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A survey of cross-layer design for VANETs

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ABSTRACT

Recently, vehicular communication systems have attracted much attention, fueled largely by the growing interest in Intelligent Transportation Systems (ITS). These systems are aimed at addressing critical issues like passenger safety and traffic congestion, by integrating information and communication technologies into transportation infrastructure and vehicles. They are built on top of self organizing networks, known as a *Vehicular Ad hoc Networks* (VANET), composed of mobile vehicles connected by wireless links. While the solutions based on the traditional layered communication system architectures such as OSI model are readily applicable, they often fail to address the fundamental problems in ad hoc networks, such as dynamic changes in the network topology. Furthermore, many ITS applications impose stringent QoS requirements, which are not met by existing ad hoc networking solutions. The paradigm of cross-layer design has been introduced as an alternative to pure layered design to develop communication protocols. Cross-layer design allows information to be exchanged and shared across layer boundaries in order to enable efficient and robust protocols. There has been several research efforts that validated the importance of cross-layer design in vehicular networks. In this article, a survey of recent work on cross-layer communication solutions for VANETs is presented. Major approaches to cross-layer protocol design is introduced, followed by an overview of corresponding cross-layer protocols. Finally, open research problems in developing efficient cross-layer protocols for next generation transportation systems are discussed.

1. Introduction

In recent years, the number of motorists has been increasing drastically due to rapid urbanization. Critical traffic problems such as accidents and traffic congestion require the development of new transportation systems. The Intelligent Transportation Systems (ITS) are the integration of telecommunication and information technologies into transportation systems to improve the safety and efficiency of transportation systems [1]. The main target of ITS is safety-related applications such as an emergency warning system which provides warning messages to vehicles in the affected area. Other informative and traveler-oriented applications include the electronic traffic information, electronic toll collection, etc.

To cater to a wide class of applications, ITS supports two types of wireless communication: *long-range* and *short-range*. The long-range communication mainly relies on the existing infrastructure networks such as cellular networks. The short-range communication, on the other hand, is based on emerging technologies such as 802.11 variants, and form mobile ad hoc networks comprised of mobile vehicles and stationary roadside equipments. The resulting network is referred to as Vehicular Ad Hoc Networks (VANETs).

VANETs support two types of communication: *vehicle-to-vehicle* (V2V) and *vehicle-to-infrastructure* (V2I). While V2V deals with communication among vehicles themselves, V2I is concerned about transmitting information between a vehicle and the fixed infrastructure that is

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installed along the road. Such infrastructure may include gateways or base stations, and they provide services such as Internet access in VANETs. Vehicular networks share a number of similarities with MANETs in terms of *self-organization*, *self-management*, and *low bandwidth*. However unlike in MANETs, the network topology in vehicular networks is highly dynamic due to fast movement of vehicles and the topology is often constrained by the road structure. Furthermore, vehicles are likely to encounter a lot of obstacles such as traffic lights, buildings, or trees, resulting in poor channel quality and connectivity. Therefore, protocols developed for traditional MANETs fail to provide reliable, high throughput, and low latency performance in VANETs. Thus, there is a pressing need for effective protocols that take the specific characteristics of vehicular networks into account.

A major setback in applying MANET protocols to VANETS is the ability to adapt to conditions such as frequent topological changes. This adaptability issue is primarily due to the fact that MANET protocols are designed based on the standard OSI model of layered network stack architecture. They follow a divide-and-conquer approach to facilitate the interoperability among different computer systems. Such an architecture offers simplicity and modularity where the functionality of one layer is completely transparent from other layers. However, such a strict-layered architecture is not flexible enough to adequately support the needs of wireless communication in highly dynamic vehicular networks.

The wireless communication in VANETs is inherently error-prone, and suffers from issues like noise, path loss and interference as in MANETs. In addition, VANETs must deal with vehicle high mobility and frequent route disruptions. Effective handling of these issues require an information exchange among layers so that one can jointly optimize different layers to achieve better throughput and good transmission latency. For example, routing protocols can leverage the information obtained from physical and MAC layers such as noise and interference levels to discover stable and best possible routes to the destination.

Table 1
Summary table.

Protocol	Objective	Summary	Cross-layer approach
Sections 4, 5			
[3]	Improve link layer communication	Packet loss triggered rate adaptation	M1-observation table
		SNR-triggered rate adaptation	M1-via control messages
SoftRate [4]	Improve link layer communication	BER-estimated rate adaptation	M1-SoftPHY interface
VFHS-MMR [5]	Minimize handover delay	Relay selection	M1-via NTM message
802.11e+ [6]	Improve link layer communication	Transmission range adaptation and QoS packet-based prioritization	M1-neighbor information
TDMA/TDD+ [8]	Improve link layer communication	Transmission power adaptation	M1-neighbor information
DFAv [9]	Improve Fairness	Transmission power adaptation	M1-neighbor information table
RPB-MACn [10]	Reduce packet collision	Transmission power adaptation of multiple channels	M1-neighbor information
LRT [11]	Maintain path connectivity	Link life-time prediction	M1-packet-based information
SBRS-OLSR [12]	Maintain path connectivity	Relay selection based on SNR values	M1-neighbor information
Section 6			
MOPR [13]	Discover most stable routes	AODV-based method	M1-neighbor information
R-AOMDV [14]	Communicate over minimum delay paths	Using hop count and retransmission count	M1-via RREQ/RREP packets
PROMPT [16]	Communicate over minimum delay paths	Distance-location relay node selection	M3-design coupling
[17]	Discover most stable routes	Route life-time prediction	M1-route information
CVIA [19]	Collision avoidance	Segment-based packet forwarding	M3-design coupling
CCBF [20]	Collision avoidance	Cluster-based packet forwarding	M3-design coupling
DBAMAC [21]	Minimize broadcast delay	Cluster-based solution	M3-design coupling
DeReHQ [22]	Discover most stable routes	Path selection based on QoS parameters	M4-path selection policy
[23]	Minimize broadcast overhead	Packet prioritization and queuing control	M4-benefit policy
CVIA-QoS [24]	Provide service garuntees	Packet prioritize scheduling	M3-design coupling
UMB/AMB [25,26]	Avoid flooding problem	802.11-based receiver contention with gateways	M3-design coupling
802.11+ [27]	Avoid flooding problem	802.11-based receiver contention	M2-design merging
Sections 7–10			
TCTC [29]	Maximize throughput, minimize end-to-end delay	Transmission rate estimation	M1-packet-based information
[30]	Maintain path connectivity	Link failures vs. network congestions	M1-via ELFN messages
ATCP [31]	Maintain path connectivity	Link failures vs. network congestions	M1-via ECN-ICMP messages
VTP [32]	Maintain path connectivity	Link failures vs. network congestions	M1-packet-based information
[34]	Maximize throughput	Adaptation of beaconing interval	M1-neighbor information
OC-MAC [36]	Maximize throughput	Maximize path utility function	M4-via JOC
DRCV [37]	Maximize throughput	Light weight congestion control	M1-channel monitoring
[38,39]	Maximize throughput	Transmission power adaptation	M1-neighbor information
Cabernet [40]	Reduce connection time to BS	QuickWiFi connection process	M2-combined functionalities
MCTP [41]	Maximize throughput	Link failures vs. network congestions	M1-via ECN-ICMP messages

The so-called *cross-layer design* has gained popularity in wireless networks due to its high performance, especially in delivering QoS support for real-time applications. In this article, we first present the overview of cross-layer design strategies and challenges associated with them. Next, we explore different cross-layer schemes in VANETs and their implementations. We concentrate on the challenges posed by vehicular networks and discuss how cross-layer solutions address these challenges to improve the overall system performance. At the end of the article, we summarize the cross-layer design approaches as shown in Table 1. We finally conclude this article by discussing important open problems, and avenues for continued research.

2. Overview of cross-layer design approaches

There have been a large number of proposals for cross-layer design in wireless networks. However, the definition of "cross-layer" is often ambiguous and inconsistent due to many interpretations. At a high-level, the cross-layer design refers to a protocol design that exploits the dependency between protocol layers to achieve desirable performance gains. The designs can be classified based on how the information is exchanged between layers. In [2], authors showed that cross-layer optimization can be done via four different approaches. The pictorial demonstration of these approaches is shown in Fig. 1, and we briefly present their details below.

1. *M1: Information flow with new interfaces*: In a traditional layered structure, protocols in each layer operate in a *modular* fashion to optimize their own set of variables. In contrast, this class of cross-layer designs promote the information flow between layers via specialized interfaces. Information obtained from other layers offers useful knowledge on network status and communication characteristics, which can then be exploited in better decision making, in adjusting parameters, etc. The information flow interface can be accomplished through additional database that is shared among layers, or through notification fields inside packets, which are passed between layers.
2. *M2: Merging of adjacent layers*: According to this strategy, the service and functionalities of adjacent layers are combined to form a single layer called *superlayer*. Since the layers are combined, joint optimization can be done directly on the superlayer as if we are building a single large uniform protocol. Evidently, this method does not require any additional interfaces. However, this approach is extreme and it uncommon due to the complexity it brings in to the superlayer. Also, this approach may have severe impact on maintenance and system stability.
3. *M3: Design coupling without new interfaces*: In this strategy, multiple layers are designed in a collaborative manner. We design one layer by looking at the functionality in another layer, thereby creating a dependency even at the time of designing. The referenced layer is called *fixed layer* (FL) and the other layer is called *designed layer* (DL). Since DL is built based on FL, there is no need for an explicit interface between them. For example, if the PHY layer is capable of multiple packet reception, then the MAC layer must be adjusted accordingly. In this particular case, PHY layer is the FL whereas MAC layer is the DL. Note that, any change in FL must be followed with an equivalent change in DL.
4. *M4: Vertical calibration across layers*: This strategy refers to adjusting parameters that span multiple layers in the stack. Since the performance seen at the level of application depends on the parameter settings of all downstream layers, it is often desirable to jointly optimize the parameters from all downstream layers. Such a method achieves better performance when compared to a method that tunes the parameters in each layer independently. The joint optimization can either be *static* i.e., performed at design time or *dynamic* i.e., performed at run-time. Dynamic optimization is evidently more complex and it requires constant information update across layers to ensure accuracy. Algorithms that fall into this category often maintains a database

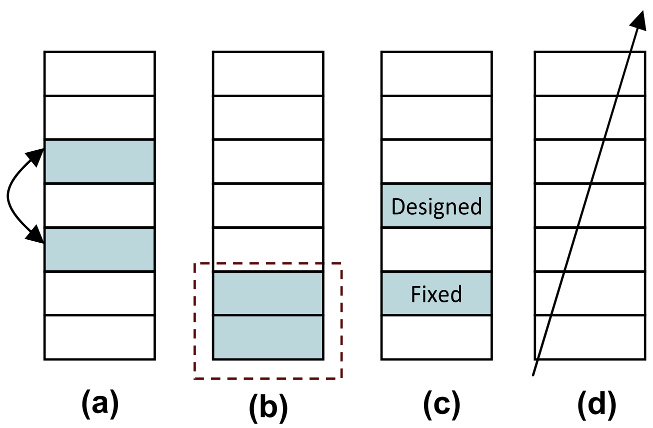

Fig. 1. Cross-layer design approaches [2] – (a) M1:information flow with new interfaces, (b) M2: merging of adjacent layers, (c) M3: design coupling without new interfaces, and (d) M4: vertical calibration across layers.

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or a repository to store the information that is shared among layers.

From this high-level classification of various design strategies, it is apparent that implementation of cross-layer protocols may require additional processing or storage capabilities. Unlike other ad hoc networks, vehicles can afford to carry high performance processing units, can potentially host large memory space, and are connected to virtually unlimited power sources. Thus, there is a high scope for future research in cross-layer protocols for VANETs. In the rest of this article, we discuss various existing protocols, and we connect them to the above-described four design strategies. A summary can be found in Table 1.

3. Cross-layer design challenges

The challenges that a designer would face while developing cross-layer protocols for vehicular networks are as follows: deciding the list of layers that need to be included in cross-layer optimizations, and determining the best strategy under a given set of performance requirements. The chosen strategy must also be able to deal with inherent performance bottlenecks related to wireless communication in VANETs.

3.1. Requirement analysis

Prior to the development of any cross-layer system, one must take the necessary requirements into consideration. The set of requirements can be of two primary types – application-oriented and performance-oriented. The former type is based on the needs of end-applications. For instance, safety-related applications require fast, reliable broadcast communication; and multimedia applications require adjustable QoS service and reliable point-to-point communication. On the other hand, performance-oriented requirements are typically set by system-wide objectives. An example of such an objective is to design a system that improves the success rate in link layer communication by allowing vehicles to adjust their transmission power adaptively. Such an objective can further be broken down into constraints like delay minimization and throughput maximization.

Given the list of objectives, the challenge in traditional layered protocol design is to decide the strategies that need to be implemented in every layer. In case of cross-layered design, one must also decide the list of layers over which the cross-layer optimization is performed. For example, safety-related applications demand a fast and reliable broadcasting mechanism for emergency messages. Such a requirement would require some form of cross-layer treatment between MAC and network layers. On the other hand, multimedia applications that require effective TCP flow control must be implemented via cross-layer optimization among transport layer and other lower layers. As we identify the list of layers that need to be optimized for a given set of requirements, one must also focus on performance, implementation cost, and design complexity. While the performance of cross-layer solutions must be better than pure layered protocols, the design complexity and implementation cost must be small. Including more number of layers in cross-layer design may improve the performance, but it may also increase the complexity and implementation cost of the solution.

3.2. Implementation strategy

Once the layers that must be optimized are determined, the next challenge is to find an appropriate strategy to implement the optimization. Current research in cross-layer protocols offer four different methods as presented in Section 2. The exact choice among these alternatives can be made by considering the following factors:

- *Amount of change from traditional layered design:* Out of all four strategies, M1 requires minimum modification to classic layered design as they rely on simple information sharing between layers. Appropriate interface such as a database is added to facilitate such an exchange of information. When compared to M1, other strategies that rely on M2 and M3 require a higher degree of modification to existing layered approaches. They require additional functionalities to be built into existing layers, and they demand more closer interactions between layers. The cross-layer design strategy M4, on the other hand, is similar to M1 as it requires all layers to collect and share information. Examples of such information include channel condition at physical layer, packet load condition at MAC layer, and network conditions at network layer.
- *Implementation cost and extensibility:* Designers must focus on protocols that have minimal implementation cost and those that are easily extendible with more advanced features. The tighter the integration between layers, the harder it would be to extend them. For example, interface-based strategies involve simple data structures that are shared between layers and hence they are easy to extend when compared to more involved strategies such as design coupling. On the other hand, the design coupling solutions typically have minimal implementation and communication cost since there is no need for additional interface between the layers. One must carefully analyze the impact of these different strategies before deciding on a particular method to implement the cross-layer protocol.

3.3. VANET specific constraints

Apart from above-mentioned issues, cross-layer protocol designs must also address the fundamental problems in VANETs such as high vehicular mobility, constant topological changes, error-prone wireless channel, and limited channel bandwidth. New cross-layer designs must handle these challenges much more efficiently when compared to traditional layered protocols.

In this article, we summarize the research that has been done so far in designing cross-layer solutions for VANETs.

We categorize existing work into different sections based on the type of interactions that the protocols demand.

4. Cross-layer design for PHY-MAC layers

Physical layer (PHY) links several vehicles within the transmission range through the wireless channel. Wireless communication at PHY layer in VANETs is severely affected by time and space varying channel properties due to the vehicle movement and environmental obstacles. Thus, many cross-layer solutions provide ability for PHY layer to observe the channel condition and to opportunistically transmit messages when current channel condition is good. The channel condition not only affects the transmitting ability but it is also affects the receiving ability of vehicles. Thus there are number of existing solutions that are based on signal strength measuring at the receivers. In this section, we discussed some of existing solutions regarding to the PHY layer parameters such as transmission rate, transmission channel, or transmission power.

4.1. Transmission rate adaptation

Transmission rate adaptation is the ability to adjust the modulation rate at which packets are transmitted according to the observed channel qualities such as *signal-to-noise ratio* (SNR) and *packet loss* rate. Since both over-selection and under-selection of the modulation rate can severely affect the communication performance, the feedback information of channel condition is useful to improve the performance. The typical control flow in this type of solutions consists of three main steps: choose initial values of target parameters; observe the system condition; and adjust the parameters accordingly. The cross-layer solutions in this section are mainly based on the information flow between MAC layer and PHY layer.

Camp and Knightly investigated cross-layer designs for modulation rate adaptation in vehicular networks targeted at urban and downtown environments [3]. Their work involves high-level interaction between the MAC and physical layers. Through extensive evaluations, they have studied two protocols for rate adaptation which are *Loss-triggered* and *SNR-triggered* under a variety of channel conditions.

According to the *loss-triggered protocol*, the transmitters determine the packet loss rate by simply monitoring the frame receptions of the packet transmission in MAC layer. If an ACK is received before the timeout event then the transmission is considered to be successful. The occurrence of timeout in MAC protocol during transmission indicates that the packet delivery process is failed. Such results of packet delivery are collected into the database that is shared between MAC and PHY layers. Each node then determines an appropriate modulation rate by following one of the two mechanisms: *consecutive-packet decision loss-triggered rate adaptation*; or *historical-decision loss-triggered rate adaptation*.

In the consecutive-packet decision mechanism, the modulation rate is adapted using the sequential rate stepping based on either consecutive successes and failures. The transmitter increases the transmission rate after a number of consecutive successful transmissions and decreases the rate after observing several consecutive failures. On the other hand, the historical-decision adaptation observes the performance of packet delivery over a period of time. Based on the observed results, the decision to increase or decrease the transmission rate is taken by the transmitting vehicle. While the first mechanism is entirely based on current activities, the second one takes the historical information into account.

Note that in loss-triggered protocols, the rate adaptation is completely taken care by the transmitter vehicle. In contrast, *SNR-triggered protocol* offloads this duty to the receiver vehicle. The receiver determines the modulation rate by monitoring the signal strength of control messages during RTS/CTS MAC contention process. While receiving a RTS packet, the receiver measures SNR value and passes the estimated rate to the transmitter as part of the CTS packet. To further improve the success percentage, the transmitter can send multiple data packets when the modulation rate is found to be higher than the base value. The multiple data packets are sent back-to-back at the same rate without additional RTS/CTS handshake. This process is called *SNR-triggered with equal air time*. To ensure the accuracy of the SNR results, the observation between MAC and PHY layers is updated per-packet evaluations.

The experiments of both loss-triggered and SNR-triggered protocols are performed on diverse channel operating conditions including fast-fading, multi-path, and interference, and on heterogeneous links. The authors found that in fast-fading environment conditions, the loss-triggered protocols underselect the modulation rate. This is due to the delay in decision process since loss-triggered protocol monitors only the consecutive transmissions before making the decision. While SNR-triggered protocols overselect from the ideal rate due to coherence time sensitivity. The problem of over-selection by SNR-triggered protocol can be addressed by using "in situ" training. Training here refers to obtaining SNR and moduration rate profile in various operating environments. Overall, such training helps SNR-based protocol to achieve higher throughput when compared to loss-triggered protocol in many areas including ability to track mobility of vehicular clients; ability to adapt the modulation rate accurately within interference-prone outdoor environments; and ability to balance resource sharing with heterogeneous links.

Vutukuru et al. argued that such a SNR-based protocol in [3] requires exhaustive training in each operating environment. To avoid such an extensive analysis, they proposed a bit rate adaptation protocol called *SoftRate* [4]. The receivers use confidence information calculated from the physical layer that is exported to higher layers via an interface called the SoftPHY interface as shown in Fig. 2. SoftPHY estimates the channel bit-error rate (BER) upon receiving a packet frame. This per-bit confidence information is called SoftPHY hints which is the value that can be obtained from the physical layer by using log-likelihood ratio mechanism.

However the bit-error rate that is calculated from SoftPHY hints usually includes the interference errors caused

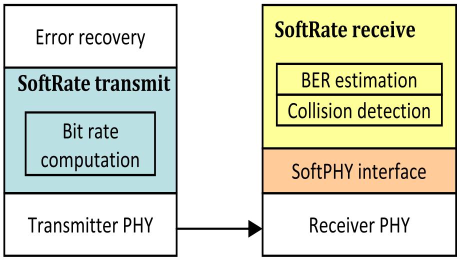

Fig. 2. SoftPHY cross-layer interaction [4].

by packet collisions. To be able to accurately estimate the interference-free channel errors, the SoftRate receiver uses a heuristic to separate out errors caused by strong interferers. The receiver then inserts this feedback information to the sender in ACK packet. Once the sender receives the estimated BER values from the receiver, it selects the best transmission bit-rate to send the next frame. This frame-based response is shown to yield higher system throughput when compared to SNR-based protocols. The authors suggest that BER is a sufficient statistic to predict the throughput and it gives a good response time to reflect the current channel conditions. SoftRate also outperforms the trained SNR-triggered of Camp and Knightly [3] when they are evaluated fading conditions based on vehicular speeds. However, this method requires more elaborate changes in the hardware implementation than competing loss-triggered and SNR-triggered protocols. In addition, both SNR-triggered and SoftRate protocols are highly dependent on the accuracy of signal measurement and they suffer from the overhead of passing the information from the receiver to the transmitter.

4.2. Channel selection

In vehicular networks, vehicle mobility is often restricted by the underlying road network topology, especially on highways. Due to this spatial relation of vehicles on the roads, multi-hop packet forwarding is one of the promising solution that a vehicle can use to communicate with other vehicles and infrastructure elements that are outside its immediate transmission range. For example, a vehicle can forward its packets toward a base station to gain an internet access even while it is driving away from the base station. Chiu et al. investigated a relay node forwarding protocol on freeways that uses WiMax (802.16) Mobile Multi-hop Relay (MMR) [5]. Since WiMax has long communication range upto 50 km (30 miles) and speed upto 1 Gbps, vehicles with WiMax can potentially act as *Relay Vehicles* (RVs) where they can help forwarding the packets to longer ranges with a small delay. Such a solution is less expensive than other methods like deploying more base stations along the road. Since WiMax may not be available for all vehicles, special vehicles such as buses or trucks can be used as RVs. RVs have full power to support communication and mobility management of their neighbors. In fact, RVs can perform neighbor management similar to cluster networks.

The challenges with this approach, however, are in the ability to maintain communication with RVs and in reducing the incremental delay incured while searching for RVs. Each network disconnection requires an expensive handover process which involves scanning for correct frequency to gain the RVs' service. A special *Vehicular Fast Handover Scheme* (VFHS) is proposed to allow Oncoming Side Vehicles (OSVs) to provide channel and location information of new RVs to disconnected vehicles (DV) as shown in Fig. 3. An OSV is a vehicle traveling in opposite traffic direction, and can accumulate the neighbors' information which is the connected vehicles (CV). The OSV inserts RVs' information into a Network Topology Message (NTM), which is then broadcasted to disconnected vehicles. The NTM message contains information from both physical layer (i.e. vehicle position and channel frequency) and MAC layer (i.e. neighbors information) of RVs. Upon receiving a NTM, the disconnected vehicle adjusts the channel frequency of its WiMAX adapter based on the selected RV value. If the DV does not receive a NTM message, it executes the standard search procedure to find new RVs.

By avoiding the expensive RV search procedure, the handover latency can significantly be reduced. The communication latency between OSVs and DV is very important here. VFHS is an example of PHY-MAC protocol that can help in reducing delay of handover process. Here the channel frequency of disconnected vehicle can be changed based on the information passing from the OSVs via NTM message. The VFHS utilization, however, may not be substantial due to the prominent relation of OSVs and RVs. The success of getting information from OSVs is mainly based on number of vehicles of the road in different direction and RVs. Since VFHS is an application and hardware specific, the success of using RVs is mainly dependent on the penetration rate of WiMax technologies.

4.3. Transmission range adaptation

Vehicle mobility affects the node connectivity of VANETs. In the sparse networks, this problem becomes much more pronounced and can cause significant packet loss. To improve the throughput in such scenarios, sender can carry the packets until it finds the next relay node or the destination. This mechanism is popularly known as *store-and-forward* where it is suitable for delay tolerant applications. To be able to serve real-time applications in sparse networks, the transmission range extension is one of possible strategy. However, increasing transmission range has many other implications. For example, increased transmission range may potentially increase the interference, which can lead to packet drops. Thus it is beneficial to increase the transmission range when vehicle density is low as the increase in interference level would be small. Alternatively, the transmission range can be reduced when vehicle density is found to be very high. Therefore in this section, the existing cross-layer design solutions are mainly based on the information flow from the MAC layer to the PHY layer. Here, MAC layer is responsible for collecting the neighbor information to the PHY layer for transmission power adjustment.

Rawat et al. proposed a joint adaptation between MAC and physical layer that mainly focuses on adaptation of transmission power and QoS message prioritization based

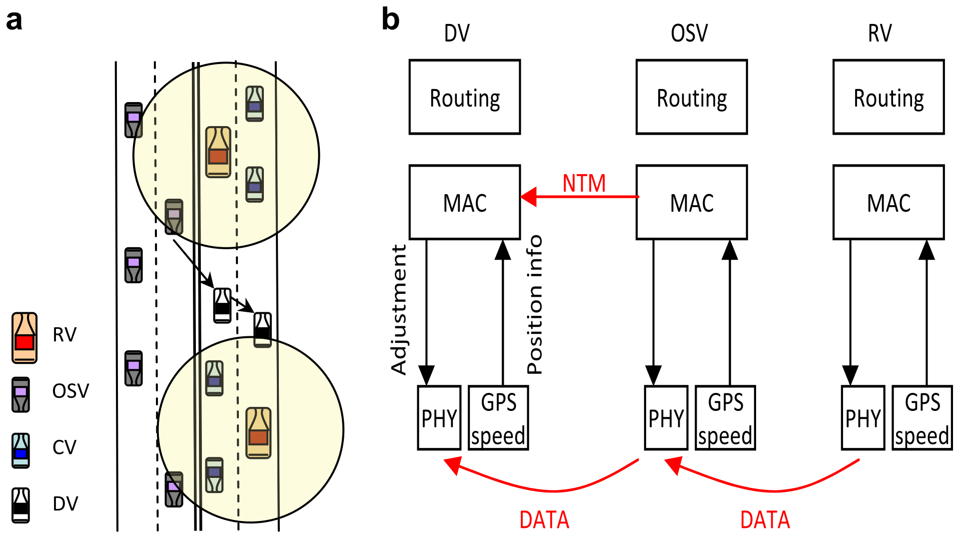

Fig. 3. (a) MMR scheme and (b) MMR cross-layer interaction [5].

on node density and contention window size [6]. Vehicles estimate the node density by gathering the neighbors information within the current transmission range. The new transmission range is then derived by adopting a traffic flow model [7] whose parameters include length of road segment, estimated vehicle density, and traffic flow constant. Here transmission power is a function of transmission range.

To support QoS applications, authors incorporated 802.11e standards for message prioritization. Here authors proposed two distinct functionalities to adjust the priority of the packets – transmission power level in physical layer and MAC channel access parameters such as minimum contention window (CWmin), maximum contention window (CWmax), and arbitration interframe space (AIFs).

By following the 802.11e standard, packets are classified into four levels of priority. The values for CWmin, CWmax, and AIF parameters are set based on the urgency level of the messages. In case of highest priority packets, the CWs and AIFs are set to smallest values and accordingly the transmission power is set to the maximum value. For other priority messages, the CWs and AIFs are set based on the priority levels and transmission power is set based on the node density. In order to make the system more dynamic, contention window size can be adapted based on collision rate in the channel and the number of back-offs.

Similarly, Caizzone et al. [8] proposed a mechanism that adjusts the transmission power adaptively based on number of neighbors. First each vehicle starts with initial transmission power. It incrementally increases the transmission power as long as the number of neighbors is within a minimum threshold, or it reaches maximum transmission power value. The transmission power is decreased when the number of neighbors greater than maximum threshold. Otherwise transmission power remains the same if the number of neighbors is within minimum and maximum threshold.

Instead of using additional exchange information to determine number of neighbors, authors proposed channel observation mechanism based on time synchronous TDMA/TDD medium access control. Vehicles monitor channel by observing the power strength and activities at each time slot. If the receiving power is lesser than a threshold, the channel is considered to be idle and the time slot status is classified as available state. If not, the channel is busy where the packet may get successfully transmitted or it may fail due to collision. Successfully transmitted slot is classified as engaged state whereas unsuccessful transmitted slot is classified as collided state. The slot that are in engaged state is counted as number of neighbor and it is used to determine transmission power. Although this protocol has low communication overhead, it is not dynamic since the transmission adaptation is based on static parameters such as maximum and minimum number of neighbors thresholds.

The above approaches [6,8] are focus on the effort of individual vehicle to adjust the transmission range based on its own observation. Asymmetrical of the transmission range, however, can cause significant effect to the system. The vehicle that has higher transmission range than neighbors can greedily consume the bandwidth and causing unfairness to neighbors that has smaller transmission range. This problem is more severe in case of emergency event where the accident vehicle who has smaller transmission rage than neighbors can not broadcast their message. *Distributed Fair Power Adjustment for Vehicular networks* (D-FPAV) [9] is aimed to provide the fairness on transmission range adaptation among the neighbors. Authors argued that adjusting transmission power should not only aim to improve the connectivity but also aware of channel conditions to provide fairness to the system.

The channel condition is mainly based on the load of the channel. D-FPAV focuses on balancing the load of control channel of 802.11 MAC protocol. The control channel supports two types of message: periodic-based and event-based. The periodic-based message or beacons is broadcasted periodically to convey information about the state of the sending vehicle such as position and speed, and

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aggregated data regarding the state of its neighbors. The event-based message is for emergency warning which requires fast and reliable propagation to farther nodes. Since event-based message is critical for VANETs, the available bandwidth should be reserved to guarantee the delivery. Authors proposed a mechanism that fairness called *max–min fairness algorithm*.

Max–min fairness algorithm is used to estimate the minimum the transmission range based on neighbors information. To estimate the fair transmission range, beacon is used to exchange the transmission power information. First a vehicle, *i*, broadcasts its the information at maximum power. In the mean time, it listens to the channel and collects neighbors' information. Based on neighbors' information, the vehicle *i* estimates the number of neighbors and computes maximum common value P_i. Then node *i* broadcasts its P_i value. Upon receiving computed maximum power level of other nodes, node *i* records them on the table. Using the neighbor table, node *i* evaluates the final transmission power by taking the minimum possible power level of all neighbors to guarantee the connectivity without overuse of the channel. A second parameter that is used control the transmission power is called MaxBeaconingLoad (MBL). Note that the maximum P_i of each node should not violate the MBL threshold. Generally, a large MBL allows more beacons message, where small MBL limits number of beacons message. In this work, authors set MBL to a fix value which is a half of available bandwidth. Possible extension of the paper is to adaptively adjust MBL to control the load of the beacon in the system.

The papers that discussed above tried to adjust the transmission power based on omnidirectional antenna. Chigan et al. introduced a solution that use multiple antennas for point-to-point communication called a Relative-Position-Based MAC Nucleus (RPB-MACn) [10]. Due to the performance degradation in 802.11 multi-hop networks is often result of packet collision and interference which are mainly caused by the hidden terminal and exposed terminal problems. Authors argued that to avoid such a problem, vehicles must have a knowledge of neighbors' positions, and they should dynamicaly adjust the transmission power to illiminate interference.

Authors proposed the *run-time static relative position relation* using eight statistically configured directional antenna over a single channel. Each antenna is configured to one relative position within tagged vehicle one-hop vicinity. In the run-time, the relative position of the neighbors is based on overhearing of communication. For instance, a tagged vehicle hears a neighbor *B* from the right antenna, it interprets the location of *B* as on the right. Such a communication allows the tagged vehicle to communication with each neighbor simultaneously. In addition, it promotes the spatial reuse capacity and collision-free communication. Essentially, RPB-MACn can also be used for collision-free multi-hop communication.

Since RPB-MACn depends on perfect channel separation which is hard to accomplished in real situation, authors proposed the channel assignment scheme which assigns different wireless channel pairs to different antenna transceivers. Each directional antenna transmits and receives messages over its own dedicated channels based on well-known channel allocation techniques such as CDMA or OFDM. In addition, authors proposed solutions to deal with other realistic situations such as non-standard surrounding positions of neighbors where vehicles are overlapped in the antenna vicinity as well as vehicles with different size and orientations. In comparison to other protocols, RPB-MACn solves the collision issue in multi-hop environment. However, the main challenges remains on the implementation cost where vehicles are required to have multiple antennas.

5. Cross-layer design of PHY-MAC-network layers

Due to high mobility of VANETs, the wireless link between two vehicles is short-lived. The channel quality information from physical layer helps the sender in predicting the link connection time, subsequently the sender can find a new receiver before the current link is disconnected. Thus cross-layer interaction between physical layer and higher layers is desirable to maintain link connectivity and improve system performance.

Sofra et al. proposed a cross-layer design that uses a metric known as Link Residual Time (LRT) [11] that is computed based on the received power that is observed at the physical layer. The value of LRT can be used to estimate the longevity of the link, and it denotes the remaining time for which the link can be used for packet transmission. LRT values can be used in higher layers to make better decisions for hand-off, scheduling, and routing packets. Each vehicle monitors and records the arrival time and the received power level for each packet that is received on the link. This time series of values is then used to estimate the value of LRT.

The process of LRT estimation has three main steps: (i) remove the noise from the data, and check if the link quality is deteriorating, (ii) estimating the model parameters that are required to compute a value for LRT, and (iii) renewing LRT estimate. The first step in the estimation process is to remove the noise in the data that may arise due to shadowing and multi-path fading. The denoising process uses a signal processing method called Empirical Mode Decomposition (EMD). Once the noise is removed, the change in link quality is observed to see if it is deteriorating. The link quality deteriorates when the sender and receiver vehicles move away from each other. On the other hand, the link quality improves when the vehicles travel towards each other. Link quality is observed via robust regression method, a modified version of the simple regression. Whenever a new packet is received, the mean squared error between the observed received power and the value estimated form the regression is computed. A possible change in the link quality is detected by comparing the error value with the error values computed in previous iterations. When the link quality is found to be deteriorating, a new estimate for LRT is computed in second and third steps. This process involves estimating parameters related to distance between the sender and the receiver and the received power values. This method is shown to predict the residual life of wireless links well before the communication failure occurs, which is valuable for higher layers to maintain path connectivity.

While Sofra et al. focused on individual nodes, Singh et al. explored the use of link connectivity information among neighbors to help in addressing the challenges in designing routing protocols for VANET environments. They proposed a cross-layer protocol called *Signal Strength Assessment Based Route Selection for OLSR* (SBRS-OLSR) [12]. In this framework, the link connectivity is based on SNR measurement, and the routing protocol is based on existing Optimized Link State Routing (OLSR).

In existing OLSR, a link-state table-driven method is used to create a routing table between any source and destination pair. Due to constant vehicular movement, routing information in OLSR table can become stale over a period of time. SBRS-OLSR therefore uses *MultiPoint Relays* (MPRs) links to help maintain the routing information. MPRs links consists of multiple MPR nodes. These links are for fast broadcast topology information. In SBRS-OLSR protocol, only MPR nodes are able to broadcast topology information. While in existing OLSR protocol, all nodes broadcast the update topology information.

To improve link connectivity, MPRs node is selected based on highest SNR values among neighbors. The determined SNR values are passed during neighbor discovery process. By capturing SNR information from the physical layer, the network layer can provide a better route that improves throughput and delay performance. Unlike cross-layer solutions in Section 4, the cross-layer design of LRT and SBR-OLSR are based on the information flow from the physical layer to the network layer.

6. Cross-layer design of network-MAC layers

One of the foremost challenges in vehicular networks is to design protocols that can handle the high mobility of vehicles and constant changes in the underlying topology. The routing protocols must deal with frequent changes in the routing topology and maintain link stability between vehicles. If the route is disconnected, a new route must be discovered instantly. In order to effectively maintain the route information in such dynamic networks, most routing protocols rely on geographic information as opposed to address-based identification that is typically used in MANETs. These techniques can be complemented with cross-layer designs that exploit the relation between MAC and network layers. For example, the routing function can leverage the information shared by the MAC function in predicting the life-time of various links, and subsequently adjust the routes, if necessary. We now present various cross-layer approaches that make use of connections between MAC and network layers.

6.1. Route selection

In multi-hop wireless communication, the shortest path or the minimum hop path is not guaranteed to be the minimum delay path between a given pair of source and destination nodes. This is mainly due to the condition of the links within the selected path. For instance in the areas that are dense with a lot of vehicles, the links are likely to experience high contention delay thereby causing high end-to-end delay. Therefore, effective routing functions must consider the quality of entire path as well as the individual link quality while routing the packets. However, information on the quality of individual links is typically known at the level of MAC layer. This information can be passed onto the network layer to select better paths that capture the current topological and communication constraints in the network.

6.1.1. Route selection through link prediction

Movement Prediction-based Routing (*MOPR*) [13] is an example for one of the earliest approaches that propose a movement prediction based routing protocol for V2V communication in VANETs. It improves the routing process by taking the vehicle movement information that is typically available in MAC layer such as position, direction, speed, and network topology into consideration. Based on such vehicular information, MOPR predicts the future location of intermediate relay nodes, which can subsequently be used to estimate the life-time of point-to-point links. As a result, MOPR is capable of dynamically select the most *stable* routes containing stable nodes that are traveling in the same direction or with the similar speed or on the same road as of the destination/source nodes. To facilitate the routing process, the vehicular information such as position and speed are explicitly maintained in the routing table. Such position prediction techniques can further be improved by making use of digital maps and navigation systems.

Similar to MOPR, Chen et al. argues that the information on intermediate nodes is critical to adjust the routes dynamically. However, unlike MOPR, Chen et al. purposed a multi-path routing protocol to reduce the frequency of route rediscovery and hence to alleviate the overhead incurred. They proposed a cross-layer Ad-hoc On-demand Multipath Distance Vector (*R-AOMDV*) [14] protocol that is based on AOMDV [15] protocol. This method makes use of a routing metric that combines hop count and transmission counts at MAC layer by taking quality of intermediate links and delay reduction into consideration. This protocol has been shown to deliver better performance than AOMDV, especially in sparse and dense urban vehicular networks.

The route discovery process employed in R-AOMDV is similar to that of AOMDV. It relies on two control packets: route request (RREQ) and route reply (RREP). The intermediate first hop nodes in RREQ and RREP packets are used to distinguish between multiple paths from source to destination. To measure quality of entire path, it adds two additional fields to RREP packets – the maximum retransmission count (MRC) that is measured in MAC layer and the total hop count that is measured in network layer. When RREP is passed back to the source, each intermediate node compares its retransmission count with the MRC and replaces it if its retransmission count value is greater than the current MRC. Thus, when RREP packet arrives at the source, the source can identify which path contains maximum MRC. As in AOMDV, a source node in R-AOMDV initiates the route discovery process whenever it can not find a path to the required destination in its route table.

Although MOPR and R-AOMDV improve the routing process by taking the link quality information into account, their rely on IP-address based neighbor information. Such a mechanism however is not suitable for VANETs and it is likely to experience high packet delays and packet loss since messages are forwarded to selected IP nodes only, even if they had moved away from the point at which the route was established. On the contrary, one must be able to find new forwarding node on-demand if the node selected by the route moves away. Such problems are more predominant in urban networks with multiple paths between source and destination, diverse node density, multiple intersections, and high packet congestion.

6.1.2. Route selection based on neighbor information and route quality

To avoid these problems due to vehicle mobility, cross-layer designs must be able to refrain the MAC function from using IP-address based methods for selecting intermediate relay nodes. Most existing routing protocols are based on location-based routing where vehicles are assumed to have knowledge of their positions via GPS. Mostly, the forwarding decision is based on vehicles' positions or distance between vehicles. Vehicles that are closer to the destination are given higher chance to become the next relay node. Such a strategy decreases the overhead incured in route discovery, and it is able to deal with the problems caused by node mobility. However, geographic protocols that follow a greedy forwarding mechanism do not have any knowledge of the path. A packet may get routed on a congested path that causes additional packet delay, or it may ultimately get dropped. To be able to transmit the packets along small delay paths, the sources node should have high-level knowledge about the possible delay that will be incured at various intermediate locations, and on various paths to the destination.

A recent delay-aware protocol called *PROMPT* [16] is a cross-layer design that aims to provide quick adaptability to frequent changes in the network topology, and also delay awareness in data delivery. It is designed for V2I communication in urban environments where packets are relayed via geographic-based intermediate nodes as shown in Fig. 4.

PROMPT adopts a position-based routing approach to alleviate the problems resulting from high node mobility. It is inexpensive as it does not rely on any explicit neighbor maintenance strategies, which are common to deal with node mobility. The roadside infrastructure known as base station broadcasts periodic beacon messages. These beacons are propagated outside the base station communication range via directional multi-hop broadcasting protocol. During beacon propagation process, each node collects route information into a path table. The route information in beacons contains locations of previous forwarding nodes and communication characteristics. A vehicle communicates to base station using the minimum delay path estimated from the path table.

Unlike IP-address based paths in MOPR and R-AOMDV, source routes in PROMPT are physical paths on the road network – they are expressed as a sequence of (street,direction) pairs. While packets is forwarded back to the base station, the MAC functions obtains such a source route information from the packets. The next forwarding node is chosen based on a receiver-based MAC channel contention methodology. Upon receiving a forwarding request from the transmitting vehicle, each relay contender determines its privilege and sets the contention time based on its privilege. The exact value of privilege can be based on several factors – for example, distance and direction of the relay nodes with respect to the selected source path and the transmitter. The relay that is in the same (street, direction) of the selected path and that is farthest from the transmitter has the highest privilege and therefore has the smallest contention time to reply the forwarding request. All other contenders drop their replies upon hearing a reply from the highest privileged node. Such a relay selection method can forward the packets towards the destination efficiently without using IP address or ID information of vehicles.

Furthermore, PROMPT does not require any explicit and expensive neighbor management strategies. To improve the bandwidth usage and to reduce contention time,

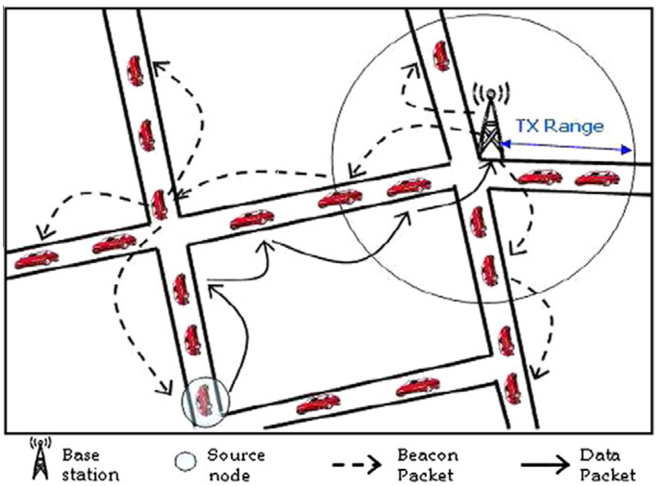

Fig. 4. PROMPT system.

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PROMPT uses a *packet train* technique where the transmitter can bundle multiple packets to the same destination into one packet train, and transmit it within a single contention period. The overall cross-layer design philosophy of PROMPT can be summarized as follows – local packet traffic statistics collected in MAC layer are used in network layer to route packets in a delay-aware manner; and minimum delay source route (street,direction) pairs found in network layer are used by the MAC layer to determine the next relay node in a manner that is not adversely affected by vehicle mobility.

Similarly, Barghi et al. proposed a protocol that predicts the life-time of communication links to select the most stable route between source and destination [17]. The objective of this paper is to overcome the overhead during gateway discovery and routing selection. Gateways advertise their service by broadcasting its location and service area. Vehicles within its service area relay the message farther into the extended transmission range of the gateway. Unlike PROMPT that uses local statistics of each hop to determine the best route, Barghi et al. uses stability metrics to predict the route life-time and selects the most stable path. Within each hop, the forwarding nodes includes their stability metrics such as positions, speed, direction. It also leverages smart broadcasting techniques like CBF [18] to reduce the overhead due to broadcast storms.

6.2. Packet collision avoidance using segment-based or cluster-based routing

The hidden terminal problem is the main performance issue in multi-hop networks. Section 7 discussed more about MAC interactions and performance degradation due to self-interference of multi-hop networks. Many existing routing protocols are awarded for these issues. In the segment-based solution, the routing protocols takes advantage of limited road structure to control hop by hop transmission. The road are divided into segments where each segment response for one-hop communication. Example of such a segment-based framework is CVIA protocol [19]. In CVIA, Korkmaz et al. aimed to develop a cross-layer protocol for highways that solves hidden terminal problem and avoid packet collision. The packet can forward through the relay nodes toward the gateway or base station. Vehicles are equipped with GPS for position information and time synchronization.

To avoid hidden terminal and interference problem, each road segment communication is alternatively switch between active and inactive phase. This phase sequence is also synchronous between adjacent segments where adjacent segments are in opposite phase. When the segments are in active communication phase, the vehicles locate inside the segments are allowed to communicate with each other. Vehicles within the same segment are within a single hop transmission, and they can exchange their locations information. Note that since adjacent segments have opposite phase, the hidden terminal problem is avoid.

Based on the phase sequences, CVIA has three main packet movement schemes for communication: intra-segment packet train movement phase, local packet gathering (LPG) phase, and inter-segment packet train movement phase. To insist the packet movements between each segment, two vehicles at the border of the segments are selected as the temporary edge routers. In the intra-segment packet train movement phase, packets are delivered from one edge router to another edge router. The flow of the packets are based on the direction of the base station. In the local packet gathering (LPG) phase, local packets of the each segments are delivered to the edge router that is closer to the base station. Each vehicles access channel randomly to avoid the collision. In the inter-segment packet train movement phase, the edge router sents the packets to another edge router that is belong to next segment. Although the CVIA solves the hidden terminal and interference effectively, the main challenges are the temporary router selection process and the segment-based synchronization.

Another solution to avoid hidden terminal problem is the cluster-based forwarding. CCBF [20] is an example of cross-layer protocols based on cluster-based forwarding. Similar to CVIA, CCBF packet forwarding scheme has two phases: inter-cluster forwarding and intra-cluster forwarding. First, CCBF selects the cluster head. During intra-cluster forwarding, cluster head assigns the channels for its neighbors. Each neighbors is allowed to transmit the packets based on assigned channel to avoid hidden terminal problem and packet lost due to collisions. The number of slots for each vehicle in CCBF can be varied and prioritized. During intra-cluster forwarding, the packets are transferred between the clusters.

Although the segment-based or cluster-based design solves packet collision issue, the main drawback of such protocols is the time synchronization among the clusters and the overhead of cluster forming process. Such strategies which divide the road into segments or organize vehicles into clusters are more suitable for highways, and they are not readily applicable for urban road structures. Mainly, urban road structures are more complex which contain multiple intersections and vehicles can have various speeds and directions.

Bononi and Di Felice introduce *Dynamic Backbone-Assisted MAC* (DBAMAC) scheme [21]. DBAMAC aims to solve the latency and overhead problems in broadcasting emergency message. In the paper, a back-bone member (BM) selection is similar to cluster head selection which is based on stability criteria such as speed, direction, and location. The communication among BM's is formed as a back-bone links to reduce transmission and contention delay. These links are mainly used to relay emergency messages. If the back-bone link is broken, DBAMAC allows other vehicle to dynamically join the connection and help relay the message. Although DBAMAC is an application-specific protocol, DBAMAC suffers from back-bone link forming similar to CVIA [19] and CCBF [20] cluster forming.

6.3. QoS support – prioritization-based solutions

There exist a number of applications that have stringent Quality of Service (QoS) requirements. For instance, it is important for all safety applications to have fast and reliable message propagation to convey traffic-related warnings to nearby vehicles as soon as possible. Similarly, multimedia applications require high bandwidth and shorter transmission delay. IEEE 802.11e standard was introduced to support packet prioritization so that services with diverse QoS requirements can be differentiated. According to this standard, the flow of different priority classes have different back-off times and channel access times. For instance, emergency messages in safety applications are transmitted with highest priority than other packets so that they experience shortest channel access time and smallest contention window compared to other packets like periodic beacon messages. Cross-layer solutions can be developed to exploit the priority classes from 802.11e at other layers for better treatment of QoS requirements.

There are number of existing solutions that are based on 802.11e standard. In [22], authors studied the QoS performance in multi-hop vehicular networks using 802.11e. They found that 802.11e protocol alone is not sufficient to meet QoS requirements because it does not take the key characteristics of VANETs like link quality, node mobility, and multi-hop interference into consideration. They have proposed a triple-constraint QoS routing protocol called *Delay-Reliability-Hop* (DeReHQ) that is an extension of the popular AODV routing mechanism. DeReHQ protocol considers the following QoS measures – link reliability, end-to-end delay, and hop count.

In DeReHQ, the optimal policy for the path selection is computed based on the above three QoS parameters. Authors argued that the quality of the path is more important than the shortest path. Thus, the link reliability should have higher priority than link delay and hop count in path selection process. These parameters are estimated based on the vehicular traffic theory which includes traffic density, vehicle speed, and distance between source and destination. In addition to path selection policy, authors suggested that priority issues of different class of application should also be implemented in routing algorithm by taking into account of the cross-layer interaction. Although DeReHQ does not offer the service differentiation, the enhancement of 802.11e can be implemented in the future work.

It is well-known that broadcast messages can easily saturate a system's performance as they consume a lot of network bandwidth. Eichler et al. [23] suggested that one can carefully design cross-layer strategies so that broadcast messages can be routed only to the interested drivers. For instance, traffic warnings in the city are not important to those drivers who are driving on the highway, or the ones that are moving away from the city. In this paper, authors proposed two strategies to emphasis the benefit values of the message. First, sender nodes quantify the benefit that their respective data packets provide to potential recipients within their neighborhood. Second, broadcast messages are prioritized according to the resulting benefit values so that the global benefit received by all the vehicles participating in the network is maximized.

To implement such a benefit-oriented approach, authors have proposed a cross-layer protocol that allows most beneficial message to get transmitted first. The application layer evaluates the benefit value for each packet before it gets to the MAC layer. The computer benefit value is included in the packet header. The benefit-based extension (BBE) is implemented in the link layer to modify the packet queueing process to account for the benefit values. The highest benefit packets are placed at the head of queue so that they spend less amount of time in the system. Existing 802.11e protocol is modified to allow highest benefit packet to have higher priority during the channel access. Here, the contention window (CW_{min}, CW_{max}), channel access timers (AIFS), persistence factor of packets are set based on their benefit levels. Persistence factor provides packets with a higher chance to win contention processes and to access the medium quicker.

The benefit calculations are based on three components: message context, vehicle context, and information context. The message context is characterized by the age of the message. The vehicle context is described by vehicle direction, distance to the last forwarder, number of reachable neighbors, vehicle speed, etc. The information context is based on time of the day, the purpose of traveling, information category, etc. With these three contexts, the benefit values of messages are derived with the assigned weight based on the class of the messages. For instance, a collision warning has higher weight for the message age parameter than other contexts.

In [22] and [23], the real-time traffic that requires higher priority channel access is supported by 802.11e-like MAC protocol. Korkmaz et al. studied the QoS support based on CVIA [19] forwarding protocol which is called *Controlled Vehicular Internet Access protocol with QoS support* (CVIA–QoS) [24]. CVIA–QoS aims to provide delay bounded throughput guarantees for soft real-time traffic in multi-hop VANETs. Authors found that 802.11e MAC protocol does not efficiently support the service guarantees to the best-effort traffic due to its randomness in channel access timing assignment. They proposed additional admission control and communication scheduling mechanisms during the contention period to provide efficient services for packet prioritization. The contention period is classified into two phases: high priority period and low priority period. A real-time packet that has high priority accesses the channel during the high priority period. In this period, the packets go through register process. Then the packets are scheduled during the transmission period to avoid packet collision. In contrast, packets in low priority period access the channel randomly using the traditional 802.11 protocol. This mechanism, as a result, can provide guarantees on the delay for time-critical real-time traffic.

6.4. Multi-hop broadcasting

The most important class of applications in the context of vehicular networks is safety-related applications, in which emergency messages that are broadcasted to surrounding vehicles must experience minimum possible delay and high reliability. Traditional techniques like flooding seriously suffer from broadcast storm problem where a large amount of bandwidth is consumed by excess number of retransmissions. When the vehicle density is high, such techniques lead to a large number of collisions and high channel contention overhead. Cross-layer protocols have been designed to alleviate this overhead by jointly

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optimizing the packet forwarding mechanism from network layer and the contention scheme in MAC layer.

Korkmaz et al. developed an urban multi-hop broadcast protocol for inter-vehicle communication systems [25]. UMB is designed to reduce the effects of problems related to broadcast storm, hidden terminals, and reliability problems in multi-hop broadcasting. The UMB protocol has two phases: directional broadcast and intersection broadcast. In the directional broadcast, the furthest vehicle from the transmitter is selected to rebroadcast the packet. It determines the farthest nodes by employing a distance-based contention approach without any knowledge about node IDs or positions of neighboring nodes.

This UMB protocol uses a 802.11-based RTS/CTS handshake to avoid hidden terminal problem by dividing the road into several segments. When the channel is available, the source vehicle sends a request-to-broadcast (RTB) packet. Once the nodes in the direction of the dissemination receive this RTB, they compute their distance to the source node. Based on this distance, they send a black-burst (channel jamming signal) so that the farthest node has the longest burst. As the nodes finish their black-burst, they listen to the channel. If a node finds that the channel to be empty, it implies that its black-burst was the longest, and subsequently it replies a clear-to-broadcast (CTB) packet. If there are multiple nodes that respond with a CTB, they collide and the source node retransmits the RTB packet. In this next contention period, only the receivers who had sent the CTB in the previous round are allowed to send the black-burst signal. To avoid further collisions, especially since the relay vehicles are located within same distance, the nodes select a random black-burst size.

On the other hand, for broadcasting packets around the intersections, Korkmaz et al. proposed to install the repeaters that can forward the packet to all road segments around the intersection. When a node reaches the intersection within the repeater communication range, it sends the packet to the repeater using the point-to-point IEEE 802.11 protocol. The repeater then forwards the packet to all other directions except in the direction in which the packet has been received. To optimize the channel utilization around the repeater nodes, vehicles around that intersection that overhears the packet can rebroadcast it directly without waiting for the repeater to retransmit. This protocol is later extended to AMB [26] in order to handle intersection scenarios more efficiently without repeaters. Unlike in UMB, AMB protocol makes the vehicles to disseminate the packets into different directions when passing by the intersections.

Nasri et al. proposed a cross-layer scheme for broadcasting at intersections in VANETs [27]. Authors argue that about 30% accidents happen in the intersection area. Thus a reliable broadcasting mechanism is very important. The key problem around an intersection is that the overlapped transmission range from one direction can block the message propagation in some other directions. To avoid flooding problem, the number of rebroadcast can be reduced based on the location of the receivers. Once vehicles receive the broadcast message, they compute the defer time based on the distance of sender and receiver before rebroadcast the message. Upon overhearing the same broadcast message, the receivers cancel the rebroadcast process. However, it is necessary that vehicles at the intersection should rebroadcast the message to different directions. To guarantee reliability in such scenarios, authors proposed a method that classifies vehicles based on their relative location and angle to the last forwarding node. To provide fast broadcasting, the routing function is merged with MAC function. The messages from network layer is directly sent to physical layer.

7. Cross-layer design for transport-MAC layers

The cross-layer design between transport and MAC layers helps in distinguishing between route interruption and channel congestion. The link disconnection problems that occur at the level of individual hops must be dealt at MAC layer. MAC protocols such as 802.11 handle link disconnection via packet retransmissions. If the sender does not receive the acknowledgements within a fixed number of retransmissions then the packet is dropped. In multi-hop vehicular networks, the issue of link disconnection is likely to be severe since the underlying network topology changes dynamically, thereby resulting in frequent packet retransmissions.

In multi-hop VANETs, the sequence of relay nodes between the source and destination nodes can be treated as a *chain*. Different links in such a chain experience different levels of interference. In [28], Majeed et al. studied the impact of these different MAC-level interference on the performance of TCP in multi-hop networks. Through an extensive simulation, they rank ordered chains with different MAC interactions based on the position of senders and receivers. For instance, sender-connected interaction, also known as exposed node terminal problem, occurs when two senders interfere each other transmissions. Authors found that sender-connected chains provide best performance in term of throughput and retransmission overhead. The difference in levels of interference among these chains contribute up to 25% difference in system throughput. Generally, the multi-hop chain requires high number of retransmissions. This retransmission wastes the bandwidth usage and potentially increase the delay and degrades throughput of the system.

The findings of MAC interactions and TCP connections in multi-hop communication are further investigated by Hamadani et al. [29]. They classified the problem into two TCP flow instabilities – intra-flow and inter-flow instability. The intra-flow instability is caused by the nodes within the same TCP connection whereas the inter-flow instability is caused by the nodes from multiple different TCP connections. They performed a detailed analysis of intra-flow instability where successive transmissions from a single TCP flow interfere with each other at the level of link layer. Such self-interference results from contention among a variety of packets – among different TCP data packets; between TCP data packets and MAC control packets; and among MAC control packets. Self interference evidently reduces the channel bandwidth utilization and causes network overload. Many packets get dropped, especially at intermediate nodes. As a result, TCP responds with fast retransmissions by reducing the congestion window

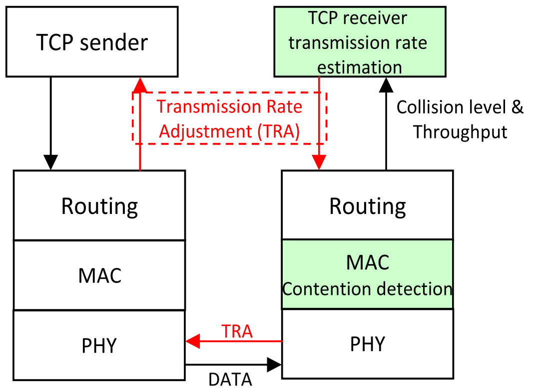

Fig. 5. TCTC cross-layer interaction [29].

size. Also, the packet generation rate at the sender is also reduced. These methods essentially control the number of packets in the system, and they help in addressing the problem of TCP intra-flow instability.

Hamadani et al. [29] have also explored the use of cross-layer design to dynamically adjust the traffic load such that the system throughput is maximized and the end-to-end delay is minimized. They have proposed *TCP ConTention Control* (TCTC) that adjusts the amount of data in the system based on the level of contention and throughput experienced by packets in each flow as shown in Fig. 5. To estimate the end-to-end contention delay, TCTC makes each packet record the amount of time spent in contending for the channel in MAC layer. This per-hop contention delay is cumulatively maintained in the packets. At the end of packet transmission, TCP receiver can estimate the average per-hop contention delay by dividing cumulative delay obtained from the packet by the total number of hops. TCP receiver also estimates the achieved throughput of the flow for each transmission. The estimated quantities are used to compute the optimum amount of traffic to achieve the maximum throughput, and lowest contention delay for each connection. Such computations are done by collecting the information from packets received over a fixed observation interval. The computed flow information is then sent back to the sender so that it can adjust the amount of traffic rate for each flow. It is also important to carefully select the duration of observation interval. If the interval is too long then the response from TCTC will be too slow to adjust to the contention level in the network. On the other hand, if the interval is too small then TCTC may become too sensitive, there by resulting in system load fluctuation. In general, the adjustment of transmission rate at TCP layer may not directly solve the channel contention problem at MAC layer. However, transmission rate adaptation does help in reducing the number of packet drops at MAC layer.

8. Cross-layer design for transport-network layers

There exist several cross-layer protocols that operate between the transport layer and lower layers. Most of these protocols are aimed at supporting real-time and multimedia applications that require a reliable end-to-end connectivity with critical QoS requirements. Cross-layer protocols are developed to assist in dealing with issues that emerge in vehicular networks. In this section, we first review the functionality of transport layer protocols, and discuss challenges that these protocols must address in the context of vehicular networks. We then explore existing cross-layer solutions between transport and routing functions.

In a traditional layered design, the transport layer is responsible for delivering data between application layers of host computers. Transport Control Protocol (TCP) is a well-known transport layer protocols that provides end-to-end reliable communication among systems. TCP includes several mechanisms like flow rate control, error recovery, and congestion avoidance. In traditional wired networks, the transmission errors or packet losses are assumed to be a result of network channel congestion since the problems due to route disconnection and channel errors are minimal. In such scenarios, the TCP sender often reduces the sending rate, and it may also adjust the congestion window size to decrease the system load. Another related and popular transport layer protocol is the User Datagram Protocol (UDP) that does not provide any explicit mechanism for delivery assurance. For safety-related and Internet access applications in VANETs, the reliable TCP protocol is more suitable than UDP protocol. We confine our discussion to TCP-based approaches.

Existing TCP-based protocols are primarily developed for wired networks where the network conditions are transparent to the transport layer. However in wireless networks, the quality of shared channel is highly dynamic, and it changes with time and system load. Packets may get dropped due to channel contention or high-level of interference. The effect of these factors is prominent in vehicular networks where the high mobility of vehicles cause frequent path disconnection. Thus in wireless networks, it is important for transport layer protocols to have some knowledge about the channel condition so that they can operate adaptively according to observed situation. Simply reducing the transmission rate when a packet transmission fails can lead to suboptimal performance, especially in critical safety applications. In addition, it can result in reduced connection throughput, under-utilized bandwidth, and fluctuations in performance.

Cross-layer protocols can be developed so that the transport layer can distinguish between errors due to network congestion and path disconnection. In multi-hop networks, packets may get dropped at intermediate relay nodes triggering the expensive route recovery process, and thereby affects the system performance significantly. Holland and Vaidya investigated the effect of mobility on TCP performance over multi-hop networks [30]. First, authors showed that TCP throughput drops significantly when node movement causes link breakage. They showed that traditional protocols such as DSR must not only provide an optimal route but they must also be able to recognize the disconnected route and quickly purge stale routes. Failure to remove the stale route results in repeated routing failures and poor performance.

The vehicular mobility can also cause significant transmission delays when TCP can not recognize the difference between a link failure and network congestion. To deal

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with this problem, packet congestion information due to the link failure should be notified to the sender. In the paper, authors proposed the use of Explicit Link Failure Notification (ELFN) to notify the sender in case of the link and route failure. The sender uses this information to avoid responding to the link failure as if congestion has occurred, and thereby it avoids corrective actions such as reduction in the size of congestion window. Whenever the destination is not reachable, there are two ways in which the ELFN notification can be passed to the sender – directly send an ICMP destination unreachable message to the sender; or use the route failure mechanism available in routing protocols such as DSR where ELFN notification can be piggybacked with the route failure messages. Once the sender receives a route failure message, it can disable congestion control mechanism, and continue to find a new route. However, this work is limited to DSR routing protocol.

Liu and Singh studied the effect of route disconnection and network partition problems that are caused by node mobility on the performance of TCP. They have proposed *Ad-hoc TCP* ATCP [31], an end-to-end solution to improve the throughput of TCP. This is a cross-layer mechanism that deals with a variety of routing issues such as packet loss due to high BER, changes in the route, network partitions, packet reordering, multi-path routing, and network congestion.

ATCP allows the network layer to obtain feedback from the intermediate nodes about the route status. During its normal operation, ATCP sender transmits the packets and stays in the "normal" state. When packets are lost due to the high bit-errors, ATCP sender moves to a state of "retransmission". In this state, the lost packets are retransmitted without adjusting the contention window. Therefore, bit-error events does not effect the overall system throughput. However when the route is disconnected due to node mobility, ATCP sender moves to a state called "persist state". In this state, the sender waits for a new route to be discovered before sending any other packets. Since the new route may have different congestion level, the size of contention window is reset as soon as a new route is discovered. When the network is truly congested, ATCP sender moves to the state of "congestion control", and contention window size is adjusted accordingly. Unlike the solution proposed by Holland and Vaidya [30], ATCP uses Explicit Congestion Notifications (ECN) to notify the sender node about network congestion, and ICMP messages to notify the events where the receiver node is unreachable. The sender moves either to "congestion control" state or "persist state" depending on whether an ECN or an ICMP message is received.

Vehicular Transport Protocol (VTP) [32] is another cross-layer design that exploits the relation between transport and routing function by making use of feedback information to identify the packet loss. Instead of using topology-based routing protocols, VTP relies on position-based routing schemes such as PBR [33] in which packets are forwarded based on a highway mobility model. In each transmission, the next reachable forwarder is selected based on its distance and position with respect to the sender vehicle.

To deal with frequent route disconnections, VTP maintains in two states – *connected* or *disrupted*. As long as ACK packets are received for each packet transmission, VTP remains in the "connected" state. When an ACK is not received, the sender calculates the expected duration for connectivity using the distance between source and receiver, and statistical information that is observed during previous packet transmissions. If the expected duration is lower than a threshold, the state of VTP is changed to *disrupted*. To acquire the state status, the VTP sender uses the per-packet feedback along intermediate nodes to determine data rate of the path during the connected state. In the disrupted state, the sender periodically probes to check if the path has been restored. Whenever an ACK is received, the status is moved from "disrupted" to "connected".

To further provide congestion control mechanisms, VTP makes use of information collected from intermediate nodes. Each intermediate node computes the minimum bandwidth that is locally available, and it feeds this information back to the sender by piggybacking the ACKs. Sender uses this information to calculate the product of bandwidth and packet delay. Such a packet-based bandwidth distribution provides fairness among the contending flows without additional maintenance of flow information.

Reliable packet transmission of TCP is of great importance in file sharing and content distribution applications. Chen et al. studied the impact of critical system parameters such as hello message exchange rate and delay timer in TCP for out-of-order delivery on the performance of both UDP and TCP [34]. They highlighted that robust routing protocols must be designed to address the problems of TCP while handling the route breakage in VANETs. They studied the joint optimization of TCP and Geo-routing (e.g., GPSR [35]) parameters to efficiently handle issues due to vehicle mobility. They then proposed an adaptive scheme where the duration of interval between consecutive HELLO messages is determined based on vehicle speeds. The out-of-order problem in TCP can be fixed by using a receiver-side out-of-order detection methodology that delays the transmission of ACK messages.

In conclusion, the ability to detect packet loss due to route disconnection, channel errors and flow congestion is of significant challenge TCP senders in wireless networks. Most existing transport and routing cross-layer protocols aimed to assist transport protocol to classify between route disconnection and route congestion problems. To do so, they implemented feedback notification message either by explicitly sending message such as ICMP or by implicitly piggybacking the information. The source node can take an appropriate action upon the receipt of the notification. If there is a route disruption, the source can wait until either a new route is discovered or until a next forwarding node is found. In case of true network congestion, the source can reduce the transmission rate to reduce the load in the system.

9. Cross-layer design for transport-network-MAC layers

The packet flow rate control is one of most important and challenging issue in transport layers designed for Internet-based communication. Several cross-layer designs that jointly optimize the transport, routing, and MAC functions to efficiently handle the issues pertaining to vehicular networks. Zhou et al. [36] jointly formulated a cross-layer design for cooperative VANETs where every node acts as a partner for other nodes to carry out multi-hop communication. The main strategy in this design is to decompose the problem into two sub problems – a flow control problem that determines the total rate at which the source node must send the packets; and a division problem that describes how to split the total rate among a set of least congested paths according to the link persistence probability that is observed in MAC layer. They have proposed two solutions: *Opportunistic Cooperation MAC* (OC-MAC) protocol and *Joint Optimal Control* (JOC) algorithm.

OC-MAC chooses the route locally in which each intermediate destination node decides whether or not to relay the packet any further. The JOC algorithm, on the other hand, jointly optimizes different layers. JOC consists of three main functions: link capacity detection at MAC layer, flow control at transport layer, and the routing design at the network layer. The objective is to maximize the path utility function by adjusting the flow rate at the transport layer. Each link adjusts its persistence probability (i.e., the probability to transmit the data) based on the flow rates for all paths in which that link is involved. Updated probabilities are transmitted to all source nodes pertaining to the current link. Each source vehicle then computes the best possible flow rate for all its paths based on the received probability information. Routing component is then responsible for sending the amount of data for destination according to the rate that is computed for that path. This sequence of steps is repeated until the system is converged. Such a joint optimization strategy is shown, via a simulation study, to provide better performance than traditional alternatives.

Instead of system optimization, Drigo et al. focused on an application-oriented protocol [37]. They worked on distributed cross-layer transmission rate control algorithm tailored for applications that require safety messages. Authors proposed a method called *Distributed Rate Control for VANETs* (DRCV) which helps in delivering packets with high reliability and with low latency. DRCV employs a cross-layer design that leverages interactions between transport layer and lower layers. The lower layer monitors the channel and acquires information such as the number of neighbors, channel busy time, and the number of received periodic messages such as beacons.

The channel monitoring is performed in a distributed fashion where each node monitors the channel locally and estimates the packet load for the next interval based on the information observed in the previous time interval. Based on the acquired information, DRCV controls the sending rate and sends it to the transport layer which is responsible for generating and adjusting the rate of periodic messages. The sending rate control mechanism consists of two main steps. First, each node dynamically set the aggregate target channel load of periodic messages generated by itself and by all its neighbors. Second, each node controls its sending rate of periodic messages in order to reach the aggregate target channel load. In the case of normal operation, the channel capacity of periodic message is set to a value that is between maximum and minimum threshold. Upon detecting of emergency message, the channel capacity of periodic messages is set to minimum threshold. This helps in reducing the transmission rate for periodic messages, and thereby giving priority to emergency messages. Although DRCV can provide efficient service to emergency messages, the approach is limited to single hop networks.

Unlike other contention control TCP, Chen et al. studies the dynamics of TCP with respect to transmission power in vehicular networks [38]. In particular, they studies the effect of tuning transmission power in various traffic density and road scenarios on the TCP throughput and latency. They found that the throughput decreases and number of hops increases as vehicle traffic density is decreased. Thus increasing the transmission power reduces number of hops resulting in improved throughput. However higher transmission power results in increasing the interference level to source neighbors and causing higher packet collision rate. Similar effects also occur for end-to-end delay performance. The throughput results, however, are different around the base station area. The throughput around base station area is increased when transmission range is decreased due to high contention. The authors showed that dynamically tuning transmission power based on vehicle positions could be used to maximize throughput and decrease global system collisions. Similar study in the context of UDP has been conducted by Khorashadi et al. [39].

10. Transport layer for wired-wireless networks

Transport layer for the wired-wireless networks such as vehicle to infrastructure (V2I) requires the interconnection between a fast fixed network and a slow mobile network. During the data transfer in wireless communication, vehicles can suffer from high packet loss rates due to high vehicle mobility, service disconnection, and lossy channel. Thus the cross-layer design solution is necessary to improve the system performance. In [40], authors introduced *Carbernet* which is a V2I protocol that delivers the data from vehicle to fixed Internet access points. Cabernet incorporates three techniques to mitigate the short connection and error-prone channel problems. First, to reduce connection time, it introduces *QuickWiFi* that combines connection processes of all layers in to a single process. Second, it avoids confusion between the lost of packets due to lossy link with packet congestion by developing *Cabernet Transport Protocol* (CTP). CTP uses a lightweight probing scheme to determine the loss rate from Internet hosts to an AP. Third, authors studied bit-rate selection mechanism and concluded that the static transmission rate at 11 Mbits/s gives optimal performance.

In Carbernet, QuickWiFi incorporates channel scanning for AP selection and connection into a single state machine running in one process. It also implements the connection loss detection by monitoring the ongoing transmission. If no transmission including beacon from AP within 500 ms., vehicle concludes that it moves away from the AP transmission range. The scanning process is resumed and running applications are notified. To further improve connection time, authors implemented an optimized scanning strategy and AP selection.

To hide intermittent connectivity and change of IP address, CTP uses a proxy to mediate between Internet hosts (server) and vehicle. Mainly the difference between normal TCP and CTP is that CTP session does not break when the IP address changes or path is disconnected. CTP end hosts maintain unique network-independent identifiers that allows CTP sessions to migrate seamlessly across APs and changing IP addresses. CTP exposes a reliable socket API to the application which provides notification feedback when connection appears or reappears. This feedback allows the node to continue transmission without an elaborate connection determination technique.

Bechler et al. introduced MCTP [41] a proxy based communication architecture for Internet access. Unlike Carbernet, MCTP allows multi-hop communication to increase the base station service area. Similar to ATCP, MCTP is located between TCP and network layers. The basic principle of MCTP is that it observes the feedback obtained from intermediate relay nodes about the IP packet flow between sender and receiver. It uses this feedback to improve the performance of TCP. ECN notification is used to indicate congestions detected by intermediate systems. The partition of the network is indicated by ICMP destination unreachable messages. This information is relevant for local communication between vehicles and vehicle to proxy. The communication between proxy and Internet server is based on standard TCP. Thus the difference between congestion and disconnection in wireless system is transparent to Internet host.

11. Open research problems

While several research and engineering efforts are made towards effective cross-layer solutions, there are several avenues that need more attention. We now describe some of those open research problems in the context of cross-layer protocols for VANETs.

- *Striking the balance between modularity and cross-layer design:* The main advantage of traditional layered protocol design is its ability to provide *modularity* and *transparency*, the implementation of protocols in individual layers can be changed and evolved in more or less independent manner. Cross-layer designs blur the gap between layers in order to facilitate fine-grain information exchange and to efficiently support wireless services. However, such a tighter integration may potentially defeat the benefits of modularity and may result in a fragile system. In the context of vehicular networks, effective message distribution via multi-hop communication often requires cooperation among the vehicles. Facilitating this cooperation among vehicles require information exchange across different protocol layers on each individual vehicle. Therefore, striking the balance between modularity and cross-layer design is even more important for vehicular networks. It may require application-specific solutions that are carefully designed by understanding the exact requirements and the nature of cross-layer design for vehicular networks in hand.
- *System stability*: Cross-layer design introduce interactions between layers that are not seen in traditional layered methods. Therefore, improper designs may result in unintended functional dependencies and they may lead the system into a state of instability [42]. The system stability is an important measure in VANETs due to the large-scale nature of the network with multiple source and destination pairs. In addition, the distribution of the vehicles in the network is often non-uniform, different road segments have sparse traffic and some other sections may have very dense vehicle traffic. Therefore, how messages are handled based on cross-layer interaction and how cross-layer implementation helps in improving such system performances must be carefully analyzed in VANETs.
- *Realistic physical layer and mobility modeling:* As evident from existing research described in earlier sections, many cross-layer designs, in one way or the other, aim to deal with the connectivity issues encountered in vehicular networks. In order to identify unintended interactions resulting from a cross-layer design, one must perform a thorough analysis of the design by considering several possible systematic and physical scenarios. Such an analysis demand strong theoretical models that capture realistic communication characteristics in the physical layer. Equally important are the mobility models that represent the movement of mobile nodes where their location, velocity, and acceleration change over time. Since the vehicle movement in VANETs is restricted to road segments, mobility models that incorporate road network topological constraints are very important in analyzing the performance of cross-layer designs.
- *Standardization of cross-layer designs:* Standardization of protocol design is required to facilitate compatibility, interoperability, and to be independent of single solutions. Existing communication standards such as IPv6 or WI–FI are not directly suitable for vehicular networks. This is because the underlying highly dynamic topological changes are unique and they severely affect the performance when we simply rely on existing protocol standards. However, cross-layer designs presented thus far are mainly application-specific, and they lack generality. As Kawadia and Kumar [42] pointed out, lack of standardized solutions leads several drawbacks, including the reduced performance. It is still unclear as to when and where different cross-layer approaches are beneficial in VANETs. While it is a significant challenge to standardize cross-layer designs, it can help in deeper understanding of potential issues, and in quick and efficient way to develop new protocols that target joint optimization of multiple layers in the stack.

References

[1] RITA Intelligent Transportation Systems (ITS), <http://www.its.dot.gov/index.htm/>.
[2] V. Srivastava, M. Motani, Cross-layer design: a survey and the road ahead, IEEE Communications Magazine 43 (12) (2005) 112–119.
[3] J. Camp, E. Knightly, Modulation rate adaptation in urban and vehicular environments: cross-layer implementation and experimental evaluation, in: J. Sangeetha (Ed.), Proceedings of the 14th ACM International Conference on Mobile Computing and Networking, ACM, 2008, pp. 315–326.

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[4] M. Vutukuru, H. Balakrishnan, K. Jamieson, Cross-layer wireless bit rate adaptation, ACM SIGCOMM Computer Communication Review 39 (4) (2009) 3–14.
[5] K. Chiu, R. Hwang, Y. Chen, Cross-layer design vehicle-aided handover scheme in VANETs, Wireless Communications and Mobile Computing (2009), doi:10.1002/wcm.861.
[6] D. Rawat, G. Yan, D. Popescu, M. Weigle, S. Olariu, Dynamic Adaptation of Joint Transmission Power and Contention Window in VANET, 2009, pp. 1–5.
[7] M. Artimy, W. Robertson, W. Phillips, Assignment of dynamic transmission range based on estimation of vehicle density, in: Proceedings of the 2nd ACM International Workshop on Vehicular Ad Hoc Networks, ACM, 2005, p. 48.
[8] G. Caizzone, P. Giacomazzi, L. Musumeci, G. Verticale, A power control algorithm with high channel availability for vehicular ad hoc networks, IEEE International Journal on Communications (ICC'05) 5 (2005) 3171–3176.
[9] M. Torrent-Moreno, P. Santi, H. Hartenstein, Distributed fair transmit power adjustment for vehicular ad hoc networks, 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks (SECON '06) 2 (2006) 479–488.
[10] C. Chigan, V. Oberoi, J. Li, Z. Wang, Rpb-macn: a relative position based collision-free mac nucleus for vehicular ad hoc networks, in: IEEE Globecom, 2006.
[11] N. Sofra, A. Gkelias, K. Leung, Link residual-time estimation for VANET cross-layer design, 2009, pp. 1–5.
[12] J. Singh, N. Bambos, B. Srinivasan, D. Clawin, Cross-layer multi-hop wireless routing for inter-vehicle communication, 2006, pp. 92–101.
[13] M. MENOUAR, M. Lenardi, F. Filali, A movement prediction based routing protocol for vehicle-to-vehicle communications, Communications, 2005.
[14] Y. Chen, Z. Xiang, W. Jian, W. Jiang, A Cross-layer AOMDV Routing Protocol for V2V Communication in Urban VANET, 2009, pp. 353–359.
[15] M. Marina, S. Das, Ad hoc on-demand multipath distance vector routing, ACM SIGMOBILE Mobile Computing and Communications Review 6 (3) (2002) 92–93.
[16] B. Jarupan, E. Ekici, PROMPT: a cross layer position-based communication protocol for delay-aware vehicular access networks, Ad Hoc Neworks (Elsevier) Journal Special Issue on Vehicular Networks, 2010.
[17] S. Barghi, A. Benslimane, C. Assi, A lifetime-based routing protocol for connecting VANETs to the Internet, 2009, pp. 1–9.
[18] H. Füßler, J. Widmer, M. Käsemann, M. Mauve, H. Hartenstein, Contention-based forwarding for mobile ad hoc networks, Ad Hoc Networks 1 (4) (2003) 351–369.
[19] G. Korkmaz, E. Ekici, F. Ozguner, A cross-layer multihop data delivery protocol with fairness guarantees for vehicular networks, IEEE Transactions on Vehicular Technology 55 (3) (2006) 865–875.
[20] B. Wiegel, Y. Gunter, H. Grossmann, Cross-Layer Design for Packet Routing in Vehicular Ad Hoc Networks, 2007, pp. 2169–2173.
[21] L. Bononi, M. Di Felice, A Cross Layered MAC and Clustering Scheme for Efficient Broadcast in VANETs, 2007, pp. 1–8.
[22] Z. Niu, W. Yao, Q. Ni, Y. Song, Study on QoS Support in 802.11e-based Multi-hop Vehicular Wireless Ad Hoc Networks, 2007, pp. 705–710.
[23] S. Eichler, C. Schroth, T. Kosch, M. Strassberger, Strategies for context-adaptive message dissemination in vehicular ad hoc networks, in: Proceedings of the 2nd International Workshop on Vehicle-to-Vehicle Communications (V2VCOM), Citeseer, 2006.
[24] G. Korkmaz, E. Ekici, F. Özgüner, Supporting real-time traffic in multihop vehicle-to-infrastructure networks, Transportation Research Part C (2010).
[25] G. Korkmaz, E. Ekici, F. Özgüner, Ü. Özgüner, Urban multi-hop broadcast protocol for inter-vehicle communication systems, in: Proceedings of the 1st ACM International Workshop on Vehicular Ad Hoc Networks, 2004, pp. 76–85.
[26] G. Korkmaz, E. Ekici, F. Ozguner, Black-burst-based multihop broadcast protocols for vehicular networks, IEEE Transactions on Vehicular Technology 56 (5 Part 2) (2007) 3159–3167.
[27] A. Nasri, M. Fathy, R. Hajisheykhi, A Cross Layered Scheme for Broadcasting at Intersections in Vehicular Ad Hoc Networks, 2009, pp. 13–17.
[28] A. Majeed, S. Razak, N. Abu-Ghazaleh, K. Harras, TCP over multi-hop wireless networks: the impact of MAC level interactions, in: Proceedings of the 8th International Conference on Ad-Hoc, Mobile and Wireless Networks, Springer, 2009, p. 15.
[29] E. Hamadani, V. Rakocevic, A cross layer solution to address tcp intra-flow performance degradation in multihop ad hoc networks, Journal of Internet Engineering 2 (1) (2008).
[30] G. Holland, N. Vaidya, Analysis of TCP performance over mobile ad hoc networks, Wireless Networks 8 (2) (2002) 275–288.
[31] J. Liu, S. Singh, ATCP: TCP for mobile ad hoc networks, IEEE Journal on Selected Areas in Communications 19 (7) (2001) 1300–1315.
[32] R. Schmilz, A. Leiggener, A. Festag, L. Eggert, W. Effelsberg, Analysis of path characteristics and transport protocol design in vehicular ad hoc networks, in: IEEE 63rd Vehicular Technology Conference, 2006 (VTC 2006-Spring), vol. 2, 2006.
[33] V. Namboodiri, L. Gao, Prediction-based routing for vehicular ad hoc networks, IEEE Transactions on Vehicular Technology 56 (4 Part 2) (2007) 2332–2345.
[34] X. Chen, H. Zhai, J. Wang, Y. Fang, TCP performance over mobile ad hoc networks, Electrical and Computer Engineering, Canadian Journal of 29 (1) (2004) 129–134.
[35] B. Karp, H. Kung, GPSR: greedy perimeter stateless routing for wireless networks, in: Proceedings of the 6th Annual International Conference on Mobile Computing and Networking, 2000, pp. 243–254.
[36] L. Zhou, B. Zheng, B. Geller, A. Wei, S. Xu, Y. Li, Cross-layer rate control, medium access control and routing design in cooperative VANET, Computer Communications 31 (12) (2008) 2870–2882.
[37] M. Drigo, W. Zhang, R. Baldessari, L. Le, A. Festag, M. Zorzi, Distributed rate control algorithm for VANETs (DRCV), in: VANET '09: Proceedings of the sixth ACM international workshop on VehiculAr InterNETworking, ACM, New York, NY, USA, 2009, pp. 119–120.
[38] A. Chen, B. Khorashadi, D. Ghosal, C. Chuah, Impact of transmission power on TCP performance in vehicular ad hoc networks, in: Proceedings of the 4th IEEE/IFIP Wireless On-demand Networks and Services, 2007, pp. 65–71.
[39] B. Khorashadi, A. Chen, D. Ghosal, C. Chuah, M. Zhang, Impact of transmission power on the performance of UDP in vehicular ad hoc networks, in: IEEE International Conference on Communications (ICC), 2007.
[40] J. Eriksson, H. Balakrishnan, S. Madden, Cabernet: vehicular content delivery using WiFi, in: MobiCom '08: Proceedings of the 14th ACM International Conference on Mobile Computing and Networking, ACM, New York, NY, USA, 2008, pp. 199–210.
[41] M. Bechler, S. Jaap, L. Wolf, An optimized tcp for Internet access of vehicular ad hoc networks, Lecture Notes in Computer Science 3462 (2005) 869–880.
[42] V. Kawadia, P. Kumar, A cautionary perspective on cross-layer design, IEEE Wireless Communications 12 (1) (2005) 3–11.

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