Cross-Layer Design in Vehicular Ad-Hoc Network with Cognitive Radio

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***Abstract* – With the increasing number of vehicles there needs to be efficient connectivity among the vehicles and the infrastructure. In vehicular network several issues may arise with respect to safety, traffic warnings, emergency response and infotainment if the quality of communication is compromised. This paper looks into how cross-layer design can be employed in improving the Quality of Service of various use-cases particular to Vehicular ad hoc Networks (VANET). The aim is to identify different challenges of communication in VANET and how cross-layer design may help provide solutions. This study also provides some insight into the applicability of cognitive radio techniques in VANET. In addition, attempt has been made to survey the prominent methods and recent advances in deep reinforcement learning to improve the communication.**

***Index Terms* – Cognitive radio (CR), cross-layer design, deep reinforcement learning (DRL), survey, vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V)**

I. Introduction

As the number of vehicles are increasing rapidly, various challenges may arise related to the quality of communication between the vehicles and other entities in a vehicular network. The quality of communication may prove to be critical in vehicular network, especially with the increase in number of autonomous vehicles in the near future. Safety, effective routing, positioning of the vehicle, sensing the traffic conditions and infotainment within the vehicle itself are some of the functionalities that are major when considering vehicular network. Terms such as vehicle-to-infrastructure (V2V), vehicle-to-vehicle (V2V), vehicle-to-everything (V2X) describe some of the types of communication that happen between the vehicles and other entities in a vehicular network. The fact that vehicles may be in constant motion while communicating with each other gives rise to a unique set of challenges in terms of communication. Heterogeneity of vehicular network is another aspect that needs different types of technologies to co-exist emphasizing on smooth communication. This needs compatibility between different sorts of communication interfaces.

Vehicular ad hoc Network (VANET) is a form of network comprising of mobile vehicles and the network infrastructure. A typical communication in VANET consists of V2V or V2I interactions. These communications are responsible to help achieve road safety, traffic cognizance, driver assistance and monitoring [1]. Several researches have been conducted on Dedicated Short-Range Communications (DSRC) [2]-[4], which is a method for effective V2I and V2V communication of safety critical messages. DSRC channels are reserved in the 5.9 GHz and have been traditionally used for V2I communication. The IEEE 1609 family of standards specify Wireless Access in Vehicular Environments (WAVE). DSRC and WAVE use IEEE 802.11p for distributing safety critical information. [5] mentions about using cross-layer methods in the MAC and the network layer to optimally use channel by removing channel contention. [6] proposes a MAC/PHY cross-layer design using optimized transmit-antenna-selection and transmit-power-adaption to solve the issue of possible interference and collision of data between the vehicles.

Cognitive Radio in VANET can be used to fulfill some of the Quality of Service (QoS) requirement of different sorts of communications (V2V, V2I) by allowing effective use of the available spectrum. With respect to vehicular network, optimal use of the radio spectrum available can improve the communication by effectively using the unused spectrum which are generally wasted [7]. [8] mentions about the use of Opportunistic Spectrum access to improve vehicular network efficiency. [9] describes a method to allow the secondary users in cognitive radio network to cooperatively sense the spectrum for the presence of primary users. This can be helpful in vehicular network where ad hoc communication (V2V) would not require a centralized common receiver to maintain the coordination.

Radio Cognition can be used with Dynamic Spectrum Access (DSA) to allow the secondary users to opportunistically use the available spectrum provided they do not cause interference with the primary users [10]. [11] mentions about the spectrum overlay and underlay techniques under the hierarchal DSA model. These techniques help the primary users and secondary users to co-exist. The spectrum overlay is concerned with “unused” spectral regions whereas spectrum underlay deals with “underused” spectral regions. Underlay techniques tends to utilize the spectrum better and operates below the noise floor of the primary users.

Deep reinforcement learning is utilized to train machine learning models to make a sequence of decisions. It consists of an agent, the environment that the agent senses and the reward or penalty that it gets for its actions. Deep reinforcement learning can be utilized in cognitive radio in a very useful way to allocation resource by observing the environment variables over physical and network layer [12]. [12] proposed using cross-layer techniques with deep reinforcement learning in an effective allocation scheme for underlay DSA. It showed that the perceived quality for video transmission had improved as measured by Mean Opinion Score (MOS). MOS has been traditionally been a reliable but costly metric of Quality of Experience (QoE). Certain algorithms can be used to help provide an accurate estimation without the depending upon a panel of users for the measurements. This helps the operation cost of using the MOS [13].

Rest of the paper is divided into following sections: Section II provides a high-level view of VANET, an overview of cross-layer design, routing, mobility aspects and cognitive radio technique. Section III describes about cross-layer design considerations in VANET. It deals with few of the challenges of communication in VANET and how cross-layer design and cognitive radio may help to resolve few of them. Section IV contains the recent advances related to deep reinforcement learning with respect to cognitive radio and how it may be applied in VANET. Section V provides the conclusion.

II. Background

This section serves as a background of some of the concepts related to vehicular networks that is important to consider when considering VANET. Also, this section describes some of the aspects of communication typical to vehicular networks. Here, these concepts are discussed at a high-level to provide an insight into their applicability in VANET. Finally, an overview of cognitive radio networks is provided to give a perspective of this work.

A. Vehicular Networks

Vehicles have different means of communicating with the outside environment. Modern vehicles are equipped with technologies such as Global Positioning System (GPS) and navigation systems. In addition, these vehicles also have technologies to communicate with other vehicles, the infrastructure, the road-side units and the pedestrians. Together, these communication technologies help these vehicles to gather the information needed to prevent collisions, perform positioning, navigating, estimating traffic and routes and a smooth experience with using multimedia. V2V, V2I, V2R communicate through various communication technologies available and tend to be heterogenous in nature. V2I, for example uses the cellular networks to communicate with the infrastructure and the road side units whereas V2V tend to be more *ad hoc* in nature constituting the VANET. Device-to-Device (D2D) communication is a concept related to 5G which is concerned with different devices communicating with each other without involving the network infrastructure. While still being at an early stage, D2D can prove to be a viable *ad hoc* communication in addition to V2V network in VANET.

Fig. 1 shows a typical scenario in which different VANET are connected to the infrastructure via base stations and the backbone network. The vehicles are capable of communicating with other vehicles in the same VANET, with possible handoff happening if a vehicle keeps moving to exit a VANET's network coverage area. VANETS also utilize the Multi-Access Edge Computing (MEC) cloud servers for offloading computational and storage burden increasing the overall system efficiency. It can be observed that different kinds of communication links are present in such a heterogenous

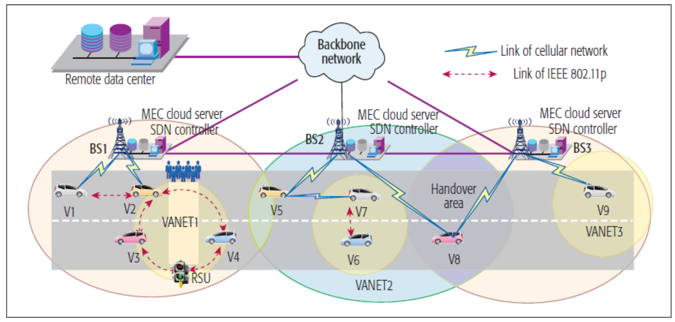

Fig. 1 Vehicular Networks [14]

network [14]. DSRC standards provide a means for effective point-to-point communication between the vehicles without involving the network infrastructures. This communication happens in the channels of 5.9 GHz band. Different standards such as IEEE 802.11p and other cellular standards need to allow for the interoperation between the heterogenous interfaces for effective vehicular network.

An important factor to consider is the availability of the spectrum for V2V, V2I communicatons. With the regulators allowing only certain spectrum for V2V and V2I, it is often challenging to utilize the alloted spectrum effectively. For example, Federal Communications Commission (FCC) has alloted a 75 MHz of radio spectrum at 5.9 GHz in the USA for V2V and V2I communication. On the other hand, the same radio spectrum cannot be used in Europe due to its non-availability. In Europe, the regulators provide 2x10 MHz for use of safety critical applications at 5.9 GHz [1]. Thus, it can be seen that radio spectrums are highly regulated and not abundant. This gives to the need to consider the challenge of utilizing the available radio spectrum effectively, especially in future when the number of vehicles conducting V2V and V2I communication may increase drastically.

B. Cross-layer Design Overview

Traditional network layer design work with a rigid structure of the protocol layers which guarantee encapsulation, modularity and easy deployability. Encapsulation, for example, can be beneficial to maintain the modularity of design but leads to extra overhead, latency and degraded QoS. Cross-layer design works in a disruptive way by allowing the information to flow between all the protocol layers (e.g., all five layers of TCP/IP model). Cross-layer design attempts to improve the network functionality, security, QoS and mobility. By carefully understanding the benefits and tradeoffs while using cross-layer design a much higher performance can be achieved in terms of wireless communication [15].

It is important to consider the classification of cross-layer designs to understand how the information can be shared among the five layers of the protocol. There are different ways to classify the cross-layer design. One classification divides the cross-layer design into manager method and non-manager method and other classification divides it among distributed and centralized categories. Fig. 2 shows how cross-layer designs are classified among non-manager method and manager method. It shows how the different layers of TCP/IP protocol stack

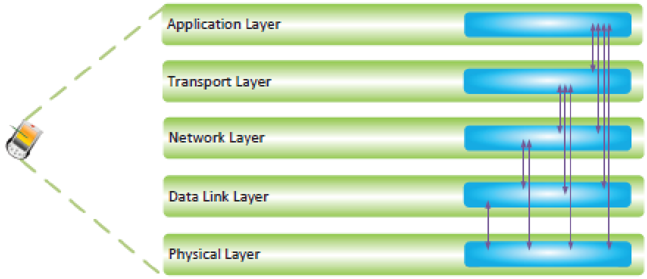

Fig. 2 Non-manager method of cross-layer design [15]

communicates with each other. Here, it can be observed that the TCP/IP protocol stack remains intact but the design enables any pair of layers to communicate with each other.

Fig. 3 shows that how a separate vertical plane allows for the direct communications between the different protocol layers. Here also the TCP/IP protocol stack is intact but the protocol layer function need modification to allow for the interaction between the different layers and the vertical plane. The second type of classifications method, divides the cross-layer design based on the organization of the network. These are broadly described as Centralized method and Distributed method [16, 17]. Centralized method is concerned with network nodes connected to a cellular base station. Distributed method classification consists of network nodes connected with each other. Distributed method may be well suited for the *ad hoc* nature of communication being discussed in this paper.

Although the cross-layer design can be beneficial for the vehicular network, it can be challenging to practically use the design at present because of the lack of universal cross-layer design. Due to the mobility aspect of the vehicular networks requiring constant handover to different networks, it becomes necessary to have a common design allowing for non-disruptive and smooth communication among various entities in VANETs.

C. Mobility

Vehicles are mobile entities and typically move at quite a high speed. Several issues related to mobility arise in the wireless communication. High speed movements may cause Doppler shift and fast fading. It is therefore important to consider the issues typical to any wireless communication in vehicular networks as well. The density of vehicles may vary from place to place which may pose as a challenge for effective communication. The sparsely occupied space by the vehicles may cause disruption of communication which is known as fragmentation. On the other hand density of vehicles at some point may cause different vehicles to struggle for the radio spectrum access. Movement of vehicles can result in a vehicle leaving its VANET and enter into another. This causes the infrastructure to intervene for handing over any connection to base station of another VANET.

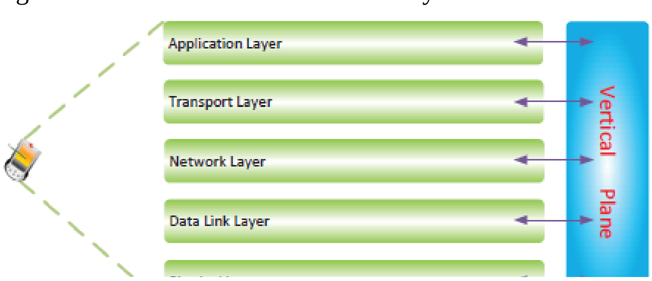

Fig. 3 Manager method of cross-layer design [15]

A number of issues arise related to handover in vehicular networks as in other mobile networks. These issues are multiplied considering because of the high speed that the vehicles may move in. Since there is considerable degree of heterogeneity involved in vehicular networks, effective handover and admission control measures can be incorporated for smooth communication. [18] discusses about the optimized admission control with vertical handoff between WLAN and CDMA networks with the focus on video traffic. This paper emphasizes on optimizing the use of radio resources jointly between WLAN and CDMA to address the QoS requirements. Such concepts may be utilized in vehicular networks in future, when different types of communication technology will be integrated. [19] addresses the issues of handoffs focusing on metro passenger information systems. It mentions about improving the end-to-end quality of video transmission by optimizing application-layer parameters and handoff decisions. Owing to similar mobility aspects in VANETs, such methods can be utilized to improve the infotainment quality in vehicles.

D. Routing in VANET

Routing in VANET is quite different from the conventional routing protocols due the dynamic nature of the topology with frequent handoffs [1]. There are different ways to forward the packets in vehicular networks. One of the ways is opportunistic forwarding which opportunistically forwards messages [20]. This method can be combined with other methods of forwarding such as trajectory-based forwarding [21] and geographic forwarding [22]. This is well suited for VANET because of frequent connection and disconnection and need for opportunistically transferring data whenever the next hop is available.

[23] emphasizes on energy-efficient routing design for *ad hoc* networks using cross-layer design. This is quite important for VANETs as increasing number of vehicles implies that some considerations be given to the energy consumption. [24] works on path selection under budget constraints when using cognitive radio networks (CRN). It mentions about a session based approach to allow maximum throughput between CR source and destination. It takes into considerations various factors such as price of the spectrum bands, budget constraints of CR source, link scheduling constraints and flow routing constraints to use them to construct a linear programming optimization problem. This research may be beneficial when using cognitive radio networks with VANET.

[25] proposes a new method to use cognitive link availability prediction for finding the duration of a link in Mobile *ad hoc* Networks (MANET). Based on this it predicts the dynamic changes in the network topology. Its goal is to mitigate frequent re-routings by predicting topology changes. This can be utilized in VANET with some modifications as this algorithm considers various aspects suited for VANET such as dynamic topology change and cognitive radio.

E. Cognitive Radio Networks

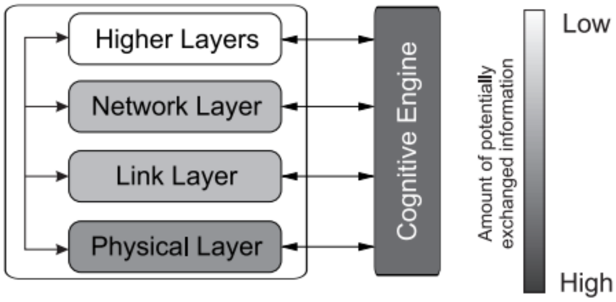

Fig. 4 Cognitive radio framework [26]

Fig. 4 describes a generic protocol stack for cognitive radio with a cognitive engine entity. Here it can be seen that there is a cognitive engine which interacts with all the layers of a protocol stack. The cognitive engine is responsible for collecting data from various aspects of the network and take decisions based on those information. It typically acts as an agent that performs tasks such as learning, reasoning, input memory, experimental databases and decision evaluation. It is responsible for providing updated parameters, new guidelines and constraints to be used on the different layers as a result of the cognition cycles. Among the amount of potentially exchanged information between the different layers and the cognitive engine, the volume may be high for the physical layer but tapering off for the higher layers [26].

Cognitive radio networks (CRN) is used in a number of cross-layer designs to effectively use the available radio spectrum for communication. Cognitive radio networks involve sensing the available spectrum with a congitive process taking into account the network conditions with an outcome of efficiently allocating spectrum to different users [27, 28]. It has been observed from FCC's reports that the available spectrum is sometimes underutilized in the spatial and temporal dimensions. In cognitive radio networks, the users are marked as primary users and the secondary users. The primary users get the priority while occupying the spectrum. Secondary users are mostly unlicensed users and can be allowed to use the licensed band of spectrum with the help of CR techniques. CR techniques require the secondary user to adjust their operating parameters after sensing the radio environment [29, 30]. However, it is quite challenging to allocate resource in CRs because of its dynamic nature and often imperfectly sensed [41].

DSA is used in conjunction with CR that allows the secondary users to access the licensed spectrum bands. CR is built upon the concept that the primary users may not be affected by interference from the secondary users. The secondary users utilize the spectrum in spatial and temporal domain opportunistically by avoiding the interference with primary users [7].

CRs perform four major functions as described in [30]. Fig. 5 shows the different functions. These functions are briefly described as follows:

- ***Spectrum Sensing:*** This function enables the users to determine the available spectrum which are not licensed.

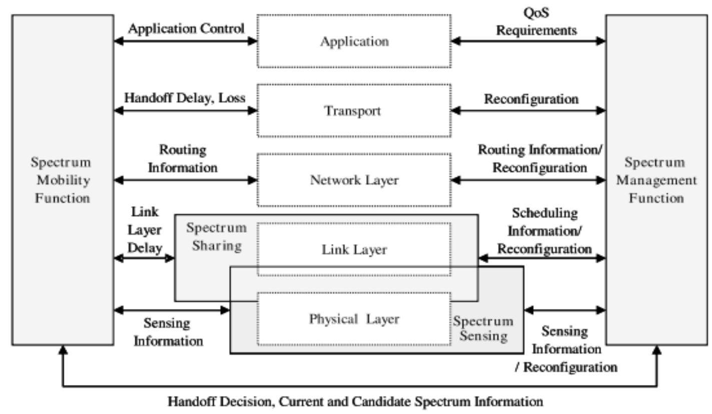

Fig. 5 CR network communication functionalities [30]

- ***Spectrum Allocation*:** This function is responsible for selecting the best spectrum to operate based on the QoS, routing and mobility requirements.
- ***Spectrum Sharing:*** This function ensures that there is no interference between the primary users and the secondary users.
- ***Spectrum Mobility:*** This function ensures that the secondary users give priority to the primary users if they need the allocated spectrum back for their use.

III. CROSS-LAYER DESIGN CONSIDERATIONS IN CR-VANET

This section focuses on different challenges and their solution by using cross-layer design with applicability of CRN wherever possible. Combination of CR with VANET is abbreviated as CR-VANET for the purpose of convenience. This section will expand upon the various concepts introduced in the previous section. This section is divided on the basis of the layers involved in the cross-layer interactions.

A. Cross-layer design involving PHY-MAC layers

Physical layer (PHY) is responsible for connecting all the vehicles to each other and to the infrastructure. In VANET, because of the constant movement of the vehicles the quality of the communication channels keeps changing rapidly because of temporal and spatial aspects of these channels. This requires an intervention by the cross-layer design to help achieve a quality communication. There are several solutions that take into account the signal strength at the receiver side to help maintain the communication quality. Cross-layer design provides means to sense the channel condition and opportunistically transmit when the channel quality is good. This may lead to using cognitive radio techniques to help sense the environment and utilize the knowledge gained to tune the parameters for effective transmission [31].

There are several techniques possible through PHY-MAC cross-layer design to tackle few of the issues. These are transmission rate adaption technique, channel selection technique, and transmission range adaptation technique [31]. Transmission rate adaption technique allows the modulation to be adjusted according to the channel quality gauged by *signal-to-noise (SNR)* ratio and *packet error rate.* The algorithm for the whole process of adjusting the modulation can be divided into three parts. The first step is to choose initial values of the parameters, second to sense the channel quality and third to adjust the parameters. Cross-layer design solution in this context is based on the communication between the MAC layer and the PHY layer. [32] investigates using adaptive modulation with Opportunistic Spectrum Access (OSA), Spectrum Sharing (SS) and sensing-based SS cognitive radio networks with the aim of achieving optimal power allocation and a good spectral efficiency. For the experiments Rayleigh fading channel has been considered which is a realistic network condition applicable to the urban settings [53].

Channel selection technique concerns with multi-hop packet forwarding in a typical vehicular network. This is important because the road topology determines the network topology in vehicular networks to some extent. For this reason, multi-hop solutions may seem quite suitable. [33] introduces the use of WiMax to create a system of multi-hop relay nodes. WiMax has a long communication range (50 km) which may be utilized well in VANET. Vehicles with WiMax capabilities can act as a useful hop and act as relay vehicles (RV). RVs can be used to manage the network by supporting other vehicles in mobility management and neighboring node's communication management. The major challenge with this approach is that RVs are mobile and can go out of range. This may cause undue latency because of scanning of new RVs in case of loss of communication with the previous RV. [34] mentions about the fast handover management techniques to counteract this type of issues. [31] proposes Very Fast Handover Scheme (VHFS) that can combat the frequent handovers in this scenario. In this scheme an Oncoming Side Vehicle (OSV) moving in opposite direction can accumulate the neighbor's information from the connected vehicles (CV). OSV can then feed this information in form of Network Topology Message (NTM) to the disconnected vehicles (DV). VHFS is a PHY-MAC protocol involving physical and MAC layer. As this protocol works closely with sensing the environment, CR can further help the process and make it more efficient. The spectrum sensing and sharing functionalities of CR can be employed here to further improve the process in all aspects.

Transmission range adaption aims at resolving the issue of packet loss in sparse networks by transmission range extension. This solution may complicate the situation when the network is dense enough to potentially cause interference. Here, MAC layer can be used to feed the information to the PHY layer to adjust the transmission power to accommodate for the network density change. Here also, CR can be employed to help adjust the parameters at the PHY layer by sensing the environment.

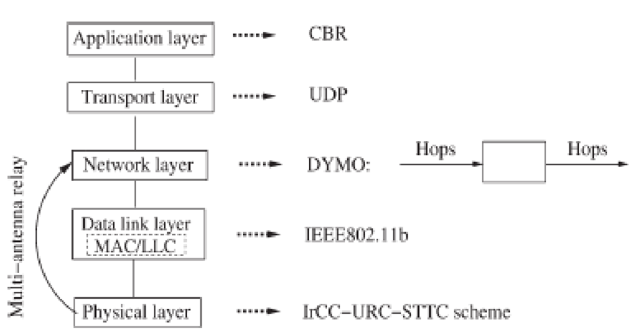

Fig. 6 PHY-Network layer cooperation for routing [23]

B. *Cross-layer design involving PHY-MAC-Network layers*

Due to the mobility aspect of VANET, the vehicles may experience lost connection due to weak wireless link. These links do not persist for very long. Hence, it is necessary to find a replacement link to maintain the connection. For this the cross-layer design must communicate between PHY and network layer to maintain a good quality communication. [35] proposes a metric known as Link Residual Time (LRT) to estimate the longevity of the link. The process of LRT estimation consists of three main steps. The first is to remove the noise from the signal and check if the signal strength is not attenuating. Second step is to estimate the model parameters to compute the value for LRT. The third step is adjusting the LRT estimation according to the sensed signal strength and following the parameter adjustments. As this information is valuable for the network layer for the purpose of routing decisions, it is made available to the network layer via the cross-layer design [31].

In the context of cross-layer based routing for *ad hoc* networks, [23] proposed an energy-efficient method that works with cooperation of the PHY and the network layer as shown in Fig. 6. [23] also touches upon Opportunistic Routing (OR) which is a paradigm of Cognitive Radio Networks. As the premises of the network environment resembles the *ad hoc* nature of VANET, these concepts can be applicable to the CR-VANET that is being considered for this work. [23, 36] describes the utilization of opportunistic routing with adjustable transmit power that involves the PHY, data link layer and the network layer.

C. *Cross-layer design involving network-MAC layers*

Due to mobility, VANET faces the problem of frequent topology change giving rise to various challenges. One of the challenges is to maintain the link quality and adjusting the routing topology. It is absolutely necessary to keep the vehicles connected all the time. Routing information about such a dynamically changing routing topology need to be stored. In VANET it may be necessary to rely on geographical information rather that basing the routing just on the IP addresses [31]. Cross-layer design can help in this respect. The interaction between MAC layer and network layer is necessary to achieve reliable routing. MAC layer is responsible for fetching the life-time of various links and passing this information to the network layer for adjusting the route.

The shortest path between two nodes does not guarantee the best link as there may be other aspects to routing than just the distance. For example, the nodes that are near to each other in a dense network may face interference, thus, decreasing the overall link quality. The MAC layer is responsible for getting the information about the individual links. When considering the links, it is necessary to consider all the paths. Therefore, path selection becomes an important aspect in VANETs.

Movement prediction-based routing (MOPR) [37] is one of the predictive methods to do movement prediction routing for V2V communication. It gathers the data from MAC layer and uses it to find the next relay node. The data consists of speed, position and network topology in order to aid the prediction of the next hop. The data is stored in the routing table. To make the algorithm more robust it may include the navigation system and maps. MOPR is known to find the most stable routes.

MOPR collects only the IP-address as part of the information it gathers from the neighbors. Since, the messages are forwarded on the basis of IP-address these nodes may not be reachable. The dependency on IP-address is not suited for VANETs as the nodes may move away from the route previously determined leading to higher delay and packet loss. Therefore, the cross-layer design must look for alternatives to IP-based forwarding. One possible solution is to use the position data from GPS. However, routes based on position does not know about the route path characteristics. The path may be congested due to high density of nodes and lead to a poor performance. Thus, the method should include an awareness of the possible delays that each path may incur. *PROMPT* [38] is another method that uses a different approach than MOPR to find the best route. PROMPT does not use the IP-address based routes, rather uses physical path of the road in from of (street, directions) tuple pairs. It collects the local packet traffic statistics in the MAC layer and forwards it to the network layer, on the basis of which it maintains the routes. Then, by using the (street, directions) pairs present in the network layer, the MAC layer determines the next best hop. This route is not affected by the movement of the vehicles. Fig. 7 shows the operations of PROMPT.

In vehicular networks certain applications need priority for QoS considerations. IEEE 802.11e standard has provisions to support packet prioritization on the basis of QoS requirements of the different services. However, this standard does not factor in the network topology, the mobility factor, link quality and the multi-hop interference consideration in the VANETs [39]. In [39], the authors propose an alternative routing protocol called *Delay-Reliability-Hop* (DeReHQ) which takes three QoS factors into consideration: link reliability, end-to-end delay, and hop count in the order of priority (higher to lower). Here, link reliability has more priority than link delay and hop count.

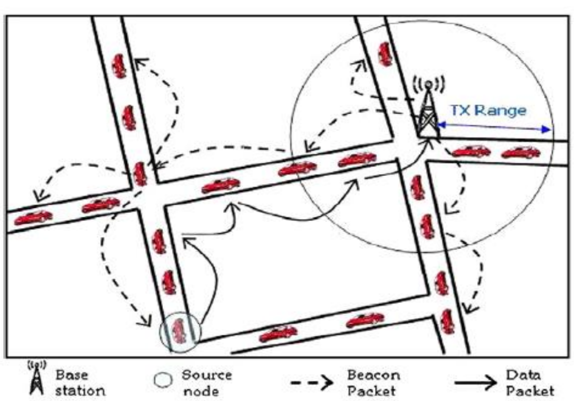

Fig. 7 PROMPT System [38]

These parameters are estimated on the basis of vehicle speed, distance between source and destination, and traffic density.

[25] describes a prediction-based topology control and routing in Cognitive Radio Mobile Ad Hoc Networks (CR-MANET). Although this paper concerns itself with CR-MANET, the concepts discussed can be applied to CR-VANET with some modifications. In addition to the cross-layer design methods discussed above, it could be beneficial to include the CRN concepts into VANET. Based on the research in [25] a distributed prediction-based cognitive topology control scheme can be used. This scheme would enable VANET to use the cognitive capability for routing. Topology control is used to determine network connectivity using the information provided by the MAC layer and the PHY layer. This method also monitors the situation when the current users get too close to the primary users. This is done to avoid the possible interference due to the closeness of the nodes. The method described in the paper does a prediction of the proximity of two nodes (primary user and current user getting into interference range), and also estimates the probability of the predicted interference. These two parameters are estimated by considering the distance between two nodes, their velocity and their movements relative to each other. This paper also mentions how to construct the cognitive distributed topology using Djikstra's algorithm which is both energy-efficient and maintains the link reliability of CR-MANET. This could be applied to CR-VANET with little modification to create an efficient routing strategy.

D. Cross-layer design involving transport-MAC layers

In VANETs, it is necessary to understand the difference between route interruption and channel congestion. In multi-hop VANETs, the underlying links at the current node may break frequently triggering frequent retransmissions, thereby, reducing the throughput of the transmission. Link disconnection problems are dealt with MAC layer protocols such as IEEE 802.11. A cross-layer design between transport and the MAC layer can help determine the difference between link disconnection problem and channel congestion.

In multi-hop VANETs, the sequence of nodes forms a chain. The interference levels for each link of the chain differ from each other. With the increase in number of interferences between the links the throughput decreases. This degradation of TCP throughput can be classified into intra-flow and inter-flow instability [40]. The intra-flow instability is caused by the nodes of the same TCP connection while the inter-flow instability is caused by the nodes of different TCP connections. Intra-flow instability may arise due to the interference between the different types of packets within the different links of the same TCP connection. These types of interferences may be between the TCP data packet and MAC control packets or between the MAC control packets. These interferences cause the network utilization to go down and eventually the overall throughput suffers. This triggers fast retransmissions by the TCP layer and a reduction of contention window. This causes the sender to send packets at slower rate than before reducing the number of packets transmitted. Overall, the intra-flow instability is removed by reducing the number of packets in the network.

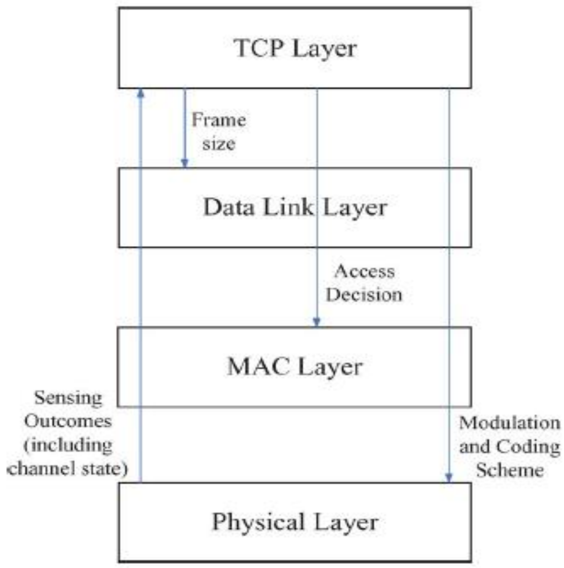

Fig. 8 Cross-layer Optimization of TCP Throughput in CRN [27]

In case of CR-VANET, the methods proposed in [27] can be incorporated with minor modifications. [27] discusses about the perception of secondary user's QoS in cognitive radio networks. It considers a cross-layer design taking into account the sensing, data-link frame size, PHY layer modulation, access decision and coding schemes for increasing the TCP throughput in a CRN. The primary user's model is modelled by using the finite state Markov's model. The secondary users may miss detect and wrongly estimate the spectrum, the system state can only be partially observed. This means that cross-layer TCP throughput optimization problem is Partially Observed Markov's Decision Problem (POMDP). [27] shows that the TCP throughput can be increased if the parameters at the lower layers are jointly optimized. Fig. 8 shows the interaction between the TCP layer and the MAC layer and PHY layer to show the flow of information in the cross-layer design involving these layers.

E. Cross-layer design involving transport-network layers

Transport layer in the traditional TCP/IP protocol stack is responsible for providing end-to-end reliable transfer of data. It takes care of the flow control, congestion avoidance and error recovery. TCP protocol was developed for the wired connections in the past. In those types of network, the underlying network topology is transparent to the transport layer. Often the network congestion problem is correctly identified and rectified by the transport layer protocols. However, in VANETs, the underlying network may not be transparent like in the wired network. In VANET, due to dynamic network topology the packets may be dropped in some intermediate node in the path causing delay by costly recovery processes. This can be solved by employing cross-layer design. Cross-layer design allows for the communication between the network layer and the transport layer. This communication would let the transport layer to know if a certain error is due to network congestion or there is link disconnection in any of the intermediate nodes.

[41] mentions about using Explicit Link Failure Notification (ELFN) to send to sender in case the link fails. This will prevent the transport layer to distinguish the link error from network congestion and not trigger a retransmission. [42] proposes *ad hoc TCP* (ATCP) to convey to the transport layer about the underlying network condition in case of error. It is a state-based solution in which it changes states according to the situation. The default state is "normal" state when the transmission does not have any problems. In case of high bit error rate, ATCP changes state to "retransmission". This triggers a retransmission without modifying the contention window, hence, saving the overhead. In case of link disconnection, it moves to "persist" state, waiting for a new route to be established. When a new route is established in this state, the contention window is reset. Lastly, when there is an actual network congestion it moves to "congestion control" state triggering the contention window adjustment and retransmissions by the transport layer.

F. Cross-layer design involving transport-network-MAC layers

There are several cross-layer designs which jointly optimize the MAC, routing and transport layer functions. This is necessary to optimize the packet flow rate control. In [44], the authors proposed a cooperative VANETs in which every node cooperates with other nodes to form a multi-node network. This method solves two different issues: one is a flow control problem which determines the flow rate and another is a division problem which describes splitting the total flow rate among the least congested paths according to link persistent probability measured at the MAC layer [31]. [44] proposes two algorithms as solutions: *Opportunistic Cooperation MAC* (OC-MAC) protocol and *Joint Optimal Control* (JOC). In OC-MAC, each node chooses route locally and each intermediate node decide whether to forward the packet or not. JOC, on the other hand, jointly performs the optimizing functions with MAC, network and transport layer. It performs link capacity detection at MAC layer, routing function at network layer and flow control at transport layer. The flow control function at transport layer is used to optimize the path utility function. This information is used to adjust the persistent probability which are made known to all the source nodes of the current link. Each source node then computes the best possible flow rate for all the paths which then is used by the routing functions as the new flow rates to transmit in. These steps are repeated till the optimal point is reached. In this manner, the cross-layer design helps to increase the packet flow rate in VANETs.

IV. Use of Deep Reinforcement Learning in CR-Vanet

Deep reinforcement learning (DRL) is a branch of machine learning which combines reinforcement learning (RL) and deep learning (DL). RL is a subfield of machine learning in which the computational agent performs some trial and error to make a decision. This problem is modelled by Markov Decision Problem (MDP). The agent is at a certain state (s) and takes an action (a), receives a reward and then transitions to a new state (s') according to the environment sensed. RL basically characterizes a learning problem. Deep learning on the other hand is a form of machine learning that uses a neural network to map a set of inputs to a set of outputs. DL and RL are combined to solve problems with multi-dimensional states that RL cannot solve alone [45].

[45] also describes the Q-learning algorithm which is a model free reinforcement learning. Q-learning algorithm efficiently estimates the Q value. Q function can be implemented in several ways. Neural network or deep neural network are two of the implementations of the Q function. When deep neural network is used to represent the Q function, it is called Deep Q-Network (DQN). Q-Network is denoted as $Q(x, a; \theta)$, where x is the state, a is action and θ is the neural network's weight parameters. Neural networks provide flexibility but compromises on stability. Using deep neural network proves to be more robust that using neural networks. DQN has several advantages as it uses certain advanced features. Firstly, it uses multi-layer deep convolutional networks which is efficient at extracting high-level features from raw data [46]. Secondly, it stores its interaction experience tuple $e(t) = (x(t), a(t), r(t), x(t+1))$ at time t into a replay memory. The idea is to use the randomly sampled batch from replay memory instead of consecutive samples in Q-learning to train the deep convolutional network. This allows using past experiences to learn the network rather than the current happenings. Thirdly, a second network may be deployed to generate target Q values. These values are used to calculate the loss for each action during training. Deep Q-function is trained to achieve the target value by minimizing the loss function given by the following equation:

$$L_i(\theta_i) = E[(y_i - Q(x, a; \theta_i)^2)] \ldots\ldots\ldots\ldots (1)$$

Here y_i is the target for iteration *i*. The targets depend upon the network weights. For optimizing the loss function, equation (1) is differentiated to find the gradient and then follows stochastic gradient descent [46].

The application of DRL in wireless networks is relatively recent. There are some recent use-cases emerging which may benefit from using DRL. [47] describes one such utility of DRL in wireless networks. It basically describes a scenario in which power consumption and task processing latency of immersive virtual reality (VR) contents are optimized by using MECs. DRL is incorporated using MEC as the decision-making agent interacting with the immersive VR video environment. This basically solves the problem of viewport rendering offloading decision optimization and downlink transmit power control. VANETs also use MECs for offloading computation work often. The solution described in [47] can be used to offload video rendering and decrease the power consumption for the vehicles. The combination of MEC and DRL is a topic of research that is in quite a lot of demand these days. In terms of vehicular networks, [48] mentions about offloading computation offloading tasks from the neighboring vehicles to the edge-computing systems such as MEC. Here, learning-based task offloading algorithm has been proposed. This algorithm enables the vehicles to learn about the offloading delay information from the adjacent vehicles in the process of task offloading and use this information to decrease the average offloading latency.

[12] uses deep reinforcement learning for cross-layer routing in cognitive radio networks. This paper takes into account the use-case of video traffic. It presents a cross-layer based allocation scheme for underlay Dynamic Spectrum Access (DSA). DSA based communication channels are quite stable and suitable for time sensitive data [49]. Therefore, it is used for live streaming, video stream, etc. [12] proposes a PHY-network cross-layer design for an *ad hoc* secondary network operating in underlay DSA. The previous works have used PHY-network cross-layer with overlay DSA [50, 51]. Using overlay DSA may be inefficient from power consumption point of view [52]. [12] proposes a cross-layer DQN scheme that balances load on a network with unequal service rates. The authors showed that their method gave a better performance than a benchmark scheme of DQN only associated with the physical layer. The authors use DQN with CR to perform resource allocation by sensing the environmental variables over physical and network layers and adjusts parameters to perform resource allocation, take routing decisions and do source compression optimally. The end result is a smooth interactive video transmission with higher MOS value. They also showed that the interference of secondary users with the primary users were below a threshold limit. This solution can easily be used in CR-VANET with some consideration given to mobility aspects.

Deep reinforcement learning has a lot of potential to be applied in several optimization problems in wireless communication. DRL can help in the optimization problems which are otherwise difficult.

V. Conclusion

This work attempted to survey various aspect of communication in VANET such as dynamic network topology, heterogeneity, cross-layer design, and advantages of incorporating cognitive radio capabilities. Various issues in the communication were pointed out with solutions using cross-layer design. An attempt was made to give an insight into how different ideas can be combined to find a better solution. For example, the use of cognitive radio with VANET was studied to examine different advantages of using it in vehicular networks and how it may help in solving certain issues. In addition, this work also touched upon the use of modern technologies such as deep reinforcement learning to help improving the communication and overall experience in VANET.

Although the cross-layer design is quite viable options, there are few challenges inherent to adopting it in VANET. Firstly, cross-layer design is not standardized to provide standard protocols which is necessary for interoperability and compatibility. Heterogenous nature of vehicular networks need to interoperate between different communication interfaces and be compatible with different protocols being used. A lack of commonality can make it difficult to adopt the cross-layer design. Secondly, as the cross-layer design has the tendency to be disruptive, it may disturb the modularity and encapsulation of layered architecture of traditional protocol stack design. There needs to be a trade-off between the cross-layer design and the traditional network architecture to reap the maximum benefits out of both types of design. Thirdly, stability must be given considerable attention while incorporating cross-layer design in vehicular networks. This is due to the fact that in cross-layer design, the different layers are made to interact in ways that are not known in the traditional design. This may cause several stability issues that may be unknown and cause major problems. Finally, the cross-layer design must be thoroughly verified before deploying it in the vehicular networks. This is because unintended effects due to cross-layer design may cause significant communication disruption. This may have detrimental effects in vehicular networks because of the safety aspects associated with it. These issues are some pointers for future work to consider for adapting cross-layer design in VANET.

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