard, which is based on early DSRC modification on 802.11, 802.11a specification. DSRC standard provides operational requirements for communication device, physical and mac layer requirement, channel assignment including its operational modes, and performance requirement for vehicular environment. 802.11p collects modifications as revisions to corresponding 802.11/802.11a PHY/MAC clauses and programming interfaces. 802.11p collection is important for product manufactures to closely follow during software development or modification of existing firmware. Implementation needs to be ensured compatible with other products on the market to avoid system bugs and performance degradation.

3.1.1.1 General Definition

DSRC standard specifies the 5.9GHz band wireless access for vehicular environment and vehicle to vehicle communication within line-of-sight distance. Line-of-sight distance scenario implies in terms of fading model, Rician distribution shall be used with considering the existence of dominant light-of-sight signal component.

The standard defines on-board unit (OBU) which include communication devices mounted on vehicles and hand-held devices and road side unit (RSU) which provides road service message broadcast and access to the wide area network. The following figures demonstrate the possible modes of communication among the basic service set (BSS) of different categories of device.

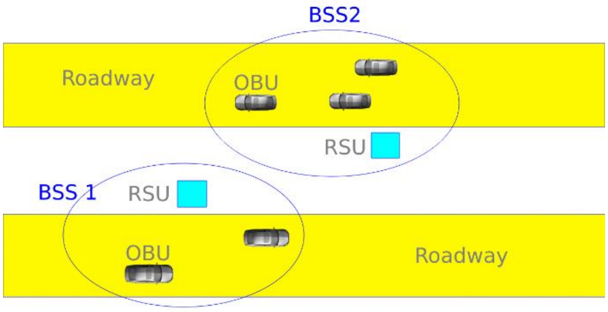

Fig 1: Communication between OBU and RSU

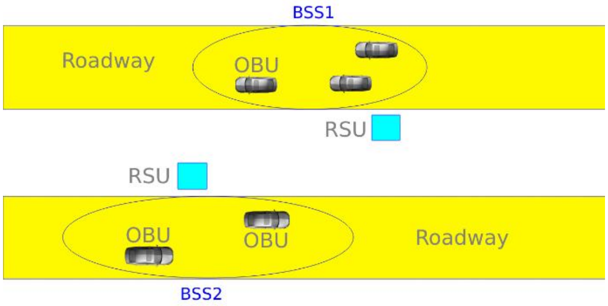

Fig 2: Communication among OBUs

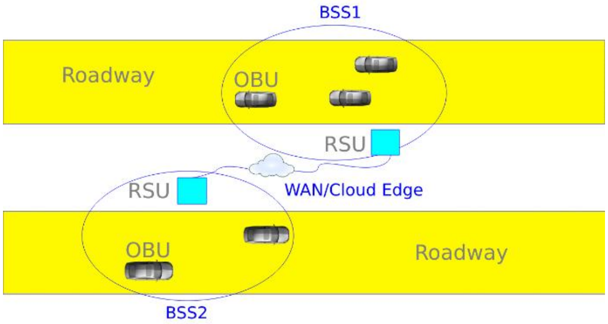

Fig 3: Wide area network access through RSUs

The communication of devices can communicate on a single channel or multiple channels according to the channelization planning. For DSRC ad hoc mode, by default all channels (the whole bandwidth) will be used in ad hoc mode communication which will be discussed later for channelization planning.

3.1.1.2 PHY Layer Modification

In 802.11 PHY layer specification two channel access methods are provided: DSSS/OFDM. DSSS PHY is dedicated to 2.4GHz band communication with maximum data rate of 11Mbps which is not used in 5GHz DSRC communication. Instead, OFDM PHY is used providing data rate up to 54Mbps, and modulation methods used include BPSK/QPSK, 16/64-QAM. Very high throughput (VHT) mode of OFDM PHY used 256-QAM in 802.11 standard is not used in DSRC [9]802.11p due to necessity of higher data rate over the constellation error, but will be used in 802.11bd with millimeter wave frequency range. The following comparison table shows the relative constellation error bound requirement for transmitter. The relative constellation error is the averaged RMS error over all sub-carriers for OFDM PHY layer protocol data unit (PPDU).

Table 1 Relative constellation error bounds required for transmitter

Modulation	Coding Rate	Relative Constellation Error (dB)
BPSK	1/2	-5
QPSK	1/2	-10
QPSK	3/4	-13
16-QAM	1/2	-16
16-QAM	3/4	-19
64-QAM	2/3	-22

64-QAM	3/4	-25
64-QAM	5/6	-27
256-QAM (not used)	3/4	-30
256-QAM (not used)	5/6	-32

Clear channel assessment (CCA) specification is important to physical layer carrier sensing. The standard defines that CCA shall indicate busy medium when detect any valid OFDM transmission with received power equal to or greater than -85 dBm (corresponding to sensitivity of the minimum 3Mbps transmission speed).

3.1.1.3 MAC Layer Modification

The MAC address for DSRC on board unit (OBU) devices are randomly generated. The different 46 bits MAC addresses for distinct units should be uncorrelated. If a unit receives the frame containing its own MAC address which indicates a duplication of MAC assignment, the unit will regenerate another uncorrelated MAC address which is the new MAC associated to that unit.

The default operation mode of channels in DSRC is defined by aunique ad hoc mode, in which the basic service set identification (BSSID) is set to all zeros during broadcasting. As modifications to 802.11 standard, there are no distributed beaconing mechanism and scanning function implemented for ad hoc reason.

In terms of cross layer information exchange, MAC layer is allowed to issue a high resolution RSSI request to physicallayer to lock the automatic gain control (AGC)[9] and ready for high resolution mode of RSSI during communication.

The contention window (CW) in CSMA/CA has been set to a constant value rather than allowing exponentially increment, and the fixed value can be specified per application requirement. The goal is to avoid uncontrolled latency caused by potential oversized CW size.

Enhanced Distributed Channel Acess (EDCA) [15]can be used to achieve better QoS in the MAC layer of 802.11n by more flexibly usage of different IFS (Inter-frame Spacing) to achieve quality of service for different service set, which is similar to the QoS idea in C-V2X. For 802.11p, the mechanism requires an application dependent designation of CW (Contention Window in MAC Layer), where the contention window size is fixed. Higher level of granularity for QoS makes resource allocation more efficient.

3.1.1.4 Channelization

The channel planning of intelligent transportation system roadside service (ITS-RS) [9] is illustrated in the following figures. For option 1 the inter-channel spacing is 10MHz, and the operating channel numbers are defined in Fig. 13. For option 2 Channel 175 and 181 are used for 20MHz bandwidth DSRC communication equipment, and on these 2 channels the MAC operational standard follows that of 802.11a. However,for DSRC 802.11p, the MAC modification shall be based on 7 channels in option 1 designated with 10MHz bandwidth each.

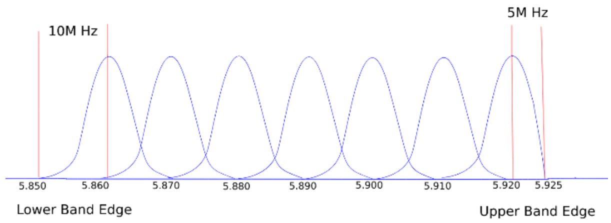

Fig 4: ITS-RS channelization option 1 diagram

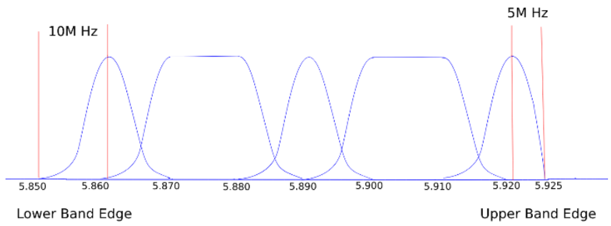

Fig 5: ITS-RS channelization option 2 diagram

Table 2 ITS-RS channel numbers designation

Regulatory Domain	Band (GHz)	Operating Channel Numbers	Channel Center Frequencies (MHz)
United States and Canada	ITS – RS (5.850 – 5.925)	172	5860
		174	5870
		175	5875 (option 2)
		176	5880
		178	5890
		180	5900
		181	5905 (option 2)
		182	5910
		184	5920

3.1.1.5 Packet Error Rate Requirement

DSRC standard specifies packet error rate (PER) should not exceed 10% for: PSDU length of 1000 bytes under 85 mph relative vehicular speed and PSDU length of 64 bytes under 120 mph relative vehicular speed.

Packet error rate (PER) shall not exceed 10% for the physical layer service data unit (PSDU) length of 1000 bytes for mandatorily supported data rate (3 Mbps, 6 Mbps and 12 Mbps) under the following conditions respectively [9]:

• Multi-path delay spread within 400ns time delay for a 5 seconds period for the same signal at the receiver.

• A maximum Doppler shift with absolute value of 2.1 kHz for a 5 seconds’ period.

• 10 dB amplitude variation of at 100 Hz rate over a 5 seconds’period.

• A simulated Rician channel with shape parameter K=10.

3.1.2 DSRC 802.11bd Improvement& Enhancement

802.11bd is backward compatible and also interoperable with 802.11p. The bandwidth increases from 10MHz in 802.11p to

20MHz. It also uses LDPC as the one used in NR-V2X, higher modulation scheme such as 256QAM, STBC (Space-time Block Code) and MIMO for increasing diversity gain. Millimeter wave range is also considered to be used.Besides these, there are several major improvements aiming to increase the reliability and throughput under challenges of various shared medium channel conditions.

802.11p was derived from 802.11a where bandwidth reduced from 20MHz to 10MHz resulting in a double longer symbol length with reduced sub-carrier spacing to 156.25 kHz, and longer symbol period better deals with multipath. However, at high doppler speed, shorter sub-carrier space tends to be more sensitive to carrier frequency shift. 802.11bd on the other hand provide option for 312.6 kHz sub-carrier spacing and miambles to cope with fast varying channels. Midamble is introduced to be inserted into the front of each symbol for channel estimation under fast varying condition, especially when LDPC is used in 802.11ax2X down-clock mode.

Another technique for increasing diversity is called Dual Channel Modulation (DCM). The user's channel is split into two coherent and far separated channel for transmission the redundant message, and as a result, one can choose either to double the data rate by increase MCS order or double the transmission duration. This method provides more robustness towards frequency selective fading.

802.11bd introduced a channel bonding technique to use the two adjacent channels for transmission when demand for throughput is needed. The mechanism is slightly different from the similar technique used in 802.11n but can choose fallback. It can be chosen together used with EDCA.

Range Extension (RE) and a blind retransmission mechanism are also included. RE is to increase the transmission power for better range coverage. Blind retransmission is to retransmit the message whenever needed. The average gain is expected to increase due to the increasing chance of successful transmission acceptance.

3.2 LTE-V2X& NR-V2X

3.2.1 LTE-V2X Standard for VANET

The LTE-V2X was proposed in 3GPP release 14 which contains two operation modes of 3 and 4. Only Mode 4 (PC5 interface) is used for direct vehicle to vehicle communication without the participation of cell tower (eNodeB). In Mode 3 vehicles resort to communicate with eNodeB to coordinate resource allocation and scheduling information. This scenario is not a strict sense of VANET and not included in the scope of discussion.

LTE-V2X mode 4 utilizes Semi-Persistent Scheduling (SPS) for coordinated shared medium access among vehicles. Semi-PersistentScheduling facilitate meta-stable resource scheduling which acts on a demand basis. Scheduling can be chosen not only for the next transmission but several consecutive ones controlled by reselection counter.Rescheduling occursonly when the current resource scheduling cannot satisfy the performance metrics for the current transmission.This meta-stable scheme helps reduce the scheduling overhead and save bandwidth. On the other hand, due to agnostic to the demand event, the resource scheduling is distributed on even time spaced reservation intervals, which shows more unpredictable performance when the message to be sent has variable length and is generated in an aperiodic manner.

The PHY layer resource allocation scheme is depicted in Figure 6. The basic resource unit is Resource Block (RB) divided in a 1ms time slot containing 14 OFDM symbols, and 180kHz frequency band which contains 12 subcarriers with each 15kHz, and multiple RBs constitute a sub-channel. PSCCH (Physical Sidelink Control Channel) occupies 2 RBs and is used to transmitted SCI (Sidelink Control Information) which contains meta information for data recovery. PSSCH (Physical Sidelink Shared Channel) is used to transmit Transport Block (TB) which contains the actual data, and each Transport Block occupies several RBs Therefore,each TB may occupy several sub-channels depending on the relative size of TB to the size of all resource blocks (RBs) each sub-channel contains. A HARQ data retransmission mechanism is also deployed on PSSCH. Besides PSCCH for sidelink control and PSSCH for data transmission, the PSBCH (Physical Sidelin Broadcast Channel) is used for broadcasting synchronization information for sidelink.

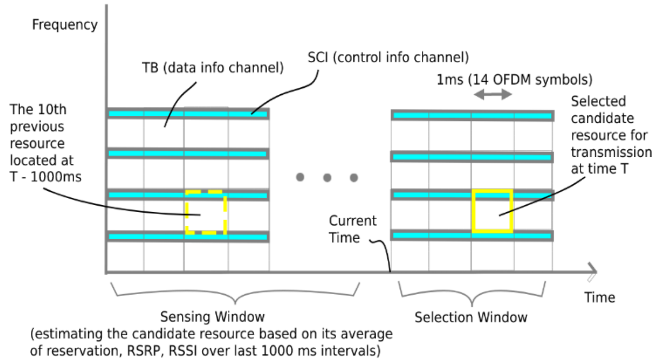

Fig 6: LTE-V2X Resource Allocation Scheme and Reservation Algorithm

Semi-Persistent Scheduling incorporate a Resource Reservation Algorithm to determine the best candidate single subframe resource which is a frequency-time chunk occupied 1ms symbols with RBs covering one SCI and one or more TBs. The algorithm determines the final pool of choice for all the candidate single subframe within current selection window (the time window that can satisfy the current packet transmission requirement). It takes into account the Reference Signal Receiving Power (RSRP), reservation history and Received Signal Strength Indicator (RSSI) averaging over last1000ms sensing window for each candidate single subframe resource.

3.2.2 NR-V2X Improvement

NR-V2X was introduced within 5G-NR domain looking for considerable improvement on performance and reliability, andthe completion of its full standard is expected to be introduced by 3GPP in release 16 in 2019. The improvement compared to LTE-V2X comes from many aspects such as coding, uplink modulation, MAC control and more flexible resource allocation scheme, with a goal to balance performance boost, energy efficiency and the versatility of application environment.

In terms of bandwidth, NR-V2X can utilize millimeter wave bands above 24GHz with a maximum 400MHz, and as well as frequencies below 6GHz with a corresponding maximum bandwidth of 100MHz, which is greater than the 20MHz in LTE-V2X.

For the uplink and downlink access methods, NR-V2X utilize OFDM for high throughput transmission,and use DFT-s-OFDM(Direct Fourier Transform Spread OFDM) for energy efficient and capable device due to its low PAPR (Peak to

Average Power Ratio) and low requirement on the device's linearity region. Where in LTE-V2X SC-FDMA is used for keeping low PAPR but lack of the high throughput benefit of OFDM. Therefore, in NR-V2X the application is able to deploy more flexible solutions based on the tradeoff between throughput, energy efficiency and device capability.

As mentioned in section 3.2.1, LTE-V2X uses HARQ [15][17] retransmission on PSSCH, and is also a blind retransmission mechanism similar to that used in 802.11bd.NR-V2X introduced a PSFCH (Physical Sidelink Feedback Channel) [13] for efficient feedback retransmission. The goal of introducing this channel is for increasing spectral efficiency and reduce processing time and overhead.The last symbol of a slot is proposed to be used as time domain resource for fast feedback. CSI (Channel State Information) is also considered to be placed in this channel, but if the payload is large, it is also considered to be placed in PSSCH.

Compared to LTE-V2X, NR-V2X provides more flexible sub-carrier spacing and symbol duration. The table 3 lists some of the available numerology.

Table 3Several NR-V2X Frame Structure Options

Index	Sub-carrier Spacing (KHz)	Number of Slots every Subbframe	Slot Duration (us)	Number of OFDM Symbol per Slot
0	15	1	1000	14
1	30	2	500	14
2	60	4	250	14/12 (Extended)
3	120	8	125	14
4	240	16	62.5	14

The shorter available symbol duration results in wider sub-carrier spacing which exhibit more robustness towards carrier frequency offset in intense doppler scenario but susceptible to multi-path and inter-symbol interference.Along with improved coding scheme from data channel turbo code and control channel convolutional code in LTE-V2X todata channel LDPC code and polar code in NR-V2X, the overall capability of copping with channels is enhanced. The CQI (Channel Quality Indicator) is evaluated by DMRS (Demodulation Reference Signal) to select the proper MCS scheme on a best effort basis especially for high density scenarios.

3.2.3 Observation and Comparison to DSRC (802.11p, 802.11bd)

802.11p is derived from 802.11a and inherit most major mechanism for share medium access. The typical characteristics CSMA/CA on a shard medium. Unlike the finer resource allocation scheme used in LTE-V2X. Obviously there are benefits in both approaches. During the evolution of 802.11p to 802.11bd and LTE-V2X to NR-V2X, a plenty of improvements shows a converging trend of between DSRC and C-V2X, at least many similar enhanced methods and improvements have been proposed.

3.2.3.1 Similar Techniques and Converging Trends

•Redundancy Mechanism (Retransmission in both, Dual Channel Modulation in 802.11bd)

•Use of Millimeter Wave Range and Higher MCS

•QoS (NR-V2X by 5G-NR nature, DSRC EDCA, AIFS)

•MIMO

• Multi-cast/Groupcast (BSS in DSRC, groupcast in NR-V2X)

• Increased Level of Granularity in Resource Allocation (More physical sidelink channelsand frame formats used in NR-V2X, Channel Bonding and flexible use of IFS in DSRC)

• Channel Coding (LDPC for both NR-V2X and 802.11bd)

• Fast Varying Channel Solution (Miambles for 802.11bd, more choices of DMRS type for NR-V2X)

4. DISCUSSION OF VANET ROUTING PROTOCOLS

The VANET routing protocol is responsible for dynamically monitoring the network topology and update the new route entries whenever the topology changes (new joining nodes or link breakage) in order to provide packets with the optimal traveling route. There have been extensive researches on routing protocols yielding remarkable improvements in terms of logic and performance. Due to the diverse application scenarios for vehicular communication environment, a desired routing protocol shall be able to provide best performance as it could in terms of packet delay, packet delivery ratio (ratio of packet successfully delivered over total transmitted packets) and packet penetration rate (throughput, averaged number of packets traveling through broadcast nodes over a period of time). The balanced performance among different environment is critical to ensure that the VANET could have reliable and stable communication performance when the scenario switches.

Within a vehicular network topology, if a node wants to communicate with another it will broadcast route request message. If the optimal route to that destination from originator already exists as route entries in the routing tables of the nodes, the message would be delivered successfully in an efficient way. Otherwise, the route which could deliver a new route request message successfully to the destination with acceptable PER (Packet Error Rate) would be the optimal route. Sometimes even though destination is located geographically within the transmission range of request vehicle node, due to channel delay or unsymmetrical channel, the direct broadcast to destination in one hop would cause high packet error rate or high delay. On the other hand, there may exist an optimal path through other vehicles for which the channel has less distortion or delay, then it is necessary to resort to routing protocol to discover this optimal path even when the destination is located within the transmission range of the route request node. If the destination is outside the source transmission range, the routing protocol tries to find the optimal route to the destination node through bridging nodes which help forward the broadcast packets and extending the transmission range of the source node.

4.1 Routing Protocols in VANET

Routing protocols in VANET operates in a versatile environment. In some scenario the topology is constant for a considerable amount of time, some scenario creates challenging situations on communication stability. PHY/MAC layer is constantly evolving to cope with the diverse application environment in VANET. However, not all issues are suitable to be solved only by low layers, and higher layers is capable or have the chance to alleviate the issues faced by low layers. Routing protocol has the ability of discovering the topology of local vehicular nodes and of coordinating the group or swarm behaviors by provide useful information about the set of links.Therefore, potentially acts like a factor of optimization solution to the entire VANET architecture. There have been a plenty of ad-hoc network routing protocols proposed, but not all of them are suitable for VANET which is the subset of ad-hoc network. Some generality proposed in these routing protocols are not practical for VANET. There are three distinct classes of ad-hoc routing protocol: table-driven (proactive), on-demand (reactive) and location-based [3][20]. For VANET, proactive routing protocols usually incur large overhead during route establishment and periodic routing table update, and therefore is not quite suitable given the diverse application scenarios of VANET. On the other hand, reactive and location-based protocols both have their own advantages in different scenarios and can be a good complement for each other. The end of this section explores the optimal hybrid routing protocol that integrates all the characteristics these protocols have for VANET architecture.

4.1.1 Table-driven (Proactive)

4.1.1.1 Destination Sequenced Distance Vectoring

According to the article, the most basic version is DSDV (Destination Sequenced Distance Vectoring Routing). This protocol is a modified version of Bellman-Ford algorithm [3] for routing discovery. It utilizes the destination assigned sequence number to distinguish the stale route and new one in order to prevent loop. The entry is constantly monitored and updated for choosing the best route with best metrics. Because it uses Bellman-Ford algorithm, the route discovery performance is less than using Dijkstra's algorithm, and the link cost are generally positive numbers in representing the communication "resistance."

Though it introduces incremental changes for routing table update during route maintenance. The overhead ofdisseminating the routing table across the entire network during route establishment is large compared to on-demand protocols. Therefore, this is not optimal for VANET application where frequency of topology change can fluctuate largely.

4.1.1.2 Clusterhead Gateway Switch Routing

The protocol is based on DSDV mentioned above. The main difference is that it first introduced cluster head concept in ad-hoc routing. The nodes spontaneously determine the cluster they belong to and the cluster head responsible for centralizing the message relay within the cluster. The cluster concept creates a hierarchical routing scheme compared to the flat scheme of DSDV.The intermediate node within the range of more than 1 cluster heads acts as a gateway to relay information between the headswhich act as the in-cluster relay.

The information for logging and update the cluster members and heads introduces additional overhead on top of DSDV, making the protocol more unsuitable for dynamic environment in VANET.

Moreover, cluster routing in this scheme also creates another issue. Though the cluster strategy forms a hierarchical structure network topology,the routing via cluster head can cause unbalanced workload and utilization among nodes, leaving other nodes resources wasted when they are not selected as cluster heads.

4.1.2 OnDemand (Reactive)

This class of routing protocol establish route whenever a routing request is generated. Compared to proactive routing scheme, the reactive behavior generally means more less frequent or no updates during route maintenance, and the message exchange during route establishment is aimed to keep at minimum enough only for "demand." Overall, the routing mechanism exhibits a temporal semantic, and more suitable for dynamic environment.

4.1.2.1 Dynamic source routing (DSR)

This protocol is implemented using source routing principle, in which the entire route list from source to destination will be included in the packet when the broadcast packet arrives at the destination node. DSR doesn't periodically broadcast route maintenance messages, and relies on link layer message to discover any invalid route due to topology change. Because of the source routing nature, multiple routes are allowed to be used for redundancy which also make it suitable for unsymmetric links.

DSR algorithm is in operation whenever there is a route request from a source node to a destination. There are three types of messages in DSR including route request, route reply, and error messages. During the route request initiation stage, the source node broadcast request packets to all nodes within its transmission range, and each node in the ad hoc network maintains a list of source node address and a unique request id pair from the most recent received route request packets. A route request packet contains a unique request id number which is used to maintain the freshness of the broadcast packet to prevent receiving duplicated packets. A route record is also maintained in the request packet, which is a list of a sequence of nodes visited by the request packet as it hopping through the network.

Nodes subsequently receive the broadcast packet drop the packet if the source address and request id pair is found in the pair list maintained by the node, which means the node has already been visited by the packet and the source address, request id pair is not expired; or otherwise if the node address is found in the route record of the packet, which means the node has already been visited by the packet but the source address and request id pair has expired in the pair list maintained by the node; or otherwise if the node address is the destination of received route request packet, a route reply message is generated containing the complete route record for this route and sent back to the source node; otherwise the node rebroadcast the packet with its own address appended in the route record in the packet.

DSR maintains the route by notification from link layer transmission failure and doesn't use any periodic broadcast maintenance message mechanism. The advantage of this implementation is the reduced overhead and energy saving [3] benefit for link breakage is only detected during data transmission whenever any node has request to send, which is a passive strategy to detect broken link. The drawback is wheneverthe topology changesand no requestsare sent within the routing group, there would be no real-time update for the new topology and optimal routing rules, and the detection of link breakage will be delayed to the next new request. This delayed or passive strategic characteristics, however,would greatly degrade the routing performance in some cases. For example, when the network topology greatly changes and large number of nodes joining in,upon data transmission enormous requests to establish links or find new routes would flood into the ad hoc network within a short period of time causing large size of overhead due to the passive routemonitoring nature of the DSR algorithm. The result isdegraded performance on an ad hoc networkof high density.

4.1.2.2 AODV

Ad-hoc on-demand distance vector routing (AODV) [5]is a loop-free distance vector routing mechanism that improves and is based on destination-sequence distance vector routing algorithm (DSDV). AODV uses three categories of messages route request (RREQ), route reply (RREP) and route error (RERR) to establish route discovery process and maintain route topology. Similar to dynamic source routing (DSR), AODV establishes a route between a source node and a destination node by broadcasting route request packet constrained by request id number for duplicated packet and loop elimination. Compared to DSR, the RREP message in AODV does more jobs to send back only the most updated routing information rather than propagating the complete route list backwards. Because AODV uses sequence number for accepting only first time received RREQ packet, it is loop free and can only be used on symmetric links. When the destination returns RREP message, only one predecessor is to accept it (unicast), and if the link is unsymmetric, the returned RREP cannot reach the predecessor reversely and thus the route establishment is failed. For VANET, the links among nodes are generally symmetric especially for local geometry, therefore AODV matches the application environment of VANET in term of link symmetry.

AODV RREQ packet contains request sequence number and destination sequence number. Request sequence number is a monotonically increasing sequence number to distinguish instinct route request packets generated by the source node, a newer RREQ generated by the same node has its request sequence number increased by 1. An intermediate node will not rebroadcast the RREQ it receives if the request sequence number in RREQ is less or equal to that of the route entries in that node, and thus RREQ duplicated rebroadcast is prevented.

RREQ broadcast message would eventually reach the destination node or the intermediate node containing the remaining path to that destination. If the node is the destination, then a RREP is generated for the reverse route. If the node contains the remain path to the destination, destination sequence number contained in RREQ packet is then compared to the destination sequence number contained in the intermediate node, and a RREP message is generated only when the destination sequence number in RREQ is greater than that of the node for that destination, and the node updates the destination sequence number in its routing table entry to the larger one contained in the RREQ. This mechanism ensures the most updated route information propagates back to the source node and quicker route establishing speed by eliminating redundant and obsolete RREP packets.

AODV is a loop-free routing mechanism due to the fact that a routing loop must has the same node visited twice by a RREP packet with the same destination sequence number, otherwise the RREP with the monotonically increasing destination sequence number increased would not be accepted by the same node twice. However, an intermediate node doesn't allow a second visit by the RREP packet with the same destination sequence number, it updates the routing table when first time receive the RREP. Therefore, AODV is a loop-free routing mechanism due to the function of destination sequence number for reverse route establishment.

Intermediate nodes receiving RREP update the timeout parameter contained in RREP packet if the RREP received is not expired indicated by timeout record. The new timeout parameter is updated to (the current time+life time) for the RREP rebroadcast. By tuning the life time for RREP the optimal routes can be selected by discarding expired RREP to ensure the response speed of reverse route discovery. The multicast provided by AODV enables more flexible multi-party wireless communication than those don't use multicast feature. The multicast feature of AODV also closely matches the groupcast/multicast concept[13][19]for NR-V2X sidelink.

4.1.2.3 Temporally-Ordered Routing Algorithm (TORA)

TORAhas a mechanism of relying on precision of time synchronization among nodes to establish routes through DAG (Directed Acyclic Graph) [3]. The precision of time is used to generated so called height metrics for each node in order to evaluate the direction of the link within DAG. Obviously, the requirement for precise time synchronization can put limit on the range of application scenario when such condition doesn't or struggle to exist. Besides this, due to the nature of coordinated DAG maintenance and restructuring, during mixed events such as link failure, route establishment and route deletion, the entire DAG structure updating could result in a dynamic oscillation and damping, and eventually the structure reaches equilibrium.

4.1.2.4 Associativity-Based Routing (ABR) & Signal Stability Routing (SSR)

ABR is characterized by the notion of link associativity and the efficient mechanism of local topology update. Associativity between each node pair is derived from beacon counting. Each node periodically broadcast beacon to its neighbors, and each the beacon counting of the receiving node from the broadcast node increases the counter by one. In this way every node maintains the beacon count from all its neighbors, and overtime the greater the count value the more "associated" the channel link from the neighbor node. In a symmetric link, the associativity is also assumed symmetric. During the route establishment process, the route request similar to DSR routing mentioned above is broadcasted, and each subsequent node receiving the broadcast message rebroadcast it.

The main difference is that during the forward phase of route discovery in DSR each intermediate broadcast node only appends its IP address to the route record, but ABR also appends the associativity metric represented by the beacon counting between its predecessor and itself (by pruning the predecessor's associativity list so that only the entry related to itself is kept) and some QoS information. Therefore, the destination node has a list of full vectors of associativity along the possible routes from the source, and it then chooses the one with best associativity value set as the optimal route.

For route maintenance,ABR has an efficient mechanism. If either the source node or the destination node moves, the original nodes on the route that are not reachable from the new position of source or destination node have their route records deleted, and for those original nodes are reachable through new partial local route as a "bridging", only partial information needs to be updated for the new local discovered the partial route.

Signal Stability Routing (SSR) is inherited from ABR by not using the associativity beacon counts but the signal strength as the indicator for strength of "link associativity." The route discovery mechanism remains the same as ABR.

4.1.3 Location-Based Routing (PositionBased)

Besides proactive and reactive routing scheme which are designed up to network layer. Positioning based routing technique takes the advantage of location informationwith acceptable precision. There are many location-based routing methods proposed, and majority of them have their own designed algorithm running at Application Layer using positioning information. Proactive and reactive algorithms mentioned above focus design on Network Layer instead, and the broadcast message is trigger from upper layer. For positioning-based technique with non-trivial calculation and evaluation, more versatile algorithms can be designed at application layer using positioning information. Greedy Perimeter Stateless Routing (GPSR) is a good example of conduct protocol design by taking into account of MAC, Network and Application Layers together for optimal performance.

4.1.3.1 Greedy Perimeter Stateless Routing (GPSR)

GPSR [6] is a scalable routing protocol not like DSR and AODV, it takes into account the growing number of routers and destinations, and the algorithm uses concepts from graph theory to partition the network into sparse link map consisting of "perimeters" or "faces" of polygon shape for perimeter mode performance.

GPSRconsists of two operation modes, greedy and perimeter. By the assumption that each node in the network is knowledgeable about the position information of the destination node by means of GPS, TOA, DTOA etc., each node only forwards its route request to the next hop node which has the closet geometric distance to the destination location, and this is called greedy mode, in this way the node keeps nearly stateless. The key design effort is focused on the "perimeter" mode, when there is no node in the transmission range having a closer location than the current node itself. When this happens, the node attempts to forward the message by the right-hand rule in a counter clockwise direction to search for neighbors which provide greedy mode operation, and along the traverse routing information is also registered in the passing nodes for bookkeeping. GPSR provides two graph methods RNG (Relative Neighborhood Graph) and GG (Gabriel Graph) to generate network link map free from link crossing for efficient routing in perimeter mode. Besides this, GPSR also takes into account the design factor of MAC layer feedback mechanism for retransmission timeout similar to DSR, which makes the design considerations taking places at MAC, Network and Application all three layers.

Besides beingnearly stateless for each node by only knowing the next hop's position, GPSR node also utilizes the forward message to append its own position information to its neighbors to minimize the cost of beaconing.

4.2 Scope of Routing Protocol Improvement For VANET

4.2.1 Hybrid Routing Combining On-Demand (Reactive) and Location-Based Protocols

In the application scenario like VANET, the dynamic environment requires the routing services more similar to on-demand basis protocol, due to the route is treated as temporary for a period of time. The evaluation of AODV shows the redundancy of realizing an on-demand routing protocol has been minimized compared to other protocols within the same class. On the other hand, the framework of configuration of AODV is flexible and the support of multicast also provides flexible QoS control.

Location-based protocol like GPSR implement non-trivial algorithm in application layer and this can inspire a more robust and comprehensive hybrid routing protocol that combine the advantage of efficient native network layer on-demand routing mechanism which is directed by the non-trivial application layer routing algorithms. At application layer more additional metrics and information can be utilized to work together with other layers for a more coherent control. Suitable artificial intelligence deployed at application layer can provide useful control mode information to the lower layer.

The scalability of GPSR combined with the efficiency and stability of AODV provides complementary characteristics to a routing protocol. AODV's multicast can be used together with the concept of cluster.By using a unified application layer algorithm, the routing protocol has a chance to become more robust and effective.

4.2.2 Swarm Intelligence Assistance in Forming Optimal Hierarchical Network Routing Topology

Swarm intelligence has been widely used in many optimization problems. The dynamic nature of VANET nodes appears self-organizing nature when they form a so called "swarm." Each node or member is directly aware of the neighbor or indirectly aware of the members far from it. The mode of topology change in vicinity of a node partially reflects the global change by self-organizing update. Therefore, the sensory perception factors such as distance measurement, relative velocity gradient, beacon signals etc. collectively are important metrics for each node making optimal decisions and mode change.Location-based routing protocol is able to use position information provided by GPS coordinate, trilateration of TDOA, TOA etc. or the rough position provided by RSSI depending on the scenarios.

Swarm intelligence on application layer can be used together with multicast for the node to make decision and act on the feedback of environment sensing. The feedback from lower layers such as PHY/MAC can be used to adjust the current topology for optimal local throughput and load balance. Of course, this only can happen when the VANET is fully autonomous. PSO (Particle Swarm Optimization) is an early method for swarm search optimization based on gradient and partially global information. In order to apply on VANET, not only the velocity gradient metric is needed to take into account but also link state information and even constraints on each node for optimal topology reorganization.

4.2.3 Broadcast Optimizationfor Broadcast Storm Control

Ad Hoc Network Routing protocols discussed above by default use 1- persistence broadcasting rule [4], that is rebroadcast any valid packet received with probability 1. Routing protocols have mechanisms to suppress duplicated packets by using filtering rule provided by sequence number function. However, that doesn't suppress rebroadcast packets before filtering rules could apply, and thus may result in high probability of packet collision for the ad hoc network with high density.

Three broadcast storm mitigation mechanisms have been proposed including weighted p-persistence, slotted 1-persistence and slotted p-persistence broadcasting rules. These optimization mechanisms require the knowledge of distance between two nodes which can be obtained through received signal strength (RSS) for coarse distance estimation or GPS information for precise distance report.

• Weighted p-persistence broadcasting rule assigns rebroadcast probability with $p = D_{ij} / R$ [4] to each node receives the broadcast message within the transmission range of the originator. R is the transmission range of broadcast node. D_{ij} is the one hop distance. Further nodes from broadcast center rebroadcast the packet with higher probability and vice versa to suppress duplicated packets with greater hop counts towards the destination.

• Slotted 1-persistence broadcasting rule assigns slotted time for nodes to transmit according to the regions they are assigned, by dividing the transmission range of broadcast node along the road into a certain number of regions (e.g., 5 or 6 regions). Nodes distance from broadcast center is negatively linear to the assigned time delay for transmission (time slot) i.e., the closer the nodes are from the broadcast center, the longer time the transmission needs to wait. This rule gives further nodes the priority to rebroadcast for faster message delivery speed with less hops.

• Slotted p-persistence broadcasting rule combines the merits from both p-persistence and slotted 1- persistence broadcasting rules for a more flexible optimal performance tuning (parameters in p-persistence and slotted 1-persistence broadcasting rules are tuned to achieve optimal performance).

The slotted p-persistence mechanism from MAC layer can be used together with the multicast function in Network Layer and clusters. By doing so, the broadcast between clusters can be reduced by setting rebroadcast probability small near the cluster center and close to one near the cluster edge. Within cluster message dissemination can be achieved by groupcast or multicast (AODC). This flexible tuning makes the use of resource more efficient, reduces the overhead and increase the reliability.

5. A DEMAND FOR CONVERGENCE OF NETWORK LAYERS AS WELL AS DIFFERENT TECHNOLOGIES FOROPTIMIZATION ANDADAPTIVE OPERATION MODES FOR VANET

Throughout the discussion above for the VANET network architecture. There is a latent demand seems to show the trends of convergence not only for the different technologies used in the same layers (DSRC and C-V2X) but also for the complementary features spread in different Network Layers. This section summarizes the observations of the convergence trend for different technologies (Horizontal Convergence) and different network layers (Vertical Convergence).

5.1 Horizontal Convergence

As summarized in section 3.2.3.1 over years the evolution of DSRC and C-V2X on PHY/MAC layers tends to implement the same technologies which have the state-of-art performance such as LDPC, millimeter wave, things similar as pilot signals (midambles for 802.11bd, DMRS for NR-V2X) etc. The most fundamental difference is the way how they access channels, time multiplexing for DSRC using CSMA/CA and time-frequency multiplexing for C-V2X. In terms of this angle, DSRC has been continuing to develop the more efficient channel access and resource utilization scheme represented by 802.11bd, and C-V2X continues on the more refined granularity of resource allocation represented by NR-V2X.

Besides the channel access control, modulations, coding and error correction seems to become more convergent and eventually they seem to choose the same technology for these aspects. In terms of application scenarios, the channel access control of DSRC maybe more suitable for local, temporal and sparse wireless connection scenario and the much-refined C-V2X resource allocation scheme can be used in long range, consistent and more dense scenarios. Both are a good complementary method to each other depending on which channel access control mechanism is more suitable.

5.2 Vertical Convergence

The discussion in section 4.2 in the view from application layer shows some benefits of keeping vertical layers more coherent when designing protocol stacks. The following provides additional ideas on network vertical coherence from the views of lower layers.

5.2.1 Scope on Cross Layer Optimization

Optimization is possible for reducing packet collision rate by attempts to extend layer functions to other layers i.e., layer cooperation or information exchange. The message from one layer may provide unique information to another layer whenever an optimization decision needs to be made.

5.2.2 PHY/MAC Carrier Sensing and Broadcasting Rule

One possible cross layer optimization is to use physical layer and MAC layer carrier sensing function to detect received signal strength from the environment. In order to be accurate on the density of transmission nodes around, average received power on PPDU of broadcast packets from neighbors after waveform decoding can be used as an indicator of the average density of the regional network. The density indicator can be used to instruct network layer broadcasting rules such as weighted p-persistence broadcasting rule. In addition to consider weighted p-persistence on a distance probabilistic broadcast basis, the higher density a network region is, the lower the rebroadcast probability should be assigned to nodes in that region. This implementation can further reduce redundant rebroadcast packets reasonably.

5.2.3 PHY Carrier Sensing and MAC QoS

The average sensing power performed by PHY carrier sensing may indicate the average density of the regional network nodes. This information provided by physical layer can be used to dynamically balance the medium access control in response to the node density of the regional area. Arbitration inter-frame space (AIFS) is a candidate to perform this cross-layer optimization method.The higher the average overall sensing power is on a node, the shorter the AIFS is assigned and vice versa. This ensures nodes resided in dense regional area have more priority to transmit packets due to higher possibility of packet collision and packet flooding in denser area. This design may help alleviate the packet flooding in dense area resulting packet loss or high packet error rate (PER).

6. CONCLUSION

This paper provides an extensive overview on application scenarios, medium access methods, medium access control, routing protocolsand protocol stack design for vehicular ad hoc network (VANET).The most recent trends on the evolution of PHY/MAC layers (802.11bd and NR-V2X) of VANET has been extensively studies. The analysis for representative ad-hoc network routing protocols has been conducted, and the suitability of these protocols to VANET environment is openly and carefully compared. Attentions are also drawn to the connections among different layers of VANET architecture which help provide better solutions and optimizations to the VANET architecture for more reliable, stable and better performance.

On the last section, the observation of horizontal convergence of technology trends in standardization and vertical convergence of network layers are also thoroughly studied, which not only provides an additional vision to the overall architecture evolution direction of VANET, but also the possibility of achieve the optimal operation of VANET in a holistic view.

Based on the analysis, the outlook for VANET architecture is focused on the convergence, compatibility and coexistence of different technologies on PHY/MAC layer (DSRC and C-V2X),the co-design of the efficient and suitable network layer routing mechanism and the more intelligent application layer algorithms for a complete protocol stack.

7. REFERENCES

[1] Fan Li and Yu Wang, “Routing in Vehicular Ad Hoc Networks: A

[2] D. B. Johnson and D. A. Maltz, “Dynamic Source Routing in Ad-hoc Wireless Networks,” in Mobile Computing, Vol. 353.

[3] E. M. Royer and Chai-Keong Toh, "A review of current routing protocols for ad hoc mobile wireless networks," in IEEE Personal Communications, vol. 6, no. 2, pp. 46-55, April 1999, doi: 10.1109/98.760423.

[4] N. Wisitpongphan et. al., “Broadcast Storm Mitigation Techniques In Vehicular Ad-hoc Networks,” IEEE Wireless Communications Transaction, December 2007

[5] C. E. Perkins, E. M. Royer and S. Das, “Ad-hoc On Demand Distance Vector Routing,” IETF RCF 3561, July 2003.

[6] Brad Karp and H. T. Kung. 2000. GPSR: greedy perimeter stateless routing for wireless networks. In Proceedings of the 6th annual international conference on Mobile computing and networking (MobiCom '00). Association for Computing Machinery, New York, NY, USA, 243–254. https://doi.org/10.1145/345910.345953

[7] “802.11 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” IEEE Standard 2016.

[8] “Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 6: Wireless Access in Vehicular.”

[9] ASTM E2213-03, “Standard Specification for Telecom and Information Exchange Between Roadside and Vehicle Systems - 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications.”

[10] Y. B. Ko and N. H. Vaidya, “Location-aided Routing (LAR) in Mobile Ad-hoc Networks,” Wireless Networks, Vol. 6, No. 4, 2000.

[11] Deborah Estrin, Daniel Zappala, Tony Li, Yakov Rekhter, and Kannan Varadhan. Source Demand Routing: Packet format and forwarding specification (version 1). Internet Draft, January 1995. Work in progress.

[12] R. Molina-Masegosa, J. Gozalvez and M. Sepulcre, "Comparison of IEEE 802.11p and LTE-V2X: An Evaluation With Periodic and Aperiodic Messages of Constant and Variable Size," in IEEE Access, vol. 8, pp. 121526-121548,2020, doi: 10.1109/ACCESS.2020.3007115.

[13] G. Naik, B. Choudhury and J. Park, "IEEE 802.11bd & 5G NR V2X: Evolution of Radio Access Technologies for V2X Communications," in IEEE Access, vol. 7, pp. 70169-70184, 2019, doi: 10.1109/ACCESS.2019.2919489.

[14] W. Anwar, N. Franchi and G. Fettweis, "Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p," 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 2019, pp. 1-7, doi: 10.1109/VTCFall.2019.8891313.

[15] V. Torgunakov, V. Loginov and E. Khorov, "A Study of the Impact of the Contention Window on the Performance of IEEE 802.11bd Networks with Channel Bonding," 2021 International Conference Engineering and Telecommunication (En&T), 2021, pp. 1-5, doi: 10.1109/EnT50460.2021.9681801.

[16] R. Jacob, W. Anwar, N. Schwarzenberg, N. Franchi and G. Fettweis, "System-level Performance Comparison of IEEE 802.11p and 802.11bd Draft in Highway Scenarios," 2020 27th International Conference on Telecommunications (ICT), 2020, pp. 1-6, doi: 10.1109/ICT49546.2020.9239538.

[17] B. Y. Yacheur, T. Ahmed and M. Mosbah, "Implementation and Assessment of IEEE 802.11BD for Improved Road Safety," 2021 IEEE 18th Annual Consumer Communications & Networking Conference (CCNC), 2021, pp. 1-6, doi: 10.1109/CCNC49032.2021.9369649.

[18] W. Anwar, A. Traßl, N. Franchi and G. Fettweis, "On the Reliability of NR-V2X and IEEE 802.11bd," 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2019, pp. 1-7, doi: 10.1109/PIMRC.2019.8904104.

[19] Y. -T. Kuo, W. -D. Shen and H. -Y. Wei, "Reliable Groupcast for NR V2X," in IEEE Access, vol. 9, pp. 152032-152046, 2021, doi: 10.1109/ACCESS.2021.3126938.

[20] Taleb, A. A. (2018). VANET Routing Protocols and Architectures: An Overview. Journal of Computer Science, 14(3), 423-434. https://doi.org/10.3844/jcssp.2018.423.434

[21] Cellular-V2X Technology Overview - Qualcommhttps://www.qualcomm.com/media/documents/files/c-v2x-technology-overview.pdf