Routing in Internet of Vehicles: A Review

JiuJun Cheng, JunLu Cheng, MengChu Zhou, *Fellow, IEEE*, FuQiang Liu, *Member, IEEE*, ShangCe Gao, and Cong Liu

***Abstract*—This work aims to provide a review of the routing protocols in the Internet of Vehicles (IoV) from routing algorithms to their evaluation approaches. We provide five different taxonomies of routing protocols. First, we classify them based on their transmission strategy into three categories: unicast, geocast, and broadcast ones. Second, we classify them into four categories based on information required to perform routing: topology-, position-, map-, and path-based ones. Third, we identify them in delay-sensitive and delay-tolerant ones. Fourth, we discuss them according to their applicability in different dimensions, i.e., 1-D, 2-D, and 3-D. Finally, we discuss their target networks, i.e., homogeneous and heterogeneous ones. As the evaluation is also a vital part in IoV routing protocol studies, we examine the evaluation approaches, i.e., simulation and real-world experiments. IoV includes not only the traditional vehicular ad hoc networks, which usually involve a small-scale and homogeneous network, but also a much larger scale and heterogeneous one. The composition of classical routing protocols and latest heterogeneous network approaches is a promising topic in the future. This work should motivate IoV researchers, practitioners, and new comers to develop IoV routing protocols and technologies.**

***Index Terms*—Internet of Vehicles, routing, VANET, LTE, WAVE, DSRC, WiMAX, heterogeneous network.**

I. Introduction

CARS and vehicles are used daily by more and more people. The biggest problem regarding their increased use is the increasing number of fatalities that occur due to accidents on the roads. The related expense and dangers have been recognized as serious problems being confronted by modern society [1]. Vehicular Ad-hoc Network (VANET) originated from Mobile Ad-hoc Network (MANET) has been under research for many years [2], [3]. As people's life style changes, various kinds of requirements about vehicular networking have been proposed.

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J. J. Cheng and J. L. Cheng are with Key Laboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai 200092, China (e-mail: chengjj@tongji.edu.cn; 1233777@tongji.edu.cn).

M. C. Zhou is with the Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102 USA and also with Key Laboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai 200092, China (e-mail: mencghu@ieee.org).

F. Q. Liu is with the School of Electronics and Information Engineering, Tongji University, Shanghai, 200092, China (e-mail: fuqiangliu@163.com).

S. C. Gao is with the Faculty of Engineering, University of Toyama, Toyama 930-8555, Japan (e-mail: gaosc@eng.u-toyama.ac.jp).

C. Liu is with Shandong University of Science and Technology, Qingdao 266590, China (e-mail: liucongchina@163.com).

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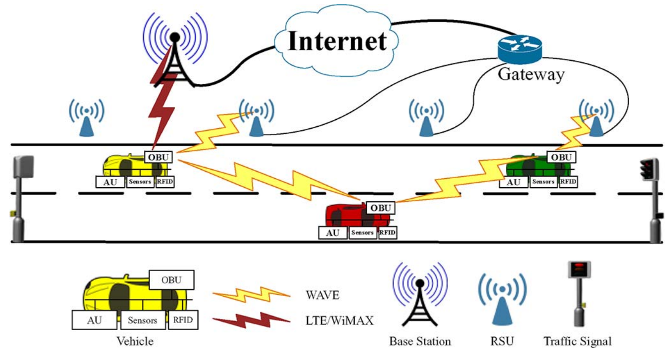

Fig. 1. Heterogeneous network structure in IoV.

Internet of Vehicles (IoV) can be seen as a superset of VANET. It extends VANET's scale, structure and applications. Different from traditional Intelligent Transportation System (ITS), it puts more emphasis on information interaction among vehicles, humans and roadside units (RSU). Its goal is to make people gain real-time road traffic information easily, to protect the travel convenience, and to improve the travel comfort. As an important branch of Internet of Things, IoV is mainly used in urban traffic environment to provide network access for drivers, passengers and traffic management personnel. IoV environment is the combination of wireless network environment and road conditions. Researchers need to consider moving vehicles and an overall complex management system. There are many real-life scenarios that require vehicle networking technologies. For example, driving on the highway or in urban scenarios, drivers wish to know the traffic situation of roads ahead and adjust their driving route according to whether an accident or traffic jam occurs on their way. By making full use of the advanced technology of IoV, people can also reduce fuel consumption and environmental pollution.

Many researchers have performed VANET studies. They develop applications, routing protocols, and simulation tools. The studies [4]–[6] give a detailed description of existing routing protocols in VANET. Al-Sultan *et al.* [1] provide a comprehensive survey reporting all the issues facing it, such as wireless access technologies, and VANET characteristics, challenges and requirements. Harri *et al.* [7] introduce a framework and propose a guideline for the generation of vehicular mobility models. But in most studies, VANET involves a small scale and homogeneous network with its applications focused on traffic efficiency and safety. In recent years, large scale and heterogeneous networks are introduced to VANET, as shown in Fig. 1, to provide more services than safety information, e.g., entertainment and environment protection. In this paper, we refer to VANET specifically as small scale and homogeneous IoV and propose the taxonomy of routing, evaluation approaches and applications of IoV.

The next section describes the routing taxonomy from five different perspectives, i.e., transmission strategy, information used, delay sensitivity, dimensions of scenarios and network architectures. Section III presents the evaluation approaches for IoV routing protocols, i.e., computer simulation and real-world experiments. Section IV draws the conclusions and discusses the future study of IoV routing protocols.

II. Routing Taxonomy

An important research aspect in IoV is its routing protocols. Several classic routing protocols like Destination-Sequenced Distance-Vector (DSDV) [8], Dynamic Source Routing (DSR) [9], and Ad-hoc On Demand Distance Vector (AODV) [10] come from the MANET study. Considering the properties of vehicles, researchers have proposed some geographic protocols like Greedy Perimeter Coordinator Routing (GPCR) [11] and Greedy Perimeter Stateless Routing (GPSR) [12]. Next, we provide a taxonomy on routing protocols in IoV based on different perspectives. It is noted that most of them are only suitable to a limited scale and solo wireless access technology.

A. Transmission Strategy

1) Unicast Routing Protocols: The main goal of unicast routing in VANET is to transmit data from a single source to a single destination via wireless multi-hops, by either using a hop-by-hop greedy forwarding mechanism or carry-and-forward one. In the former, intermediate vehicles in a routing path should relay data as soon as possible from a source to a destination. In the latter, they can carry data until a forward decision is made by their routing algorithm. In many studies, the term, a routing protocol, refers specifically to unicast routing. We can divide unicast routing into four categories: topology, position, map and path-based ones based on the information used, to be discussed later.

2) Geocast Routing Protocols: Geocast routing [13] is basically location-based multicast routing. Its objective is to deliver a packet from a source node to all other nodes with a specified geographical region, called Zone of Relevance. Many VANET applications can benefit from it. Geocast can be implemented with a multicast service by simply defining the multicast group to be the set of nodes in a certain geographic region [5]. Bachir and Benslimane [14] propose an Inter-Vehicles Geocast protocol (IVG) to broadcast an alarm message to all the vehicles being in a risk area on a highway by selecting a relay node based on a defer time algorithm.

Maihöfer and Eberhardt [15] propose a cache scheme and distance-aware neighborhood selection scheme to deal with constant neighborhood changes and unstable routing paths. Their main idea is to add a small cache to the routing layer that holds those packets that a node cannot forward instantly. Kihl *et al.* [16] propose a distributed robust geocast protocol (DRG) for inter-vehicle communication. Its goal is to deliver packets to vehicles located in a specific static geographic region. A vehicle should receive or drop packets according to its current location only. Experimental results show that the reliability of DRG is comparable or even higher than that of the highly redundant flooding protocol. DRG adapts itself to fit a network topology and ensures a high delivery ratio in a sparse network at the expense of high overhead, while it efficiently delivers the packets in a dense network.

Traffic lights are useful to Geocast Routing. In [17], Kaiwartya1 *et al.* propose a Traffic light-based Time Stable Geocast (T-TSG) routing protocol for informing vehicles after an accident in an urban vehicular environment. It makes full use of traffic light behavior and vehicle distribution information near an accident spot. Its performance analysis shows that it has better message delivery rate, more negligible network load and lower end-to-end delay than a normal flooding based approach. User routines can also be used as an important piece of information for helping the decision-making process of VANET services. In [18], Celes *et al.* propose a spatial information-based approach for routing in VANETs (GeoSPIN) based on daily movements of users. Simulation results show that user trajectories can be combined with a geocast strategy to improve the data delivery rate in sparse VANETs. Mobility patterns in individual trajectories can be well-used to assist the decision making process of message forwarding.

Dannheim *et al.* [19] present a procedure for generating IPv6 multicast addresses, which encodes longitude and latitude of a message through easy calculation. The proposed addressing mechanism is simple and resource-efficient for filtering according to distance.

3) Broadcast Routing Protocols: Broadcast is a frequently used routing method in VANETs, to share traffic, weather, emergency, road condition information among vehicles, and to deliver advertisements and announcements. It is also used in unicast routing protocols at its routing discovery phase to find an efficient route to a destination. When a message needs to be disseminated to the vehicles beyond a direct transmission range, a multi-hop scheme is used [5].

Durresi *et al.* [20] present an emergency broadcast protocol, called BROADCOMM, based on geographical routing in a partitioned highway. Sensors installed in cars continuously gather important information and any detected emergency triggers immediate broadcast. This protocol outperforms the flooding-based ones in the message broadcasting delay and routing overhead owing to its hierarchical scheme, makes it possible to implement different distribution policies, thereby giving a differentiated service and improved QoS.

Urban Multi-Hop Broadcast protocol (UMB) [21] is designed to address the issue related to broadcast storms, hidden nodes, and reliability of multi-hop broadcast in urban areas. It is composed of two phases, directional and intersection broadcast. In the first phase, a sender selects the farthest node without knowing the ID or position of its neighbors. In the second phase, repeaters installed in the intersection forward the packets to all road segments. As shown in Fig. 2, vehicle A uses the directional broadcast to reach vehicle B. As A is out of the transmission range of repeater C but B is in the range, B communicates with C. Once C receives the message, it initiates intersection broadcasts to the north and south directions. Since repeater D is also in the transmission range of C, C also sends the packet to D.

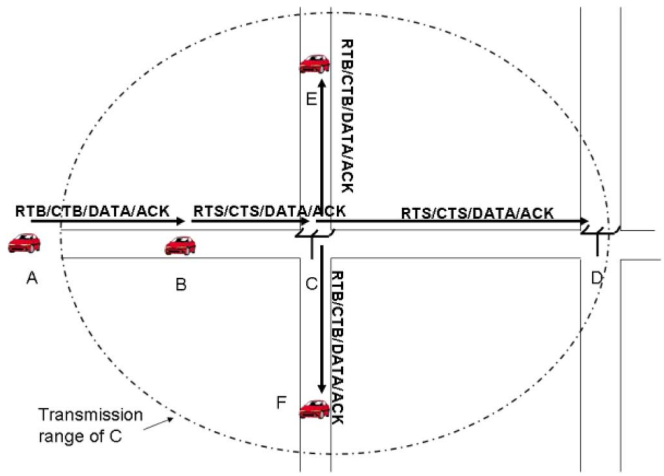

Fig. 2. UMB protocol [21].

Tonguz *et al.* [22] propose a Distributed Vehicular broadCAST protocol, called DV-CAST, for multi-hop broadcast in VANET based on a routing solution in [23]. It is suitable for both dense and sparse traffic scenarios on highways and can reduce the broadcasting overhead according to [4]. Their further work presents a lightweight, zero-infrastructure support Urban Vehicular broadCAST protocol, called UV-CAST [24] that addresses both the broadcast storm and disconnected network problems in urban VANETs by utilizing both direct relays through multi-hop transmissions and indirect packet relays through a "store-carry-forward" mechanism. This work is recognized as the first one about broadcast routing protocols in urban VANETs.

Another broadcast protocol, named DHVN (Dissemination protocol for Heterogeneous Cooperative Vehicular Networks), is given in [25]. It considers: (i) road topology, (ii) network connectivity and possible partitioning in case of low traffic density, and (iii) heterogeneous communication capabilities of vehicles. It solves the message loss problem and enhances the delivery ratio.

Fang and Luo [26] propose a two-timer-based broadcast routing algorithm for VANETs. Two timers are utilized to decide whether a node forwards its received packet. The first timer is used to stabilize the receiving process and updates the relative distance before it expires; while the second one ensures that only the farthest receiver would forward the packet. The proposed protocol is totally distributed and only relies on GPS information, but it has faster packet penetration speed and smaller delay compared with slotted one-persistence algorithm [27] and the traditional flooding-based one [28].

B. Information Required

1) Topology-Based Routing: DSDV [8] is a table-driven routing scheme for VANET based on the Bellman-Ford algorithm. It solves the routing loop problem. Each entry in the routing table contains a sequence number, the sequence numbers are even if a link is present; and else odd. The number is generated by the destination, and the emitter needs to send out the next update with this number. Routing information is distributed among nodes by sending full dumps infrequently and smaller incremental updates more frequently.

DSR [9] is an on-demand protocol designed to restrict the bandwidth consumed by control packets in VANET by eliminating the periodic table-update messages required in a table-driven approach. The major difference between this and other on-demand routing protocols is that it is beacon-less and hence does not require to transmit periodic hello packets (beacons), which are used by a node to inform its neighbors of its presence. The basic approach of this protocol (and all other on-demand routing protocols) during a route construction phase is to establish a route by flooding RouteRequest packets in the network. The destination node, once receiving a RouteRequest packet, responds by sending a RouteReply packet back to the source, which carries the route traversed by the RouteRequest packet received.

In AODV [10], the network is silent until a connection is needed. At that point the network node that needs a connection broadcasts a request for connection. Other AODV nodes forward this message, and record the node from which they hear, creating an explosion of temporary routes back to the needy node. When a node receives such a message and already has a route to the desired node, it sends a message backwards through a temporary route to the requesting node. The needy node then begins using the route that has the least number of hops through other nodes. Unused entries in the routing tables are recycled after a time. When a link fails, a routing error is passed back to a transmitting node, and the process repeats.

Because of the dynamic nature of the mobile nodes in VANET, finding and maintaining routes are very challenging for topology-based routing protocols.

2) Position-Based Routing: Greedy Perimeter Coordinator Routing (GPCR) [11] forwards packets along the road according to vehicle movement. All packets are given the first priority to be forwarded to a junction node in order to determine the next hop. Nevertheless, GPCR cannot completely solve the local maximum problem that while forwarding, the node may reach the situation where its distance to the destination is closer than its neighbours distance to the destination.

Greedy Perimeter Stateless Routing (GPSR) [12] is a responsive and efficient routing protocol for mobile wireless networks. Instead of using graph-theoretic notions of the shortest paths and transitive reachability to find routes, it uses the positions of nodes to make packet forwarding decisions. It uses greedy forwarding to forward packets to nodes that are always progressively closer to the destination. In regions of a network where such a greedy path does not exist (i.e., the only path requires that one move temporarily farther away from the destination), the forwarding node switches the packet into its perimeter mode, and forwards the packet by using a simple planar graph traversal. Greedy forwarding resumes when the packet reaches a node closer to the destination.

In [29], an Intersection-based Geographical Routing Protocol (IGRP) is given to solve the QoS routing problem in VANET in an urban scenario. It uses a genetic algorithm to find the optimal solution satisfying QoS constraints on several performance metrics of building backbone routes based on intermediate and adjacent road intersections toward the Internet gateway. It outperforms GPSR and GPCR at the expense of computation.

Bana *et al.* [30] propose a novel robust, self-organizing architecture for MANET, called space division multiple access (SDMA). SDMA provides users with access to a communication channel based on their location. It provides collision-free access to the communication medium for users and facilitates communication address resolution among them. To improve its bandwidth efficiency, they propose Enhanced SDMA. It overcomes SDMA's disadvantage of the bandwidth efficiency decrease with a decreasing number of users.

A fully deployed RSU infrastructure may not be economically feasible, and packet delivery rate may be low in this environment. In order to maximize packet delivery rate, Driscoll *et al.* [31] propose a hybrid vehicular routing protocol, named Infrastructure Enhanced Geographic Routing Protocol (IEGRP). It facilitates unicast routing by dynamically changing its routing decisions in the presence of RSU infrastructure.

3) Map-Based Routing: Geographic Source Routing (GSR) [32] forwards packets according to the forwarding path, which is calculated based on vehicle location and placement on the map. However, it fails to cope with the sparse connectivity problem when the vehicle density on roads is too low. In [33], Xiang *et al.* propose Geographic Stateless VANET Routing (GeoSVR). It combines node locations with a digital map and uses an improved restricted forwarding algorithm to address unreliable wireless channel issues. The simulations and real-world experiments are performed to evaluate its performances. Their results show that GeoSVR can provide higher packet delivery ratio with comparable latency to AODV and GPSR's. Nzouonta *et al.* [34] present a class of routing protocols called road-based using vehicular traffic (RBVT) routing. RBVT leverages real-time vehicular traffic information to create road-based paths consisting of successions of road intersections that have, with high probability, network connectivity among them. For dense networks, they optimize the forwarding by using a distributed receiver-based election of next hops based on a multicriterion prioritization function.

Traffic lights greatly impact routing in urban areas. In [35], Chang *et al.* propose Shortest-Path-Based Traffic-Light-Aware Routing (STAR) with traffic light considerations. The signals of traffic lights on the intersection and traffic patterns are used together to determine how packets should be forwarded. STAR achieves shorter average delay, higher delivery ratio and higher TCP throughput for urban VANET communications than Virtual Vertex Routing [36], Greedy Traffic Aware Routing [37] and Green-Light-First-based [35] protocols.

4) Path-Based Routing: Vehicle-Assisted Data Delivery (VADD) protocols adopting a carry and forward mechanism are proposed in [38]. It makes use of the predicable vehicle mobility to calculate the packet delivery delay and find the next road to forward a packet. Three different forwarding protocols: Location First Probe, Direction First Probe and Hybrid-VADD are proposed to select the optimal path. Experimental results show that they outperform DSR, the epidemic routing protocol [39] and GPSR with buffer in terms of packet delivery ratio, data packet delay and traffic overhead. Among them, Hybrid-VADD has the best performance.

C. Delay Sensitivity

1) Delay-Sensitive: A delay-sensitive vehicular routing protocol needs exchange road information rapidly. Li and Boukhatem [40] propose such a protocol by using ant colony optimization. It periodically estimates the road segment delay and uses an ant colony optimization concept to set up the initial end-to-end best delay path, then maintains the path by using periodic proactive ants sampling. It outperforms GPSR in regard to delivery ratio, average end-to-end delay and overhead in their experiments. Two main reasons account for such behavior. Initially, it selects optimal routing paths depending on the delay, which promises that more data packets can be transmitted successfully in a certain period of time. Besides, based on pheromone tables, it opportunistically chooses for data packets the optimal next intersection. This scheme helps spread the traffic load over the network, which can relieve the congestion of routing paths and maintain a high delivery ratio.

2) Delay-Tolerant: Different from delay-sensitive routing protocols, delay-tolerant network (DTN) ones can deal with the cases with occasional lack of connectivity, and thus often use a carry and forward mechanism. Their representative is GeoSpray [41], which combines a hybrid approach between multiple-copy and single-copy schemes to make routing decisions based on geographical location data. The former is started in the beginning, and the latter is activated when GeoSpray finds alternative paths. It is shown that GeoSpray improves significantly the delivery probability and reduces the delivery delay, compared to other DTN routing protocols like the epidemic, Spray and Wait [42], and Probabilistic Routing Protocol using History of Encounters and Transitivity [43].

One of the main challenges for DTN routing protocols is to limit network transmissions while achieving a high degree of network coverage. In [44], Khanna *et al.* propose Disrupted Adaptive Routing (DAR). As a gossip-based approach to DTNs, it exhibits a phase transition property for delivery ratio and has an adaptive algorithm to compute gossip probabilities based on the phase transition thresholds in random networks. Experimental results show that DAR reduces the network transmissions more than the traditional epidemic routing protocols and improves delivery ratio and lower average packet delay.

In delay tolerant applications, the unicast routing overhead can be relaxed by using two-hop relay routing. Lee *et al.* [45] investigate the throughput and delay scaling properties of multicasting and propose RelayCast. It is a scalable multicast routing scheme that extends the two-hop relay algorithm in DTNs. Experimental results show that it is much more scalable than ODMRP [46].

D. Dimensions of Scenarios

1) Routing in 1D Scenarios: A 1D scenario is the simplest one for a routing protocol in IoV. Here 1D does not mean that vehicles are in the same line, but they are moving at the same direction or the exactly opposite direction. A classic example is the highway, and a stretch of the road without intersection can be also treated as a 1D scenario. As researchers often start studying a complicated topic from its simplified version, 1D scenario is also a good start point for studying routing protocols in the real world.

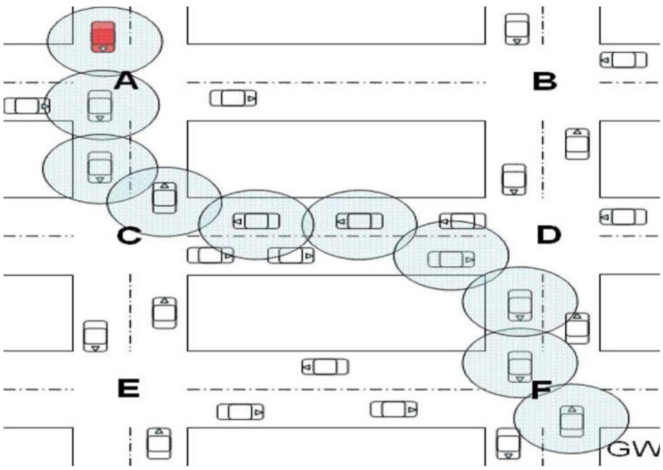

Fig. 3. IGRP builds routes based on intermediate and adjacent road intersections toward the gateway [29].

Some geocast and broadcast routing protocols are designed and evaluated in 1D scenarios, e.g., IVG [14], BROADCOMM [20], and DV-CAST [22].

2) Routing in 2D Scenarios: Existing routing protocols in IoV are mainly analyzed and designed based on ideal 2D scenarios. They can be called plane-based routing protocols [47]. Typical ones are position-based and map-based routing protocols such as GPSR and GSR.

For example, IGRP [29] builds routes based on intermediate and adjacent road intersections toward the gateway. As shown in Fig. 3, Saleet *et al.* consider an urban scenario where the network consists of vehicles and stationary Internet gateways that do not provide full city coverage. Hence, a source node (the red or dark shaded car in Fig. 3) needs to know the route that it should use to forward data packets to the Internet gateway (GW in the bottom right of Fig. 3). IGRP uses sequences of intersections to construct backbone routes and select one of them that has, with high probability, the most "connected" road segments, which is A–C–D–F in Fig. 3. The intersections are all in the same plane. As a result, IGRP cannot distinguish the intersections of a viaduct.

So are DRG [16], GeoSVR [33], RBVT [34], STAR [35], and many other position and map based protocols. Lin *et al.* [47] explain the issues caused by the existing plane-based routing protocols when applied in 3D scenarios by taking GPSR [12] as an example. They conclude that GPSR may slack the route hop and delivery ratio in the realistic 3D scenarios for two reasons:

i. The unnecessary occurrence of interlayer transmission for GPSR in 3D scenarios causes the route hop count to increase, and
ii. In the road topologies including roads with different road layers, the right-hand principle, which traverses the interior of a closed polygonal region in clock-wise edge order, may sometimes increase the possibility of packet loss.

They give a road a defined attribute, road layer. Roads in the different planes mean that they have different road layers. They also conduct a series of simulations comparing the performance of GPSR in 2D and 3D scenarios and allege that 3D scenarios indeed make a bad effect on the performance of the plane-based routing protocols.

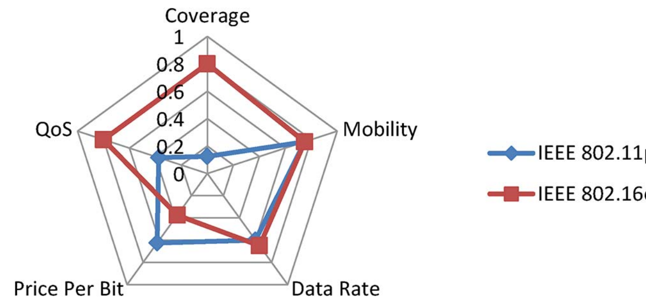

Fig. 4. Comparison of Mobile WiMAX and WAVE [49].

3) Routing in 3D Scenarios: To address the issues about the plane-based routing protocols in 3D scenarios mentioned above, Lin *et al.* [47] propose a Three-Dimensional scenario oriented Routing (TDR) protocol for VANETs. Utilizing 3D information, TDR establishes a route hop by hop and transmits packets as far as possible to the optimal immediate neighbor node, which is located on the same plane with the current forwarding node. Their experimental results show that the delivery ratio of TDR is higher, and its end-to-end delay and average hop count is lower than GPSR in 3D scenarios respectively.

As far as we know, their work is the only one considering the 3D scenarios' impact on routing protocols in IoV. In the near future, when a large scale IoV is put in use, the problems caused by the extremely complicated road topology in the real world may bring same troubles to the IoV operations with the existing routing protocols. Researchers could take the altitude and 3D scenarios into their future studies and evaluate the routing protocols discussed under 2D scenarios.

E. Target Network Types

1) Routing in Homogeneous Network: Most of the traditional VANET routing protocols have one common assumption that all packets are transmitted via a short distance wireless technology, e.g., wireless access in vehicular environments (WAVE) standards [48]. As a result, those routing algorithms' performance is often analyzed and compared under simulations with a WAVE MAC layer parameter. In [49], Dorge *et al.* compare Mobile WiMAX and WAVE under five different metrics and show a graphical comparison in a normalized unit scale as shown in Fig. 4. The former outperforms the latter in QoS, coverage, mobility and data rate except price per bit. They propose Mobile WiMAX as a network opportunity for VANET and evaluate the performance under such a homogeneous WiMAX network of several routing protocols such as AODV [10], DSR [9], and DSDV [8].

From their work, we can see in a homogeneous vehicular network, no matter which underlying wireless access technology is used, the routing protocols work well for most of time. Hence, they can be directly used in the part of IoV with same radio technology.

2) Routing in Heterogeneous Network: The main reason why IoV is more complicated than VANET is that IoV often includes different radio access technologies, thereby leading to a heterogeneous network. Handoff is a classical problem in heterogeneous networks including IoV. The possibility to switch from one access technology to another based on performance,

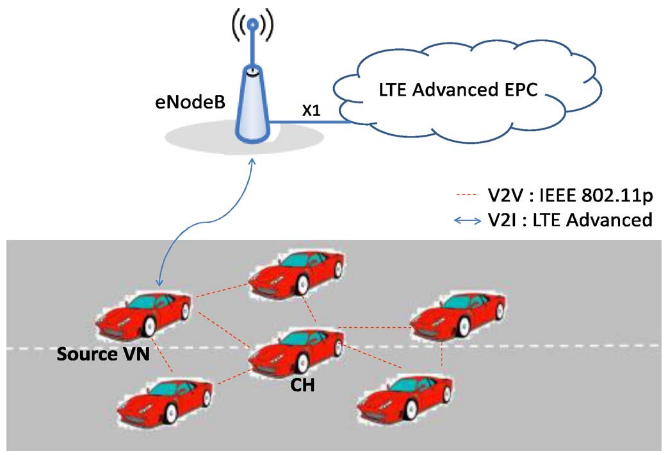

Fig. 5. VANET with LTE-A Infrastructure [51].

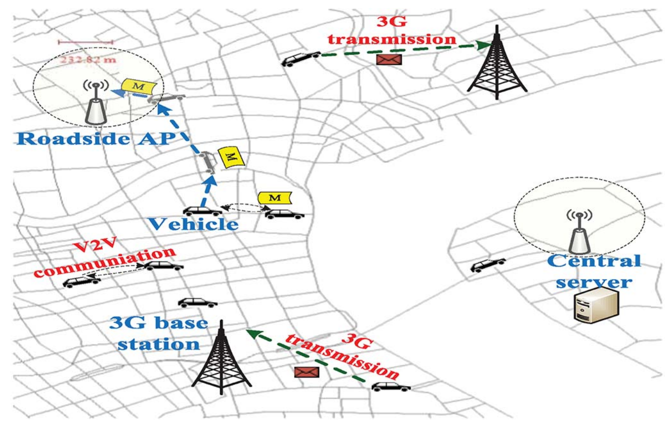

Fig. 6. Illustration of 3G-assisted data delivery in VANETs [53].

availability or economic reasons, while maintaining active connections, is called vertical handoff [50]. Huang *et al.* [50] review more than ten vertical handoff decision-making algorithm proposed in the literature and point out that those solutions may not be effective in the context of IoV. They propose an optimal distributed vertical handoff strategy especially for vehicular heterogeneous networks, i.e., IoV. Their performance evaluations under different scenarios show that without V2V capability, in order to minimize the cost of communications or alternatively minimize the communication time, using vertical handoff is an appropriate choice in lower vehicle speeds, whereas it would be better to avoid vertical handoff and stay in the cellular network at higher speeds. Furthermore, they demonstrate that if V2V communication is also possible, the combination of WLAN, cellular network, and ad hoc networking outperforms any other networking strategies they have considered in terms of transmission time and cost. Their conclusions reveal the effectiveness of bringing more wireless access technologies into VANET to construct a heterogeneous network.

Another approach to routing in a large scale heterogeneous network is clustering. After nodes are clustered and each cluster elects its head, the remaining question for a source node is making the decision about selecting which vehicle will play a proxy role, i.e., gateway to the infrastructure of a wide area radio access technology. In [51], Zhioua *et al.* choose Long Term Evolution Advanced as the second wireless interface as shown in Fig. 5 and compare three possible alternatives for gateway selection:

i. Choose a cluster head as the default gateway,
ii. Choose another vehicle as a gateway candidate, and
iii. Directly attach to the infrastructure, when there is no gateway between the source and infrastructure.

They design an adaptive multi-criteria and attributes decentralized gateway selection algorithm called QoS based Gateway Selection algorithm. It is better than the deterministic approach using the cluster head by default [51].

Li *et al.* [52] deploy a similar cellular-VANET heterogeneous network architecture to realize efficient data dissemination by selecting mobile gateways in clusters. They formulate the selection as a coalition game and construct a coalition formation algorithm composed of three stages. First, every vehicle discovers its neighbors such that it can acquire a potential partner that can cooperate with. Second, every vehicle including the selected gateways invests the possibility of switching into a top preferred coalition. By applying the switch rule, a vehicle can easily leave the current coalition and join a new one. After several switch operations, vehicles will not find any coalition that can provide more utility and the algorithm ends.

Data delivery plays a key role in all networks including IoV, since almost all applications require efficient data delivery. Zhao *et al.* [53] consider vehicles' sensory data gathering application in a client/server architecture through roadside access points as shown in Fig. 6. To resolve the difficulty to find a connected path and the issue of very limited link capacity, they exploit 3G mobile technology to assist data delivery (3GDD). Their approach allocates 3G budget to each time slot by solving an integer linear programming problem formulation of the original optimization problem. It then selects those packets that are most unlikely delivered via VANET for 3G transmissions.

Thus, in their approach, the core problem is through which radio technology a packet should be transmitted when the network becomes heterogeneous. In this situation, traditional homogeneous routing algorithms can no longer find a forwarding path.

Instead of proposing new routing algorithms, integrating existing routing approaches is a promising direction. In [54], Shafiee *et al.* propose a routing protocol for forwarding packets through the combination of WLAN and WiMAX hops called WLAN-WiMAX Double-Technology Routing (WWDTR). It uses a position-based routing approach over the parts of the route in which packets are forwarded via WLAN radios, in order to handle relatively fast changes of the topology with respect to the shorter transmission ranges of WLAN-enabled vehicles. Meanwhile, topology-based routing is employed over the parts of the route in which packets are forwarded via WiMAX radios, given the more stable routes comprised of WiMAX-enabled vehicles, thus yielding a hybrid routing scheme.

Their simulation results show that their proposed routing protocol achieves the best possible performance in terms of delivery ratio and delivery delay for a given budget, whereas in pure position-based or pure topology-based routing schemes sacrificing the performance or budget may be inevitable in many scenarios. The significant advantage of such a hybrid routing scheme shows the potential advancement of IoV over a pure VANET.

Since many applications in heterogeneous IoV eventually links with the Internet, they need to be compatible with Internet Protocol (IP). A network node requires an IP address in order to communicate with its peers within an IP network [55]. Originating from a cellular network, IP addressing and mobility management are important in order to support seamless communication [56]. According to [57], a mobility issue is usually addressed by using Mobile IPv6 [58] with Network Mobility extension [59]. But this mechanism needs a central server, which is stateful. In a stateless procedure, nodes configure and assign addresses automatically without the aid of a central mechanism, which is called auto-configuration.

Researchers [57] present a review of IPv6 vehicle auto-configuration techniques. They identify four main trends: prefix delegation, neighbor discovery extension, geographical networking and future Internet initiatives. In particular, they show the inefficiency of legacy prefix delegation approaches in dynamic scenarios due to its control overhead and induced delay.

Vehicle Identification Number that is a unique and mandatory identity of each vehicle worldwide is promising for auto configuration in IoVs without infrastructure intersections. Imadali *et al.* [60] use them to build a scalable and hierarchical IPv6 addressing space that identifies up to 251 distinct vehicles and compare the proposed technique with others in [57].

To confirm the uniqueness of an IP address, a grid-based duplicate address detection scheme is proposed in [61]. Nodes use the grid's length, central location and their GPS location to generate a grid number and attach to packets. Duplication can be detected if nodes receive packets containing the same IP but different grid numbers.

To sum up, we can resolve routing problems in heterogeneous IoV by determining:

a) the timing of handoff,
b) the gateway node in a VANET, and
c) the wireless technology with which a packet is transmitted, and
d) the IP addressing and mobility management of vehicles.

The first two approaches treat the routing as a problem of making decision about which technology a connection will use, while the third one makes the choice for every packet and even in the process of forwarding a packet. Which one or combination is the most suitable remains an open problem.

F. Summary

The IoV routing layer must efficiently handle rapid topology changes and a fragmented network. Nevertheless, current well known ad hoc routing protocols fail to fully address these specific needs. Traditional topology-based routing protocols are suitable for a vehicular network. Position, map and path-based routing protocols are promising for communication in vehicular networks. However, the stateless nature of geographic forwarding in these protocols prevents them from predicting topology holes (network fragmentation) in node distribution [62], [63]. Thus, frequent fragmentation of a network significantly degrades their performance [64]. Many protocols only work in 1D and 2D scenarios and have poor performance in the real world 3D scenarios. A brief summary of all the protocols we have reviewed is given in Table I.

Reliable communication between vehicles requires out-of-band means (over cellular network or relaying base stations). For more reliable communication, a heterogeneous vehicular network architecture is needed [64], [65]. Hence, we need a set of well-defined routing protocols to address the problems caused by the large scale and heterogeneous nature of IoV and to handle different delay and/or throughput requirements from applications.

III. Evaluation Approaches

It is important to evaluate the performance of a network under various routing protocols in order to know their applicability, advantages and disadvantages [1], [66]. Both real-world experiments and simulations are adopted. We first discuss the widely used simulations and then the important but hard-to-conduct real-world experiments.

A. Traffic Simulation

A critical aspect in a simulation study of IoV is the need for a mobility model reflecting the real behavior of vehicular traffic. Moreover, mobility models are required to be dynamically reconfigurable in order to reflect the effects of a particular communication protocol on vehicular traffic. The community has therefore worked on the development, or revamping, of mobility models specific to vehicular motions [7].

Harri *et al.* [7] make a detailed survey on the existing vehicular mobility models that can be divided into four different classes:

a) Synthetic ones wrapping mathematical models,
b) Survey-based ones that extract mobility patterns from surveys,
c) Trace-based ones that generate mobility patterns from real mobility traces, and
d) Traffic simulator-based ones where the mobility traces are extracted from a detailed traffic simulator.

They point out that a misunderstanding exists in the community about the word "realistic" and the only method to assess the realism is by comparing the motion patterns with real topologies, which is called validation. In their opinion, VanetMobiSim [67] and STRAW [68] in the category of isolated models, or MoVes [69] and AutoMesh [70] in the category of embedded models, are able to fulfill all requirements for realistic modeling of vehicular motion patterns. In a federated category, solutions like TraNS [71] or MSIE [72] provide a full control of vehicular mobility in reaction to vehicular safety applications. They also notice the need for the agreement on a common set of traffic parameters as well as benchmark values for the evaluation metrics in order to obtain a fair comparison in different environments.

TABLE I
SUMMARY OF ROUTING PROTOCOLS IN IoV

Routing Protocols	Routing Type	Information Used	Delay Sensitivity	Scenarios	Network
DSDV [8]	Unicast	Topology-based	Delay-sensitive	1D/2D	Homogeneous
DSR [9]	Unicast	Topology-based	Delay-sensitive	1D/2D	Homogeneous
AODV [10]	Unicast	Topology-based	Delay-sensitive	1D/2D	Homogeneous
GPCR [11]	Unicast	Position-based	Delay-tolerant	2D	Homogeneous
GPSR [12]	Unicast	Position-based	Delay-tolerant	2D	Homogeneous
IVG [14]	Geocast	Position-based	Delay-sensitive	1D	Homogeneous
Cached Geocast [15]	Geocast	Position-based	Delay-tolerant	2D	Homogeneous
DRG [16]	Geocast	Position-based	Delay-sensitive	2D	Homogeneous
T-TSG [17]	Geocast	Position-based	Delay-sensitive	2D	Homogeneous
GeoSPIN [18]	Geocast	Position-based	Delay-tolerant	2D	Homogeneous
BROADCOMM [20]	Broadcast	N/A	Delay-sensitive	1D	Homogeneous
Flooding UMB [21]	Broadcast	Map-based	Delay-sensitive	2D	Homogeneous
DV-CAST [22]	Broadcast	Local information	Delay-tolerant	1D	Homogeneous
UV-CAST [24]	Broadcast	Local information	Delay-tolerant	2D	Homogeneous
DHVN [25]	Broadcast	Position-based	Delay-tolerant	2D	Heterogeneous
Two-timer based [26]	Broadcast	Position-based	Delay-sensitive	2D	Homogeneous
IGRP [29]	Unicast	Position-based	Delay-tolerant	2D	Homogeneous
SDMA [30]	Unicast	Position-based	Delay-tolerant	2D	Homogeneous
IEGRP [31]	Unicast	Position-based	Delay-tolerant	2D	Homogeneous
GSR [32]	Unicast	Map-based	Delay-tolerant	2D	Homogeneous
GeoSVR [33]	Unicast	Map-based	Delay-tolerant	2D	Homogeneous
RBVT [34]	Unicast	Map-based	Both	2D	Homogeneous
STAR [35]	Unicast	Map-based	Delay-tolerant	2D	Homogeneous
VADD [38]	Unicast	Path-based	Delay-tolerant	2D	Homogeneous
Ant colony based [40]	Unicast	Map-based	Delay-sensitive	2D	Homogeneous
GeoSpray [41]	Unicast	Position-based	Delay-tolerant	2D	Homogeneous
DAR [44]	Unicast	N/A	Delay-tolerant	2D	Homogeneous
RelayCast [45]	Unicast	N/A	Delay-tolerant	2D	Homogeneous
TDR [47]	Unicast	Position-based	Delay-sensitive	3D	Homogeneous
3GDD [53]	Unicast	N/A	Delay-sensitive	2D	Heterogeneous
WWDTR [54]	Unicast	Position/Topology-based	Delay-sensitive	2D	Heterogeneous

1) Datasets: Although a mobility model is usually sufficient for traffic simulation, applying a well-configured dataset can be very helpful for researchers to focus on their own topics. Such dataset can be a benchmark used to compare different approaches.

Huang *et al.* [73] have gathered three-month GPS data in a 40-second interval from over 4000 taxis in the downtown area of Shanghai, China and reconstruct the traces by mapping the data onto a digital map, determining the routes between every two consecutive data samples and interpolating points into the intervals. The resulting dataset is called SUVnet and available online [74].

Naumov *et al.* [75] use a multi-agent traffic simulator developed at ETH Zurich to generate a 24 hour detailed car traffic trace file. The file contains detailed simulation results for the area in the Canton of Zurich, which includes main country highways. Around 260 000 vehicles are involved in the simulation with more than 25 million recorded vehicles direction/speed changes in an area of around 250 km $\times$ 260 km. The data are also available online for free use [76].

In [77], Uppoor and Fiore introduce a large-scale dataset called TAPASCologne as shown in Fig. 7. It combines a real-world road topology, accurate microscopic mobility modeling, realistic traffic demand, and state-of-art traffic assignment, to generate a large-scale synthetic trace of the car traffic over a typical 24 hours in a 400 km^2 region around the city of Cologne in Germany, comprising more than 700 000 individual car trips. It is the largest scale vehicular mobility trace to date, and is downloadable [78].

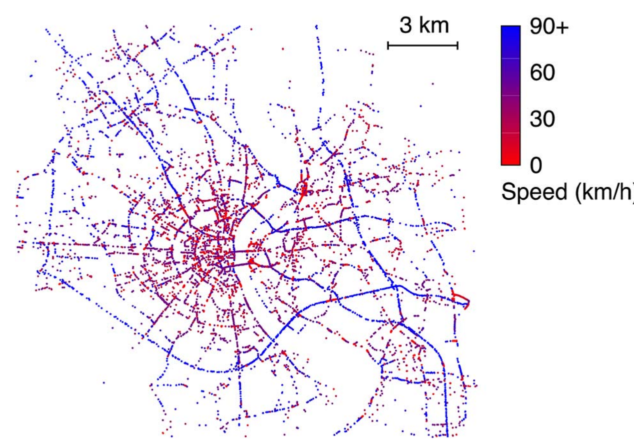

Fig. 7. Final TAPASCologne dataset. Snapshot of the traffic status at 7:00 A.M., in a 400 km^2 region centered on the city of Köln [77]. Blue vehicles are moving, whereas bright red ones are still.

B. Network Simulation

The mobility models, as described earlier, are generally used to produce node movement traces that are then fed to a network simulator. The simulator then controls the communication among mobile nodes. The most appropriate way to evaluate the performance of a network is to deploy simulations that provide the results closest to real-world observations [79].

As summarized in Table II, various simulation tools have been used to evaluate the performance of routing protocols in IoV. Because vehicular networks involve solely wireless

TABLE II
SUMMARY OF POPULAR NETWORK SIMULATORS

Network Simulator	OPNET	QualNet [81]	ns-2	ns-3	J-Sim [82]	OMNeT++/ OMNEST [83]	SWANS [84]
License	Commercial/ RPM Modeler University Program	Commercial/ SCALABLE EDU Program	GNU GPLv2	GNU GPLv2	BSD License	Academic/ Commercial	Academic
Written Language	Unknown	C/C++	C++	C++	Java	C++	Java
Simulation Language	C/C++	C/C++	C++/OTcl	C++/Python	Java/Tcl/ Perl/Python	C++/NED	Java/Python
GUI IDE	Yes	Yes	No	No	No	Yes	No
Officially Supported OS	Windows	Windows(VS)/ Linux	Linux/FreeBSD/ OS X/Solaris/ Win dows (Cygwin)	Linux/FreeBSD /Windows (Cygwin)	Windows /OS X/Linux	Windows/OS X/Linux	Windows/ OS X/Linux
Source Code Avaliablity	Only for simulation modules	Yes	Yes	Yes	Yes	Yes	Yes
Officially Supported Wireless Technology	WiFi/LTE/UM TS/WiMAX/ Zigbee/Satellite	Wi-Fi/WiMAX /GSM/UMTS/ LTE/Zigbee	Wi-Fi/Satellite/ Cellular	Wi-Fi/WiMAX/ LTE	Wi-Fi	None (through external models)	Wi-Fi (IEEE 802.11b)
Mobility Model Included	No	Yes	No	No	No	No	No

communications, all of them can be used to support simulations with mobile wireless nodes. Table II lists seven popular network simulators. Most of them offer their source code but require users to provide their own mobility models.

A significant factor that influences the realism of a network simulation result is the propagation model. It involves two important aspects: large-scale path loss and small-scale fading [85]. The former is used to determine the mean received signal power at a particular distance from a transmitter. The latter generally involves the modeling of multi-path fading, power delay profile, and Doppler spectrum. It is worth noting that they can greatly impact the packet error rate performance.

Radio signals are influenced by six main factors: free-space path loss, shadowing, reflection, diffraction, fading and Doppler shift [86].Van Eenennaam [87] has surveyed commonly-used propagation models and classified them into two categories: deterministic ones such as Free Space, Two-ray Ground and Ray Tracing models, and probabilistic ones, e.g., Log-Normal Shadowing, Rayleigh, Longley-Rice and Nakagami models.

Sommer and Dressler [88] first reveal that the commonly used simplified Two-Ray Ground path loss models is of no benefit in comparison with the basic Free Space model for WAVE transmissions by experiments on the road in real world. In contrast, according to their measurement results, the Two-Ray Interference model leads to a better approximation, as shown in Fig. 8. Sommer *et al.* [89] conclude that the use of the detailed Two-Ray Interference model substantially improves the quality of the predicted path loss in vehicular environments by integrating the model into the Veins vehicular network simulation framework and validating it based on both analytical methods and extensive real-world measurements.

Straightforward ray-tracing approaches do not scale to the number of simulated nodes and transmissions as required in IoV scenarios, and even the models that rely on preprocessing steps can be prohibitively time-consuming in medium-scale simulation scenarios [90]. Hence, the unit disc model is widely used in the analysis of the IoV topology characteristics due

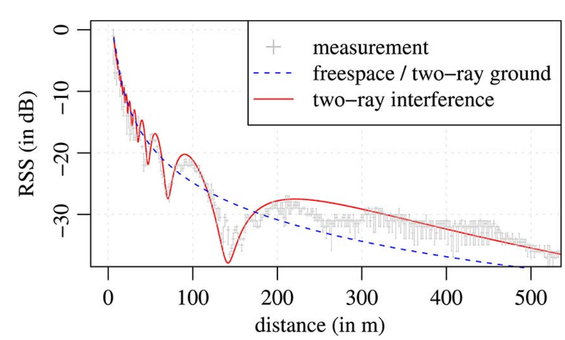

Fig. 8. Received signal strength vs. distance between sender and receiver. Overlay of measurement results, predictions by the Freespace, Two-Ray Ground, Two-Ray Interference models [88].

to its simplicity. Topological characteristics are analyzed under realistic traffic flows along the highway with different channel models [91]. It is concluded that a finely tuned log normal model should be used instead of a unit disc model that is commonly used but inaccurate, and an obstacle-based one that is accurate but hard to implement.

We suggest researchers to use a propagation model whose accuracy is at least higher than the unit disc or Free Space model. With the emergence of the cloud computing, extensive computation can be fed into clouds. Hence, researchers will be able to choose more realistic but time-consuming models like ray-tracing in their future studies.

C. Integrated Framework

Two approaches, i.e., loose and tight integrations, can be used to combine the traffic and network simulations. The former uses separate mobility and network simulators. The mobility one generates the mobility of vehicles and records the vehicular movements into trace files. The network one imports these trace files, but there is no direct interaction between the two simulators. The latter does not use trace files but rather embed

TABLE III
SUMMARY OF TIGHTLY INTEGRATED SIMULATION FRAMEWORKS

Famework	Direction of communication	No. of events queue	Mobility model	Network simulator	Visualizable	Features and Restriction
SWANS++ [93]	One-way	N/A	STRAW [68]	SWANS	Yes	• Simple intersegment mobility • Origin–destination mobility
GrooveNet [94], [95]	One-way	N/A	Roadnav [96]	Self-developed	Yes	The ability to integrate simulated vehicles with real vehicles
TraNS [71]	One-way (network-centric mode) Two-way (application-centric mode)	Two	SUMO	ns-2	Yes	An interface convertes the mobility commands from ns-2 to a sequence of mobility primitive commands such as stop, change lane, and change speed, which can be sent to SUMO
Veins [97], [98]	Two-way	Two	SUMO	OMNeT++	Yes	A full-featured WAVE model [99]
ITETRIS [100]	Two-way	Two	SUMO	ns-3	Yes	The successor of TraNS [92]
NCTUns 4.0 [101]	Two-way	One	Self-developed	Self-developed	Yes	• Prespecified mode • Autopilot mode • Difficult to extend
Gorgorin *et al.* [102]	Two-way	One	VISSIM	Self-developed	Yes	• The mobility model has been validated against traces taken from a German and a U.S highway. • A model to compute fuel consumption and pollutant emissions
ASH [103]	Two-way	One	IDM vehicular mobility model and MOBIL lane changing	SWANS	No	• Node types: mobile communicating, mobile silent, static communicating, and static silent nodes • Only highway
VNS [92]	Two-way	One	Redesigned DIVERT 2.0	ns-3	Yes	Rapid neighbour searching during wireless transmissions by using a quadtree

both mobility and network simulators into a single vehicular network simulator. In some cases, the mobility and network models should communicate, e.g., providing feedback from the network one to adjust parameters of vehicular movement. For example, in traffic congestion notification systems, the receipt of certain network messages may cause a vehicle to change its path, e.g., taking an early exit. In collision avoidance systems, network messages may cause a vehicle to slow down to avoid an accident. This type of feedback is not supported by the former [79], [92].

Table III lists nine tightly integrated simulation frameworks, implemented in the following ways:

i. One-way communication (from a mobility model to a network), which is suitable for simulating infotainment-related VANET applications, including Internet connectivity, multimedia, and peer-to-peer content sharing. The communication affects no vehicle movement;
ii. Two-way communication and two event queues, which is appropriate for safety-related and traffic information applications where feedback from the network affects vehicle movements. It consumes more memory and execution time than the next one where only one event queue is needed; and
iii. Two-way communication and a single event queue. It removes the burden of synchronizing the two types of events and is more efficient from the execution and memory perspectives than the one with two event queues, but it is not easy for maintenance and extension [79].

Among all these frameworks, we recommend researchers to choose Veins [97], [98] or ITETRIS [100] because these two combine the most popular mobility model SUMO with a latest network simulator, which provides many modern features in programming. Especially in Veins, a full-featured WAVE model is available, which may offer a more accurate result via network simulations.

D. Real-World Experiments

Although it is crucial to test and evaluate protocol implementations in real testbed environments as well as logistic difficulties, economic issues and technology limitations, it is definitely not sufficient to study IoV via simulations only. It is necessary to validate the research in the real world.

Neves *et al.* [104] present a set of experiments by using a WAVE physical layer implementation based on the open-source driver, under both line of sight (LOS) and non-line of sight (NLOS) conditions. A huge difference in communication ranges between them (950 m in LOS versus less than 100 m in NLOS) is observed. The results obtained in simulations of NLOS scenarios carried out with ns-3 are far from the real-world measurements because of the low-accuracy propagation models.

Most existing experiments involve only a limited number of vehicles for the lack of sufficient vehicles enabled with communication interfaces that support WAVE-based networking, which has prevented the run of any large-scale experiment [105]. Fortunately, there appear several promising researches that may be able to resolve the problem.

In a hybrid mode of GrooveNet [94], [95], it is possible to communicate between a small number of real vehicles and a large number of simulated vehicles by using the same protocol implementation, algorithms and packet types. Fig. 9 illustrates a scenario about two real vehicles that are not within their direct communication range of each other. But messages between them can be forwarded over the cellular interface to a remote server that simulates all simulated vehicles in the vicinity and

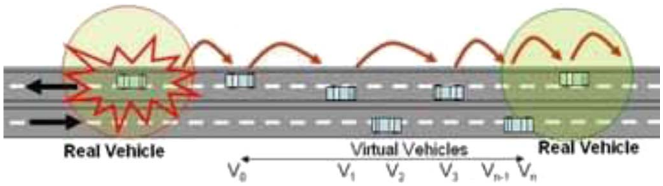

Fig. 9. A hybrid simulation with two real vehicles communicating across multiple simulated vehicles [95].

updates the network state with a triggered event. GrooveNet's unique ability to integrate simulated vehicles with real ones allows it to function as testbed software as well as a simulator.

Amoroso *et al.* [105] devise the guidelines that should be followed to reconstruct the situation that a communication protocol would experience on a street while running on a VANET, as a function of three variables, i.e., the number of hops traversed by communication packets, vehicle density and channel conditions. It is possible by recreating the conditions (hops, vehicular density and channel conditions) that a communication packet would encounter on an arbitrarily long path between two vehicles, by simply utilizing a few vehicles that emulate those conditions. They show that it is possible to perform sound vehicular experiments that would require the use of many cars with only a few vehicles, while resembling, as closely as possible, the situation that would be experienced in reality. In brief, they propose a virtual overlay network, composed of relaying and interfering vehicles, on top of a platoon made of only a few vehicles. Such overlay network supports the implementation of experiments where communication packets can travel for an arbitrary number of hops, while experiencing the interference of an arbitrary number of vehicular transmitters as the physical channel characteristics vary.

Marfia *et al.* [106] propose a further step forward: importing the use of cognitive radios to investigate how different frequency bands and different frequency switching time can affect the performance of communication protocols in vehicular environments. They show that cognitive interfaces can play a role as an additional tunable dimension to be used within an experimental platform where highly dense vehicular testbeds can be structured, even in the presence of only a few real vehicles. They show, in particular, that cognitive interfaces can be: 1) used to test new strategies that deal with the scarcity of the radio spectrum in a vehicular environment, and 2) utilized to assess IoV protocol performances as a function of different variables. For example, they provide some experimental results obtained from a highway accident warning system and a cognitive network. Their techniques are promising in the future real world experiments for IoV.

IV. Conclusion

The Internet started with some small-scale local area networks. After the development of protocols for Internetworking, i.e., the Internet protocol suite (TCP/IP) and implementation in ARPANET, the concept of a world-wide network of interconnected TCP/IP networks, called the Internet, was introduced [107]. Likewise, IoV needs a general protocol suite for horizontal networking in order to realize IoV and web of things, as illustrated in Fig. 10. In such a suite, the routing protocol is a vital but hard part owing to the difficulty of finding routes in a highly dynamic IoV.

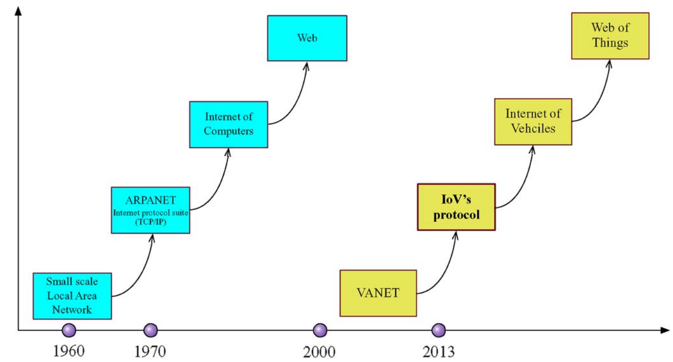

Fig. 10. Evolution of IoV.

This paper reviews routing protocols of IoV, from their design to evaluation. Based on their transmission strategy we have three categories: unicast, geocast and broadcast ones. In many studies, a routing protocol refers specifically to those in the first category. Applications such as accident warnings, information about bad road conditions, emergency vehicle preemption, and generic information services (e.g., facts on tourism or free parking) can benefit from the second type protocols [108]. Both types of routing algorithms may use the last type, i.e., broadcast protocols in some stages of their routing process.

Based on information they require, we have four categories: topology, position, map and path-based ones. Most classical ones from MANET fall into the first category. Because of the dynamic nature of the mobile nodes in IoV, finding and maintaining routes is very challenging with them. Hence, researchers propose other kinds of routing protocols. Most of them aim to solve the problems in a special scenario or small-scale homogeneous network, i.e., VANET. Their effectiveness in large-scale heterogeneous networks remains unexplored.

Based on delay sensitivity, we identify them into delay-sensitive and delay-tolerant ones. The former is most suitable for those safety-related information services, such as accident or sudden hard breaking notification [109] and obstacle warning [110], and for video streaming [111] or online games [112] in IoV. The latter can be used in the applications that requires large throughput but can tolerate some small delays, e.g., cooperative downloading [113] and infotainment applications [114], [115].

According to their dimensions, we have 1D, 2D and 3D scenarios. The first two are called plane-based routings, and show poor performances in the real world for the lack of consideration of the third vertical dimension. Hence, future study should pay more attention to the last one.

Based on their target network types, we have homogeneous and heterogeneous networks. Most traditional ones are only feasible in the former. We review and summarize the existing routing approaches in a heterogeneous IoV. The composition of classical VANET routing protocols and latest heterogeneous network approaches will be an exciting topic in the future IoV studies.

Next we look into their evaluation approaches, i.e., computer simulation and real-world experiments. Simulation is widely accepted owing to both technological and financial difficulties in obtaining real-world testbeds. Tightly integrated simulation frameworks are the most promising tools to examine proposed ideas for IoV. Yet, researchers never give up real world experiments that are conducted to verify and optimize the simulation tools. Some technologies [94], [95], [105], [106] have been proposed to make them possible with only a few real vehicles with all needed IoV communication capabilities.

IoV includes not only the traditional VANET but also a much sizable and heterogeneous network structure. In order to make IoV work in the real world, we suggest researchers to validate their studies not only in small-scale homogeneous networks but also in such large-scale heterogeneous ones in order to make vehicles on roads really become the third information space right after homes and offices.

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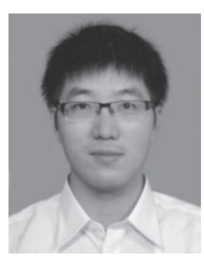
JiuJun Cheng received the Ph.D. degree from Beijing University of Posts and Telecommunications, Beijing, China, in 2006. He is currently an Associate Professor with Tongji University, Shanghai, China. In 2009, he was a Visiting Professor at Aalto University, Espoo, Finland. He has over 30 publications, including conference and journal papers. His research interests span the area of mobile computing and social network with a focus on mobile/Internet interworking, service computing, and Internet of Vehicles.

JunLu Cheng received the B.E. degree in computer science and technology from Tongji University, Shanghai, China, in 2012, where he is currently working toward the master's degree with the College of Electronics and Information Engineering. His research interests are routing algorithms and simulations in Internet of Vehicles and mobile computing.

MengChu Zhou (S'88–M'90–SM'93–F'03) received the B.S. degree in control engineering from Nanjing University of Science and Technology, Nanjing, China, in 1983; the M.S. degree in automatic control from Beijing Institute of Technology, Beijing, China, in 1986; and the Ph.D. degree in computer and systems engineering from Rensselaer Polytechnic Institute, Troy, NY, USA, in 1990. He joined New Jersey Institute of Technology, Newark, NJ, USA, in 1990 and is now a Distinguished Professor of Electrical and Computer Engineering. He is currently a Professor at Tongji University, Shanghai, China. He has over 600 publications, including 12 books, more than 290 journal papers (the majority in IEEE Transactions), and 28 book-chapters. His research interests are in Petri nets, sensor networks, web services, semiconductor manufacturing, transportation, and energy systems. Prof. Zhou is a Life Member of the Chinese Association for Science and Technology, USA, and served as its President in 1999. He is also a Fellow of IFAC and AAAS. He is the founding Editor of IEEE Press Book Series on Systems Science and Engineering and an Associate Editor of IEEE TRANSACTIONS ON SYSTEMS, MAN AND CYBERNETICS: SYSTEMS, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, and IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS.

FuQiang Liu (M'09) received the bachelor's degree from Tianjin University, Tianjin, China, in 1987 and the Ph.D. degree from China University of Mining and Technology, Beijing, China, in 1996. He is a Professor at the School of Electronics and Information Engineering, Tongji University, Shanghai, China, and currently serves as the Director of the Broadband Wireless Communication and Multimedia Laboratory. He is a Guest Professor of the National Institute of Informatics, Japan.

He has published more than 300 scientific papers and nine books. He has participated in numerous national research projects in China and also received research funding from USA, Finland, EU, and Japan. His research mainly focuses on theories and technologies of broadband wireless communications (5G mobile communication) and their applications in automotive and intelligent transportation systems.



ShangCe Gao received the Ph.D. degree in innovative life science from University of Toyama, Toyama, Japan, in 2011. He is currently an Associate Professor with the Faculty of Engineering, University of Toyama. From 2011 to 2012, he was an Associate Research Fellow with Key Laboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai, China. From 2012 to 2014, he was an Associate Professor with the College of Information Sciences and Technology, Donghua University, Shanghai. His main research interests include mobile computing, nature-inspired technologies, and neural networks for optimization and real-world applications. Dr. Gao received the Shanghai Rising-Star Scientist award, the Chen-Guang Scholar of Shanghai award, the Outstanding Academic Performance Award of IEICE, and the Outstanding Academic Achievement Award of IPSJ.

Cong Liu received the bachelor's degree in computer science and technology from Shandong University of Science and Technology, Qingdao, China in 2013, and he is currently working toward the master's degree with the College of Information Science and Engineering. His research interests are in the areas of Petri nets, service composition, business process management, process mining and Internet of Vehicles. He took part in several national and provincial scientific research programs and has published more than 10 papers in journals and conferences.