SPECIAL SECTION ON RESOURCE MANAGEMENT IN VEHICULAR AD-HOC NETWORKS: ENERGY MANAGEMENT, COMMUNICATION PROTOCOL AND FUTURE APPLICATIONS

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# Routing in Vehicular Ad-hoc Networks: A Survey on Single- and Cross-Layer Design Techniques, and Perspectives

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**ABSTRACT** Vehicular ad-hoc networks (VANETs) play an important role in intelligent transportation systems for improving security and efficiency. However, due to dynamic characteristics of the vehicular environment, routing remains a significant challenge in the VANETs. While single-layer routing protocols based on the traditional layered open systems interconnection (OSI) model are readily available, they often do not make use of important parameters at the lower three layers of the OSI model when making routing decision. Hence, for making optimal routing decision to gain superior network performance, there is a need to design cross-layer routing that allows information exchange between layers. In this article, a survey of the existing single-layer and cross-layer routing techniques in VANETs is presented, emphasizing on cross-layer routing protocols that utilize information at the physical, medium access control and network layers as routing parameters. An overview and challenges of routing are given, followed by a brief discussion of single-layer routing with more focus on geographic routing. Cross-layer routing protocols are then discussed in detail. The article then elaborates on some advantages and disadvantages of the existing routing approaches, cross-layer routing parameter selection and cross-layer design issues. Finally, some open research challenges in developing efficient routing protocols in the VANETs are highlighted.

**INDEX TERMS** Cross-layer design, routing protocols, single-layer, vehicular ad-hoc networks (VANETs).

## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| A-STAR | Anchor-based street and traffic aware routing |
| AMGR | Adaptive multipath geographic routing |
| AODV | Ad-hoc on-demand distance vector |
| AOMDV | Ad-hoc on-demand multipath distance vector |
| CAR | Connectivity-aware routing |
| CCH | Control channel |
| CLDB | Cross-layer decision based |
| CLWPR | Cross-layer, weighted, position-based routing |
| CN | Common neighborhood |
| CnF | Carry and forward |
| CPQ | Complete path quality |
| CQI | Channel quality indicator |
| DBD | Distributed beaconless dissemination |
| DPPR | Driving path predication based routing |
| DSRC | Dedicated short range communications |
| EEG | Electroencephalogram |
| ETE | End-to-End |
| GPS | Global positioning system |
| GPSR | Greedy perimeter stateless routing |
| GPSR-L | Greedy perimeter stateless routing with lifetime |
| GSR | Geographic source routing |
| GyTAR | Greedy traffic-aware routing |
| HRN | Hyper relay node |
| IDM | Information distribution message |
| IG | Improved geographical |
| INS | Inertial navigation system |
| IPv6 | Internet Protocol version six |

| | |
|---|---|
| ITS | Intelligent transportation systems |
| LBRP | Lifetime-aware beacon-less routing protocol |
| LD-CROP | Location- and delay-aware cross-layer communication in V2I multihop vehicular networks |
| LIAITHON | Location-aware multipath video streaming |
| LIAITHON+ | An upgraded version of LIAITHON |
| LLC | Logical link control |
| LUT | Last updated time-stamp |
| MAC | Medium access control |
| MANET | Mobile ad-hoc network |
| MHCLD | Multi-hop cross-layer decision based |
| MLME | MAC layer management entity |
| MORA | Movement-based routing algorithm |
| MoVe | Motion vector |
| MP2R | Mobility prediction progressive routing |
| MPR | Multipoint relay |
| MT | Microtopology |
| MURU | Multi-hop routing protocol for urban vehicular ad-hoc networks |
| NET | Network layer |
| OBU | On-board unit |
| OLSR | Optimized link state routing |
| OSI | Open Systems Interconnection |
| PDR | Packet delivery ratio |
| PHY | Physical layer |
| PLME | Physical layer management entity |
| PROMPT | Cross-layer position-based communication protocol for delay-aware vehicular access networks |
| QoS | Quality of service |
| R-AOMDV | Cross-layer ad-hoc on-demand multipath distance vector with retransmission counts metric |
| RIVER | Reliable inter-vehicular routing |
| RSSI | Received signal strength indicator |
| RSU | Roadside unit |
| SAMQ | Situation-aware multiconstrained QoS |
| SBRS-OLSR | Signal strength assessment based route selection for OLSR |
| SCH | Service channel |
| SCRP | Stable connected dominating sets based routing protocol |
| SINR | Signal-to-interference-plus-noise ratio |
| SLBF | Self-adaptive and link-aware beaconless forwarding |
| SNR | Signal-to-noise ratio |
| SRPMT | Street-centric routing protocol based on MT |
| SWF-GPSR | Speed wave forecasted-GPSR |
| TCP/IP | Transmission Control Protocol/Internet Protocol |
| TOPOCBF | Road topology-aware contention-based forwarding |
| UDP | User Datagram Protocol |
| V2I | Vehicle-to-Infrastructure |
| V2V | Vehicle-to-Vehicle |
| VADD | Vehicle-assisted data delivery |
| VANET | Vehicular ad-hoc network |
| VIRTUS | Video reactive tracking-based unicast |
| WAVE | Wireless access in vehicular environments |
| WME | WAVE management entity |
| WSMP | WAVE short-message protocol |

## I. INTRODUCTION

Recent advancements in wireless communication technologies and the increase in the number of road accidents have led to the development of transport safety approaches in intelligent transportation systems (ITS) [1]. The ITS, aiming to improve the safety and efficiency of transportation systems, supports two types of wireless communications: long-range and short-range. Long-range communication mainly relies on the existing infrastructure networks, such as cellular networks. Short-range communication, on the other hand, is based on emerging technologies such as IEEE 802.11 variants, and forms an ad-hoc network that comprises mobile vehicles and stationary roadside equipments, collectively referred to as vehicular ad-hoc networks (VANETs) [2]. In VANETs, vehicles are equipped with wireless sensors and on-board units that enable wireless connectivity among them [3].

VANETs are considered as a sub-class of mobile ad-hoc networks (MANETs) [4], due to some similar characteristics they possess such as infrastructure independence, self-organization and management, low bandwidth and short radio transmission range. However, existing MANET routing protocols cannot be applied directly in VANETs, and when deployed in VANET environments result in poor route convergence, low communication throughput and frequent route disruptions. This is mainly due to the high mobility of vehicles and the dynamic network topology of VANETs [2], [5], [6]. Other distinguishing characteristics of VANETs from MANETs are as follows: 1) the movement of vehicles is limited to road topology, 2) the vehicles can afford significant computing, communication and sensing capabilities, and 3) the vehicles can provide continuous transmission power themselves to support these functions. In VANETs, network topology is highly dynamic due to fast movement of vehicles, and topology is often obstructed by road structure. Vehicles are likely to encounter many obstacles such as traffic lights, buildings, trees, and road junctions, which result in poor channel quality and connectivity. Therefore, protocols developed for traditional MANETs fail to provide reliability, low latency, and high throughput performance in VANETs. The distinct features and challenging characteristics of VANETs have drawn attention from both academia and industry [7].

### A. MOTIVATION

Although a significant amount of work has been done in VANETs, problems like short communication time, shadowing and Doppler effect, due to above mentioned unique characteristics of VANETs, make the routing difficult [8]. According to [7], providing good delay performance under the constraints of vehicular speed and high dynamic topology is still a major issue. One reason for this is that majority of routing protocols developed for VANETs are based on single-layer approach that does not offer sufficient flexibility to adequately support the needs of wireless communication in highly dynamic vehicular networks, and hence might not satisfy the stringent quality of service (QoS) requirements. Effective handling of this issue requires information exchange between layers (in order to jointly optimize different layers) so as to achieve better network performance, thereby signifying the need to use cross-layer design. Cross-layer design approach exploits the dependency between protocol layers to achieve desirable performance gains [2].

While there exist a significant survey work on VANETs, most of them do not exclusively focus on cross-layer routing protocols that make use of the routing parameters in the lower three layers of the Transmission Control Protocol/Internet Protocol (TCP/IP) or Open Systems Interconnection (OSI) model [9], i.e., at the physical (PHY), medium access control (MAC) and network (NET) layers. Prior research has shown that leveraging information related to wireless channel characteristics typically available at the PHY and MAC layers while making routing decisions may improve the robustness of the routing protocols against issues such as congestion and interference, thus allowing better overall network performance [2], [10], [11].

### B. EXISTING WORK

Survey work in [1], [3], [7], and [12] give detailed overviews of VANETs. Work in [13] and [14] discuss the characteristics and challenges of routing in VANETs, general classification of routing protocols, and some existing single-layer routing protocols. In-depth reviews of position-based and broadcast single-layer routing protocols in VANETs are given in [15], [16], and [17]. A recent survey work in [18] concentrates on the protocol stack and application requirements of VANETs and also an overview of the current state-of-the-art about data communication in VANETs. In [2], on the other hand, although the authors have briefly explained some of the cross-layer routing mechanisms, their focus is toward all kinds of cross-layer communication solutions employed in VANET.

### C. KEY HIGHLIGHTS

In this article, we present a survey of the existing single-layer and cross-layer routing techniques in VANETs, emphasizing the cross-layer protocols that utilize information from the PHY, MAC and NET layers as routing parameters. The key highlights of the article are as follows:

- An overview of VANETs is given, including a brief description of their (i) applications in ITS, (ii) system architecture, (iii) networking requirements, and (iv) unique characteristics and challenges.
- A review of the differences between VANET and MANET followed by a discussion of various routing challenges and design alternatives specific to VANET.
- Two major categories of single-layer routing protocols are presented, focusing more on geographic routing. Topology-based routing finds less scope in vehicular environments due to its degraded network performance [12], [13]. Some of the problems incurred by topology-based routing in VANETs are discussed in Section IV-A. This is followed by a brief survey of various geographic routing protocols with classifications based on two different perspectives: routing mechanism and geographic metric used.
- A detailed survey on various cross-layer routing protocols, covering their main mechanisms, cross-layer routing parameters and possible limitations.
- A discussion involving the trade-offs between various routing methods, cross-layer routing parameters and cross-layer designs.
- Finally, the article presents some of the open research issues in single-layer and cross-layer routing.

The rest of the article is organized as follows. Section II gives a brief overview of VANET including its applications, architecture, requirements and challenges. Section III highlights the challenges of routing in VANET by first reviewing the differences between VANET and MANET, and then VANET specific routing challenges and design alternatives. Section IV classifies single-layer routing protocols in VANET into topology-based and geographic routing, followed by further classification of geographic routing based on two perspectives. A concise summary of various geographic routing protocols is then presented. Section V reviews the concept of cross-layer routing, highlights the limitations of single-layer routing approaches, cross-layer routing parameters and then explains the existing cross-layer routing approaches in VANETs. Section VI highlights some open research issues related to the routing approach, cross-layer routing parameter selection and cross-layer design in VANETs. Finally, Section VII concludes the article with a summary emphasizing some key points in developing efficient routing protocols for VANETs. The complete content organization of the article is shown in Fig. 1.

## II. OVERVIEW OF VEHICULAR Ad-hoc NETWORKS

### A. APPLICATIONS

VANET applications can be classified into four categories: safety, public service, driving improvement, and comfort services [12], [19].

#### 1) SAFETY

Road safety applications send warning messages to drivers about dangerous situations in order to make driving safer. Serious situations may include dangerous road features, e.g. curves, abnormal traffic and road conditions, and danger of collision [19]. According to the vehicular safety communication consortium, there are eight safety related

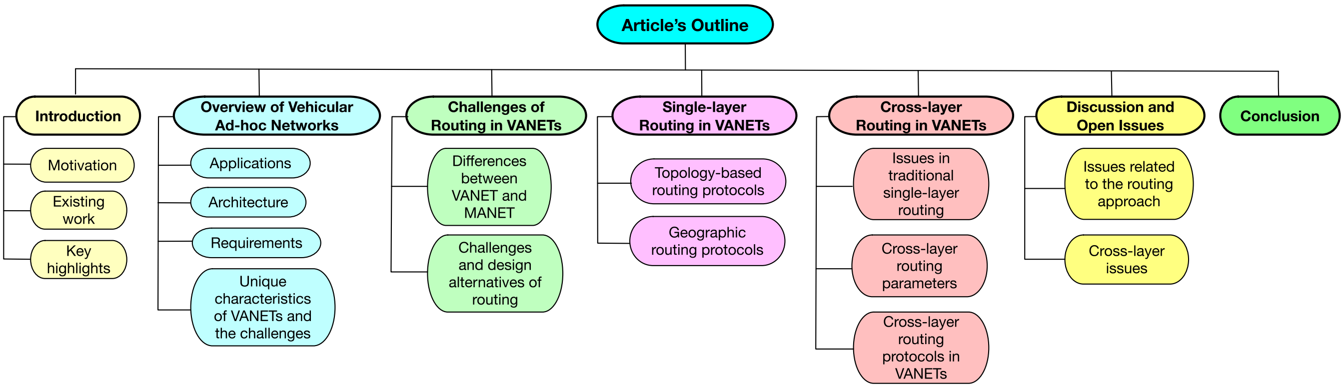


**FIGURE 1.** **Content organization of the article.**

applications: pre-crash sensing, curve speed, lane change, traffic signal violation, emergency electronic brake light and cooperative forward collision alert, stop sign movement and left turn assistant. As mentioned in [20], one possible future application is to collect driver's behavioral and physiological information recorded by sensors located at various parts of the driver's body through in-vehicle communication, and then, transmit the data to a monitoring center using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The driver's behavioral information, such as facial expression and blink rate, and physiological signals, such as heart-rate variability and electroencephalogram (EEG) signals, give vital health related information about the driver's fatigue and drowsiness condition [20]. Warning signals can be sent to both the driver and the authorities in case of driver's abnormal health conditions. Apart from this, other safety related applications, such as overtaking vehicle warning, emergency vehicle warning, hazardous location notification and control loss warning, are described in [12]. Since these applications are critical, their messages should have a deep penetration across the entire network and must be reliably delivered within a short time [3].

#### 2) PUBLIC SERVICE

These applications support the work of public services such as police, ambulance and other emergency units. Usage of virtual sirens or signal preemption enables the emergency units to reach their destination faster. Other public services include traffic surveillance applications such as electronic license plate [19].

#### 3) DRIVING IMPROVEMENT

Such applications aid in improving traffic efficiency and management. Driving improvement applications update local information and street maps, thereby smoothening the vehicle traffic flow and upgrading the level of traffic coordination and assistance [12]. Two applications that contribute to the improvement of the driver efficiency are discussed in [18]. The first application concentrates on making the traffic flow at crossroads and intersections smoother by making use of virtual traffic lights, while the second application aims at providing the driver with the least congested route toward destination.

#### 4) COMFORT SERVICES

These services provide infotainment applications to drivers and passengers, either by enabling passengers to communicate with each other or by offering entertainment services such as internet connectivity and media downloading. These applications are also used for commercial purposes such as advertisements and electronic toll [3].

### *B. ARCHITECTURE*

This subsection gives a brief information about the system architecture of VANETs. It first introduces the communication architecture, where different types of interactions in vehicular environment are highlighted, followed by a review of the layered architecture.

#### 1) COMMUNICATION ARCHITECTURE

Communication in vehicular environment as described in [7] can be categorized into four types: in-vehicle, V2V, V2I communications and vehicle to broadband cloud communication. In-vehicle communication between on-board units (OBUs) such as sensors is required inside the vehicle to facilitate various driver and public safety applications by allowing the detection of the vehicle's performance and especially driver's fatigue and drowsiness [20]. V2V takes place between vehicles and can provide a data exchange platform for the drivers to share information and warning messages so as to expand driver assistance. V2I is an interaction between the vehicle and the roadside unit (RSU), and can be used for enabling real-time traffic or weather updates for drivers and to provide environmental sensing and monitoring. Vehicle to broadband cloud communication involves the exchange of messages between vehicles and broadband cloud, and can be used for active driver assistance and vehicle tracking.

#### 2) LAYERED ARCHITECTURE IN VANETs

Wireless access in vehicular environments (WAVE) architecture comprises two main protocols, namely, IEEE 802.11p [21] and IEEE 1609.x. Fig. 2 shows the WAVE architecture.

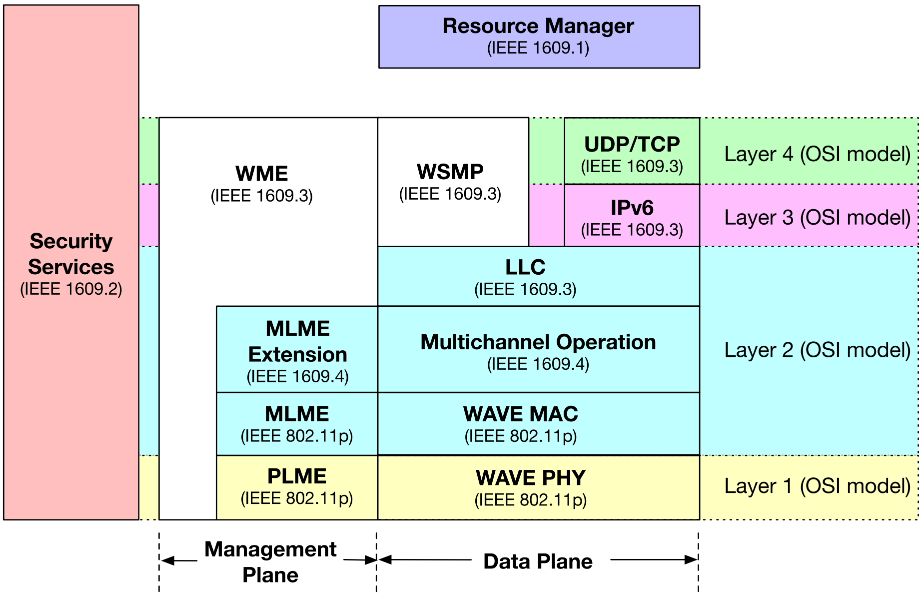


**FIGURE 2.** WAVE architecture, based on [22].

IEEE 802.11p is an approved amendment to the IEEE 802.11 standard [23] that incorporates WAVE and functions primarily at the PHY and MAC layers of the stack. The allocation of dedicated short range communications (DSRC) spectrum band [24] in the United States, which aims to develop public safety applications and improve traffic flow, has led to the kick off of this standard. IEEE 802.11p enables WAVE-compliant stations to function in a highly dynamic environment and allows message exchange without the need to join a base service set. The 802.11 MAC controlled WAVE interface functions and signaling techniques are also defined by this standard [25]. IEEE 802.11p depends on one control channel (CCH), which is reserved for transporting system control and safety messages, and 4 to 6 service channels (SCHs) used for transmission of non-safety data packets [26].

IEEE 1609 is an upper layer standard planned to work with IEEE 802.11p and represents a family of standards that function in the middle layers of the protocol stack to flexibly support safety applications in VANETs. The family consists of four standards: IEEE 1609.1 [27], 1609.2 [28], 1609.3 [29] and 1609.4 [30]. IEEE 1609.1 enables applications to establish communication between OBUs mounted in vehicles and remote sites through RSUs using a specific WAVE application known as resource manager. Secure message formats and their processing by WAVE devices is specified by the IEEE 1609.2 standard. The processing aims at securing application and WAVE management messages. The administrative operations that support main security functions are also specified. WAVE short-message protocol is used by applications to transfer short messages to all intended parties in time, whereas IPv6 is used for less demanding applications. IEEE 1609.3 assists in establishing wireless communication among vehicles and between vehicles and RSUs, by specifying services that operate at the NET and transport layers. IEEE 1609.4 enables multichannel wireless communication between WAVE devices by defining supporting MAC sublayer services and functions.

### C. REQUIREMENTS

Authors in [12] provide a brief explanation of vehicular networking requirements while classifying the requirements based on strategy, system capability and economical terms. In general, to enable vehicular networking, vehicles and static infrastructure alongside the road must fulfill some basic requirement. They must have a set of wireless transmitter and receiver on-board, and should be capable of performing V2V and V2I communications. They must possess the ability to disseminate information in various modes such as unicast, broadcast, multicast and geocast. Other than these requirements, security and privacy must also be satisfied. Although navigational tools such as global positioning system (GPS) and street maps are not a must, they are highly encouraged since location information would provide significant assistance in VANETs. Other than the system requirements, vehicular networks also have certain performance requirements such as high packet delivery ratio (PDR) and low delay, especially for safety applications [31].

### D. UNIQUE CHARACTERISTICS OF VANETs AND THE CHALLENGES

Specific characteristics of vehicular environments pose significant challenges for efficient communication in VANETs. Some of these, derived from [19], [32], are explained here.

#### 1) MOBILITY

Nodes in VANET environment can be RSUs, vehicles in traffic jam (stationary or almost stationary) or fast moving vehicles (velocity up to 200 km/hr). These extreme cases have their own challenges in the communication system between the nodes. In case of high velocity, the mutual communication window will be small (few seconds) due to small transmission range. Also, for high relative velocity, the communication system has to cope with the Doppler effect, frequent link failures, wastage of network bandwidth, and high end-to-end (ETE) delay. For the other extreme cases (slow or no mobility), although nodes have high period of message exchange, they must deal with the problems related to high vehicular traffic density such as frequent data collision, channel fading, message dropping due to expired waiting time, and other interference problems.

#### 2) MOVEMENT PATTERN

Node movement is not arbitrary but follows a predefined path (roads). However, different roads have different characteristics. Urban roads are denser in nature, with many vehicles, buildings and other obstacles when compared to rural and highway roads. These variations in characteristics may also pose some challenge for efficient communications. For instance, highway roads are highly ordered whereas the urban roads are the opposite.

#### 3) TRAFFIC DENSITY

A node may be in high density network, i.e., in a traffic jam, or in low density network, i.e., on a highway with no or very few vehicles around. In case of low density, instead of immediate message forwarding, an advance information message dissemination using store-and-forward message must be done. Also, the same message may be repeated by the same vehicle multiple times. In case of high density, the opposite must be achieved with only selected vehicles allowed to send repeated messages. Node density not only depends on the road but also on time. Node density is usually high during day hours when compared to night time.

#### 4) HETEROGENEITY

Different nodes have different characteristics in VANETs depending upon their applications. They may be stationary, such as RSUs, or moving, such as vehicles. In addition, they may be categorized into different levels based on their application requirements. For instance, vehicles can be classified into private, authority and maintenance vehicles whereas RSUs can be those that emit data or those that are equipped with complete ad-hoc features. Also, unlike vehicles, RSUs do not require a privacy feature. Hence, a VANET system must provide services based on requirements of a node.

## III. CHALLENGES OF ROUTING IN VANETs

### A. DIFFERENCES BETWEEN VANET AND MANET

Routing still remains a significant research issue in VANETs [13]. The aim of VANET routing protocol is to make use of intermediate vehicles as relays in order to deliver data packet to the intended recipient. Vehicular networks are different from other ad-hoc networks such as MANETs, and have their own constraints that put significant challenge for the routing, as mentioned in section II-D. However, they also have certain features, such as constrained mobility and access to positional information, that offer support while routing. The differences between VANET and MANET, adapted from [14], [33]–[35], are highlighted in Table 1.

**TABLE 1.** Differences between VANET and MANET, based on [14], [33]–[35].

| Parameter | VANET | MANET |
|---|---|---|
| Network size | Large | Medium |
| Node mobility | High | Low |
| Movement pattern | Regular | Random |
| Energy limitation | Very low | High |
| Computation power | High | Low |
| Memory capacity | High | Low |
| Location dependency | Very high | Low |
| Localized operation | More often | Less often |

### B. CHALLENGES AND DESIGN ALTERNATIVES OF ROUTING

It is thus required to design routing protocol that takes into consideration the challenges and characteristics of the vehicular network. Some of the technical challenges and design alternatives are as follows [13], [14], [19], [36]:

#### 1) SCALABILITY

One of the major characteristics of VANETs is scalability [14]. Hence, the performance of the routing protocol must have minimum impact on varying number of vehicles in the network [19]. This is achievable if the protocol is capable of performing localized operations where routing decisions taken by a node are solely based on information available in its vicinity. This eliminates the need for the node to know the topology of the entire network, thereby reducing the control overhead.

#### 2) NEIGHBORHOOD DISCOVERY

One of the elementary part of the routing protocol is neighborhood discovery, which can be done either during route establishment or by sending one hop control messages called beacons. Usage of small periodic interval for beaconing may result in increased control overhead, while large periodic interval for beaconing implies stale neighborhood information. Hence, a proper selection of periodic interval for beaconing offering good trade-off between control overhead and updated information is required. Some schemes use adaptive beaconing [37] based on certain characteristics of the vehicular environment such as mobility and density. Another recent and more appealing approach is the beaconless approach [38], [39], which involves reactive discovery of neighbors during forwarding of data packets.

#### 3) DATA FORWARDING

Traditional ad-hoc routing protocols maintain routing tables that contain information of next hop to reach the destination based on certain criteria. Although these kinds of routing protocols have been implemented in VANETs, they result in degraded performance, especially in highly dynamic environments [13]. A possible solution to this is to route data on per hop basis, where a forwarding node routes the data packet according to its neighborhood at the exact time of forwarding the message.

#### 4) UNEVEN VEHICLE DENSITY

The vehicular environment also faces the issue of uneven vehicle density, where some regions may have sparse traffic conditions while others may be dense [19]. The routing protocol needs to adapt to the varying traffic density conditions. In case the region is heavily congested, the protocol must be capable of finding a path offering minimum congestion. In sparse traffic conditions, a vehicle can store the message until a suitable forwarding opportunity appears. Moreover, it would be preferable to have an adaptive scheme [40] that changes its operation mode based on the traffic condition.

#### 5) USE OF POSITIONAL INFORMATION

Vehicles in VANET have access to positional information through navigational tools such as GPS. This information can offer significant advantages to routing solutions [16]. It is highly encouraged for routing protocols to take into account the positional information while selecting path and neighbors as these will further assist in enhancing the routing performance.

#### 6) PREDICTION OF FUTURE POSITIONS

The constrained movement pattern and the access to positional information allow a vehicle to predict future positions. This information can assist the protocol to make efficient routing decisions [41]. However, care must be taken in the prediction process as inaccurate information may lead to selection of a non-optimal path.

The next section classifies some well-known routing protocols into various categories and gives brief description of each.

## IV. SINGLE-LAYER ROUTING IN VANETs

The classification of routing protocols in VANETs depends on a number of factors. Most of the routing protocol classification is based on information dissemination mode. Authors in [13] and [33] classified the routing protocols into topology-, position-, cluster-, broadcast- and geocast-based routing. A more holistic classification was presented in [14], where the major classification was based on the type of communications (V2V and V2I). VANET routing protocols were also classified based on the type of information they use [36]. Our classification of the VANET routing protocols is based on [42] and involves two major categories: Topology-based routing and Geographic routing.

### *A. TOPOLOGY-BASED ROUTING PROTOCOLS*

Topology-based routing protocols use the link information in order to forward data packets. Here, a route is established through control packets prior to data transmission. Topology-based routing protocols are further classified into proactive, reactive and hybrid protocols.

#### 1) PROACTIVE ROUTING

A proactive routing protocol establishes the routing path based on shortest path algorithm, and then maintains the path by storing routing information associated with nodes in a table form. These tables are shared between neighboring nodes and are updated when a change in the network topology occurs. Although this protocol achieves low latency, it occupies a major part of accessible bandwidth for maintaining unused routes. Also, the protocol does not respond well to link failures and, hence, is not suitable for VANETs [14], [33].

#### 2) REACTIVE ROUTING

Reactive routing protocol, also known as on-demand routing, determines routing path on requirement and maintains solely routing paths that are currently in use. The protocol consumes less bandwidth, has low memory requirement, and responds well to link failures. However, on-demand route finding results in high latency [33].

#### 3) HYBRID ROUTING

Hybrid ad-hoc routing combines features of proactive and reactive techniques to minimize routing overhead and delay during the route discovery process. However, hybrid protocols do not work well under high mobility conditions and frequent topological changes [14], [33].

Since the vehicular environment is highly mobile, traditional topology-based routing protocols do not perform well in dynamic network topologies due to their poor route convergence and low communication throughput [13]. In [43], the performance of a well-known topology-based routing protocol namely ad-hoc on-demand distance vector (AODV) [44] was tested with six vehicles and it was noted that AODV performed poorly in establishing long routes. Also, in [45] it was highlighted through simulation results that routes found out by conventional topology-based routing protocols become invalid even prior to getting fully established. Another issue with traditional routing protocols is the significant overhead caused during route discovery and maintenance [12]. Overall, topology-based routing protocols find less scope in VANETs and are more suitable for small scale networks with few hops between a source and its destination. Thus, we limit the focus of the survey of single-layer routing protocols to geographic routing.

### *B. GEOGRAPHIC ROUTING PROTOCOLS*

Vehicle movement in VANETs is generally bidirectional, limited by road structure and any location related information could be vital while making a routing decision. Recent advancements in self-configuring localization mechanisms and the wide-spread adoption of GPS have paved way for geographic routing. Such routing strategy makes use of geographical location information obtained from street maps, traffic models or navigational systems on board, and has been identified as a more promising routing technique for VANETs. Authors in [46] showed that the usage of emaps while making routing decision improved the packet reception rate. Furthermore, unlike topology-based routing, the geographic routing does not maintain routing tables and the next best hop is selected based on location related information. This approach enables geographic routing protocols to route efficiently even in highly mobile conditions. We have further classified geographic routing protocols based on two perspectives: routing mechanism and geographic metric used. As an in-depth analysis of various geographic routing protocols already exists in [15] and [16], we present a concise summary of some of the well-known and most recent protocols in Table 2, highlighting their classification based on the two aforementioned perspectives and their main routing approach.

#### 1) CLASSIFICATION BASED ON ROUTING MECHANISM

Routing mechanism can be categorized depending upon whether or not a routing protocol uses beacon messages. These messages are typically used by vehicles to periodically exchange information among neighbors prior to data transmission. The categorization is as follows:

- **Beacon-based:** This category includes the routing protocols [41], [47]–[57], [62], [63], [65]–[67] that make use of beacon messages to update information among neighbors. These protocols are sender-based, since a sender already knows its immediate neighbors, and thereby selects the best neighboring node toward destination.
- **Beaconless-based:** Also known as receiver-based, routing protocols [38], [39], [58], [59], [61], [64] in this category do not depend upon exchange of beacon messages. Here, receiving nodes decide whether or not to take part in the routing process. Generally, the receiver-based techniques have two aspects: forwarding and waiting time criteria. The forwarding criteria decides whether or not the receiving nodes will participate in the ongoing communication. Once the receiving nodes satisfy a forwarding criteria, they contend to be a next hop forwarder based on timer-based criteria.

#### 2) CLASSIFICATION BASED ON GEOGRAPHIC METRIC

The geographic metric used by the routing protocol could be static positional information such as location coordinates or information related to mobility of vehicles such as speed, direction etc. Based on these, we have classified the routing protocols as follows:

- **Location-based:** This category of routing protocols [47], [48], [53], [54], [57]–[61], [63] makes use of static positional information for making routing decisions, where every node knows the location coordinates of its own, its neighboring nodes and in some cases the coordinates of the destination. The positional information is available through preloaded maps, GPS or any other navigational system. In case of unavailability of GPS signal or maps, various localization services are also used to estimate the position of the vehicles.
- **Mobility-based:** Routing based only on static positional information of nodes might not be efficient due to high mobility of vehicles in VANETs. Routing protocols [38], [39], [41], [49]–[51], [55], [56], [62], [64]–[67] under this category consider mobility related information such as speed and other movement characteristics of vehicles, while making routing decisions to further facilitate the development of robust and stable data forwarding under high mobility conditions. Extracting this kind of information requires defining a vehicular mobility model that offers an accurate and realistic description of the movement of vehicles.

## V. CROSS-LAYER ROUTING IN VANETs

### A. ISSUES IN TRADITIONAL SINGLE-LAYER ROUTING

Single-layer routing is based on the strict layered approach, where there is not enough flexibility to adequately support the needs of wireless communications, especially in highly dynamic vehicular networks, and might not satisfy the stringent QoS requirements. Traditional routing approaches optimize performance measures such as ETE delay and PDR without considering explicitly whether a wireless channel can support the transmission or a particular node has sufficient space in its buffer to store a data packet for the duration of processing time. This can result in retransmission requests from other nodes, thereby making the network congested, and in turn may lead to poor network performance [2], [6], [68]. Some of the common issues that usually occur in the single-layer routing approaches are highlighted as follows:

#### 1) CONGESTION

This occurs mostly when limited buffer space of a node is full, which in turn leads to packet dropping. It may also occur in dense areas, where multiple nodes may send data packets simultaneously, leading to frequent collision and in turn to throughput reduction and packet loss [69]. Multiple routes discovered based on single-layer approach may contain some common nodes along the ETE path from source to destination. These common nodes may become a bottleneck during the course of communication and then causing congestion.

#### 2) INTERFERENCE

This usually occurs when unwanted signals from other transmissions get added up with transmitting signals. Interference can be categorized into two types: *intra-flow interference* and *inter-flow interference*. Intra-flow interference occurs when transmission between neighboring nodes in a path interfere with each other. Inter-flow interference, also called *path cou-*

**TABLE 2.** Various geographic routing protocols in VANETs and their routing approach.

| Protocol | Classification Criteria | | Approach |
|---|---|---|---|
| | *Routing Mechanism* | *Geographic Metric* | |
| Greedy perimeter stateless routing (GPSR) [47] (2000) | Beacon-based | Location-based | Greedy and perimeter based shortest path forwarding |
| Anchor-based street and traffic aware routing (A-STAR) [48] (2004) | Beacon-based | Location-based | Traffic aware routing involving greedy packet forwarding through junctions |
| Motion vector (MoVe) [49] (2005) | Beacon-based | Mobility-based | Vehicle's velocity based shortest path selection |
| Movement-based routing algorithm (MORA) [50] (2006) | Beacon-based | Mobility-based | Hop count and vehicle's movement information based distributed routing |
| Multi-hop routing protocol for urban vehicular ad-hoc networks (MURU) [51] (2006) | Beacon-based | Mobility-based | Velocity and trajectory information based robust path selection |
| Connectivity-aware routing (CAR) [52] (2007) | Beacon-based | Location-based | Connection establishment using preferred group broadcast and advanced greedy forwarding based packet forwarding |
| Greedy traffic-aware routing (GyTAR) [53] (2007) | Beacon-based | Location-based | Anchor-based routing utilizing vehicular traffic density |
| Geographic source routing (GSR) [54] (2003) | Beacon-based | Location-based | Reactive location service based next hop finding and route selection using digital maps |
| Greedy perimeter stateless routing with lifetime (GPSR-L) [55] (2008) | Beacon-based | Mobility-based | Lifetime based modified GPSR |
| Vehicle-assisted data delivery (VADD) [56] (2008) | Beacon-based | Mobility-based | Enhanced carry and forward mechanism with mobility prediction |
| Reliable inter-vehicular routing (RIVER) [57] (2012) | Beacon-based | Location-based | Network reliability based routing involving optimized greedy strategy for data forwarding |
| Video reactive tracking-based unicast (VIRTUS) [58] (2012) | Beaconless | Location-based | Beaconless receiver-based approach to support video streaming |
| Location-aware multipath video streaming (LIAITHON) [59] (2012) | Beaconless | Location-based | Enhancement over VIRTUS offering two path solution |
| Road topology-aware contention-based forwarding (TOPOCBF) [60] (2013) | Beacon-based | Location-based | Contention-based routing based on multihop connectivity of road segment |
| An upgraded version of LIAITHON (LIAITHON+) [61] (2014) | Beaconless | Location-based | Enhancement over LIAITHON offering three path solution |
| Driving path predication based routing (DPPR) [62] (2013) | Beacon-based | Mobility-based | Routing based on driving path characteristics |
| Speed wave forecasted-GPSR (SWF-GPSR) [41] (2013) | Beacon-based | Mobility-based | Modified GPSR that makes use of speed fluctuation of vehicles to predict stable paths |
| Improved geographical (IG) [63] (2015) | Beacon-based | Location-based | Distance, direction and beacon reception rate based geographic forwarding |
| Distributed beaconless dissemination (DBD) [38] (2015) | Beaconless | Mobility-based | Adaptive routing strategy to support real-time video transmission while minimizing packet duplication |
| Situation-aware multiconstrained QoS (SAMQ) [64] (2015) | Beaconless | Mobility-based | Bio-inspired routing with situational awareness to achieve reliable data transmission |
| VehiHealth [65] (2016) | Beacon-based | Mobility-based | Intersection based data forwarding to facilitate healthcare system |
| Stable connected dominating sets based routing protocol (SCRP) [66] (2016) | Beacon-based | Mobility-based | Road segment based route selection to prevent local maxima problem and to balance data traffic on multiple routing paths |
| Adaptive multipath geographic routing (AMGR) [67] (2016) | Beacon-based | Mobility-based | Adaptive routing through multiple independent paths to enable video streaming |
| Lifetime-aware beacon-less routing protocol (LBRP) [39] (2016) | Beaconless | Mobility-based | A lifetime aware routing strategy to support large volume content transmission |

*pling*, occurs due to interference among the nearby nodes in different paths. Unlike noise, which is random, interference has the same structure as that of the desired signal, and it also undergoes fading effect. This makes interference hard to detect or control and, hence, it is considered as one of the main performance limiting factors in most wireless networks [70]–[72].

Effective handling of these issues requires information utilization from different layers of the OSI model while making routing decisions. This signifies the need for cross-layer routing protocols that will be discussed in the next subsection.

### B. CROSS-LAYER ROUTING PARAMETERS

Cross-layer routing exploits the dependency between protocol layers to achieve desirable performance gains. In other words, it allows information exchange among different layers to achieve improvements in network performance [2]. A general cross-layer routing decision involving the OSI lower three layers is illustrated in Fig. 3. Incorporating parameters at the PHY, MAC and NET layers while making routing

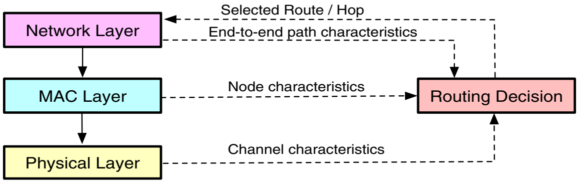


**FIGURE 3.** Illustration of routing decision based on the OSI lower three layers (PHY, MAC, NET).

decisions will enable the routing protocol to be more robust against issues such as congestion and interference. Wireless channel characteristics such as signal-to-interference-plus-noise ratio (SINR) typically available at the PHY layer play a vital role in determining interference [72]. Parameters related to node characteristics such as buffer space [69], retransmission count [73], etc. are available at the MAC layer and their inclusion in the routing decision may assist in minimizing congestion and packet drops. These parameters along with the traditional ETE path characteristics such as hop count, round-trip time at the NET layer can be used while making routing decisions in order to achieve high network performance. Accordingly, the selected route or next hop at the NET layer will have minimum effect from the above mentioned issues.

### C. CROSS-LAYER ROUTING PROTOCOLS IN VANETs

Fig. 4 classifies the existing cross-layer routing protocols based on (i) cross-layer routing parameters, (ii) routing mechanism and (iii) geographic metric used. As shown in Fig. 4, *No geometric used* indicates that no geographic metric has been used by the cross-layer routing protocol. Individual cross-layer routing protocols that utilize information from the PHY, MAC and NET layers as routing parameters are discussed in the subsections to follow.

#### 1) SIGNAL STRENGTH ASSESSMENT BASED ROUTE SELECTION FOR OLSR (SBRS-OLSR)

(2006) In SBRS-OLSR [74], the authors proposed a cross-layer ad-hoc routing approach based on link connectivity assessment. The enhanced protocol is based on optimized link state routing (OLSR) [75] and utilizes the benefit of cross-layer information exchange among the PHY, MAC and NET layers. Specifically, SBRS-OLSR makes use of multipoint relays (MPRs) concept present in OLSR to maintain the routing information where only the selected MPR nodes broadcast topological information. However, the conventional MPR selection process is modified by considering a new cross-layer routing parameter named *affinity* $\alpha$ as basis for route selection. The affinity $\alpha$, also known as residual link lifetime, was originally proposed in [76] and is defined as the time for which a node remains in another node's communication range. In other words, $\alpha$ is used to predict the lifespan of a link between the two nodes and is a function of $\lambda_{current}$, $\rho$ and $\lambda_{th}$. Here, $\lambda_{current}$ is the current signal-to-noise ratio (SNR), $\rho$ is the rate of change of SNR due to mobility and $\lambda_{th}$ is a threshold value that represents the minimum SNR required for a link to be in connected state [74]. As highlighted in [76], a positive $\rho$ implies that the two nodes are approaching toward each other, thereby indicating long lifespan of the link. Hence, at that instant of time, $\alpha$ is not computed and is assumed to be in *high* state. Links with $\alpha$ in *high* state are given the highest priority during route selection. In contrast, a negative $\rho$ means that the two nodes are moving away from each other, which indicates shorter lifespan of the link. In this case, $\alpha$ between two nodes is periodically computed as follows [74]:

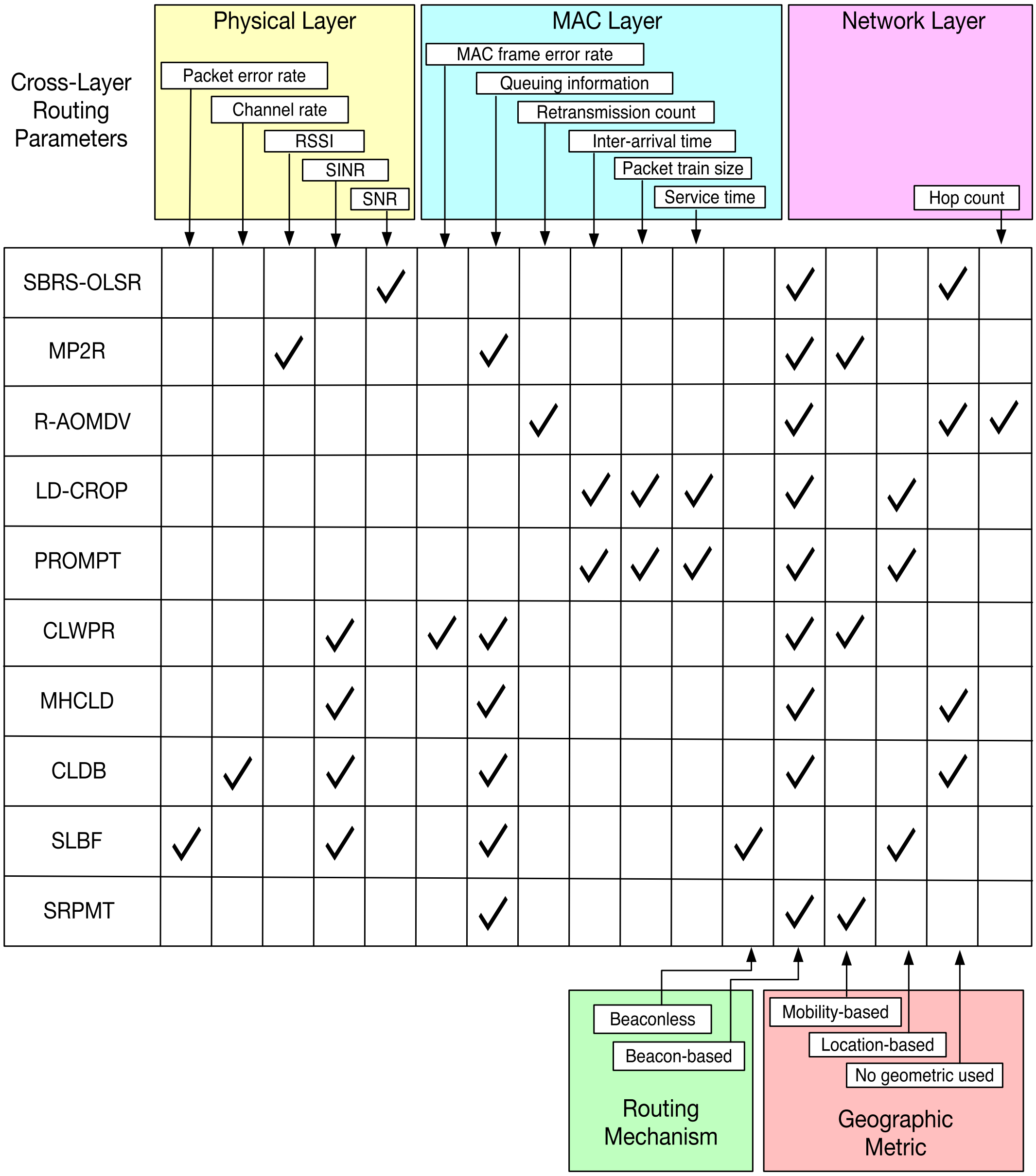
$$\alpha = \frac{\lambda_{current} - \lambda_{th}}{|\rho|}. \tag{1}$$

The routes offering higher values of minimum affinity and SNR along the hops to the destination are then considered during route selection. Apart from this, all nodes maintain neighbor table where they classify their neighboring nodes as usable or unusable based on their SNR values. All the protocol related operations of neighbors are assigned to the ones that are marked as usable. Although nodes maintain the list of nodes marked as unusable, they neither take part in broadcasting HELLO messages nor they are selected as MPRs. Simulation results show that SBRS-OLSR adapts well to high variations in network connectivity by selecting stable routes. However, the protocol has not been tested in high density and mobility environment and requires further investigation. Also, the estimate $\alpha$ used is not very accurate as it does not consider realistic mobility and signal attenuation models [77]. A more accurate method for estimating $\alpha$ is presented in [78], where the minimum distance that will be accomplished between two vehicles on the course of their movement is taken into account.

#### 2) MOBILITY PREDICTION PROGRESSIVE ROUTING (MP2R)

(2008) MP2R [79] utilizes mobility prediction information to jointly optimize routing, MAC and beam control of directional antennas. MP2R takes into account the characteristics of the vehicular network while selecting a next forwarder based on the most recent network topology, and also adapts well to high mobility.

Fig. 5 shows the packet forwarding framework for each node in MP2R. Here, nodes are assumed to be equipped with wireless LAN card, navigational systems such as GPS or inertial navigation system (INS), and a switch beam antenna. Position and neighboring tables are maintained by each node for storing the position, speed, direction and link quality, and load associated with neighboring nodes. This information is periodically exchanged between adjacent nodes through information distribution messages (IDMs). Only IDMs with fresh time-stamp are processed and used to update the entries in the corresponding tables. Position prediction is based on the position, speed and direction information of the node. The predicted position is then utilized during progress calculation in the forwarding decision and for antenna beam control. Using the information from position table, neighboring nodes in the direction of the destination are found out as potential candidates for packet forwarding and their progress toward destination is computed. The next forwarding node is then selected based on its link quality, load and predicted progress toward destination. The link quality is in turn deduced from the received signal strength indicator (RSSI) obtained at the PHY layer, whereas the load reflects node's



| | Packet error rate | Channel rate | RSSI | SINR | SNR | MAC frame error rate | Queuing information | Retransmission count | Inter-arrival time | Packet train size | Service time | Beaconless | Beacon-based | Mobility-based | Location-based | No geometric used | Hop count |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SBRS-OLSR | | | | | ✓ | | | | | | | | ✓ | | | ✓ | |
| MP2R | | | ✓ | | | | ✓ | | | | | | ✓ | ✓ | | | |
| R-AOMDV | | | | | | | | ✓ | | | | | ✓ | | | ✓ | ✓ |
| LD-CROP | | | | | | | | | ✓ | ✓ | ✓ | | ✓ | | ✓ | | |
| PROMPT | | | | | | | | | ✓ | ✓ | ✓ | | ✓ | | ✓ | | |
| CLWPR | | | | ✓ | | ✓ | ✓ | | | | | | ✓ | ✓ | | | |
| MHCLD | | | | ✓ | | | ✓ | | | | | | ✓ | | | ✓ | |
| CLDB | | ✓ | | ✓ | | | ✓ | | | | | | ✓ | | | ✓ | |
| SLBF | ✓ | | | ✓ | | | ✓ | | | | | ✓ | | | ✓ | | |
| SRPMT | | | | | | | ✓ | | | | | | ✓ | ✓ | | | |

**FIGURE 4.** Classification diagram of existing cross-layer routing protocols based on (i) cross-layer routing parameters, (ii) routing mechanism and (iii) geographic metric used.

queue length information and is typically available at the MAC layer. To deal with high mobility, nodes in MP2R delay their forwarding decision until the packet is taken out of the output queue and is to be actually transmitted. In this way, the current network topology is used when a packet is transmitted. Finally, the beam of the directional antenna is computed based on the predicted position information. Usage of position prediction in the packet forwarding of MP2R significantly reduces the packet transmission counts. Load consideration also results in reduced average waiting time as the accumulated packets are distributed among different forwarders. However, RSSI may not truly reflect the link quality as it does not take into account the interference and noise parameters and, hence, the next hop selected may have issues related to interference and noise.

### 3) CROSS-LAYER AD-HOC ON-DEMAND MULTIPATH DISTANCE VECTOR WITH RETRANSMISSION COUNTS METRIC (R-AOMDV)

(2009) The R-AOMDV [73] protocol reduces route discovery frequency by using the features of multipath routing protocol. R-AOMDV utilizes a new cross-layer routing metric which is a combination of hop counts and retransmission counts. The retransmission counts metric is considered for two reasons. Firstly, it reflects link quality and, secondly, it can be measured easily. Here, the maximum retransmission

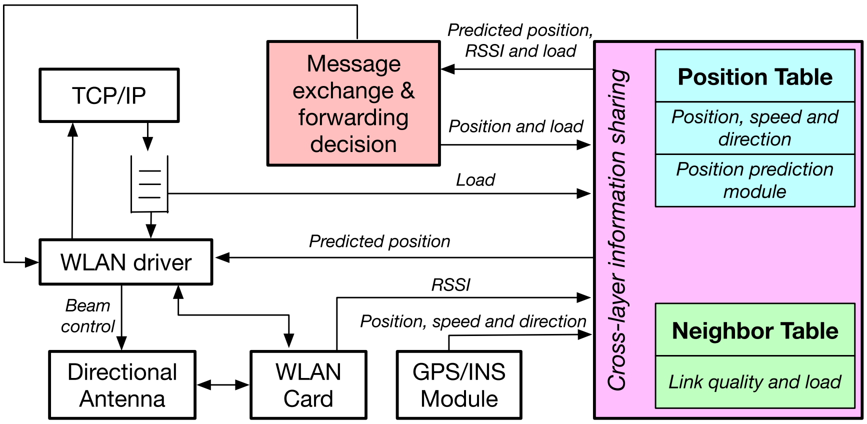


**FIGURE 5.** Packet forwarding framework of each node in MP2R, adapted from [79].

counts are recorded along the path from destination to source and from source to destination during the transmission of route reply and route retransmission packets, respectively. The performance of R-AOMDV when tested against ad-hoc on-demand multipath distance vector (AOMDV) routing protocol [80] under a Pareto distribution [81] based traffic model offered slight performance improvements over AOMDV, in two different scenarios (high and low densities). However, R-AOMDV still results in significant packet loss and delay.

### 4) LOCATION- AND DELAY-AWARE CROSS-LAYER COMMUNICATION IN V2I MULTIHOP VEHICULAR NETWORKS (LD-CROP)

(2009) A data delivery system named LD-CROP [82] relays packets over low delay paths to a fixed base station or access point. Here, the packet traffic information typically available at the MAC layer is monitored and updated periodically, after which packets are routed over low delay paths. Specifically, the framework comprises three principles. Firstly, a light weight traffic information propagation system is used, where vehicles periodically exchange the concise summary of packet traffic information based on local observation. The collected local traffic is then used in making high level routing decisions by selecting smaller delay paths over the road-map. Finally, the selected path is changed only when another path offers significant improvements in terms of path quality. This is done to reduce oscillations in terms of selected route. Beacons containing base station ID, sequence number, path, time to live, and complete path quality (CPQ), are constantly shared between vehicles. Each vehicle maintains path table to store path information of different routes. CPQ field comprises three statistics: service time, inter-arrival time and packet train size. Service time is the total time required for channel contention and actual transmission. Inter-arrival time is the time elapsed between two consecutive packet arrivals in the queue. Packet train size reflects the average value of the number of packets sent in a single transmission period. After reception of a beacon, the receiving vehicle checks the beacon's last updated time-stamp (LUT). If LUT is greater than the threshold, the route is considered stale and, hence, the beacon is discarded while also removing path information from the path table. Otherwise, the receiving vehicle adds its location information to the beacon's path field and its own path table while also adding its CPQ information. It then decrements the time to live and updates the time-stamp before rebroadcasting the updated beacon. Broadcasting approach according to [83] is used here. The path offering the highest path quality is then selected for routing. Also, if the receiving vehicle already has a packet with the same path, then it is considered as hyper relay node (HRN), where the packets are bundled (also known as packet train) before being sent. LD-CROP outperforms VADD [56] protocol at different packet generation rates, in terms of estimated packet delay, actual packet delay, success percentage, and fairness index. One of the reasons being the cross-layer features present in LD-CROP. Also, the train packet mechanism used in LD-CROP results in less contention and, hence, in improved delay performance, when compared to VADD.

### 5) CROSS-LAYER POSITION-BASED COMMUNICATION PROTOCOL FOR DELAY-AWARE VEHICULAR ACCESS NETWORKS (PROMPT)

(2010) PROMPT [84] is an enhancement of LD-CROP. It retains V2I communication capability while undergoing some modifications. Along with delay awareness, PROMPT utilizes position-based source routing that adapts well to high mobility and frequently varying network topology. Here, the base station (fixed infrastructure) performs periodic beaconing. Beacon propagation is outwards according to the broadcasting approach in [83]. Information in the beacons is almost the same as that of LD-CROP, with some changes in path information table. Here, the average and variance values of the service time and the inter-arrival time, along with the average value of the batch (packet train) size, are collected as statistics in the path information field. Information from beacons is then used to estimate delay and select the minimum delay path. The source routes selected in PROMPT are nothing but physical paths on the road network and are expressed as a sequence of (street, direction) pairs. Intermediate relay nodes are selected based on receiver-based MAC channel contention methodology, where each relay assigns contention time depending on its privilege. Privilege is calculated based on the direction and distance of the forwarding node from the transmitter. An intermediate relay node with the highest privilege is assigned with the lowest contention time. Multiple packets to the destination are bundled together using packet train technique and transmitted within single contention period to reduce contention time and improve bandwidth usage. Usage of local traffic characteristics available at the MAC layer results in accurate delay prediction, thereby improving the ETE delay performance of PROMPT.

### 6) CROSS-LAYER WEIGHTED POSITION-BASED ROUTING (CLWPR)

(2011) CLWPR [46] is a unicast, multihop routing protocol based on opportunistic forwarding. Here, information available at the PHY and MAC layers along with the positional information is used as routing metrics for making next hop selection. HELLO beacons containing node position, node velocity, node heading, road ID, node utilization, MAC frame error rate and number of cached packets, are periodically exchanged between nodes. SINR is recorded by nodes on beacon reception. The obtained information is used to determine the weight $W$ of the available next hops which is computed as follows [46]:

$$\begin{aligned} W = {} & f_1 \times d + f_2 \times N_{angle} + f_3 \times N_{road} + f_4 \times U \\ & + f_5 \times E_{mac} + f_6 \times n_{cp} + f_7 \times w_\sigma, \end{aligned} \tag{2}$$

where $f_1$, $f_2$, $f_3$, $f_4$, $f_5$, $f_6$ and $f_7$ are the weighting factors and $d$ is the distance from destination measured on road obtained through emaps. $N_{angle}$ and $N_{road}$ are the normalized weights of the angle and road parameter, respectively. Utilization $U$ is the number of packets in node's queue. $E_{mac}$ and $w_\sigma$ are the MAC frame error rate and the weighted SINR, respectively, and reflect propagation effects such as interference and shadowing. $w_\sigma$ represents the weight of the received packet's SINR and is used as one of the routing metrics to filter out nodes experiencing high interference that are usually present at the border. $n_{cp}$ is the number of cached packets from carry-and-forward (CnF) mechanism. The CnF mechanism was deployed in sparse network density conditions to reduce packet drops. Finally, the hop with minimum weight is then selected. The performance of CLWPR when tested against GPSR in urban environment, outperforms GPSR. Indeed, GPSR neither uses any map information nor does it have the capability to predict the node's position. In contrast, CLWPR usage of emaps information results in improved packet reception rate. Also, consideration of link quality in terms of SINR further assists in minimizing ETE delay. However, the usage of CnF mechanism, although it reduces packet drops in sparse network conditions, also results in increased ETE delay.

### 7) MULTI-HOP CROSS-LAYER DECISION BASED (MHCLD)

(2014) An efficient cross-layer routing mechanism for VANETs with a new neighbor selection criteria is presented in [85]. MHCLD routing considers the PHY and MAC layer parameters, such as SINR and queuing information, into the NET layer while routing with the aim to improve performance in terms of ETE delay. The flow diagram of the scheme is depicted in Fig. 6. As shown in Fig. 6, MHCLD is divided into two parts: common neighborhood (CN) formation, and routing. In the CN formation part, [85] presents two cases highlighting the criteria for a neighbor node selection. In the first case, only channel quality indicator (CQI) is considered as a basis for a neighbor selection. If the CQI is greater than a threshold, then the node is considered as neighbor. In the second case, both the CQI and queuing information are considered as a basis for a neighbor node selection, i.e., if the CQI is greater than a threshold and the queue is not full, then the node is considered as neighbor. Here, the CQI is measured in terms of SINR information. In the routing part, the forwarding node first checks whether the destination is present in its neighbor list and, if it obtains an affirmative response, it sends the data to destination. Otherwise, it arranges the CQIs of all the neighbors in descending order and then selects the neighbor with its CQI placed in the first index, i.e., the neighbor with the least CQI in the neighbor list but greater than the threshold. This is done with the assumption that the smaller the CQI, the farther the neighboring node, but the threshold ensures that the selected neighboring node has the minimum CQI to be eligible as a forwarder. MHCLD outperforms GPSR and PROMPT techniques as it takes less number of hops to reach the destination. However, the performance of MHCLD degrades in the presence of high variations in network dynamics.

### 8) CROSS-LAYER DECISION BASED (CLDB)

(2015) CLDB [86] routing protocol is an extended work of MHCLD, where individual channel rate associated with each link is used as routing metric and is calculated using information available at the PHY and MAC layers. Here, the CN formation is based on the average data rates. The average data rate $\Upsilon_{xy}$ between nodes $x$ and $y$, is calculated as [86]

$$\Upsilon_{xy} = \mathbb{E}[\log_2(1 + \sigma_{xy})], \tag{3}$$

where $\mathbb{E}[.]$ is the mathematical expression for the expected value denoting the weighted average of all possible values and $\sigma_{xy}$ is the measured SINR between nodes $x$ and $y$. The inclusion of data rate in the routing scheme is done to avoid transmission failures and minimize overhead due to control packets. Max-Rate scheduling is then used to select the vehicle with the best instantaneous data rate at each time slot. Usage of a scheduler not only guarantees successful

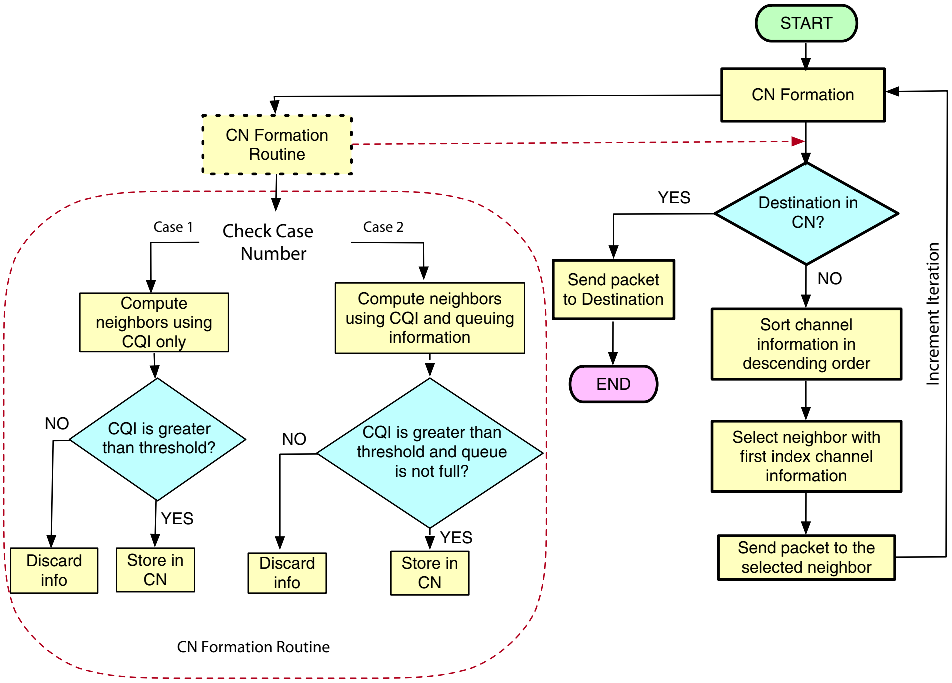


**FIGURE 6.** **Simplified flow diagram of MHCLD, adapted from [85].**

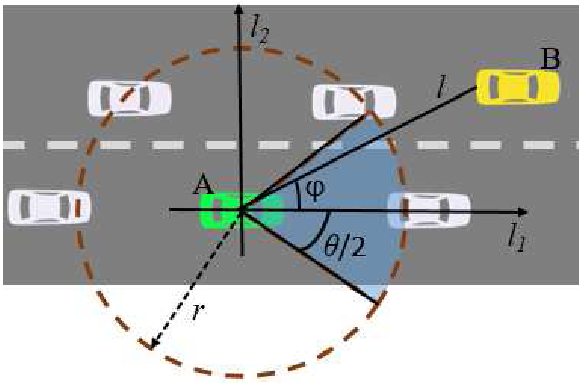


**FIGURE 7.** **Illustration of forwarding zone, adapted from [87].**

packet transmission, but also results in high system throughput. CLDB when analyzed under different vehicle densities through simulations although performing well in dense network conditions, its performance decreases in sparse conditions.

### 9) SELF-ADAPTIVE AND LINK-AWARE BEACONLESS FORWARDING (SLBF)

(2015) SLBF [87] is a cross-layer receiver-based data forwarding scheme comprising two main features: forwarding zone and waiting time calculation. The forwarding zone is further defined into two parts: direction and angle size computation. An illustration is shown in Fig. 7.

The green vehicle $A$, with transmission range $r$, is the current forwarder, and the yellow vehicle $B$ represents the destination. $l_1$ is the moving direction of the current forwarder, and $l_2$ is the line perpendicular to $l_1$. $l$ is the line connecting destination and current forwarder, whereas $\varphi$ is the intersection angle between $l$ and $l_1$. The blue colored area represents the forwarding zone, which is along the road and in the direction of the destination. $\varphi$ is responsible for determining the direction of forwarding vehicle. If $\varphi$ is less than 90°, then the direction of the forwarding vehicle is forward along the road. Otherwise, the direction is backward along the road. The forwarding angle $\theta$ computation is based on packet's time interval from current forwarder to last forwarder and the threshold value of the average time required for single hop.

Waiting time for the receiving node is calculated using link quality and traffic load information. Link quality is in turn computed by making use of duration time and packet error rate. Duration time is the maximum time the receiving node stays in the communication range of its last hop. It is determined by making use of location information of receiving node and last hop, and speed information of the receiving node. The packet error rate concept is based on the bit error rate which is calculated using SINR information available at the PHY layer. Traffic load here is defined as the ratio of actual queue length to buffer space length. The forwarder inserts its positional information, forwarding zone, the ID number of destination and forwarding time point in the data packet before broadcasting it in its wireless range. The receiving node contends for forwarding right only if it is present in the forwarding zone. Otherwise, it discards the packet. The SLBF protocol performs well in high mobility

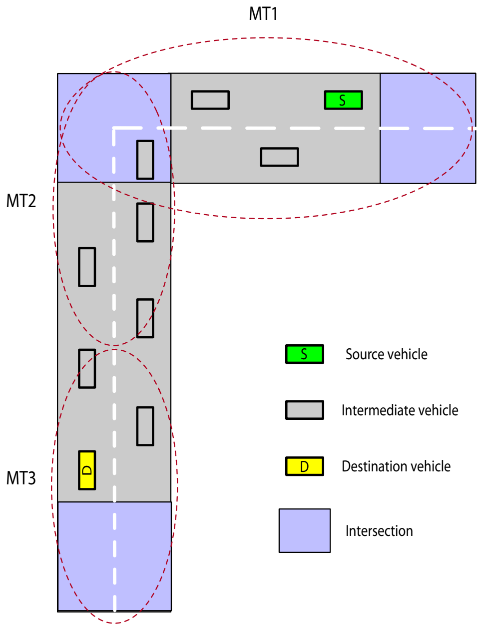


**FIGURE 8.** An illustration of microtopology, MT, showing three MTs (MT1, MT2 and MT3), adapted from [88].

conditions and results in improved performance in terms of ETE delay, PDR and average number of hops. However, one possible drawback of the receiver-based schemes is the unwanted multiple path formation when two or more receiving nodes are out of communication range from each other, e.g., at the intersections. This results in redundant packets flowing in the network, which leads to increased overhead and packet collisions.

#### 10) STREET-CENTRIC ROUTING PROTOCOL BASED ON MT (SRPMT)

(2016) Authors in [88] proposed a routing protocol that takes decision based on routing-related characteristics of the streets. They introduced a novel concept known as microtopology (MT) which is a street level segment comprised of vehicles and wireless links among them. MT comprises a single street representing a part of the entire topology of VANET. In networking terms, it is a subset of entire routing path, meaning the packet has to pass through one end side of MT to the other side of MT. An illustration of MT is shown in Fig. 8 with three MTs (MT1, MT2 and MT3), where an MT is defined as a street between two intersections or in case of longer streets, it is defined as a part of the street. The second definition of MT above aims to minimize the search algorithm complexity.

Vehicles periodically broadcast beacon packets exchanging information related to location, velocity and buffer condition such that each vehicle is aware of the end side to end side performance of current MT. Routing-related characteristics of street includes static attributes such as length of the street segment as well as dynamic attributes namely vehicle density, connectivity, mobility of vehicles and existing data traffic. SRPMT is comprised of two strategies: routing decision of the next MT and packet forwarding within the MTs. Routing decision of the next MT selects the next street as part of a routing path, and the decision is taken based on the end side to end side performance of MT. Specifically, an MT with the shortest estimated delay toward destination is chosen. The estimated delay of MT toward destination is computed as the sum of MT's end side to end side delay $D_{MT}$, and the estimated remote delay $D_{RD}$ from the end side of the MT to the destination. $D_{RD}$ is calculated as [88]

$$D_{RD} = \frac{d_{sp} \times l_p}{r \times \Upsilon}, \tag{4}$$

where $d_{sp}$ is the shortest path distance from the end side of MT to the destination, $l_p$ is the packet size, $r$ is the communication range and $\Upsilon$ is the data transmission rate. $D_{MT}$ further includes two types of delays. The first type is the time taken for the packets to pass through the intermediate links within an MT and can be calculated as the sum of queuing, contention and transmission delay. The other delay is induced due to storing and carrying packets and is computed as the ratio of packet carrying distance to the velocity of packet carrying vehicle. The packet relaying strategy within MT involves the optimal next hop selection of neighboring vehicle having the highest geographical progress toward end side of MT in the transmission direction. The network performance of SRPMT was evaluated in terms of PDR, average ETE delay and normalized routing overhead, by varying parameters such as vehicle density, data transmission rate, number of source and maximum allowable velocity. The performance of SRPMT was compared with GPSR [47] and GyTAR [53] and simulation results highlight the superior network performance offered by SRPMT. However, SRPMT forwards the packet within the MT solely based on geographical progress and does not consider the wireless channel characteristics of the vehicle, thereby the selected vehicle may not satisfy the link quality requirements for packet forwarding.

Table 3 summarizes the above mentioned cross-layer routing protocols highlighting their aim, key feature, performance metrics and limitation.

## VI. DISCUSSION AND OPEN ISSUES

The survey carried out in this paper implies that considerable work have already been done to develop efficient routing protocols for vehicular networks, using both single-layer and cross-layer approaches. However, there are still open issues related to the routing approach and cross-layer design that require further attention and research.

### A. ISSUES RELATED TO THE ROUTING APPROACH

#### 1) BEACON-BASED VS. BEACONLESS ROUTING

One of the advantages of beacon-based schemes is that it enables a sending node to take instantaneous routing decision to select the next best-hop node as the sending node already knows all its neighbors, resulting in improved delay performance. However, there are still some issues in beacon-

**TABLE 3.** Various cross-layer routing protocols in VANETs and their key characteristics.

| Protocol | Aim | Key Feature | Performance Metrics | Limitation |
|---|---|---|---|---|
| SBRS-OLSR [74] (2006) | Select stable routing paths | Affinity-based next hop selection | Throughput | Not considering interference in affinity computation |
| MP2R [79] (2008) | Improve reliability | Mobility prediction based packet forwarding and antenna beam control | Packet Error rate and Packet Transmission count | RSSI may not exactly reflect link quality as it does not take into account interference and noise |
| R-AOMDV [73] (2009) | Reduce route discovery process and minimize delay | Modified AOMDV mechanism using hop count and retransmission count as routing metrics | PDR, ETE delay and Routing Overhead | High packet loss and delay |
| LD-CROP [82] (2009) | Route data packet over low delay path | Location and delay awareness. Train packet mechanism | Delay, Delivery success percentage and fairness index | Not considering channel characteristics at PHY layer |
| PROMPT [84] (2010) | Route data packet over low delay path | Location and delay awareness. Privilege based intermediate relay selection. Train packet mechanism | ETE Delay, Packet loss rate and Fairness index | Not considering channel characteristics at PHY layer |
| CLWPR [46] (2011) | Improve overall routing efficiency | Emaps usage for extracting position information. CnF mechanism usage in sparse network conditions | PDR and Average ETE Delay | Increased ETE delay due to usage of caching packets |
| MHCLD [85] (2014) | Improve overall routing efficiency | SINR and queuing information based CN formation and next hop selection | Number of hops | Low performance in highly dynamic network conditions |
| CLDB [86] (2015) | Achieve QoS requirements | Channel rate and queuing information based CN formation and next hop selection | Packet Drop Ratio, Average transmit Delay, throughput and channel utilization ratio | Low performance in sparse network conditions |
| SLBF [87] (2015) | Improve reliability | Forwarding zone computation based on direction and angle size. Waiting time calculation based on link quality and traffic load | PDR, ETE delay and average hops | Multipath formation when two receiving nodes are out of transmission range of each other |
| SRPMT [88] (2016) | Improve overall network performance | MT-based routing involving selection of next street with shortest estimated delay toward destination | PDR, Average ETE delay and Normalized routing overhead | Not consider wireless channel characteristics during packet forwarding process within MT |

based schemes. The size of a beacon message is very small compared to data packet and could easily pass through links that are weakly connected. On the contrary, data packets because of their size may not be able to pass through such links. Hence, in order to avoid such links along with location information, information related to link quality should also be shared during beaconing. Another issue for beaconing is the beacon overhead, which increases with the vehicle density and is mainly caused due to redundant beacon. The beacon overhead per second $O_b$ is calculated as [37]

$$O_b = \frac{n \times l_b}{t}, \tag{5}$$

where $n$ is the number of nodes, $l_b$ is the beacon size, and $t$ is the periodic time interval after which beacons get propagated by the vehicles. The beacon size depends on the amount of information included. Hence, in order to reduce the beacon overhead, there is a need to limit the number of nodes that broadcast beacons. Authors in [37] highlight one such adaptive beaconing strategy, where the number of beacon propagating nodes between two intersections are significantly reduced. However, an intersection independent adaptive beaconing scheme would provide a global solution to beacon overhead and is an open issue for future research.

Another alternative is to make use of beaconless routing that does not need periodic information sharing. This will not only reduce overhead but will also minimize packet collision and the packet drop rate, due to the absence of redundant beacons flowing through the network. However, lack of information sharing among nodes also implies that nodes have no knowledge about their neighbors and, hence, cannot instantly identify the next-hop node for data transmission, thus resulting in increased ETE delay. According to [37], the ETE delay $D_{ete}$ for transmitting a packet is calculated as

$$D_{ete} = \sum_{i=1}^{n_{hops}} \frac{1}{\tau_i}, \tag{6}$$

where $n_{hops}$ denotes the number of hops involved between source and destination nodes, and $\tau_i$ represents the road density for hop $i$ computed as the ratio of the number of nodes to the road length. In high vehicle density conditions, the delay is expected to be small since a large number of nodes implies higher chances of next-hop node selection. However, since the node does not have any information about its neighbors, the delay is still higher when compared to routing protocols using beacon-based approach. Hence, minimizing the transmission delay in beaconless routing protocols is an open research issue. Apart from this, beaconless approaches are also more prone to multipath formation, leading to redundant data packets flowing in the network [37]. Thus, effective measures should be employed to restrict the number of potential forwarders such that there is only formation of single path between source and destination.

### 2) DENSE VS. SPARSE NETWORK CONDITION

The vehicular environment has varying network characteristics. For instance, during peak hours the network is dense with large number of vehicles moving in different directions at different speeds, whereas during other hours there may be none or very few vehicles moving on the road. In dense conditions, although route discovery is relatively easy, there is a high chance of packet collision and unwanted overhead. Here, limiting the number of redundant packets flowing in the network and suppressing the interference from other transmissions is key to efficient routing. Although the sparse conditions are almost free from these issues, they experience other issues related to maintaining connectivity and packet drop. Most of the routing mechanisms targeting sparse networks are based on modification of the CnF mechanism. Methods such as considering opposite lane and static infrastructure in case when no suitable forwarder is ahead must be considered by the current forwarding node. Overall, a routing protocol must be adaptive to these two extreme network conditions. One such adaptive strategy is presented in [40], where a cognitive module is used to switch between AODV and pseudo-proactive strategy based on network parameters such as number of nodes and instantaneous speed. However, the area of adaptive routing based on network characteristics is still an open issue and requires further research.

### 3) ROUTE ESTABLISHMENT VS. HOP-BY-HOP FORWARDING

As previously discussed, traditional topology-based routing protocols do not perform well in VANETs. One of the main reasons is that they establish route through the use of control packets prior to data transmission and in high mobility conditions, routes often breakup after some time. A better alternative often used by geographic routing is the hop-by-hop forwarding, where the next hop is selected based on some statistics and suits well the vehicular environment. However, in scenarios where data rate is high, next-hop discovery for every packet could be computationally expensive and may incur some delay. In such cases, some form of temporary route management technique could be developed, where after the first hop-by-hop discovery of a route from source to destination, the route is maintained for some time. The route could be maintained for the period until all nodes present along the route remain in the communication range of each other.

## *B. CROSS-LAYER ISSUES*

### 1) CROSS-LAYER ROUTING PARAMETER SELECTION

One of the fundamental features in cross-layer routing protocols is the routing parameter selection from different layers that is utilized in making routing decisions. While it is important to consider the wireless channel characteristics typically available at the PHY layer during the routing process, it is also equally significant to ensure that the right parameter has been selected based on the application requirements. For instance, RSSI is a good indicator of signal strength, but it neglects noise and interference phenomena. Noise although is considered in the SNR, interference is neglected. SINR is a better PHY layer routing parameter as it considers interference along with signal strength and noise. Affinity [74], derived from SNR information is also an effective parameter giving information regarding the time during which the nodes are going to be in transmission range of each other. This information can be readily used in future research for next-hop node selection mechanisms and route maintenance. In addition, affinity can also be calculated more accurately by utilizing SINR instead of SNR. Queuing information typically available at the MAC layer, although widely used, still remains an important routing parameter as it gives valuable information regarding buffer space that is vital for avoiding packet drops. Other than this, parameters giving information related to packet traffic have also been used to select path with lower delay. As shown in [46] and [73], another approach is to use a composite parameter formed by combining different routing parameters. However, the selection of routing parameters depends on the protocol's objectives and the application scenario being considered. Overall, it can be reiterated that proper selection of routing parameters at different layers of the OSI model remains an open research issue that requires further exploration.

### 2) CROSS-LAYER DESIGN

Apart from the discussion above, there exists some general yet open issues that developers are facing while designing cross-layer protocols for wireless networks. Some of them adapted from [10], [89]–[92] are highlighted as follows:

- As defined in [11], cross-layer design is nothing but the violation of reference layered communication architecture, where there are direct communications between protocols at non-adjacent layers, or variables are shared between non-adjacent layers. Although a cross-layer approach aims for improving performance, if it is not done in an appropriate way, it may shatter the encapsulation of layers, leading to dis-organization of the layered communication architecture. In addition, modification or any further enhancement of such cross-layer design is very difficult. Hence, there is a need to minimize the violations to the layer modularity while performing cross-layer interactions. However, preserving modularity of the layered architecture is one of the most challenging open research issue while designing cross-layer protocols.
- Information flow between different layers in a cross-layer design sometime gives rise to unintended dependencies among layers, causing performance degradation of the overall system. Therefore, cross-layer interaction among different layers should be carefully managed.

- Wireless networks comprise wide and diverse applications. Different applications have different set of performance requirements, and the requirements may change during the network operation. Hence, there is a need to develop a universal cross-layer architecture that offers enough flexibility to deal with wide and diverse range of applications.

Summarizing the above discussion, some of the open research challenges for both single- and cross-layer routing are as follows:

- Reducing the number of beacon messages used in existing beacon-based scheme in order to achieve low overhead.
- Minimizing transmission delay and avoiding unwanted multipath formation in current beaconless routing schemes.
- Making current routing schemes highly adaptive to changing network conditions of VANET, while also providing superior network performance.
- Use of temporary route maintenance concept in existing routing schemes to support high data rate applications in VANET, while also achieving low overhead and delay.
- Developing a composite parameter for routing, comprising appropriate cross-layer parameters and effectively addressing the issues at PHY, MAC and NET layers.
- Designing a cross-layer system having minimum violation of layer modularity, reduced inter-layer dependencies, and being flexible enough to support diverse range of applications.

## VII. CONCLUSION

VANETs play a vital role in the ITS for the future, and routing is a crucial aspect of VANET's applications. From this survey, it can be reiterated that the inclusion of cross-layer information while routing plays a significant role in improving the performance of a routing protocol. However, the appropriate selection of routing parameters from different layers still remains an open issue, along with the elementary cross-layer design issues usually experienced in all kinds of wireless networks. Geographic routing appears to be more promising approach as compared to traditional topology-based routing, where the use of location information offers an additional advantage for achieving superior performance. However, a routing protocol designer needs to consider the trade-offs that exist between various routing approaches. The routing approach must cope well with the challenging characteristics and dynamic network topology of the vehicular environment. Overall, the concept of efficient routing in VANETs still remains a key and widely open research issue.

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