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Review:

Unicast routing protocols for urban vehicular networks: review, taxonomy, and open research issues*

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Abstract: Over the past few years, numerous traffic safety applications have been developed using vehicular ad hoc networks (VANETs). These applications represent public interest and require network-wide dissemination techniques. On the other hand, certain non-safety applications do not require network-wide dissemination techniques. Such applications can be characterized by their individual interest between two vehicles that are geographically apart. In the existing literature, several proposals of unicast protocols exist that can be used for these non-safety applications. Among the proposals, unicast protocols for city scenarios are considered to be most challenging. This implies that in city scenarios unicast protocols show minimal persistence towards highly dynamic vehicular characteristics, including mobility, road structure, and physical environment. Unlike other studies, this review is motivated by the diversity of vehicular characteristics and difficulty of unicast protocol adaption in city scenarios. The review starts with the categorization of unicast protocols for city scenarios according to their requirement for a predefined unicast path. Then, properties of typical city roads are discussed, which helps to explore limitations in efficient unicast communication. Through an exhaustive literature review, we propose a thematic taxonomy based on different aspects of unicast protocol operation. It is followed by a review of selected unicast protocols for city scenarios that reveal their fundamental characteristics. Several significant parameters from the taxonomy are used to qualitatively compare the reviewed protocols. Qualitative comparison also includes critical investigation of distinct approaches taken by researchers in experimental protocol evaluation. As an outcome of this review, we point out open research issues in unicast routing.

Key words: Unicast protocols, Taxonomy, Protocol review, Vehicular ad hoc networks, Geographic routing
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1 Introduction

A growing number of vehicles and technological developments in wireless communications have transformed vehicles on roads into a distributed communication system referred to as the vehicular ad hoc network (VANET). Contemporary vehicles have ample storage, power resources, and access to location services such as the Global Positioning System (GPS). In addition, on-board units (OBUs) enable vehicles to perform spontaneous wireless communication by using a technology called wireless access for vehicular environment (WAVE) (Uzcategui and Acosta-Marum, 2009). This perspective represents a distributed network in which a vehicle can communicate with a peer vehicle or a roadside unit (RSU) for a range of telematics applications.

Applications for VANETs are divided into two categories: safety and non-safety (Chu and Huang, 2007; Schoch *et al.*, 2008; Papadimitratos *et al.*, 2009; Hossain *et al.*, 2010; Martinez *et al.*, 2010; Shevade

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et al., 2010; Zhou *et al.*, 2011; Ahmed *et al.*, 2013).

The key motivation for VANETs comes from the safety of passengers while traveling on roads. Safety applications are represented by public interest that aims to address a diverse set of problems. For instance, safety alerts about obstacles on roads, abnormal road conditions, vehicle collision avoidance, and adaptive cruise control can significantly improve passenger safety by avoiding potential hazzards on roads (Willke *et al.*, 2009). This implies that information related to public interest requires network-wide dissemination techniques owing to a common objective shared among all vehicles (Chen *et al.*, 2010; Hall, 2011; Felice *et al.*, 2012; Panichpapiboon and Pattara-atikom, 2012). On the other hand, non-safety applications are motivated by the comfort of passengers while commuting. Non-safety applications are represented by the individual interest of particular vehicles and RSUs involved in communication. For instance, accessing Internet on highway requires communication between a particular vehicle and RSU acting as an access point. Similarly, other applications representing individual interest include multi-player gaming (Tonguz and Boban, 2010) and live video streaming using point-to-point (P2P) links (to name a few, Chu and Huang (2007) and Zhou *et al.* (2011)). This implies that information related to individual interest requires services of unicast protocols for particular vehicles involved in communication, which serves as the focal point of this review.

The key communication requirements for non-safety applications include network connectivity and long-lasting links for effective transmission. Unlike highways, urban roads have higher vehicular density which translates into better connectivity. However, connectivity is inconsistent; that is, it can be defined by vehicular density during peak hours, stoppages at traffic signals, and vehicle slowdowns caused by speed limits. Thus, urban roads exhibit a higher degree of connectivity than highways and are suitable for applications that require unicast communications.

Unicast communications in urban scenarios face communication challenges owing to the unique properties of vehicular networks. Specifically, these challenges originate from inconsistent mobility patterns (Schoch *et al.*, 2008), communication infrastructure, and physical infrastructure (Wisitpongphan *et al.*, 2007; Schmidt *et al.*, 2009). Unicast protocols for urban scenarios adapt various techniques to overcome such challenges. In recent years, a number of unicast protocols have been proposed for urban scenarios to provide robust communications. To provide an initial classification, we categorize these protocols into two main groups (Fig. 1). The two groups employ path-dependent and path-independent routing approaches, respectively.

These two groups of approaches differ in their methods of unicast path selection and subsequent data forwarding.

In path-dependent approaches, a unicast path that connects the sending and receiving vehicles is established. Path establishment is a process of identifying a unicast link which contains a sequence of vehicles or a sequence of intersections. This process involves the acquisition of network information through an exchange of control messages, available location services, or both. Path selection is followed

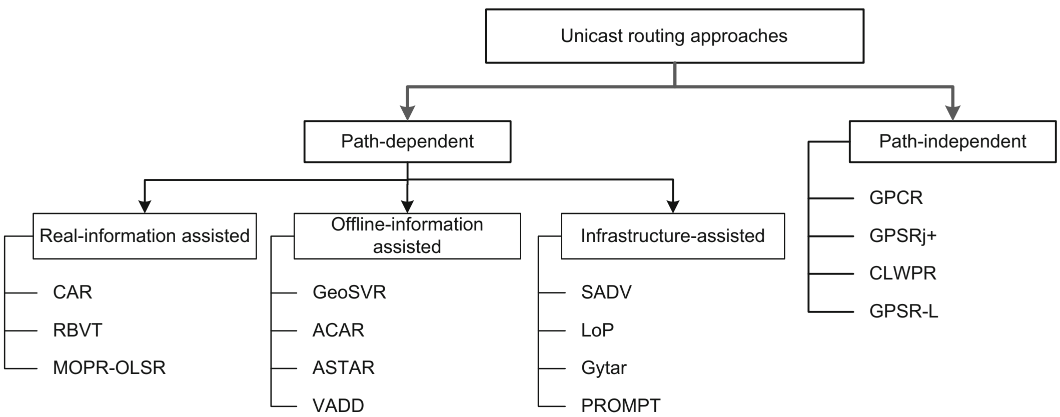

Fig. 1 Initial unicast protocol classification showing two major groups of routing approaches

by one-hop relay vehicle selection. Subsequently, packets are sent to relays within the unicast path. Thus, the transmission packet carries information about the destination vehicle and the identified unicast path.

In path-independent approaches, a vehicle does not need a connected path between the sending and receiving vehicles. Unicast transmission is based on the local topology information of a vehicle, which is acquired through one-hop neighbor discovery. In addition, the source needs destination location through location services, such as in Li *et al.* (2000), Käsemann *et al.* (2002), and Kieß *et al.* (2004). In other words, path-independent approaches have a one-step process that includes only relay selection; thus, a packet sent through this type of approach includes only destination location. Fig. 1 shows the unicast protocol classification and the corresponding unicast protocols reviewed in the current study.

Previous studies reviewed different protocol paradigms or classified protocols as position-based and topology-based (Bernsen and Manivannan, 2009; Fonseca and Vazão, 2013). The current study aims to present a qualitative review of unicast protocols in urban scenarios with emphasis on the applicability of unicast protocols in urban scenarios.

Table 1 lists all acronyms used in this review and their corresponding meanings.

Table 1 List of acronyms

Acronym	Description
VANET	Vehicular ad hoc network
GPS	Global Positioning System
OBU	On-board unit
WAVE	Wireless access for vehicular environments
ITS	Intelligent transportation services
RSU	Road side unit
V2V	Vehicle to vehicle
MANET	Mobile ad hoc network
OSI	Open system interconnection
RA	Routing approach
PO	Probing objective
RcA	Recovery approach
RS	Relay selection
ND/PD	Neighbor discovery/Path discovery
CLRT	Control load reducing technique
UMB	Urban multi-hop broadcast
PGB	Preferred group broadcast
TTL	Time to live
PS	Probing scope
RMT	Route metric type
PG	Probing granularity
FO	Forwarding objective
G-active	Global active
G-passive	Global passive
RTS/CTS	Request to send/Clear to send
PDR	Packet delivery ratio
E2ED	End-to-end delay
ROv	Routing overhead
POv	Packet overhead
COv	Control overhead
PL	Path length
NT	Network throughput
PLR	Packet loss ratio
SL	Storage load

2 Background

In this section, we discuss the urban scenario and its limiting factors in desirable communication. Then, we present corresponding requirements on protocol design that can reduce limitations on effective communication. Finally, relative to these requirements, we discuss fundamental building blocks of unicast protocols.

2.1 Limitations on effective communication

Principles of unicast communication in VANETs are similar to those in mobile ad hoc networks (MANETs). Explicitly, both networks employ the multi-hop transmission strategy as a foundation for useful communication. However, several factors complicate the applicability of the unicast protocol in urban scenarios. Road organization in cities is defined by connected road segments via intersections. This organization can be illustrated as a geometrical grid or a more realistic and less geometrical road topology (Fig. 2). The latter can be acquired as a graph of real road topologies from digital maps such as Bureau (http://www.census.gov/geo/maps-data/data/tiger.html).

In addition to road organization, related characteristics of unique mobility patterns and infrastructure act as limiting factors in effective communication. Existing trends in protocol evaluation also restrict the true assessment of the strengths and weaknesses of a proposed protocol. We identify these aspects as constraints (Table 2), and discuss their effects on unicast communication and evaluation.

2.1.1 Mobility

A constraint group is defined by speed patterns and the number of possible routes for vehicles. Vehicular speed in the urban scenario is highly variable

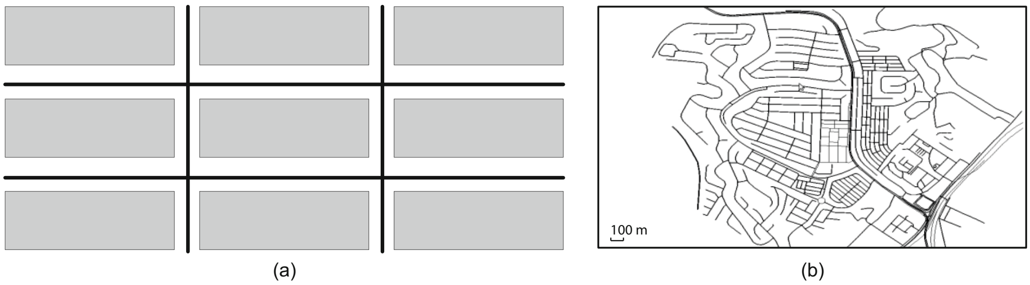

Fig. 2 Urban road organization as a 3 × 3 grid (a) and real road topology acquired through a digital map (b)

Table 2 Constraints in urban vehicular networks and properties and effects on communication

Constraint	Property	Effect
Mobility	Speed patterns	Short-lived links
	Available routes	Route selection with insufficient vehicles
Physical infrastructure	Vehicular density	Redundant links, sparse links
	Obstacles	Reduced network visibility, signal fading, hidden nodes
Communication infrastructure	Wireless spectrum	Contention, control overhead
Protocol evaluation	Simulation platforms	Communication assumptions, inconsistent protocol comparison

because of the presence of road segments, speed limits, number of lanes, and traffic signs at intersections (Schoch *et al.*, 2008). Therefore, effective link lifetime depends on the difference between the speed patterns of connected vehicles. For instance, vehicles on the same lane or waiting at an intersection have minimal speed difference and therefore have good connectivity. Meanwhile, vehicles on opposite lanes experience intermittent connectivity because of high speed differences. Numerous possible travel routes are available for a vehicle in urban scenarios, and the connectivity on road segments differs from one another given the varying number of vehicles.

2.1.2 Physical infrastructure

Physical infrastructure signifies vehicular density and obstacles that affect communication. During rush hours, urban roads have high vehicular density with multiple links for communication. Although multiple links provide useful link redundancy for links that failed, vehicles may experience reception of multiple copies of the same data through multiple links. Lack of vehicles causes sparse links, which in turn halts communication temporarily or permanently. Moreover, obstacles between vehicles reduce network visibility to the point at which vehicles cannot detect one another. Hidden node problems commonly produce simultaneous transmissions from multiple senders, thereby causing packet collisions at the receiving vehicle (Schmidt *et al.*, 2009; Jarupan and Ekici, 2011). Signal fading as a result of obstacles is a related concern for communication. Fading can constrain transmission quality to the extent that packets are dropped by the receiving vehicle (Schmidt *et al.*, 2009).

2.1.3 Communication infrastructure

The 5 GHz wireless spectrum imposes limitations on unicast communication (Wisitpongphan *et al.*, 2007; Schmidt *et al.*, 2009). Specifically, the shared and limited nature of a wireless spectrum presents significant limitations during the phases of path discovery and subsequent data forwarding. In other words, during these phases, vehicles should acquire channel resources before starting communication. Under a growing number of active vehicles, contention for acquisition of wireless spectrum increases and causes a competitive communication environment. Furthermore, mobility demands periodic exchange of control messages for vehicles to maintain an updated network view. These messages require consistent transmission and availability of a wireless medium. These messages, called beacons, add to the control overhead and cause vehicles to have an outdated view of network topology.

2.1.4 Protocol evaluation

Aside from presenting the aforementioned constraints, Table 2 also lists protocol evaluation as a constraint. Real-world VANET test bed deployment is costly (Martinez *et al.*, 2011; Stanica *et al.*, 2011). Thus, new protocol proposals are evaluated using different simulation platforms. Existing simulation platforms have several models for macroscopic and microscopic mobility for real-time mobility patterns (Harri *et al.*, 2009). Protocols are also evaluated in the presence of predefined communication models by simulating the communication behaviors at a particular open system interconnection (OSI) layer. Nevertheless, several underlying communication assumptions are made for communication that cannot be modeled as real. Evaluations of the strengths and weaknesses of a proposed protocol are inappropriate. Moreover, comparison of proposed protocols with suitable candidate solutions is often neglected, thereby hiding performance gains of a proposed protocol over its competitors. Section 5 describes the evaluation aspects of the proposed protocols. These effects show that certain necessary requirements are imposed on the unicast protocol to reduce the effects of limitations. We highlight these requirements in the following.

2.2 Requirements of unicast communication in urban vehicular networks

Certain design requirements are used for effective communication in urban scenarios to reduce the related effects of constraints. These requirements are summarized in Table 3. The multi-hop communication strategy is the basic communication requirement for ad hoc networks with mobility. In addition, unicast protocols require robust link selection to account for short-lived links. Robustness can be defined based on different communication factors, such as effective link lifetime or link communication delay. In addition, the inconsistent number of vehicles at different road segments requires strategies that can identify connectivity information before communication. Accordingly, unicast communication may use infrastructure support at intersections and request/response mechanisms.

The loop mitigation technique in the presence of redundant links is a major requirement to save limited wireless resources. This technique involves knowledge of available links and history of transmitted data. Related solutions may include preventing transmission of a previously received packet or monitoring subsequent transmission of received data from other vehicles. Meanwhile, sparse links require seamless convergence techniques during communication to retain data until a new link is found. In addition, the improvement of network visibility choice of location for route calculation is significant. Protocols typically choose to perform route selection at road intersections to extend network visibility by encompassing other road segments.

Table 3 Requirements for effective communication in urban vehicular networks

Constraint	Requirements
Mobility	Multi-hop communication strategy, robust link selection mechanisms, route/road segment awareness
Physical infrastructure	Loop mitigation techniques, efficient recovery strategies, choice of location for link selection
Communication infrastructure	Channel contention provisioning, load reduction techniques
Protocol evaluation	Real-time evaluation metrics, competing comparisons

The alleviation of channel contention is challenging during high communication activity, and protocols must have provisions for guaranteed availability of wireless medium when needed. Protocols employ different mechanisms, such as adaptive discovery strategies based on the communication requirements of vehicles, to reduce the control load during exchange of periodic messages. Alternatively, certain protocols use vehicular density to adapt the frequency of periodic messages.

Protocol evaluation demands real-time evaluation that includes minimal communication assumptions and comparison with existing competing protocol solutions. Evaluation metrics and comparisons should relate to the objective functions of a proposed protocol. Likewise, protocol comparisons should reveal the strengths and weaknesses of a proposed protocol, as discussed in Section 5.

These requirements indicate that fundamental building blocks of unicast protocols are designed to reduce the effects of constraints. The next section describes these building blocks as unicast protocol operation.

2.3 Unicast protocol operation in urban vehicular networks

The path-dependent approach comprises two processes: path selection and relay selection. The path-independent approach has only one process of relay selection (Fig. 3). In the path-dependent approach, route calculation is followed by a separate relay selection mechanism. The two-step process gradually reassesses the calculated route by selecting and forwarding data one hop at a time. The path-independent approach has an opportunistic approach to transmitting data; that is, instead of using route calculation, it uses destination location and transmission proceeds by selecting and forwarding a relay at each hop. This one-step process avoids the complexities of path calculation, which arguably lasts shorter than the required transmission time for data (Blum *et al.*, 2004).

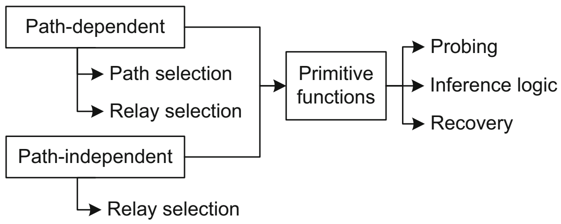

Fig. 3 Probing, inference logic, and recovery as primitive functions of path selection and relay selection

Three sub-processes referred to as primitive functions can be associated with the two processes described. These primitive functions include probing, inference logic, and recovery (Fig. 3). Probing is the process of acquiring network state information. In path selection, probing exhibits a network-wide scope that spans the vehicular network between the source and the destination. Meanwhile, in relay selection, probing has a local scope that includes neighbors within the transmission range of a vehicle. Inference logic is the local process that takes place within a vehicle after probing. This process estimates the probed network information in selecting a unicast path or a single relay. Recovery is the process that handles communication interruptions. Interruptions denote failure in an identified unicast path or the absence of a relay vehicle. Unicast protocols for urban scenarios have various choices of probing, inference logic, and recovery mechanisms. We use this background information to review existing unicast protocols.

2.4 Related surveys

Despite extensive studies on communication protocols for VANETs, only a few surveys on unicast routing have been conducted (Bernsen and Manivannan, 2009; Fonseca and Vazão, 2013). Some surveys provided an overall examination of communication paradigms, including unicast, multicast, and broadcast (Li and Wang, 2007; Lee *et al.*, 2009; Casteigts *et al.*, 2011; Taysi and Yavuz, 2012). In Bernsen and Manivannan (2009), unicast protocols were compared by using design objectives, characteristics, and assumptions. A broad classification of unicast protocols was presented through a discussion of features of geographic unicast, delay-tolerant unicast, and quality of service unicast. The comparison also included protocols for both urban and highway scenarios. Based on such classification, several protocols were critically analyzed with respect to independent routing operations.

Fonseca and Vazão (2013) presented a feasibility study of unicast protocols for both urban and highway scenarios. The study highlighted the defining characteristics of both scenarios and classified topology-based as well as position-based protocols. The protocols were also compared on the basis of regular parameters, such as the strategy, overhead, availability, resilience, and latency.

Unlike Bernsen and Manivannan (2009) and Fonseca and Vazão (2013), our study emphasizes the applicability of unicast routing in urban scenarios. We discuss the significant properties of urban scenarios and the corresponding limitations on communication. Using an initial unicast protocol classification, we present an extended taxonomy that classifies unicast protocols based on underlying protocol operations. Unlike Fonseca and Vazão (2013), our study includes only VANET-specific protocols, which are then reviewed based on routing approaches. For comparison, parameters from the taxonomy are used to analyze the similarities and deviations of reviewed protocols. We compare unicast protocols with one another based on existing trends in performance evaluation. Potential research directions are also proposed based on the results.

3 Thematic taxonomy

In the literature, two major classification approaches have been used for routing in VANETs. The first classification approach, which includes topology- and position-based protocols, is based on the required information for routing (Bernsen and Manivannan, 2009). The second classification approach, which includes proactive and reactive protocols, uses the time of path calculation (Lee *et al.*, 2009). In the current study, we use a different classification approach in which primitive functions of routing approaches are used as baselines for classification. Such classification is important in evaluating path-dependent and path-independent routing approaches. In this section, we extend the initial classification of routing approaches into a thematic taxonomy (Fig. 4). Then we review corresponding unicast protocols in each routing category and conduct a qualitative evaluation of the routing approaches based on different evaluation metrics in Section 4.6.

3.1 Thematic taxonomy based on primitive functions of unicast routing

A thematic taxonomy based on primitive functions is important to identify the strengths and weaknesses of protocols in urban scenarios. This classification includes routing approaches (RAs), probing scope (PS), probing objective (PO), inference logic (IL), recovery approach (RcA), and relay selection (RS). Fig. 4 illustrates a path-dependent approach with three sub-categories based on the nature of required information and infrastructure. The real-information-assisted approach uses real-time traffic and network information to estimate a unicast path. The offline-information-assisted approach uses information acquired through location services and digital maps for path calculation. Meanwhile, the infrastructure-assisted approach uses RSUs at intersections for unicast link selection and communication. The path-independent approach does not have sub-categories.

Sensing network characteristics before calculating a route and selecting a relay node is an essential feature of path and relay selection. Features such as probing scope are relevant in this area. Probing scope varies among different protocols; that is, it can be trivial, offline, or real-time by nature. Probing objectives signify desired characteristics in unicast paths. These objectives are opportunism, network connectivity, delay awareness, path stability, and link stability. The path specifies a complete unicast path and the link specifies connection between two adjacent vehicles.

Inference logic is a local method used by OBUs to evaluate probed information for selecting a path or relay. We classify inference logic as moving average, instantaneous, and probabilistic. The recovery approach refers to strategies for path and relay recovery during communication. Depending on the routing approach, the recovery approach can be of two types, namely, end-to-end and en-route. Both types include further techniques for route convergence, as presented in Fig. 4.

The relay selection process lists mechanisms for selecting a forwarding vehicle within a calculated unicast path. A relay vehicle is selected by the sending vehicle (i.e., sender oriented) or by the receiver (i.e., receiver oriented) when it elects itself. However, as Fig. 4 shows, the definition of a preferred relay varies.

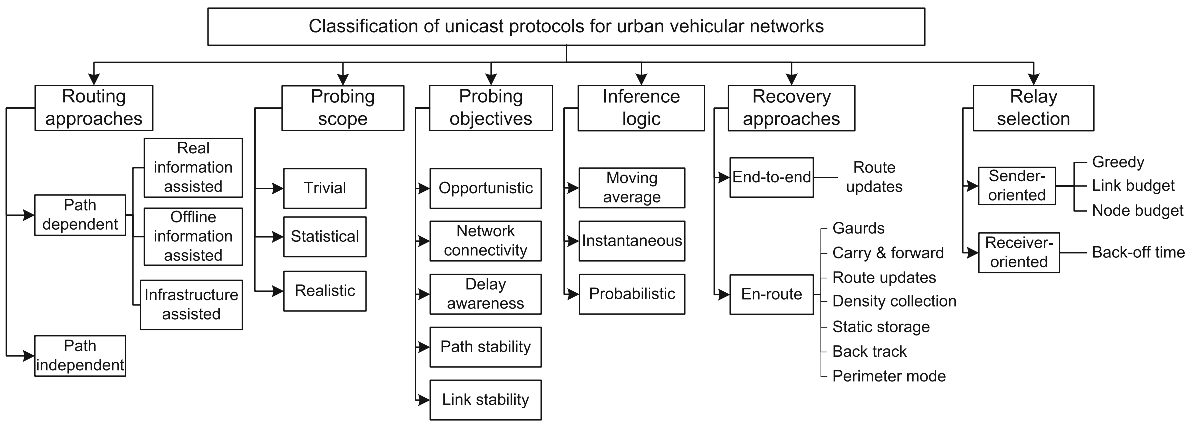

Fig. 4 Thematic taxonomy of unicast protocols based on routing approaches and corresponding primitive functions

4 Protocol review

This section presents a review of unicast protocols based on the identified routing approaches and their implications on protocol communication. The specific communication features of protocols include probing objectives (PO), neighbor discovery/path discovery (ND/PD), control load reducing technique (CLRT), probed parameters, relay selection (RS), and requirement of digital maps. Subsequently, implications on routing approaches are discussed and an operational comparison is conducted based on different metrics. Table 4 presents a qualitative summary of reviewed unicast routing protocols.

4.1 Description of communication features for unicast protocol review

In Table 4, the column named RA associates a protocol with the identified routing approach. The probing objective is the design motivation of probing the network to identify a unicast link or a relay. Accordingly, probing can identify the status of network connectivity, delay awareness of a unicast path, path stability information, link stability information, and opportunistic selection of relay nodes.

Neighbor discovery and path discovery denote the frequency of neighbor discovery and the type of path discovery, respectively. The adaptive value of neighbor discovery specifies the dynamic rate of control messages with respect to network status, whereas the periodic value specifies the consistent rate of control messages. Reactive path discovery indicates path calculation when data transmission is required. Similarly, in proactive PD, a path already exists for an anticipated transmission. The control load reducing technique efficiently reduces control overhead during neighbor and path discovery by using the shared wireless spectrum. Possible values include preferred group broadcast (PGB), role-based multicast, periodic unicast, urban multihop broadcast (UMB), and pruning algorithms. A value of zero indicates the absence of the control load reducing technique. The column 'parameter' in Table 4 shows the network information acquired during probing. The recovery approach denotes the techniques used to recover from interruptions during communication. 'End-to-end' denotes complete path recovery, whereas 'en-route' includes recovery techniques during transmission. Finally, 'map' signifies the requirement of digital maps for route calculation with values of 'yes' and 'no'.

The next section uses the classification of routing approaches along with the communication features described for unicast protocol review.

4.2 Real-information-assisted approach

In the real-information-assisted approach, unicast protocols probe the vehicular network for real traffic and communication statistics. Probing for real-time network information requires control messages that flow from the source to the destination and vice versa. Subsequently, a unicast path that comprises a sequence of distinct nodes or intersections is calculated.

Based on a unicast proposal in Naumov and Gross (2007), a path is established using real-time information in urban vehicular networks. The objective of path calculation is to identify a degree of connectivity among multiple available paths by using network layer request and response messages. Every vehicle knows its one-hop neighbor through neighbor discovery. A vehicle uses dynamic frequency for neighbor discovery to reduce control message overhead; that is, the frequency of control messages is adjusted in direct proportion to the vehicular density of its neighbor. It has a reactive approach for path discovery, which requires the protocol to establish a path if needed. In addition, unlike flooding, path discovery is performed through the preferred group broadcast mechanism (Naumov *et al.*, 2006), which decreases the effects of spatial broadcast. Control messages record parameters, such as the velocity vectors, number of hops, and number of neighbors of each relay node. This information is used by the destination to identify a path with degree of connectivity. The identified path comprises distinct vehicles whose identifiers are subsequently sent to the source. To avoid recalculation of a complete route during route failure, the protocol uses the en-route recovery strategy through special nodes within the route. In en-route recovery, intermediate vehicles, known as guards, keep track of path changes. Accordingly, an intermediate vehicle can alter the packet header with a better path during transmission.

A real-information-assisted approach with two variations in path discovery type, reactive and proactive, was presented in Nzouonta *et al.* (2009). The reactive protocol aims to reduce control load

Table 4 Summary of unicast routing review based on thematic taxonomy

Protocol	RA	PO	ND-PD	CLRT	Parameter(s)	RcA	Map
CAR (Naumov and Gross, 2007)	RIA	Network connectivity	AR	PGB (Naumov *et al.*, 2006)	Number of hops + average number of neighbors + speed vector + path delay	En-route (guards)	No
RBVT-R (Nzouonta *et al.*, 2009)	RIA	Network connectivity	PR	Role based multicast (Briesemeister and Hommel, 2000)	Number of intersections	End-to-end (route update)	No
RBVT-P (Nzouonta *et al.*, 2009)	RIA	Network connectivity	PP	Periodic unicast	Number of intersections + speed vector	En-route (carry and forward)	No
MOPR-OLSR (Menouar *et al.*, 2007)	RIA	Path stability	PP	MPR (Jacquet *et al.*, 2001)	Speed vector	None	No
GeoSVR (Xiang *et al.*, 2013)	OIA	Network connectivity	PR	Pruning	Street width + number of intersections	En-route (carry and forward)	Yes
ACAR (Yang *et al.*, 2008)	OIA	Network connectivity	PR	Pruning	Traffic density + road topology + average speed	En-route (density collection)	Yes
A-STAR (Seet *et al.*, 2004)	OIA	Network connectivity	PR	N/A	Weighted city bus lines	En-route (route updates)	Yes
VADD (Zhao and Cao, 2008)	OIA	Delay awareness	PR	Pruning	Vehicular density + expected delay of road segment	En-route (carry and forward)	Yes
SADV (Ding and Xiao, 2010)	IA	Delay awareness	PR	None	Waiting time + expected road segment delay	En-route (carry and forward + static storage)	Yes
LoP (Nicolas *et al.*, 2009)	IA	Delay awareness	PR	None	Link transportation time	Unknown	Yes
Gytar (Jerbi *et al.*, 2006)	IA	Network connectivity	PR	None	Vehicle density + curve metric	En-route (carry and forward)	Yes
PROMPT (Jarupan and Ekici, 2010)	IA	Delay awareness	PR	UMB (Korkmaz *et al.*, 2007)	Inter-arrival rate + service time for packets and batch	unknown	Yes
GPCR (Lochert *et al.*, 2005)	PI	Opportunistic	PR	N/A	Distance of relay from the intersection	En-route (back track)	No
GPSRj+ (Lee *et al.*, 2007)	PI	Opportunistic	PR	N/A	Coordinate comparison of intersection node and its neighbors	En-route (back track)	No
CLWPR (Katsaros *et al.*, 2011)	PI	Opportunistic	PR	N/A	SNIR + frame error rate + offline separation distance	En-route (carry and forward)	Yes
GPSR-L (Rao *et al.*, 2008)	PI	Link stability	PR	N/A	Transmission range + speed vector	En-route (perimeter mode)	No

RA: routing approach; PO: probing objective; ND-PD: neighbor discovery/path discovery; CLRT: control load reducing technique; RcA: recovery approach. RIA: real information assisted; OIA: offline information assisted; IA: infrastructure assisted; PI: path independent. AR: adaptive-reactive; PR: periodic-reactive; PP: periodic-proactive. PGB: preferred group broadcast; MPR: multi-point relay; UMB: urban multi-hop broadcast. SNIR: signal to noise plus interference ratio during route discovery and the proactive protocol aims to reduce path calculation time but incurs more control load as a tradeoff. The reactive protocol broadcasts the network with control messages toward a destination. Intermediate nodes use a multicast approach for rebroadcasting control messages; that is, rebroadcast is employed as a function of the farthest node with highest priority. In addition, the TTL field is used to avoid continuous roaming in the network. Unlike calculating a path as a sequence of distinct vehicles (Naumov and Gross, 2007), the control messages of the TTL field record the path as a sequence of intersections. This approach avoids the need of every vehicle for neighbor discovery and allows any vehicle to transfer data within the unicast path. In case of link failure, such an approach employs an end-to-end recovery strategy wherein an update is sent all the way from the source to the destination and vice versa. In the proactive version of this protocol, vehicles generate periodic control packets that traverse through road segments in a unicast fashion. In this manner, the packets record reachable road segments as a sequence of intersections. Accordingly, topology information is made available through broadcast to the neighbor vehicles. The proactive version of this protocol assumes availability of a unicast path. Thus, its recovery strategy is employed for relay selection, which is carry and forward.

Another protocol based on the optimized link state protocol (Jacquet *et al.*, 2001) was presented in Menouar *et al.* (2007), where the end-to-end path was calculated using real-time information probing. The path comprises distinct vehicles that make up the most stable path. Path stability defines the effective lifetime of a unicast path for communication. The selection is based on periodic neighbor discovery messages which are used to obtain the speed vector information of neighbor vehicles. The sending vehicle selects one of its neighbors (i.e., multi-point relay) for control data dissemination. However, unlike in Jacquet *et al.* (2001), the selection of relay is based on link lifetime; that is, each vehicle periodically sends updates about its multi-point relay for neighbors to calculate a network topology view. Given proactive path discovery, the protocol considers a route to be always available and hence has no recovery strategy.

4.3 Offline-information-assisted approach

The offline-information-assisted approach uses statistical information from digital maps and position services in making unicast path selection. The offline probed information specifies various traffic statistics and road conditions. Based on the offline information, the associated control load reducing technique indicates techniques to reduce the sample size of digital maps, such as pruning. The choice of unicast path selection based on offline information varies across different unicast protocols.

Xiang *et al.* (2013) proposed a reactive approach for path discovery using digital maps. This approach depends on periodic network layer messages for neighbor discovery. Probing acquires road properties such as road width assigned in digital maps. Probing uses a simple probabilistic assumption that the width of a road is directly proportional to the number of vehicles occupying the road. Therefore, the objective of such a protocol is to find a connected path. However, in a large urban network, probing each road segment on a digital map is computationally expensive (Zhao and Cao, 2008). Pruning is used to reduce the sample size of the map by cropping a portion of map between the source and the destination. The cropped portion includes the reduced number of potential paths. Then, Dijkstra's algorithm is used to calculate a connected path that is a sequence of intersections. This path contains a minimum number of intersections with a maximum number of wide road segments. If a relay is not found during transmission, then the vehicle uses the carry-and-forward recovery strategy until a suitable relay is found.

Yang *et al.* (2008) presented a probabilistic offline metric for a connected route. In path calculation, a digital map is probed for parameters such as traffic density, average velocity, and the road topology between the source and the destination. Thus, a path with more vehicular density is considered equivalent to a vehicle with more neighbors. The qualified path is subsequently added in the packet and sent to the destination. This method also uses pruning to reduce the possible number of unicast paths as well as an en-route recovery strategy to verify the traversed path at the destination; that is, each relay vehicle appends its neighbor density information into a data packet during transmission. At the destination, a vehicle determines if the calculated path is consistent with the traversed path. If inconsistencies are found, the destination vehicle informs the source vehicle.

Seet *et al.* (2004) used a predefined weighted digital map based on a connectivity heuristic. On this map, the streets are marked to reflect the existence of a city bus fleet. At the source, the map is probed on demand to find the best possible path with road segments that contain more city bus lines. A packet is then sent to the destination using the identified path. A connectivity heuristic based on bus fleet information is not accurate and a vehicle may encounter no neighbor vehicles to transmit the data. Therefore, in the absence of a relay vehicle, the protocol uses the en-route mechanism as its recovery approach. This approach restricts other vehicles from transmitting on the same unicast path when a vehicle detects communication failure.

By contrast, offline information is used for delay aware routes in another protocol (Zhao and Cao, 2008). A unicast path is selected by vehicles at intersections and not by the source vehicle within a road segment. Unlike other protocols in this category (Yang *et al.*, 2008; Xiang *et al.*, 2013), this protocol uses dynamic selection of a road segment and avoids the need for an end-to-end path. The probed information through digital maps represents vehicular density, length of road segments between two intersections, and average velocity of the road segment. This information serves as a baseline for probabilistic estimation of delay of a road segment. The process is repeated at every intersection to choose the best road segment until successful delivery is achieved. The recovery strategy is based on the carry-and-forward technique.

4.4 Infrastructure-assisted approach

The infrastructure-assisted approach aims to deliver far-reaching network information to vehicles that require transmission. Pure vehicle-to-vehicle (V2V) communication has limitations in transmission to a certain degree of hop counts. These limitations can be addressed by installing RSUs at the intersections of urban roads. RSUs use either real-time or offline information for unicast paths.

Path calculation in Ding and Xiao (2010) finds a delay-aware unicast path using infrastructure support. Aside from the protocol requirement of digital maps in vehicles, the protocol requires RSUs to be equipped with digital maps. RSUs at intersections proactively transmit control messages that are relayed by vehicles until they reach the next RSU. Meanwhile, vehicles use the reactive approach for path calculation as well as information from RSUs to acquire information about a road segment. Path calculation employs the same probabilistic model as in Zhao and Cao (2008) to identify delays on a road segment. However, the model is further extended with an expected waiting time that corresponds to the infrastructure. Adjacent RSUs in a road segment estimate average arrival time and vehicular density of road segments based on offline information acquired from maps. At an intersection, a vehicle applies one of the two possible recovery strategies; that is, in the absence of a next hop, it carries the data along or sends the data to a static node for storage. The model does not mention any mechanism for reducing control load.

The delay aware protocol in Nicolas *et al.* (2009) uses delays of road segments by using adjacent RSU communication. A vehicle requiring transmission performs routing after receiving latency information of road segments from RSUs. As part of delay calculation, every RSU uses network layer periodic messages, including transmission time. The messages traverse through multiple hops and are carried by vehicles toward the next RSU. Upon receipt of the messages, the RSU calculates the difference between the transmit time and receive time, and then records the delay. Accordingly, downstream RSUs are updated about the relative delay of each road segment. The protocol does not explicitly specify any control load-reducing technique. Meanwhile, carry-and-forward is used as the recovery approach during interruption of communication between RSUs.

The infrastructure-assisted routing approach in Jerbi *et al.* (2006) assumes the presence of sensors at intersections and aims to identify a connected road segment for unicast transmission. The sensors collect the vehicular density of a road segment by using periodic control messages. These messages are flooded and lack mechanisms to reduce control overhead. Such an approach also uses digital maps to obtain the Euclidean distance from the source to the destination. This measure provides a distance proximity, which is also known as the curve metric of a junction from the destination. As a result, a unicast path denotes a junction with minimal distance toward the destination and subsequent road segments with higher vehicular density. In the case of communication interruption, vehicles use carry-and-forward as an en-route recovery strategy.

Jarupan and Ekici (2010) proposed an infrastructure for unicast route delay estimation. This protocol differs from the protocols used in Jerbi *et al.* (2006), Nicolas *et al.* (2009), and Ding and Xiao (2010) for unicast path discovery. In this protocol, vehicles can perform path discovery within the road segment. In other words, a vehicle on a street can calculate a unicast path without being close to the intersection. This proposal also assumes wired connectivity between the RSUs of adjacent road segments. RSUs use periodic messages to disseminate delay aware information to other vehicles. These messages also serve as means of probing network parameters, including node utilization during propagation from one relay to another specified by packet arrival and service rates. The protocol uses the approach presented in Korkmaz *et al.* (2007) to reduce control load. Before transmitting data, a vehicle performs a lookup and puts the route in the packet header. This protocol does not specify any recovery strategy during transmission.

4.5 Path-independent approach

Unicast protocols that use a path-independent approach for data transmission do not require prior knowledge of the end-to-end path. Such an approach aims to reduce the overhead of path discovery, the lifetime of which is insignificant with respect to data transmission time (Blum *et al.*, 2004). As a result, unicast routing protocols under this category use an opportunistic approach to data forwarding. This approach requires only position information of destination and probing that is limited to one-hop neighbor discovery.

Lochert *et al.* (2005) presented a classic unicast routing protocol that requires trivial information about the position of a destination node. In urban scenarios, a decision about transmission direction at intersections is vital. This decision is performed by vehicles near an intersection. As part of probing, every vehicle sends periodic control messages that contain its location, direction, and distance from its destination. Upon receipt of data, a vehicle at an intersection forwards the packet to a relay vehicle that is closer to its destination and is traveling toward the direction of the destination. The en-route recovery strategy is used in the absence of a relay vehicle. This strategy requires a vehicle to send the packet toward the previous intersection to find an alternate road segment by taking advantage of the presence of vehicles at the previous intersection. Thus, this strategy initiates another opportunistic forwarding in a new direction.

Lee *et al.* (2007) presented a variant of opportunistic forwarding in which relay vehicle selection is improved. The protocol operation is the same as in Lochert *et al.* (2005), except that the role of a vehicle at an intersection is additive. The periodic control message of every vehicle includes its coordinates, direction, and distance information. A transmitting vehicle can avoid a relay vehicle at one-hop distance by monitoring such information. If the sending vehicle shares the transmission range of the neighbor of its one-hop relay vehicle, then the one-hop relay is bypassed and data is sent to its neighbor. This approach reduces the hop count within a traveled path and therefore reduces transmission delays. This approach does not use the control load reducing technique for periodic control messages. The recovery strategy also uses the back-track mechanism by sending the data back to the previous intersections, as in Lochert *et al.* (2005).

A more recent routing protocol for opportunistic forwarding was proposed by Katsaros *et al.* (2011). This protocol aims to transmit data opportunistically by monitoring link quality. A vehicle periodically monitors its link status and frame error rate status. The probed parameters also include digital maps, which are used to calculate the separation distance between the source and the destination on the real-time road topology. Besides the location information, control messages are evaluated based on signal strength and frame error rates, making neighbor selection flexible by choosing a neighbor with better signal strength and error rates. This protocol uses the carry-and-forward mechanism as its recovery approach.

The opportunistic approach in Rao *et al.* (2008) aims to find link stability toward its relay vehicle. To achieve this transmission range of vehicles, the speed vector is probed during neighbor discovery. This information is used to estimate the link lifetime between two neighbors. An extra timer is used to represent the calculated lifetime. Moreover, a vehicle reestablishes or removes the lifetime counter by acquiring neighbor state information through periodic messages. The recovery approach is inherited from the protocol in Karp and Kung (2000), which uses perimeter mode in the case of a missing relay vehicle.

4.6 Evaluation of routing approaches

Based on the protocol review, we identify significant characteristics that can be used to evaluate the performance of routing approaches. Metrics for qualitative evaluation include overhead, latency, connectivity awareness, optimal route, and scalability (Table 5). The design of a routing approach refers to the plan for executing unicast communication. It can be used as a metric to specify the degree of design complexity of a routing approach. A high degree of complexity includes a design plan with comprehensive requirements of information acquired for path selection and subsequent mechanisms for data forwarding. In the real-information-assisted approach, a high degree of complexity corresponds to the routing procedures including request/response, relay selection, and control load reduction. Offline-information-assisted and infrastructure-assisted approaches have moderate design complexity. In the offline-information-assisted approach, complicated request/response procedures are avoided by probing available offline data. Alternatively, the infrastructure-assisted approach requires vehicles to be aware of the infrastructure, which further simplifies the process of path calculation. The path-independent approach has the least complexity because it does not require path calculation; that is, its communication is completely dependent on local topology information and destination position.

Overhead indicates the load on a network or the local load on vehicle during the path calculation phase. The probing of real-time network information generates the highest overhead on a network because of the use of end-to-end request/response mechanisms. The probing of offline statistical information generates less overhead because of local pruning mechanism. Accordingly, overhead in the offline-assisted approach has a moderate value. Similarly, the infrastructure-assisted approach has a moderate overhead that corresponds to the awareness of adjacent RSUs. The path-independent approach depends only on destination location information, which results in low overhead.

Latency has one-to-one correspondence with overhead; that is, high overhead produces delays in path calculation, which results in transmission latency from the source to the destination and vice versa. Table 5 shows the values for latency.

Connectivity awareness is a significant requirement in the unicast protocol. Successful communication depends on prior identification of connectivity at a particular road segment, which is possible only through real-time information probing by the source vehicle or through infrastructure support. Offline information and path-independent approaches cannot be used to assess connectivity on roads.

Finding an optimal route for data transmission is the primary goal of a routing approach. A guaranteed route is possible only through an end-to-end real-information-assisted approach. Offline information produces a probabilistic route because of inaccuracies in statistical data. Alternatively, infrastructure support has progressive optimal route identification relative to the network view of RSUs limited to adjacent RSUs. In other words, an optimal route builds up gradually in terms of road segments during transmission. For path-dependent approaches, the concept of optimal route is opportunistic; that is, data might reach the destination in the presence of sufficient connectivity.

Finally, we define the scalability of routing approaches as upward (↑) and downward (↓). Upward scalability indicates effective communication under an increasing number of active vehicles, whereas downward scalability indicates effective communi-

Table 5 Evaluation of routing approaches based on design and operational characteristics

Routing approach	Design	Overhead	Latency	Connectivity awareness	Optimal route	Scalability
Real information assisted	Complex	High	High	✓	Guaranteed	×
Offline information assisted	Relatively simple	Moderate	Moderate	×	Probable	↑
Infrastructure assisted	Relatively simple	Moderate	Moderate	✓	Gradual	↑ and ↓
Path independent	Simple	Low	Low	×	Opportunistic	↑

cation under low vehicular density with sparse links. Real-information-assisted approaches are not scalable (×) in both conditions; that is, control overhead grows under an increasing number of active vehicles. In addition, route failures require new instantiation of route discovery mechanism, which results in high cost of link convergence. Meanwhile, route discovery is time consuming and may fail to find a route for communication in sparse connectivity. Offline-information-assisted, path-independent, and infrastructure-assisted approaches are upward scalable. Errors in offline statistical information decrease with increasing vehicular density. For instance, in Xiang *et al.* (2013), the accuracy in associating higher road width with better connectivity increased with higher vehicular density on roads. Similarly, in the path-independent approach, the success rate of opportunistic transmission increases in direct proportion to vehicular density. The infrastructure-assisted approach is downward scalable. In sparse connectivity, vehicles can store data on an infrastructure to avoid faulty transmission on a suboptimal route. Upon identification of an adequate vehicle, RSUs transmit the stored data through an optimal route.

5 Qualitative unicast protocol comparison

This section presents a qualitative comparison of the reviewed unicast protocols from two aspects. First, we derive parameters from the taxonomy to identify commonalities and deviations among the reviewed protocols. Second, existing evaluation trends are explored as reference points to compare protocol evaluation metrics and the nature of competing comparisons of unicast protocols.

5.1 Protocol comparison based on derived parameters from thematic taxonomy

We define different metrics including scope and accuracy, route metric consistency, implementation cost, forwarding efficiency, and the computational strategy, to assess the similarities and deviations among protocols. Each of these metrics can be defined using parameters from the thematic taxonomy, such as probing scope (PS), route metric type (RMT), probing granularity (PG), relay selection (RS), forwarding objective (FO), and inference logic (IL). The comparison is summarized in Table 6.

5.1.1 Scope and accuracy

Scope and accuracy show the granularities of required network information as well as its accuracy for unicast path discovery or one-hop relay vehicle selection. We define it using probing scope parameter which has three possible values including (1) local, (2) global, and (3) segment: (1) The local attribute refers to position information acquired through GPS and one-hop control messages. This information is used by some protocols as the only means of path selection (Lochert *et al.*, 2005; Lee *et al.*, 2007; Rao *et al.*, 2008; Katsaros *et al.*, 2011). The rest of the protocols use local information only for relay selection within a road segment. (2) The global (active/passive) attribute specifies that the source vehicle has complete knowledge of the road topology. However, this information can be acquired actively (G-active) or passively (G-passive). In the G-active approach, the source vehicle probes the network by using messages in the form of request and response, such as in Seet *et al.* (2004), Menouar *et al.* (2007), Naumov and Gross (2007), and Nzouonta *et al.* (2009). Additionally, in Jarupan and Ekici (2010), the probing mechanism employed infrastructure so that the source did not have to probe the complete network. The G-passive approach also requires complete topology information of urban roads, but this information comes from digital maps and provides an approximation of instant traffic and road characteristics (passive approach). This approach strikes a tradeoff between the local approach (absent topology) and G-active approach (realistic topology). (3) The value of a segment signifies information related to a particular part of the vehicular network. For instance, probing techniques described in Jerbi *et al.* (2006), Nicolas *et al.* (2009), and Ding and Xiao (2010) used information about adjacent road segments by querying RSUs. A vehicle at an intersection cannot accurately monitor the network information of a road segment. Therefore, at every intersection, a vehicle dynamically selects the next road segment for transmission.

5.1.2 Route metric stability

The stability of a route metric denotes the consistency of probed parameters (route metric) for path

Table 6 Protocol comparison of unicast protocols based on the parameters from thematic taxonomy

Protocol	PS	RMT	PG	RS	FO	IL
CAR (Naumov and Gross, 2007)	Ga	Dyn	Iso	SO (greedy)	Anchor proximity	MA
RBVT-R (Nzouonta *et al.*, 2009)	Ga	Dyn	Iso	RO (backoff)	Transmission quality	Inst
RBVT-P (Nzouonta *et al.*, 2009)	Ga	Dyn	Iso	RO (backoff)	Transmission quality	Inst
MOPR-OLSR (Menouar *et al.*, 2007)	Ga	Dyn	Emb	SO (link budget)	Maximum global link stability	Inst
GeoSVR (Xiang *et al.*, 2013)	Gp	Stat	Iso	SO (link budget)	Restricted forwarding	Prob
ACAR (Yang *et al.*, 2008)	Gp	Stat	Iso	SO (node budget)	Reduced packet error rates	Prob
A-STAR (Seet *et al.*, 2004)	Gp	Stat	Iso	SO (greedy)	Maximum forwarding towards destination	Prob
VADD (Zhao and Cao, 2008)	Gp	Stat	Iso	SO (greedy)	Location first/direction first	Prob
SADV (Ding and Xiao, 2010)	Seg	Dyn	Iso	SO (greedy)	Static anchor proximity	MA
GyTAR (Jerbi *et al.*, 2006)	Seg	Dyn	Iso	SO (greedy)	Static anchor proximity	Inst
LoP (Nicolas *et al.*, 2009)	Seg	Dyn	Iso	SO (greedy)	Static anchor proximity	Inst
PROMPT (Jarupan and Ekici, 2010)	Ga	Dyn	Iso	RO (backoff)	Role based	MA
GPCR (Lochert *et al.*, 2005)	Local	Dyn	Emb	SO (greedy)	Junction proximity	Inst
GPSRj+ (Lee *et al.*, 2007)	Local	Dyn	Emb	SO (greedy)	Junction proximity	Inst
CLWPR (Katsaros *et al.*, 2011)	Local	Dyn	Emb	SO (link budget + node budget)	Transmission quality	Inst
GPSR-L (Rao *et al.*, 2008)	Local	Dyn	Emb	SO (link budget)	Link stability	Inst

PS: probing scope; RMT: route metric type; PG: robing granularity; RS: relay selection; FO: forwarding objective; IL: inference logic. Ga: G-active; Gp: G-passive; Seg: segment. Dyn: dynamic; Stat: static. Iso: isolated; Emb: embedded. SO: sender-oriented; RO: receiver-oriented. MA: moving average; Inst: instantaneous; Prob: probabilistic

selection. We use route metric type as a parameter that defines the stability of probed parameters. This parameter has a static value in protocols with G-passive information granularity; that is, the values of probed parameters remain static throughout the process of unicast transmission. For instance, in Xiang *et al.* (2013), the width of an individual road was used as a route metric that remained unchanged during unicast communication. Similarly, the value of the route metric specifying bus lanes on a weighted digital map does not change during communication (Seet *et al.*, 2004). Static metric type is considered stable but is inflexible and inaccurate because of limitation of offline statistical information. Meanwhile, protocols with G-active and segment-level information granularity (Lochert *et al.*, 2005; Jerbi *et al.*, 2006; Lee *et al.*, 2007; Menouar *et al.*, 2007; Naumov and Gross, 2007; Nicolas *et al.*, 2009; Nzouonta *et al.*, 2009; Ding and Xiao, 2010; Jarupan and Ekici, 2010; Katsaros *et al.*, 2011) have a dynamic route metric; in other words, dynamic route metrics are more realistic than static metrics because they consider the features of the dynamic vehicular network for route calculation. The probed parameters represent real-time traffic information and therefore change as a function of space and time during packet forwarding. A dynamic metric is more realistic and more accurate than a static metric but lacks stability.

5.1.3 Implementation cost

Implementation cost specifies the level of complexity of a protocol in terms of the number of probing instances. We use probing granularity as a parameter to show the implementation cost of a protocol. Before data transmission, a network is probed for certain parameters of path selection followed by the mechanism of relay selection for transmission. If probing for path and relay selection is performed as a unit step, then probing granularity has an embedded value, as shown in Lochert *et al.* (2005), Lee *et al.* (2007), Menouar *et al.* (2007), Rao *et al.* (2008), and Katsaros *et al.* (2011). The protocol in Menouar *et al.* (2007) is the only one with G-active information granularity and embedded probing granularity considered in the current review. This protocol proactively calculates an end-to-end path where the data is forwarded by selecting a neighbor vehicle found during the path calculation phase without further probing. Similarly, path-independent approaches in Lochert *et al.* (2005), Lee *et al.* (2007), and Katsaros *et al.* (2011) have embedded probing granularity. The embedded approach for unicast protocols involves less implementation cost because the network is probed only once for path and relay selection. However, embedded probing granularity lacks the ability to reassess the link consistency during relay selection. Protocols in Seet *et al.* (2004), Jerbi *et al.* (2006), Naumov and Gross (2007), Yang *et al.* (2008), Zhao and Cao (2008), Nicolas *et al.* (2009), Nzouonta *et al.* (2009), Ding and Xiao (2010), Jarupan and Ekici (2010), and Xiang *et al.* (2013) have isolated probing granularity, which exploits the fact that multiple potential relay vehicles exist within a found path. Therefore, as a subsequent process to path selection, a unicast path is distinctly probed for selection of a suitable relay vehicle. This approach is more dynamic because it increases the protocol's complexity as a tradeoff for better communication performance.

5.1.4 Forwarding efficiency

Forwarding corresponds to the actual transmission where data is sent toward a suitable relay vehicle. The RS attribute can be used to evaluate forwarding efficiency, while the forwarding objective comprises a list of corresponding objectives desired by RS. The logic used in RS is employed either at the source/intermediate vehicle (sender-oriented) or at the receiver itself (receiver-oriented). Most protocols use sender-oriented RS in which a source specifies the relay vehicle. For relay selection, Nzouonta *et al.* (2009) and Jarupan and Ekici (2010) used a receiver-oriented mechanism in which a receiver elects itself for reception of transmission. Sender- and receiver-oriented approaches have contrasting definitions of a suitable relay.

In the sender-oriented approach, relay that uses distance information from the destination is known as the greedy approach (Karp and Kung, 2000). However, distance information varies. For relay selection, Jerbi *et al.* (2006), Nicolas *et al.* (2009), and Ding and Xiao (2010) used an infrastructure to select a node with minimal distance to the RSU. Similarly, for greedy selection, Lochert *et al.* (2005), Lee *et al.* (2007), Naumov and Gross (2007), and Rao *et al.* (2008) signified opportunistic forwarding toward a random relay that has minimal distance to the intersection. In Zhao and Cao (2008), a vehicle selects a relay that is closest to the destination and has the same direction as the destination or a relay that has the same direction as the destination without being close to the destination. The sender-oriented greedy approach has a simple implementation but lacks dynamism. That is, the criterion of utilizing distance in relay selection is subject to signal distortion and packet drops, which in turn increases communication delays. A more intelligent RS approach is the consideration of link and node utilization of a relay (Menouar *et al.*, 2007; Rao *et al.*, 2008; Yang *et al.*, 2008; Katsaros *et al.*, 2011; Xiang *et al.*, 2013). The protocol in Menouar *et al.* (2007) performs relay selection based on a pre-computed link budget that specifies complete unicast path lifetime. Similarly, lifetime in Rao *et al.* (2008) represents the lifetime of a one-hop relay link. In Xiang *et al.* (2013), a restricted transmission range was proposed to overcome the limitations of greedy relay selection. Using this approach, the probability of packet drops for increasing distances is minimized. A more robust form of relay selection that can actively monitor the signal strength and node capacity of potential relay was presented in Katsaros *et al.* (2011). A probabilistic model for relay selection that estimates the packet error rate during transmission for a particular relay was presented in Yang *et al.* (2008). Accordingly, a relay with less probability of packet error is selected. Sender-oriented relay selection approaches have a more adaptive relay selection than receiver-oriented approaches but they include communication overhead, particularly during link- and node-budget calculations. In other words, a sender requires additional signal level and node level information besides the location and speed vector information that affects forwarding efficiency.

The receiver-oriented selection is an alternative approach to reduce RS overhead and enhance efficiency. In Nzouonta *et al.* (2009), a potential relay vehicle uses a back-off function upon transmission request from the source to estimate its own suitability as a relay. The receiver considers the received signal power of the received message, the transmission range, and its own distance from the sender. A relay closest to the destination with better signal strength piggybacks the sender as a candidate relay. Similarly, in Jarupan and Ekici (2010), self-relay selection uses network layer packets that define the functions of a relay; that is, a back-off time at the receiver represents the levels of priority. The RSU has the highest priority followed by a relay with existing packets to the same destination in use. Then, the relay with the same traveling direction as the destination becomes the next highest priority. If none of the aforementioned cases exits, then the lowest priority is assigned to a relay going in the opposite direction. The receiver-oriented approach avoids the use of neighbor table management at sender/intermediate nodes. Unlike the RS in Jarupan and Ekici (2010), the RS in Nzouonta *et al.* (2009) uses RTS/CTS frames, which reduces the overhead by avoiding the need for network layer control packets.

5.1.5 Computational strategy

The computational strategy is the pattern in which probed information is interpreted or analyzed by a vehicle. We use the inference logic attribute to compare computational strategies employed by different protocols. The attribute value of inference logic signifies the forwarding aspect only for path-independent routing approaches, whereas it relates to path calculation as well for path-dependent approaches. Possible values for inference logic include moving average, instantaneous, and probabilistic.

Moving average refers to an overall representation of the network state based on the average value of probed parameters. The value of inference logic for probed parameters in Naumov and Gross (2007) and Ding and Xiao (2010) is identified as the moving average. The number of hops in Naumov and Gross (2007) is considered as a sequential value after reception at the destination. However, recorded delay at each relay is considered as an average delay value for the complete traversed path from the source to the destination. Similarly, the probed delay value in Ding and Xiao (2010) shows the average hop-by-hop delay of a particular road segment. The accuracy of the moving average is subject to effective estimation of a threshold value for the acceptable probed parameters. For an end-to-end path, this approach may overlook individual vehicles with extremely few delays caused by an average value (Naumov and Gross, 2007). This disadvantage was partly resolved by the inference logic in Jarupan and Ekici (2010), which associates a timeout value for the recorded delay of a path.

Most protocols in our review evaluate the probed parameters based on an instant received value (Lochert *et al.*, 2005; Jerbi *et al.*, 2006; Lee *et al.*, 2007; Menouar *et al.*, 2007; Rao *et al.*, 2008; Nicolas *et al.*, 2009; Nzouonta *et al.*, 2009; Katsaros *et al.*, 2011). The strategy in Nzouonta *et al.* (2009) calculates the number of intersections at the destination to notify the source about the best route. Similarly, the route reply in Menouar *et al.* (2007) contains link stability values for all links in a complete path. Unlike in the moving average approach, the vehicle selects an instant value of the lowest bound of an individual link within a path. In Jerbi *et al.* (2006), the vehicular density and distance of the neighbor junction to the destination junction were used as measures for the connected route. In Nicolas *et al.* (2009), instant values of transmission delay at static nodes served as the selection criteria for a particular road section.

Finally, probabilistic inference logic is associated with protocols that use offline information for path discovery. Digital maps represent approximations of traffic information; thus, a probabilistic model for decision making is necessary. Inference logic based on the delay model and on acquired offline information about vehicular density on road sections was used in Zhao and Cao (2008). A probabilistic model that uses vehicular density, vehicle arriving rates, and average speeds was also used in Seet *et al.* (2004) for connectivity assessment of road segments. The protocol in Xiang *et al.* (2013) employs a probabilistic evaluation by modeling road widths for network connectivity. Probabilistic evaluation is crucial in an uncertain communication environment, such as VANETs. However, probabilistic inference logic that contains only offline information is not highly useful because of the relative errors in offline data.

5.2 Protocol comparison based on existing evaluation trends used in simulation platforms

As discussed in the preceding sections, the qualitative analysis of unicast protocols can be performed based on protocol classification and parametric comparison. However, quantitative evaluation of the protocols requires real-time VANET deployment and comprehensive simulations. Real-time VANET deployment is costly, and the idea of evaluating a protocol in all possible scenarios is overwhelming. Therefore, most protocols are evaluated through simulations by using evaluation metrics that signify the performance of a protocol.

A typical VANET simulator architecture includes two separate components: (1) traffic simulator and (2) network simulator (Fig. 5). The traffic simulator produces the mobility traces and the network simulator produces simulation traces. Initially, the traffic simulator requires input in form of road topology and vehicular characteristics.

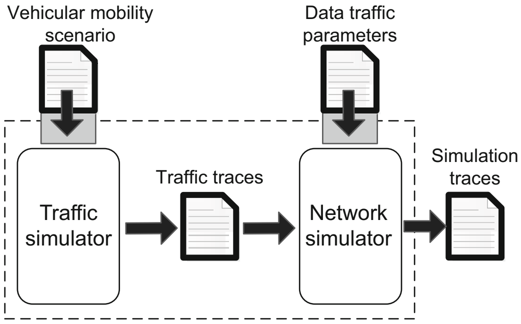

Fig. 5 Typical simulation architecture for vehicular ad hoc networks

For instance, road topology includes the number of lanes in road, number of intersections, location of RSUs, and speed limits. On the other hand, vehicular characteristics include velocity, vehicular density on roads, vehicle arrival, and departure rates (Martinez *et al.*, 2011). This input corresponds to the vehicular mobility scenario and can be provided to the traffic generator through mobility generator tools such as those proposed by Karnadi *et al.* (2007), Martinez *et al.* (2008), and Behrisch *et al.* (2011). The output of the mobility generator is called the traffic trace file, which shows the characteristics of each vehicle at every time instance of the simulation time. This trace file acts as an input to the network simulator that models the communication behavior of VANET. It includes detailed logic behind packet level transmission, reception, channel states, and physical layer details for communicating vehicles. Some examples of popular network simulators include Varga (2001), NS-2 (http://www.isi.edu/nsnam/ns/), and Henderson *et al.* (2008). The network simulator produces simulation traces that can be quantitatively analyzed through suitable evaluation metrics and highlights the performance of the proposed solution.

However, obtainable quantitative comparisons in the proposed protocols lack inclusive evaluation and comparisons with candidate solutions (Stojmenovic, 2008). In this section, we highlight frequently used evaluation metrics for unicast protocols to better comprehend the quantitative efficacy of protocols.

5.2.1 Evaluation metrics

We classify the commonly used evaluation metrics into four categories, including the delivery ratio, delay factor, overhead, and miscellaneous (Table 7). These categories represent the focus of performance evaluation of unicast protocols. Table 7 lists the defined evaluation category, metric name, corresponding mathematical form, preferred value, and the unit of measurement. The packet delivery ratio (PDR) and end-to-end delay (E2ED) are fundamental evaluation metrics used in most unicast protocols. Delivery specifies the success rate of a protocol as a ratio of received packets over a measure of all sent packets. Delay specifies the latency incurred in seconds during a unicast communication session. Preferred values for delivery and delay are high and low, respectively. The overhead category contains routing overhead (ROv), packet overhead (POv), and control overhead (COv), which specify transmitted control bytes to the number of received packets, single received packet, and per unit data byte, respectively. The preferred value for the overhead is low, which also indicates the measure of scalability of a unicast protocol. The category named the miscellaneous category contains path length (PL), network throughput (NT), packet loss ratio (PLR), and storage load (SL). PL denotes the number of hops in a unicast link with a preferred value of ‘low’. NT refers to the number of packets sent per unit time and is rarely used for evaluation in VANETs. PLR denotes the ratio of lost packets over all transmitted packets. SL is used in situations where a protocol employs the carry-and-forward strategy in a relay and on RSUs. SL is measured in packet/s and its preferred value is ‘low’.

The evaluation metrics in Table 7 represent generic definitions; thus, they are evaluated as a function of correlating VANET aspects in the context of VANETs. Table 8 presents a list of evaluation metrics with respect to certain communication and vehicular aspects, as denoted by the first column. As shown in Table 8, most researchers comprehensively evaluated the performance of unicast protocols using PDR and E2ED evaluation metrics. However, evaluation of a unicast protocol lacks competing comparison. In the next section, we discuss the trend evaluation based on evaluation metrics and choice of protocols for comparison.

5.2.2 Competing comparison

Generally, protocols are evaluated to judge the different features of a unicast protocol. Such comparison is useful in identifying the significance

Table 7 Frequently used evaluation metrics for unicast routing in urban vehicular networks

Category	Metric	Mathematical form	Preferred value	Units
Delivery	Packet delivery ratio (PDR)	$\frac{\sum(\text{received packets at destination})}{\sum(\text{sent packets by source})} \times 100\%$	High	
Delay	End-to-end delay (E2ED)	$\frac{\sum(\text{received time} - \text{sent time})}{\sum(\text{received packets})}$	Low	s
Overhead	Routing overhead (ROv)	$\frac{\sum(\text{control bytes sent})}{\sum(\text{received packets})}$	Low	bit
	Packet overhead (POv)	$\frac{\sum(\text{control bytes sent})}{\text{single received packet}}$	Low	bit/packet
	Control overhead (COv)	$\frac{\sum(\text{control bytes})}{\text{per unit data byte}}$	Low	bit/packet
Miscellaneous	Path length (PL)	$\sum(\text{hops within a route})$	Low	hop
	Network throughput (NT)	$\frac{\sum(\text{packets sent from srctodst})}{\text{unit time}}$	High	kb/s
	Packet loss ratio (PLR)	$\frac{\sum(\text{lost packets})}{\sum(\text{lost packets} + \text{received packets})} \times 100\%$	Low	
	Storage load (SL)	$\frac{\text{rate of packet arrival at static node}}{\sum(\text{vehicles in a network})}$	Low	packet/s

of one protocol over another based on carefully chosen individual evaluation metrics. However, most researchers overlooked the comparison of a protocol with a competitive protocol designed for the same objective. Unicast communication protocols are designed for a particular objective that is identified by the probing objective. Therefore, the performance evaluation of unicast protocols should be against protocols with similar objectives.

Table 9 presents a list of reviewed protocols and existing trends in protocol evaluation, including the protocols for comparison under the column named 'compared-against'. The 'evaluation metric' column shows the type of evaluation metric in the form of 'characteristic'. For instance, PDR-12 denotes the PDR calculated with respect to the number of vehicles. The columns named 'superior' and 'inferior' respectively show the strengths and weaknesses of a proposed protocol in relation to the compared-against protocol. Finally, the column named 'competitive' denotes whether the comparison is competitive or not with the possible values of 'yes' and 'no'. We do not consider competitiveness in the choice of evaluation metrics, which is the subject of an extensive independent study.

The objective of connectivity awareness is common among the reviewed protocols, such as in Seet *et al.* (2004), Jerbi *et al.* (2006), Naumov and Gross (2007), Yang *et al.* (2008), Nzouonta *et al.* (2009), and Xiang *et al.* (2013). The protocol in Naumov and Gross (2007) is compared against classic geographic protocols in Karp and Kung (2000) and Naumov *et al.* (2006) with respect to the evaluation metrics shown in Table 8. These classic protocols are based on the opportunistic routing approach; the protocol in Naumov *et al.* (2006) is designed to improve discrepancies in the perimeter mode of the protocol in Karp and Kung (2000). Therefore, the comparison of these protocols is not considered competitive. The protocol in Nzouonta *et al.* (2009) is compared against the protocols that have similar routing approaches, such as in Perkins and Royer (1999) and Jacquet *et al.* (2001). However, the protocols in Perkins and Royer (1999) and Jacquet *et al.* (2001) are designed to find an end-to-end path and to reduce the effects of routing overhead, respectively. Therefore, comparing the protocol in Nzouonta *et al.* (2009) with these protocols is justified for evaluating the significance of route calculation mechanisms. However, according to design objectives, a competitive comparison of the protocol in Nzouonta *et al.* (2009) with those

Table 8 Evaluation metrics used by unicast protocols with respect to VANET characteristics

No.	VANET characteristic	Unicast routing protocol in which the evaluation metric is used: PDR	E2ED	ROv	POv	COv	PS	NT	PLR	SL
1	Generic	–	–	–	Nzouonta *et al.* (2009)	–	–	–	–	–
2	Transmission rate	Jarupan and Ekici (2010)	Jarupan and Ekici (2010)	–	–	–	–	–	–	–
3	Sending rate	Jerbi *et al.* (2006); Yang *et al.* (2008); Zhao and Cao (2008)	Jerbi *et al.* (2006); Yang *et al.* (2008); Zhao and Cao (2008)	Jerbi *et al.* (2006); Zhao and Cao (2008)	–	Nzouonta *et al.* (2009)	Yang *et al.* (2008)	Zhao and Cao (2008)	–	
4	Traveled distance	–	Nicolas *et al.* (2009)	–	–	–	–	–	–	–
5	Buffer size	Zhao and Cao (2008)	Zhao and Cao (2008)	–	–	–	–	–	–	–
6	Storage time	Katsaros *et al.* (2011)	Katsaros *et al.* (2011)	–	–	–	–	–	–	–
7	Euclidean distance	Lochert *et al.* (2005); Nicolas *et al.* (2009)	Xiang *et al.* (2013)	–	–	–	Lochert *et al.* (2005)	–	–	–
8	Sent packets	–	Ding and Xiao (2010)	–	–	–	–	–	–	–
9	Vehicle speed	Katsaros *et al.* (2011); Xiang *et al.* (2013)	Katsaros *et al.* (2011); Xiang *et al.* (2013)	–	–	–	–	–	–	–
10	Per node load	Jarupan and Ekici (2010)	Jarupan and Ekici (2010)	–	–	Jarupan and Ekici (2010)	–	–	–	–
11	Number of sources	Nzouonta *et al.* (2009); Jarupan and Ekici (2010)	Jarupan and Ekici (2010)	–	–	–	–	–	–	–
12	Number of vehicles	Seet *et al.* (2004); Jerbi *et al.* (2006); Naumov and Gross (2007); Lee *et al.* (2007); Zhao and Cao (2008); Rao *et al.* (2008); Rao *et al.* (2008); Nzouonta *et al.* (2009); Jarupan and Ekici (2010)	Seet *et al.* (2004); Jerbi *et al.* (2006); Lee *et al.* (2007); Naumov and Gross (2007); Zhao and Cao (2008); Nzouonta *et al.* (2009); Ding and Xiao (2010); Jarupan and Ekici (2010)	Jerbi *et al.* (2006); Naumov and Gross (2007); Ding and Xiao (2010)	Ding and Xiao (2010)	Ding and Xiao (2010)	Seet *et al.* (2004); Lee *et al.* (2007)	–	Rao *et al.* (2008)	Ding and Xiao (2010)
13	Packet size	Menouar *et al.* (2007); Zhao and Cao (2008)	Menouar *et al.* (2007); Zhao and Cao (2008)	Menouar *et al.* (2007)	–	–	–	–	–	–
14	Beacon interval	Rao *et al.* (2008)	–	–	–	–	–	–	–	–

PDR: packet delivery ratio; E2ED: end-to-end delay; ROv: routing overhead; POv: packet overhead; COv: control overhead; PS: probing scope; NT: network throughput; PLR: packet loss ratio; SL: storage load in Seet *et al.* (2004), Naumov and Gross (2007), and Yang *et al.* (2008) is overlooked. Meanwhile, the comparison of the protocol in Yang *et al.* (2008) with a connectivity aware unicast protocol in Naumov and Gross (2007) is considered competitive. Alternatively, comparison of connectivity-aware protocols in Seet *et al.* (2004) and Jerbi *et al.* (2006) is not competitive with opportunistic protocols in Ko and Vaidya (1998), Karp and Kung (2000), and Lochert *et al.* (2003). The only real implementation of protocol was conducted in Xiang *et al.* (2013) and compared with classic unicast protocols in Perkins and Royer (1999) and Karp and Kung (2000). However, the most appropriate competitors of the protocol in Xiang *et al.* (2013) in terms of objective functions are the protocols in Seet *et al.* (2004), Jerbi *et al.* (2006), Naumov and Gross (2007), and Yang *et al.* (2008). The unicast protocol proposed by Xiang *et al.* (2013) is unique, because it is tested in a real-time vehicular network; however, the protocol lacks competing comparison.

Path stability is an objective of the protocols in Menouar *et al.* (2007) and Rao *et al.* (2008). Both protocols lack competing comparison; that is, their comparison includes classic mobile ad hoc protocols that are not VANET specific. Alternatively, a more suitable choice for competing comparison with Schnaufer and Effelsberg (2008) has been overlooked.

Protocols in Zhao and Cao (2008), Nicolas *et al.* (2009), Ding and Xiao (2010), and Jarupan and Ekici (2010) are classified under the delay aware routing objective. The protocol in Zhao and Cao (2008) is considered as a trademark to introduce the delay aware model for routing in vehicular networks. Its comparison is considered competitive because it uses a modified version of the protocol in Karp and Kung (2000) with buffer extensions. Use of buffers mimics a competitive behavior of the store-and-forward technique employed in Zhao and Cao (2008). Another delay aware protocol in Ding and Xiao (2010) uses static nodes at intersection as opposed to the protocol in Zhao and Cao (2008). These two protocols share the same design objective, which makes their comparison competitive. The protocol in Nicolas *et al.* (2009) uses infrastructure at intersections to estimate the delay aware route. However, its comparison with the protocol in Karp and Kung (2000) is not competitive because of the information acquired through digital maps for a shortest route. Meanwhile, the protocol in Jarupan and Ekici (2010) is comprehensively compared with trademark protocols, such as that in Zhao and Cao (2008). The performance gains of this protocol are reported in the table and the evaluation is considered competitive.

Unicast transmission toward the destination with an objective to get closer to the destination without route calculation is grouped under the objective of opportunistic forwarding (Lochert *et al.*, 2005; Lee *et al.*, 2007; Katsaros *et al.*, 2011). The protocol in Lochert *et al.* (2005) improves the performance of opportunistic forwarding in Karp and Kung (2000) in terms of the delivery ratio, and its path length demonstrates a competitive evaluation. Similarly, the protocol in Lee *et al.* (2007) is competitively compared with that in Lochert *et al.* (2005) based on the delivery ratio and path length. These metrics are used in the protocol proposed by Lee *et al.* (2007) to improve the performance of the protocol in Lochert *et al.* (2005). The protocol in Katsaros *et al.* (2011) is compared with a classical version of the protocol in Karp and Kung (2000). These two protocols share the same objective, but their performance evaluation is not competitive. In other words, the protocols in Lochert *et al.* (2005) and Lee *et al.* (2007) have shown better performance than the protocol in Karp and Kung (2000) in terms of path length and the delivery ratio. However, quantitative evaluation of the protocol in Katsaros *et al.* (2011) does not include comparisons with the protocols in Lochert *et al.* (2005) and Lee *et al.* (2007).

6 Issues and challenges for progressive routing in VANETs

Different unicast routing protocols for urban vehicular networks have been reviewed and qualitatively compared with one another in the preceding sections. This study observes that certain aspects in protocol communication and competing performance evaluation can be improved. We point out these aspects as issues to be addressed in the context of the presented review of unicast protocols.

6.1 Beacon transmission optimization

One-hop neighbor discovery is a periodic and ongoing activity in unicast routing protocols due to constant vehicular mobility. It is conducted

Table 9 Unicast protocol evaluation and competitive comparison

Protocol	Compared-against	Evaluation metric	Superior	Inferior	Competitive
CAR	Karp and Kung (2000); Naumov *et al.* (2006)	E2ED-12, ROv-12, PDR-12	All	None	No
RBVT	Karp and Kung (2000); Perkins and Royer (1999); Jacquet *et al.* (2001); Lochert *et al.* (2003)	PDR-11, PDR-12, E2ED-12, PS-3, POv-1	All	None	No
MOPR-OLSR	Jacquet *et al.* (2001)	PDR-13, E2ED-13, ROv-13	PDR-13, ROv-13	E2ED-13	No
GPSR-L	Karp and Kung (2000)	PDR-12	All	None	No
GeoSVR	Perkins and Royer (1999); Karp and Kung (2000)	PDR-9, E2ED-7, E2ED-9	All	None	No
ACAR	Karp and Kung (2000); Lochert *et al.* (2003); Naumov and Gross (2007)	PDR-3, E2ED-3, NT-3	All	None	Yes
A-STAR	Karp and Kung (2000); Lochert *et al.* (2003)	PDR-12, E2ED-12	All	None	No
VADD	Self; Karp and Kung (2000) with buffers	PDR-3, PDR-5, PDR-13, E2ED-3, E2ED-5, E2ED-13, ROv-3, PLR-3	All	None	Yes
SADV	Zhao and Cao (2008)	E2ED-8, E2ED-12, ROv-12, POv-12, COv-12, SL-12	All	None	Yes
GyTAR	Ko and Vaidya (1998); Lochert *et al.* (2003)	PDR-3, PDR-12, E2ED-3, E2ED-12, ROv-3, ROv-12	All	None	No
LoP	Lochert *et al.* (2003)	PDR-7, E2ED-4	All	None	No
PROMPT	Johnson *et al.* (2001); Lee *et al.* (2007); Naumov and Gross (2007); Zhao and Cao (2008)	PDR-2, PDR-(10-12), E2ED-2, E2ED-(10-11), COv-10,	All	None	Yes
GPCR	Karp and Kung (2000)	PDR-7, PS-7	All	None	Yes
GPSRj+	Karp and Kung (2000); Lochert *et al.* (2005)	PDR-12, E2ED-12, PS-12	All	None	Yes
CLWPR	Karp and Kung (2000)	PDR-6, PDR-9, E2ED-6, E2ED-9	All	None	No
GPSR-L	Karp and Kung (2000)	PDR-12, PDR-14, PLR-12	All	None	No

using small messages called beacons. However, unlike MANETs, beacon messages in VANETs are primarily used for vehicular safety applications, independent of routing protocols. This implies that beacons in VANETs can provide two distinct services: (1) services for safety applications and (2) services for one-hop neighborhood information. As a primary service for safety applications, beacons are being researched to optimize their periodic transmission for reliable communication of safety applications (Willke *et al.*, 2009; Schmidt *et al.*, 2010; Sepulcre *et al.*, 2011). On the other hand, it has been shown that by optimizing the transmission of periodic beacons in MANETs, unicast path accuracy as well as topology awareness can be improved significantly (Chen *et al.*, 2013). With this context, it remains an open challenge to investigate the implications of beacon transmission optimization on unicast path accuracy and topology awareness in VANETS. In addition, it requires novel beacon transmission mechanisms, such that a balance is established between reliable communication of safety applications and accuracy of the unicast path and topology.

6.2 Realistic evaluation metrics

A common supposition that vehicles have real-time access to the position information of the destination vehicle through some location services, such as in Li *et al.* (2000), Käsemann *et al.* (2002), and Kieß *et al.* (2004), is considered in the reviewed unicast protocols. This assumption is valid for all vehicles in a network regardless of their communication activity. Obtaining real-time position information without delays is disputed as it requires beacon transmissions across the vehicular network. In addition, vehicles that do not participate in communication add to unnecessary overhead on a network. Protocols that employ an offline-information-assisted approach for path calculation, such as those in Seet *et al.* (2004), Yang *et al.* (2008), Zhao and

Cao (2008), and Xiang *et al.* (2013), incur computational load during the pruning process. However, as shown in Table 8, none of the reviewed protocols use evaluation metrics that represent delays for fetching position information and computational load during path calculation. Therefore, real-time protocol evaluation requires composite evaluation metrics that cover such aspects.

6.3 Inter-layer communication standardization

This study shows that different protocols consider diverse sets of communication aspects for path calculation and data forwarding. Protocols achieve these sets by incorporating auxiliary information into the network layer routing process (Jarupan and Ekici, 2011). Auxiliary information may come from GPS devices or through the cross-layer interaction among the network, data link, and physical layers. In the reviewed unicast protocols, dissimilar communication approaches are used for inter-layer interaction. This difference can be attributed to the lack of standardization in the cross-layer interactions of OSI layers. Consequently, an inter-layer OSI interaction is difficult to correlate with a particular VANET communication aspect. Further research should focus on the challenging task of developing standards for inter-layer interaction for communication in VANETs.

7 Summary and conclusions

We presented in this paper a review of unicast protocols for urban vehicular networks. First, we identified two main categories of routing approaches and evaluated an urban scenario and its limitations on effective protocol communications. Then, we presented a thematic taxonomy based on routing approaches and their corresponding primitive functions. A unicast protocol review showed the implications of routing protocols followed by an operational comparison of the routing approaches. Qualitative protocol comparison was conducted by defining different metrics, including scope and accuracy, route metric stability, implementation cost, forwarding efficiency, and the computational strategy. We also highlighted the competitiveness of protocol evaluation by identifying frequently used evaluation metrics and corresponding objectives of compared protocols. Finally, open issues and challenges that demand further research were highlighted.

We conclude that an extensive study on unicast communication protocols with particular routing approaches can provide sufficient potential solutions for non-safety applications in urban VANETs. However, a review motivated by routing approaches is essential to understand the applicability of unicast protocols in urban scenarios. Based on our findings, we conclude that the accuracy of a unicast path for path selection depends on the primitive functions of probing, inference logic, and the recovery strategy. Active probing scope and instantaneous inference of probed parameters produce the most accurate unicast path but suffer from frequent probing and evaluation because of constant mobility and dynamic topology. In a subsequent communication operation denoted as relay selection, most of the protocols use network layer beacon messages to select one-hop relay. On the contrary, lightweight techniques that use data link layer messages, such as RTS/CTS, for relay self-election are more suitable for reducing relay selection overhead. In addition, the effects of beacon optimization on neighbor discovery in unicast protocols, competitive performance evaluations, and inter-layer communication standards lack investigation. As a result, lack of accuracy of unicast path and topology, unreliable protocol evaluation by intentionally avoiding comparison with candidate solutions, and incoherent protocol designs caused by lack of inter-layer standards are prominent among unicast protocols. Therefore, beacon transmission optimization with joint adaption for safety applications as well as unicast paths, performance evaluation with competing solutions by using real-time evaluation metrics, and standards for inter-layer communication for coherent protocol designs demand further research to ensure progressive routing in vehicular ad hoc networks.

In the future we will investigate integration of adaptive beacon mechanisms with unicast communication protocols for enhanced performance of infotainment applications and safety applications messages such as decentralized environmental notification messages (DENM) (ETSI, 2010).

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