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Review

Network Management and Monitoring Solutions for Vehicular Networks: A Survey

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Abstract: Vehicular networks are emerging as a promising technology that enables reliable and low-cost solutions for intelligent transport systems (ITSs), mainly due to their enormous potential to be considered for multiple purposes and scenarios. These networks are characterized by unique and challenging features such as packet fragmentation, low node density, short contact duration, and network disruption. These features may result in the absence of a path between the source and destination nodes, which is one of the most challenging issues faced by this type of network. To overcome some of these problems, it is necessary to provide vehicular networks with sophisticated tools or methodologies to implement monitoring and management operations. However, designing efficient solutions for this type of network is not an easy task due to its particular characteristics. This paper elaborates on a comprehensive survey focusing on promising proposals to deal with monitoring and management functionalities in vehicular networks. This work aims not only to present the state of the art on monitoring and management solutions but also to analyze their benefits and drawbacks, identify open issues, and provide guidelines for further contributions.

Keywords: delay-tolerant network; vehicular communications; vehicular ad hoc network; vehicular delay-tolerant network; intelligent transport systems; monitoring; network management

1. Introduction

Vehicular networks [1–3] are emerging as a promising alternative to the conventional Internet, allowing the implementation of low-cost infrastructures to enable the deployment of services and applications, especially in regions where network infrastructure is not available [4]. To overcome the lack of network infrastructure, vehicular networks use vehicles, with wireless communication devices, to create a temporary self-organized network [5]. Following this approach, such networks can provide communications support for multiple environments (e.g., urban, remote/rural, and catastrophic) [6–8]. For example, several road traffic optimization and road safety applications [9–13] were designed to provide driving assistance. Despite their applicability, the absence of an end-to-end path in vehicular networks raises several issues that must be overcome [14]. Sporadic contact opportunities between network nodes, long and variable message delivery delay and high error rates are examples of these problems. To solve some of these issues, several network architectures have been proposed [15].

Vehicular ad hoc networks (VANETs) [16,17] exploit vehicles as mobile nodes, exposing them to traffic conditions and regulations. In such networks, vehicles may interact with other vehicles or with roadside infrastructures. Following this approach, most of the proposals for VANETs consider three different types of network infrastructure to enable communications between vehicles [18–20]: (i) an ad hoc infrastructure where vehicles communicate with other vehicles (V2V); (ii) an infrastructure with several roadside units (RSUs) with wireless capabilities that may communicate with vehicles (V2I); and (iii) an infrastructure combining both V2I and V2V. Common to all these approaches is the assumption of end-to-end connectivity, which makes VANET architecture susceptible to frequent disconnection, network fragmentation, and long delays.

The delay-tolerant network (DTN) architecture [21–24] supports intermittent communication between network nodes. It defines a message-oriented overlay layer called a "Bundle Layer" and places it above the transport layer of the interconnected networks. With this approach, the bundle layer intends to allow heterogeneous networks with distinct characteristics, like different transmission media, to establish communications [22]. The bundle layer is also responsive, in order to generate the application data units called "bundles", which represent the entire amount of information that a DTN node needs to transmit to another one. The Bundle Protocol defines a hop-by-hop transfer methodology that assigns to nodes the responsibility to retain bundle copies until they transferred it to another node. This approach allows the implementation of a store-carry-and-forward paradigm that exploits the high mobility of mobile nodes to enable communication between nodes, building a hop-by-hop session for data transfer. Following a DTN approach and gathering contributions from other technologies, vehicular delay-tolerant networks (VDTNs) [25,26] propose a network architecture where the communication is divided into two phases (control and data planes), allowing implementation of an out-of-band signaling strategy. Although they also define the bundle as its protocol data unit, VDTNs place the bundle layer beneath the network layer. In VDTNs the bundle layer is known as Bundle Aggregation and De-aggregation (BAD) layer, which is responsible for aggregating incoming IP data packets into bundle messages, allowing forwarding of larger packets (called bundles) instead of small IP (Internet Protocol) datagrams. This approach results in fewer round-trip exchanges and lower routing costs, which is very important in scenarios with a high round-trip time. The bundle layer is also responsible for transmitting and receiving bundles between network nodes by employing a store-carry-and-forward bundle switching paradigm, which is very useful when end-to-end connections are not assured.

This architecture supports three distinct types of nodes: terminal, relay, and mobile nodes. Terminal nodes are responsible for generating and receiving data. Relay nodes are usually placed at a crossroads and have a large storage capability, which allows them to store a large amount of data that will be forwarded to mobile nodes when a contact opportunity arises. These devices also aim to increase the number of contact opportunities, which will improve the data delivery rate [27]. Finally, mobile nodes are used to collect, store, and deliver data to the final destination. Mobile nodes can also act as terminal nodes when they generate data or are the final destination of data.

Despite all the achievements and problems solved by, the above-presented architectures, there remain some key issues that must be solved in order to increase confidence in the use of vehicular networks. For example, in such challenging environments, the network must be capable of dealing with traffic constraints, constant topology changes due to the high mobility of nodes, frequent communication and data losses, and limited network resources. It is expected that by implementing network management and monitoring operations and mechanisms (e.g., routing optimization algorithms, handoff methodologies, and resources constraints detection), some of these issues and constraints can be overcome [28]. Usually, network management operations are ensured by routing protocols, because they have the sole purpose of routing packets in the best interests of the network. However, external solutions are needed to optimize the parameters of routing protocols. Such an approach may lead to more stable topologies and lower control traffic overhead, increasing the delivery ratio and decreasing the end-to-end delay and resource consumption (e.g., bandwidth and energy). Different types of solutions for management purposes were proposed for wireless networks [29–32]; however, due to the unique characteristics of vehicular networks, they cannot be directly applied. Some of them may be adapted to make them work in vehicular networks; nevertheless, new mechanisms must be proposed.

To promote further investigation, this paper analyzes and discusses the most relevant research efforts related to management and monitoring techniques for ad hoc and vehicular networks. It also focuses on how the proposed solutions are designed or adapted for deployment in such networks. The paper begins with an overview of mobility management approaches that attempt to solve several issues pertaining to the high mobility of mobile nodes and the highly dynamic network topology. Both problems are emphasized by mobile node density and network flows. To overcome these problems and improve network performance, traffic management methodologies are considered. Moreover, the possible absence of a direct path between a message source and its destination introduces in vehicular networks several concerns associated with latency, data integrity, and resource consumption. Solutions designed to solve these concerns are studied and discussed in detail. Finally, a discussion on network management practices is presented in which open issues for vehicular networks are identified. Thus, the main contributions of this paper are the following:

- Identification and description of the most relevant challenges and constraints regarding network monitoring and management in vehicular networks;
- A detailed review of the state of the art considering the most relevant contributions to the implementation of monitoring and management functionalities in wireless and vehicular environments;
- A discussion on network management and monitoring techniques for vehicular networks;
- Identification of open issues for further research.

The remainder of this survey is organized into five sections. Section 2 describes the challenges and the most relevant activities that are considered to achieve management and monitoring objectives for vehicular networks. Section 3 gives details on mobility management and how these approaches can be deployed. Section 4 summarizes the most important contributions related to traffic management and monitoring, enumerating the most important proposals for this type of solution. Section 5 provides an overview of the state of the art in communications, services, data, and resource management strategies. The final section presents the main conclusions drawn from this study and points to several research topics that may be addressed as future work.

2. Challenges to the Implementation of Management/Monitoring Activities in Vehicular Networks

Network management and monitoring functionalities allow the operation of disparate networks, which involves handling the exchange of thousands of messages coming from multiple devices with different communication requirements and architectures. Contrary to the traditional Internet, implementing management and monitoring functionalities in vehicular networks is not an easy task. The unique characteristics (e.g., possible absence of an end-to-end path, intermittent connectivity, dynamic topology, node mobility, and node density) of such architectures raise several challenges that must be considered to propose efficient management and monitoring approaches. This section overviews the most relevant trials raised by vehicular networks that may have a significant impact on management and monitoring activities.

2.1. Dynamic Ad Hoc Topology and Node Mobility

The highly dynamic network topology due to mobile nodes' density and mobility is one of the most challenging issues that must overcome in vehicular networks. As the network topology constantly changes over time, a priori topology planning is not possible for a network administrator. Therefore, new nodes may join or exit the network at any moment, changing not only the network topology but also the node density, which can cause several problems concerning route discovery, leading to suboptimal routes and structures. This situation results in a huge waste of resources. A possible solution that reduces the impact of the highly dynamic topology and minimizes the effects of such issues, thus enabling high-speed and seamless services for vehicular networks [33], is to design mobility management methodologies (described and analyzed in Section 3) dealing with network routes and structure updates aiming to reflect the current state of the network topology [34]. However, mobility protocols present performance limitations (e.g., latency) in highly dynamic scenarios and inefficient methodologies may result not only in a large wastage of resources but also in suboptimal routes [35].

The aforementioned problem is exacerbated by the movement of mobile nodes, which is influenced by traffic rules and road conditions (e.g., congestion, traffic lights, and rules, pedestrians). This situation may lead to significant delays while traveling, which has a negative impact not only in the performance of mobile nodes but also on the overall network. For example, traffic congestion may lead to an increase in energy consumption and message delivery delay. To overcome this problem, efficient traffic and routing management and monitoring strategies are required (as described in Section 4). These strategies may consider traffic prediction mechanisms that aim to avoid road congestion or route optimization algorithms that can choose the best paths to deliver a message to its final destination.

2.2. Bandwidth and Resource Limitations

Due to the velocity of mobile nodes and the nature of wireless channels, communication bandwidth may be far lower in vehicular networks. Conversely, the packet loss rate tends to be higher when compared to the traditional Internet. Aggravating this problem further is the fact that vehicular networks are also characterized by short contact duration, which limits the volume of data that can be transferred at each contact opportunity, which imposes serious limitations for the proposed multimedia sharing applications.

Limited network resources can further exacerbate this situation, because nodes may be forced to avoid following the protocol, to prevent their data from being compromised. To promote and incite the development of new applications and services, new and different management approaches for communications, data, and resource management should be employed in vehicular environments (as described in Section 5). For example, some approaches to monitoring network conditions can be proposed that provide complete reports and statistics to network administrators, helping them create measures to improve the overall network performance. Moreover, this may allow performance problems, such as unnecessary bandwidth consumption, to be researched.

3. Mobility Management

Network mobility management operations are responsible for managing and maintaining Internet connectivity between groups of mobile nodes, aiming to achieve optimal network performance (Figure 1). Mobility management proposals for vehicular networks should be designed taking into consideration the specific requirements of vehicular networks: communications between vehicles (V2V) and between vehicles and some kind of roadside infrastructure (V2I). Based on these two types of communications, a taxonomy for mobility approaches can be defined. In V2V communications, most of the mobility management schemes focus on route discovery and maintenance [34], which involves highly dynamic topologies, location, and handoff issues. On the other hand, proposed schemes concerning to mobility in V2I communications entail host and network issues, such as route optimization and integration with VANETs. Most of them consider some Internet mobility management protocols (e.g., Mobile IPv4 [36] and Mobile IPv6 [37]). However, the common implementation of these protocols introduces high handover latency and increases the amount of data loss, as shown in [38].

The most relevant proposals and approaches for monitoring and management functionalities are presented and discussed in this section as well as the major open issues, which will allow new approaches to be proposed that can overcome some of these issues.

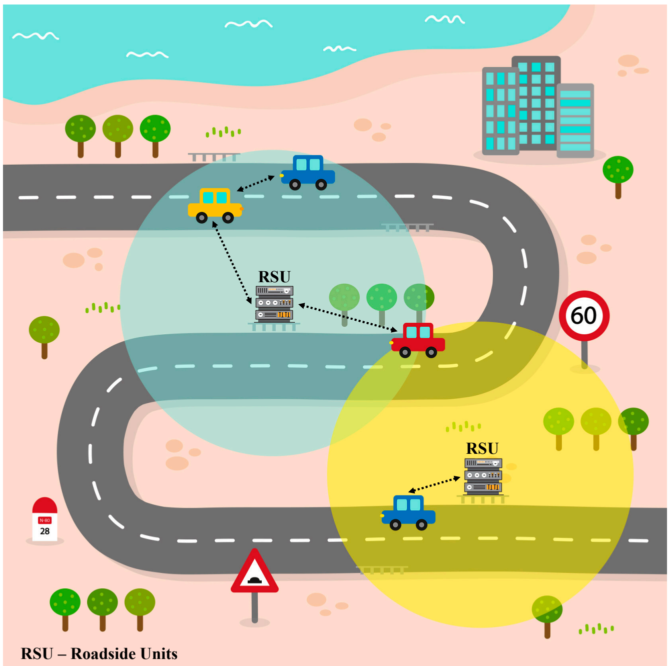

Figure 1. Example of a vehicular network scenario, considering both types of communication between nodes (V2V and V2I), where mobility management functions are needed to enable communication between different groups of mobile nodes.

3.1. Mobility Mechanisms for V2V Communication

Communication between vehicles (V2V) raises several issues (e.g., movement detection or handoff decision) that must be overcome to increase the reliability of vehicular networks. Different protocols, schemes, and approaches may be considered. Network Mobility (NEMO) for Network Mobility Support (NBS) [39] was proposed to allow MIPv6 to manage a set of moving nodes to provide a continuous network connection. To accomplish this task, individual mobile nodes have their home agent (HA), which controls all data forwarded between nodes. Although improvements were achieved by this approach, a triangle routing problem may compromise its performance because the HA controls the path between the correspondent and mobile nodes, establishing the third vertex of the communication triangle. To deal with this problem, MIRON [40,41], NERON [42], and SINEMO [43] were proposed. To deploy NEMO in vehicular networks, several approaches, schemes, and applications were proposed [44–49]. From these, two stand out. In [47], the authors designed a novel mobility management scheme that divides vehicles into different clusters based on geographical distance and related velocity. This approach aims to create different mobile networks where ad hoc intra-communication is initiated by routing protocols, decreasing not only the handoff latency but also the number of lost packets. Following a similar approach, the work presented in [49] proposes a fast handoff scheme that uses assistance nodes to deliver new care addresses to mobile routers, helping them scan network channels while reducing the network handoff latency. Simulation results have shown that this scheme manages to reduce handoff latency while maintaining the packet interval.

Optimized NEMO (ONEMO) [50] was designed as a route optimization method that attempted to offer a different path solution from the default bidirectional tunnel maintained by NBS. This is achieved by transferring the responsibilities of the HA to the corresponding router (CR). This task is accomplished by implementing a discovery scheme in mobile routers that aims to find its CR. This scheme sends a discovery request to all addresses derived from the corresponding network node prefix. When a bidirectional tunnel is established, the entire traffic from the network starts to be controlled by the HA. Studies have shown that ONEMO manages to decrease the packet overhead. In [51], the authors proposed and evaluated a seamless flow mobility management architecture that attempts to maximize the network throughput by allowing different types of network interfaces at the same time. To maintain the low latency and packet loss rate, this architecture schedules messages according to three different types of applications: safety, comfort, and user. This architecture assumes that all vehicles move in urban environments executing different classes of applications. Two group-based network mobility management schemes (FP-NEMO and IFP-NEMO) for vehicular networks were proposed in [52] that aim to improve the handover performance of NEMO. These management schemes implement an approach that establishes multiple tunnels at the same time to be used by a group of passing vehicles. This approach aims to decrease the handover latency by pre-established tunnels only with vehicles that share the same geographic characteristics. Performance studies conducted through simulation and analytical models showed that a performance improvement decreased the signaling overhead, the packet transmission cost, and the handover latency.

Park et al. [53] designed a scheme to deal with the problem of fast IP mobility. In this scheme, several interfaces with wireless capability are considered to eliminate the packet loss problem in the case of fast handover. These interfaces extended the HMIPv6 standard [54] to implement a multi-tunnel approach between HMIPv6 MAP and mobile gateways. Following this scheme, it is possible to overcome some performance limitations (e.g., handover latency and packet loss) of HMIPv6 and MIPv6.

Carvalho et al. [55] studied the effects of both centralized and distributed mobility strategies in vehicular networks. Both approaches are evaluated through several environments that consider Mobile IPv6 and Dynamic Mobile IP Anchoring models. Performance studies conducted to evaluate the behavior of these strategies concluded that distributed approaches achieved better results concerning data loss and delay when compared to centralized methodologies. A handoff protocol for VANETs was proposed in [56]. This protocol takes advantage of the introduction of a link expiration time variable and combines this information with road topology and traffic information to maximize the performance of the links established between vehicles.

3.2. Mobility Mechanisms for V2I Communication

In vehicular networks, a direct connection between vehicles and roadside infrastructure may not be available. For this reason, conventional MIPv6-based solutions for mobility management must be adapted for application to vehicular networks. Peng et al. [57] proposed a scheme to allow the integration of VANETs with fixed IP networks. To accomplish this, the scheme considers several parameters: (i) street layout, (ii) distance between vehicles, and (iii) base stations with the ability to manage vehicle mobility. It also implements a novel approach, allowing multiple base stations to communicate simultaneously with destination vehicles closer to them. Performance studies showed that with this approach it is possible to improve not only the network connectivity but also the delivery ratio.

Clustering for Open Inter-Vehicle Communication Networks (COIN) [58] aims to enable mobility functionalities without the need for a fixed infrastructure. This is accomplished by an approach where the cluster head selection is performed taking into consideration the drivers' intentions and the constant changes in the distance between vehicles, defining a stable clustering strategy. In [59], the authors proposed a location-aware framework to deal with reactive mobility management. This framework is based on mobility predictions to optimize MANET protocols to be deployed in VANETs. This framework aims to achieve kinetic mobility management to suppress the periodic beaconing process, which is widely considered by ad hoc protocols for mobility adaptation. With this approach, the time interval for the mobile topology is correctly anticipated.

A region-based location-service management protocol (RLSMP) [60] was purposed to take advantage of node locations to build geographic clusters. With this approach, location information is restricted to a set of nodes belonging to a specific geographical cluster in the network. RLSMP then defines the central cell of the cluster as the HA. This agent is responsible for storing and updating the current location information about all nodes that it supervises. Vehicular Ad Hoc Route Optimization for NEMO (VARON) [61] enables secure communication between moving vehicles without the need for infrastructure. This approach allows the establishment of a secure hop-by-hop binding procedure using cryptographically generated addresses and public keys, providing a security level similar to the IPv4 by reusing Mobile IPv6 security concepts. Studies have shown that VARON is effective in dense scenarios, but inefficient for sparse scenarios.

In [62], the authors designed an architecture to minimize the handover time by executing flow management operations based on application classes for communication between vehicles. These application classes are considered to set the minimum requirements to perform the handover process. To help in this process, the flow manager examines the status of active connections that use Wi-Fi, LTE (Long Term Evolution), and 802.11p. Chekkouri et al. [63] proposed a novel architecture to deal with vehicle mobility and the small coverage of small cells for V2I communications. The authors integrated 4G LTE-A heterogeneous networks in VANETs to improve how this kind of networks deal with mobility. This is accomplished by the proposal of a new network-based mobile gateway that efficiently relays traffic from passing-by vehicles. This gateway operation is further extended by an anchor-based mobility scheme that takes advantage of inter-domain procedures. MobiVNDN [64] is a distributed framework that aims to mitigate the degradation of communications performance in vehicular networks due to the high mobility of network nodes (vehicles) and also to the use of wireless communications. MobiVNDN takes into consideration broadcast storms, network partition, and message redundancy to create a robust and efficient mechanism that improves communication even in an environment where nodes share their communication medium with multiple applications. Khabbaz et al. proposed a Vehicular Mobility Management (VMM) scheme [65] to improve data communication services by regulating the vehicle's navigational parameters. This approach allows vehicles to keep the communications with others only on the coverage range of their OnBoard Units. By using a mathematical model that evaluates the quality of service of each link, authors manage to increase the probability of vehicles establishes multi-hop paths between arbitrary pairs of network nodes. In [66], the authors presented a distributed group mobility management scheme (DMM) to deal with frequent handovers caused by the high mobility of vehicles. This scheme is based on blockchain and is intended to reduce the handover latency. To achieve this purpose, it uses signaling authentication and aggregates messages authentication codes with one-time passwords mechanisms.

3.3. Discussion and Open Issues

The high mobility of mobile nodes imposes several limitations, such as a significant increase in the number of hops needed to deliver messages to their final destination, which contributes to the handoff degradation performance. Hence, mobility models (e.g., random waypoint) consider the arbitrary direction and speed selection to make handoff decisions, making these models unsuitable for performance evaluation due to their inability to deal with mobility. This section aims to provide a sampling of contributions with the common objective of taking advantage of node mobility and network topology flexibility to improve the performance of vehicular networks.

As future research directions on this topic and to continue increasing confidence in vehicular networks, mobility models must be capable of dealing with multiple requests competing simultaneously for the same limited bandwidth, which may raise security issues. To minimize such issues, measures to protect data from unauthorized access and ensure proper address configuration can be implemented. Another possible solution to solve this problem is to equip mobility models with management capabilities to balance the priorities of safety information and user requests. Finally, protocols being executed on the transport and application layers need to be adapted and optimized to deal with mobility and perform correctly in vehicular environments.

Table 1 offers an overview of meaningful approaches to dealing with mobility in vehicular networks, highlighting the most important advantages and drawbacks of each method. A comparison between all the proposals is also presented in this table.

Table 1. Summary of different approaches to dealing with mobility in vehicular networks.

References	Route Optimization	Signaling	Latency	Packet Loss	V2V Optimization
[40,41]	Communication between entities (mobile router and home agent) is established through a two-directional tunnel.	Fixed nodes request that each mobile router execute the routing optimization process with their corresponding node considering MIPv6.	High	High	No
[42]	A two-directional channel is set up to allow participating entities (mobile router and home agent) to communicate.	The MR nests behind a root-MR and updates its Nest Gate Table by sending an Unsolicited Neighbor Advertisement.	Low	Low	No
[43]	Proxy mobile router, creating a tunnel to the corresponding node.	Each time a mobile router moves to a different home network, it establishes a new point of connection, setting up a new care address. After that, it informs its home agent by sending a binding update.	Low	Low	Yes
[47]	Divides vehicles into different clusters creating different mobile networks where intra-communication is allowed. Communication in the same cluster is performed by some kind of ad hoc routing protocol.	Nodes in a cluster are classified according to their functionality. Center nodes provide mobile router functions. Head nodes are vehicles in front of the cluster, and consequently, tail nodes are nodes at the end of the cluster. Any other nodes are treated as general nodes.	Low	Low	Yes
[49]	Mobile routers, with the help of assistance nodes, are responsible for obtaining channels states in order to perform address changes before the handoff process takes place.	It considers different metrics (e.g., position, speed, and direction) to create clusters of nodes. In each cluster, a specific node acts as the mobile router, while others have to communicate through it to establish a connection with the backbone.	Low	Low	Yes
[50]	The mobile router and the home agent communicate with each other considering a bidirectional tunnel, allowing packets to be forwarded through multiple home agents with multiple levels of encapsulation.	Signaling messages are needed to establish an optimal path.	High	High	Yes
[51]	The local mobility anchor and the mobile access gateway (MAG) establish an IP-in-IP bidirectional tunnel to forward all data traffic belonging to the mobile nodes. No bidirectional tunnel is established between the MAGs.	Mobility-related layer 3 (L3) signaling messages are exchanged considering a wireless link.	Low	Low	Yes
[52]	Each mobile access gateway (MAG) is configured with its own neighboring MAG list, allowing it to know which mobile routers can be handed over. Bulk messages are introduced to allow the pre-establishment of tunnels between groups of mobile routers and MAGs.	FP-NEMO was designed to deal with the signaling burden. It establishes multiple tunnels simultaneously for a large group of passing vehicles sending single tunnel-establishment messages.	Low	Low	Yes

Table 1. *Cont.*

References	Route Optimization	Signaling	Latency	Packet Loss	V2V Optimization
[54]	Mobile nodes establish a connection with the mobility anchor point in order to forward packets through a two-directional tunnel.	Signaling exchanges require that nodes update their location.	Low	Low	Yes
[57]	Base stations are placed at the end of road intersections, allowing establishment of a one-dimensional ad hoc network, which represents a multi-hop cell.	Signaling packets are broadcasted through base stations to the related ad hoc network.	Low	Low	Yes
[58]	Clusters have to choose a head node. This selection is performed take into consideration the dynamics of the network and driver intentions.	Use driver intentions as input to the clustering algorithm.	Low	Low	Yes
[60]	Clusters are created taking into account node locations. This proposal allows performance of several important tasks, such as message aggregations, which help solve the problem related to the huge number of control signals.	Nodes use Global Positioning System (GPS) devices to map their location in the grid and calculate the cluster cell they are in. Network nodes have full knowledge of the cluster, grid, and cell sizes.	Low	Low	Yes
[61]	Intra-NEMO optimization.	Generated by the cryptographic system.	Low	Low	Yes

4. Traffic Management

The design and deployment of traffic management solutions are expected to improve traffic flows, which will help detect and reduce traffic jams and accidents (Figure 2). With flow optimization, it is also possible to reduce resource consumption and vehicle emissions [67]. Usually, traffic management is achieved by taking into account the operation of routing protocols and how they manage data. Based on these two features, schemes to deal with traffic management can be classified in a taxonomy considering two main activities: Prediction and Optimization. To enable the prediction process, road traffic information must be collected using some kind of methodology. In [68], the authors presented a taxonomy for road traffic information collection that is used to implement traffic prediction functionalities. According to this taxonomy, predictive methodologies may gather data using analytical models [69,70], fixed sensors [71], mobile phones [72,73], or mobile devices (e.g., smartphones) combined with GPS receivers [74–76]. After the prediction process, the collected information must be evaluated by a routing control [77–79] or traffic signal control [70,80] methodology to implement a traffic optimization strategy. Vehicles driven by humans can then use this information to reduce road congestion. In this section, the most important contributions for both activities are presented and discussed. Afterward, some open issues are also identified as a starting point for the proposal of new methodologies to deal with traffic management operations and problems.

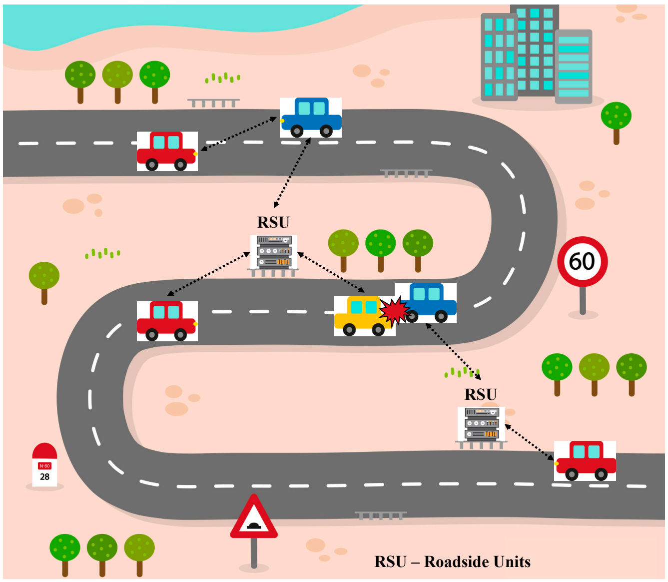

Figure 2. Example of a vehicular network scenario where traffic and route management/monitoring solutions are needed to detect and deal with road constraints, in order to improve the overall network performance.

4.1. Traffic Prediction in Vehicular Networks

Several ITS applications consider prediction methods to determine how flows (e.g., paths, links, and nodes) change with time and traffic intensity. The information collected by such methods can be used by traffic systems to provide real-time information. Commonly, traffic models consider three different measures to model traffic streams: speed, node density, and node flow. This subsection overviews the most relevant proposals related to traffic prediction for vehicular networks, grouping them according to the way that road traffic information is collected.

Analytical models have been proposed to study traffic models in different scenarios without the need for an infrastructure to collect information from the network. Castillo et al. [81] designed a graph-theory-based methodology supported by two approaches (i.e., algebraic and topological) that solve the observability problem. This methodology determines which flow should be considered after the observation process, independently of route choice probabilities. The obtained results showed that a topological approach achieves better results because it consumes fewer network resources and involves no rounding errors. In [82], a modeling framework for urban traffic system was proposed that allows the structure of urban traffic systems to be studied and node interactions to be understood, by systematically defining the components and their behavior that are necessary to enable driver simulations. To describe the structure and behavior of the components, a multi-level Petri-net-based formalism [83] was considered. A cellular automata approach to building traffic mobility models was designed in [84]. This approach provides rules for grouping vehicle motion based on a traffic signal coordination model of road intersections. An aggregation methodology to predict traffic flows in vehicular environments was proposed in [85]. To accomplish the prediction task, this methodology bases its operation on four different parameters: the moving average (MA), exponential smoothing, autoregressive MA (ARIMA), and the neural network (NN) model. All parameters consider the traffic information collected over several days (24 h/day), which are generated taking into account three different time series (i.e., weekly, daily, and hourly). The NN parameter then collects the prediction of each model in the aggregation stage to give a final prediction. An adaptive hybrid fuzzy-rule-based system (FRBS) [86] was proposed to model and forecast traffic flows in urban arterial networks. It considers powerful structures capable of handling faults and unpredictability. They can perform either online or offline, owing to the deployment of a genetic algorithm and an expert's knowledge model. A traffic prediction model to control and coordinate urban traffic networks was designed in [87]. This model takes advantage of a mixed-integer linear model to increase network optimization. Studies conducted through simulation have shown the accuracy of this model in reducing the computational complexity, thereby increasing its applicability in real environments. A theoretical framework to estimate traffic speed was proposed in [88]. It combines low-resolution position data with other data sources to solve the problem some probe vehicles have in providing accurate positions. With this approach, this framework manages to estimate traffic speed more accurately.

Another way to predict traffic behaviors and create optimized solutions is to collect data from moving vehicles using fixed sensors placed at roadsides. By using these devices, it is possible to collect several metrics, such as the current vehicle speed, the number of passing vehicles, or vehicle flow. Following this data collection methodology, a framework based on non-conventional techniques to predict the speed at single-loop detectors is proposed in [71]. From the framework predictions, it is possible to obtain a length-based vehicle classification that is further compared with concurrent measurements from video and dual-loop detectors. Tyagi et al. [89] designed a traffic flow estimation system that gathers information about moving vehicles from a single roadside microphone. The microphone allows tire and engine noise and occasional honks, among others sounds, to be gathered. The collected sounds are optimized using algorithms to extract short-term spectral features. This optimization allows traffic flows to be classified according to three different density states: Jammed (0–10 km/h), Medium-Flow (10–40 km/h), and Free-Flow (40 km/h and above). To improve the optimization process, an approach is proposed in [90] that considers the Cambridge Systematics from NGSIM [91] to collect traffic information (e.g., flow, density, and speed) from vehicle trajectories.

Another possible solution to the problem of collecting traffic information uses mobile phones. To perform this task, they should send, from time to time, measurement reports to the core of the cellular network. This approach avoids the installation and preservation of fixed infrastructures and sensors. Following this approach, Valerio et al. [72] considered the use of cellular network infrastructure as the base of a system designed to estimate road traffic. This is accomplished by collecting signaling messages from the mobile network. Another system to collect real-time urban traffic was proposed in [73] by employing the LocHNES (Localizing and Handling Network Event Systems) framework to collect information about the instantaneous positions of buses and taxis, providing information about traffic on roads. This platform was deployed and evaluated in a real environment (Rome, Italy).

Mobile phones may be combined with vehicles equipped with Global Positioning System (GPS) devices and antennas. This approach allows vehicle positions to be gathered and data to be sent to dedicated servers with a global system for mobile communications (GSM) transmitters. Li et al. [76] designed a method to determine recurrent congestion points using historical probe car data. The method was tested in Beijing for 57 days, considering 7000 taxis. Analysis of the proposed method resulted in several evaluation models for recurrent congestion points. In [92], the authors proposed a sensing estimation algorithm that implements a monitoring center for traffic estimation. This monitoring center receives location and speed information updates from probe vehicles. Probe vehicles are equipped with GPS receivers, allowing them to know their current speed and location. Studies conducted in Shanghai, with 4000 taxis, have shown that hidden structures with traffic condition matrices underlie the probe data. Kang-Ching et al. [93] also exploited probe vehicles equipped with GPS devices to optimize traffic status estimation. Data assimilation techniques and Newtonian relaxation methods are considered to integrate probe data into macroscopic traffic models. In [94], a management system (PRTMS) for VANETs was designed to predict traffic flows considering a communications infrastructure based on the IEEE 802.11p standard. This approach implemented together with a modified linear prediction algorithm, allows a PRTMS to be deployed in scenarios with multiple road intersections. A central controller is also implemented to detect congestions and re-route vehicles in case of traffic congestion. DTMon [95] was proposed as a dynamic traffic monitoring system to gather information about traffic conditions. To accomplish this task, it uses traffic information from moving vehicles collected by roadside infrastructures to generate reports for traffic management systems. Rong Du et al. [96] designed two patrol algorithms and a sampling rule based on the relation between the disparity of samples and traffic estimation errors, which allows the paths of floating cars to be set, thus enabling them to participate in traffic monitoring functions. Studies showed that the sampling rule combined with a patrol algorithm reduces estimation errors. In [97], the authors proposed a protocol specifically designed to send secure messages, the goal being to improve the network quality of service. These messages are sent assuming that all participating vehicles have GPS devices, which allows them to know their exact location when experiencing some failure or accident. When this type of situation occurs, vehicles broadcast their position to vehicles behind them. This approach allows the focus of traffic congestion to be determined, enabling a geocasting packet transmission approach. GeoWave [98] is a network protocol that uses IEEE 802.11p to exchange useful messages that are used by an active/passive safety system. With GeoWave, vehicles exchange crucial information with their neighbors or with RSUs, enabling the network infrastructure to continuously gather information about traffic conditions. In [99], the authors introduced a predictive system to calculate the best path between two points. This system is capable of dealing with the single characteristics of different types of obstacles and road structures while planning the optimal path to be followed by vehicles. It also implements a quadratic model with a predictive controller, allowing the solution of an important issue related to two-dimensional obstacle avoidance. To model the proposed system, the authors considered the CarSim vehicle model.

4.2. Traffic Optimization in Vehicular Networks

In the literature, the most efficient and commonly considered approaches to deal with traffic optimization are divided into two classes: traffic light control and routing algorithms for vehicles. Traffic light control can be described as a joint decision regarding the duration of the signal phases associated with each signalized intersection in the network. It can be implemented considering either a fixed-time or an adaptive-time method. When a fixed-time method is considered, the history of traffic statistics is used to set cycle time and the duration of one light, ignoring all the changes in traffic conditions. On the other hand, adaptive methods set the amount of time of a cycle and the duration of one light according to real-time information about traffic and road conditions. Routing algorithms for vehicles are used to inform drivers about optimal routes (e.g., routes free from traffic congestion), taking into account a set of constraints such as shortest path or time intervals.

Diakiki et al. [100] proposed a multivariable regulator approach (TUC) to deal with traffic signal control in urban scenarios. It employs the store-and-forward paradigm to formulate the urban traffic control problem. It also uses linear quadratic regulator theory to create a network-wide signal control suitable for roads with a high level of congestion. In [101], a hybrid strategy for real-time traffic signal control for urban scenarios was designed. This approach adapts its functionality based on traffic conditions. If a road is under saturated signalized junctions, traffic signals are controlled using a real-time Webster-type demand-drive strategy. When the road is close to saturation, this strategy changes its behavior to control signalized junctions with TUC. A technique to control real-time signals was evaluated through an API proposed in [102]. This technique allows traffic fluctuations to be detected in real-time because it considers a dynamic programming approach combined with adaptive signal control methodologies.

Zegeye et al. [103] proposed a receding-horizon parameterized traffic control approach that combines prediction adaptation and nonlinear models with faster computation speed. This approach also implements a theoretical strategy to design control laws for variable speed limits and ramp metering. An architecture that bases its operation on Markovian properties combined with geometric fuzzy sets was designed in [104]. In defines all agents to have equal decision capabilities, and their operation is based on five modules that operate concurrently. Agents are associated with an intersection and receive information from sensors, which allow them to calculate the duration of green phases. To perform this task, they consider the results gathered by two different modules. The data collection module determines the queue count, while the communication module regulates the status of each neighboring intersection. All this information is put together with an average flow rate.

Oliveira et al. [105] proposed a framework to deal with multi-agent control of linear dynamic systems. This approach allows breaking down a centralized model by employing distributed agents to solve small parts of the predictive control problem. To achieve this goal, each agent senses, and controls the variables for its part of the problem, communicating with its neighbors to obtain their variables to coordinate their actions.

StreetSmart [106] traffic is a platform that uses the standard GPS driving aid to effectively discover and disseminate traffic congestion routes to drivers. This platform was designed to exchange information only on areas with unexpected traffic conditions. To determine traffic patterns, this platform uses a combination of clustering and epidemic communication. It allows each vehicle to build a speed map containing other vehicles' speeds to transmit it to its neighbors. Shinji et al. [107] designed an automobile control method that attenuates the effects of traffic congestion by taking advantage of an ad hoc communication methodology among vehicles. Each vehicle shares information about traffic conditions, allowing other vehicles to calculate a suitable congestion-free route. BeeJamA [108] is a distributed traffic control model that controls vehicle traffic based on the Bee Hive routing algorithm [109]. In this model, vehicles are guided under a decentralized control system. Hussain et al. [110] proposed a protocol to manage congestion situations and avoid deadlocks in urban environments. This is accomplished by guiding vehicles to routes free of congestion, using the infrastructure placed at traffic lights to collect information about nearby vehicles and neighboring infrastructures. The TraffCon routing algorithm [111,112] was designed to deal with traffic congestion problems and seeks to improve road capacity and decrease fuel consumption and trip times. To deploy TraffCon, each vehicle must be equipped with a GPS receiver connected to some kind of wireless computing device with an interface that can show to the driver useful information about traffic conditions. By allowing direct communications with individual vehicles, this routing protocol aims to exert great influence on the transportation system. The *i*CAR-II routing protocol [113] was proposed to enable data communication between vehicular applications and Internet services. This protocol allows vehicles to forecast the existence of local connectivity and to update location servers with crucial and real-time information. *i*CAR-II succeeds in building a global and scalable network topology.

Backfrieder et al. [114] proposed a traffic optimization system based on a novel estimation algorithm called Predictive Congestion Minimization in Combination with an A* (PCMA*). This algorithm is designed to calculate routes for users that are far away from their final destination. This suggestion may bring about significant advantages because users far away from congestion points can early react to potential jams. It uses a wide area of timely notification approach that takes into consideration the current state of roads. To perform traffic optimization in VANETs, a protocol called Fuzzy Bacterial Foraging Optimization Zone-Based Routing was proposed in [115]. This protocol tries to find, in a short period of time, the most stable short route to a target under uncertain conditions. To accomplish this, it uses three techniques: (i) Zone-Based Routing to provide stability; (ii) Bacterial Foraging Optimization to calculate the shortest routes; and (iii) fuzzy logic to deal with uncertain conditions. In [116], the authors designed an algorithm capable of dealing with traffic-collision-free path-finding and route optimization between two points. With the aim of optimizing performance, this algorithm considers a system composed of three distinct models: prediction of destination points, region formation, and optimized route selection. Li et al. [117] proposed the AQRV routing protocol, which has the ability to select the best intersection path for a vehicle to deliver data to its final destination. It considers three metrics: the connectivity probability, packet delivery ratio, and delivery delay. In other words, the best path for a vehicle to follow is the one with a higher connectivity probability and delivery ratio and a lower delay. Thus, the authors considered an ant colony optimization methodology to solve the problem of route selection.

Gupte et al. [118] designed a model called VANET-based Autonomous Management that makes routing decisions based on the travel paths of nearby vehicles. This model allows vehicles to exchange information about route selection, congestion, and traffic alerts, which allows them to make decisions about the best path to select. It also considers traffic light controllers to solve congestion situations, which dynamically shifts the traffic patterns considering not only vehicle destinations but also road conditions. Two delay-tolerant routing algorithms to deal with traffic in vehicular networks were proposed in [119]. The first one, delay-bounded minimum-cost forwarding (D-Greedy), handles local changes in traffic conditions by focusing on the number of vehicles and their speed. The second algorithm, D-MinCost, focuses on global traffic conditions, calculating vehicle speed and density in the entire network. Both algorithms reduce the number of transmissions needed to deliver messages to their final destination. Prakash et al. [120] proposed a path selection algorithm that aims to reduce not only the trip time but also fuel consumption. To accomplish this goal, this algorithm ensures the best path selection by combining information about the origin and destination of each vehicle with an approach where vehicles could choose a new direction at each road intersection. An opportunistic traffic management system was proposed in [121] for traffic optimization in vehicular networks. It uses vehicles to exchange individually crowd-sourced traffic information to dynamically recalculate new routes. This work also quantified the effects of deploying a decentralized traffic-based navigation system by performing real experiments in Portland (USA) downtown.

In [122], a traffic optimization data-driven approach was proposed to deal with the control of vehicles equipped with wireless communication devices. This approach tries to overcome several V2V communication issues (e.g., limited communication range or input saturation) by exploiting recent advances in approximate/adaptive dynamic programming. Won et al. [123] designed a jam control protocol that considers vehicle-to-vehicle communications and a three-phase traffic theory to detect and avoid traffic jams. To calculate traffic jam dynamics, a fuzzy inference model is deployed together with a V2V-based jam detection algorithm. By treating traffic jams as a dynamic phenomenon instead of a binary event, this protocol aims to overcome some issues regarding the mitigation of phantom jams. In [124], a congestion control strategy was proposed to deal with packet loss in high-congestion road intersections. This approach uses RSUs placed at road intersections to collect, filter, and cluster warning messages, in an attempt to decrease their delivery delay and drop ratio. This strategy was able to reduce the number of traffic collisions, increasing significantly the number of warning messages delivered to passing vehicles.

A driver monitoring system to improve road safety was proposed in [125]. This system uses different parameters to make traffic decisions. For example, it considers the vehicle's temperature, noise level, driver heart, and respiratory rates. Based on the data collected by sensors, the system can analyze the ability of the driver to safely operate a vehicle and decide which is the best action to take to avoid traffic collisions. Zheng et al. [126] studied how RSUs should be placed to mitigate their placement problem in traffic flow monitoring systems to improve the security of passing by vehicles. They proposed three algorithms to place RSUs on roadside based on specific characteristics of traffic flows. To improve the use of resources and decrease the number of deployed RSUs, the authors proposed an extension to a credential propagation mechanism by using vehicle-to-vehicle communications to increase the coverage of each RSU. An intelligent smart vehicle monitoring and assistant system, supported by cloud computing and mobile applications, was proposed in [127]. This system uses a set of novel techniques to improve collision avoidance, accident detection, and video/photo surveillance mechanisms. Most of these techniques consider the speed-based lane change model to reduce traffic congestion which will result in fewer road accidents due to improper lane change. A vehicle traffic management system (dEASY) is proposed in [128] to deal with traffic events that may have an impact on the overall network performance. This system considers three different layers to implement an architecture that is capable to deal with the selection of the best vehicle to forward data by implementing an altruistic approach to choose alternative routes. Guidoni et al. [129] proposed Re-Route, which is a traffic management service that uses nodes density to implement a traffic model capable to detect congested routes. By detecting congested routes, Re-Route aims to reduce traffic jams and improve traffic flows. The idea behind this scheme is to reduce jams instead of moving them to other roads.

4.3. Discussion and Open Issues

Solutions for dealing with network flows and node density takes into consideration two phases: prediction and optimization. Regarding the prediction phase, several methodologies are considered to collect data. For example, analytical models produce optimal results when dealing with small networks. However, they have several limitations for dealing with large-scale networks. Mesoscopic and macroscopic models may be considered to overcome such limitations. Fixed sensors can also be considered as an alternative; however, they are an expensive solution when compared to analytical models. Mobile devices allow building cost-effective services because they are commonly used, and cellular networks have wide coverage. However, it is necessary to create additional filtering algorithms to deal with the differences between terminals held by pedestrians and those that are located inside vehicles. GPS receivers integrated into smartphones or tablets may be used to replace mobile devices aiming to provide more powerful solutions to be deployed in remote regions. Table 2 provides a summary and offers a comparative analysis between the above-described approaches to dealing with traffic estimation.

Table 2. Summary of different types of approaches to traffic estimation/prediction.

How Data Are Collected	References	Conceptual Characteristics	Advantages and Limitations
Analytical Methods	[81]	The information is updated when item information is available, considering a step-by-step methodology.	**Advantages** It may be implemented to assess different what-if scenarios without the need for installing sensors and roadside infrastructures. **Limitations** Limited to small networks. It cannot provide exact and optimal solutions.
	[82]	Agent-based microscopic simulation. Vehicles are defined as mobile agents, and their interactions with the vehicular environment are used to set the network traffic.	
	[84]	Street segments are built based on road crossings and modeled following the NaSch model. To improve system feasibility and take into account vehicles at road intersections, a set of additional rules is defined, taking into consideration traffic lights placed at crossroads.	
	[85]	Considers all the information collected by three different traces of traffic: hourly, daily, and weekly. Predictions are made taking into consideration the responses of three models: moving average, exponential smoothing, and autoregressive moving average.	
	[86]	It considers powerful structures with the ability to store data for the capability to handle faults and unpredictability. It can perform either online or offline, owing to the implementation of a genetic algorithm and an expert's knowledge model.	
	[87]	Uses a mixed-integer linear model to solve the optimization problem. Divides the network into small sub-networks to enable multiple distributed controllers.	
	[88]	To solve the accuracy problem of vehicle locations, this proposal combines a set of data sources with flat-resolution position data.	
Fixed Sensors	[71]	It classifies vehicles according to their estimated speed considering single-loop detectors combined with some classification methodologies used in dual-loop detectors.	**Advantages** Real data is collected in real-time, which allows estimating traffic flows accurately. **Limitations** Costs involving installation and maintenance of sensors. Sensors have specific properties such as sensibility to noise and limited coverage. They are designed to be deployed only in highways and urban scenarios.
	[89]	Estimates the traffic density classes considering cumulative roadside acoustic signals and a model that determines probability distributions based on traffic density stages.	
	[90]	Bases its operation on a 2D stochastic signal determined through an analytic model that is capable of handling mean-square errors and sensor spacing curves. It is deployed in environments that require optimal sensor performance.	

Table 2. *Cont.*

How Data Are Collected	References	Conceptual Characteristics	Advantages and Limitations
Mobile phones	[72]	Cellular network infrastructures are used as the basis of the system operation, allowing the collection of signaling messages that will be used to implement traffic estimation functionalities.	**Advantages** The great popularity of this type of device allows the collection of data from traffic conditions without the installation of road sensors. **Limitations** A filtering process has to be implemented to distinguish pedestrians from vehicles. It is less accurate than GPS.
	[73]	It is proposed for urban scenarios where real-time traffic is collected by a framework that considers the instantaneous positions of buses and taxis to estimate road traffic conditions.	
GPS Receivers	[76]	Traffic estimation models consider the travel capabilities of vehicles and link speeds to determine and evaluate congestion levels.	**Advantages** Uses GPS receivers to collect traffic flows in real-time, which provides accurate information from each road segment. **Limitations** Limited coverage due to the limited number of probe cars. It also has to satisfy privacy constraints.
	[92]	It tries to solve an issue related to the lack of traffic information in some traffic estimation conditions through the use of techniques that consider offline data analytics algorithms.	
	[93]	Vehicles are used to increase traffic estimation feasibility. Probe data are integrated into macroscopic traffic models through data assimilation techniques.	
	[94]	Traffic prediction flows are calculated on the basis of a communications infrastructure deployed using the IEEE 802.11p standard. It uses a modified prediction algorithm to support scenarios with multiple intersections. A central controller is also implemented to detect congestions and re-route vehicles in case of traffic congestion.	
	[95]	Traffic conditions are estimated on the basis of several reports collected by roadside devices that are delivered to management systems.	
	[96]	It implements an approach that is capable of overcoming estimation errors that arise from the disparity of samples. This approach bases its operation on two patrol algorithms that set the path of floating cars in order to force them to participate in the estimation process.	
	[97]	Secure messages are forwarded, the objective being to increase the network QoS. This process is performed by a geocasting protocol that assumes that all participating vehicles have GPS devices so that they can know their own location.	
	[98]	Uses IEEE 802.11p to exchange useful messages that are used by an active/passive safety system. Vehicles exchange crucial information with their neighbors or with roadside units (RSUs), enabling the network infrastructure to continuously gather information about traffic conditions.	

On the other hand, when dealing with traffic optimization, two types of control approaches may be considered: traffic signal and vehicular routing. Traffic signal control proposals optimize the signal-phase duration at each intersection, improving traffic flow. Finding an optimal choice of green periods is a challenging task due to flow variations and the need for real-time computations. Vehicular routing control aims to provide optimal management services as well as personal navigation solutions. Because new orders arrive arbitrarily, solutions for vehicular routing control require a re-optimization process. Further investigations may focus on the proposed fast algorithms with low memory consumption. Table 3 summarizes and presents a comparative analysis between the above-described approaches to traffic optimization.

Table 3. Summary of different types of approaches to traffic optimization.

Optimization Approach	References	Conceptual Characteristics	Advantages and Limitations
Traffic light control	[100]	Considers the store-and-forward paradigm to formulate the urban traffic control problem. It also considers linear quadratic regulator theory to create a network-wide signal control suitable for roads with a high level of congestion.	**Advantages** This approach allows traffic flows to be controlled by considering a combination of the decisions regarding the duration of signal phases assigned to each signalized intersection in the network. **Limitations** Traffic flow changes and computation time limitations make the provision of global optimization for the network a very difficult task.
	[101]	It implements an approach to traffic congestion using a strategy where road intersections are controlled by driver's demands.	
	[102]	It implements a technique where real-time signals are controlled by adaptive signal control methodologies combined with dynamic programming approaches.	
	[103]	It proposes a traffic control approach to adapt predictions combining nonlinear models with a theoretical strategy to design control laws capable of dealing with variable speed limits and ramp metering.	
	[104]	Adopts a distributed multi-agent-based approach. Geometric fuzzy sets of traffic are combined with Markovian properties to deal with multiple levels of ambiguity found in traffic controllers.	
Forwarding protocols for vehicles	[106]	GPS devices are used to help this platform to discover and disseminate information regarding road congestion alerts. Communication follows an epidemic approach to determine traffic patterns.	**Advantages** It allows vehicle drivers to choose the most suitable route for their purposes. **Limitations** Requires the use of fast algorithms capable of managing memory space. Designing new algorithms is more complex.
	[107]	The effects of traffic jams are reduced through the implementation of an automotive control method where each network node gathers traffic information each time it establishes an ad hoc connection with another vehicle. This approach allows vehicles to calculate and determine a congestion-free path.	
	[108]	Communication links are dynamically updated considering distributed algorithms that select a better route for each vehicle taking into consideration its destination.	
	[110]	To avoid road congestion, this approach exploits roadside devices placed at traffic lights to collect information about passing vehicles. This information is also considered to solve traffic congestion situations, guiding vehicles to clear routes.	
	[111,112]	Increase road capacity by considering a set of vehicles with wireless communications capabilities to spread information about the state of the network. Each vehicle must have a visual interface to show to the driver useful information regarding traffic jams.	
	[118]	Routing decisions are made taking into consideration the paths followed by nearby vehicles. At each contact opportunity, vehicles exchange information about traffic jams and alerts, allowing them to choose the best new path to follow.	
	[119]	Proposed routing protocols can to handle traffic conditions, taking into consideration local and global network statistics (e.g., vehicle speed and density);	
	[120]	It uses an algorithm to calculate the best path between two different locations, taking into consideration the information collected by vehicles that travel in paths near both locations.	
	[121]	Uses vehicles to exchange individually crowd-sourced traffic information to dynamically recalculate new routes.	

5. Communication, Data, and Resource Management

With the growing interest in vehicular networks and the maturity of routing protocols for wireless and ad hoc networks, innovative applications and services have been proposed. However, to design efficient applications, they must take into account the particular characteristics of this type of network. For example, node positioning and connectivity, communication intermittence and fairness, latency, and resource limitations may have a significant impact on network performance (Figure 3). Additionally, the increasing number of technologies available to vehicles makes communication and resource management, two of the major issues that must be solved when dealing with vehicular networks [130]. To overcome some of these limitations, new methodologies must be designed to be capable of handling communication, resources, and data management and monitoring. This section details the most important proposals for each functionality.

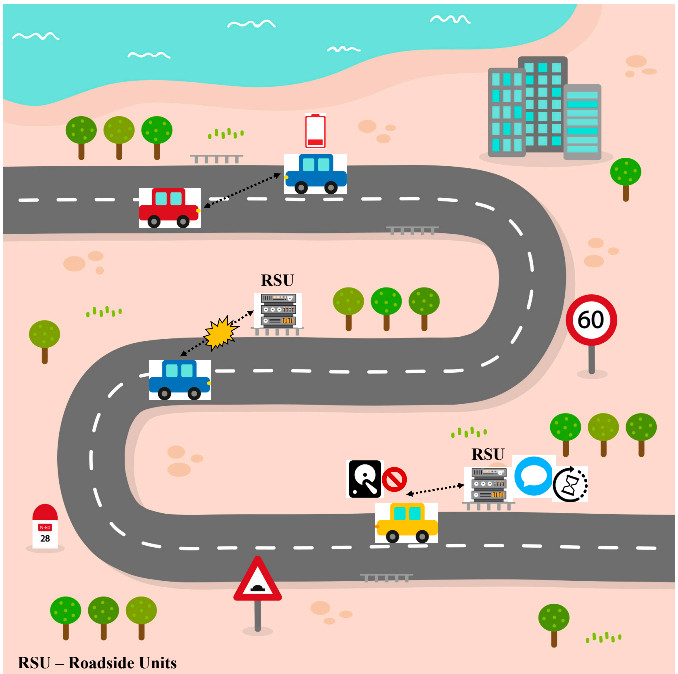

Figure 3. The limitations of a vehicular network scenario (e.g., low power, full storage, message's time-to-live, bandwidth) that new communication, data, and resource methodologies must deal with to improve overall network performance.

5.1. Communication Management

The intermittence and latency that characterizes communication in vehicular networks are the major factors responsible for the huge amount of packet loss, data deterioration, and low quality of communication channels. This problem is worsened by the possible absence of a path between origin and destination messages.

In an attempt to solve some of these issues, a framework for services and communication management, called SCM, was proposed in [131]. This framework aims to ensure that the deployed ITS service requirements are met by selecting the appropriate data dissemination method and the underlying heterogeneous communication network. This is achieved by using two network-performance-reporting techniques that consider simple policy-based procedures and metrics. MOCA [132] was designed to enable reliable communication in vehicular environments. It employs distributed channel selection and cognitive radio technology to access the frequency spectrum. It then uses the information (e.g., speed and direction) gathered from the frequency channels of moving vehicles to predict the channel quality. To ensure optimal channel performance, MOCA employs the signal-to-noise ratio (SNR) and the bit error rate. In [133], the authors proposed a solution to manage the network communications infrastructure by designing an algorithm with the ability to discover RSUs based on partial information collected by vehicles. This algorithm bases its operation on the information regarding vehicle density combined with migration ratios. With this approach, it can handle traffic fluctuations. It also assumes the use of stationary, virtual, and mobile RSUs. Studies were conducted that consider realistic mobility traces from the city of Cologne, Germany. The authors demonstrated that to achieve optimized performance, knowledge of the full matrix of vehicles is not necessary. Cao et al. [134] designed a novel framework to manage communication that disseminates information regarding charging stations. This framework exploits public transportation vehicles (e.g., buses) as access points, to inform moving vehicles about network and charging station conditions. This approach allows the creation of a low-cost and flexible communications infrastructure. Communication between vehicles is based on a publish/subscribe paradigm, which was demonstrated by the authors to be an efficient way of propagating information across the network.

Woo et al. developed a location mechanism called MG-LSM [135] that aims to enhance mobile node communication. It dynamically groups moving vehicles into regions according to their destination point. Each region has a fixed location server and a group leader (usually a mobile node in the center of the group). The group leader is responsible for collecting and maintaining information about the exact location of nearby vehicles. Periodically, it reports location changes in the group to the fixed location server. The location server then maintains the reported information and replies to the location queries made by group members. When a foreign vehicle makes a location request, the location server performs inter-region information exchange to solve the trade-off problem, providing regional proximity and binding stability between vehicles. Patil et al. [136] designed a Voronoi-diagram-based algorithm to place RSUs using as evaluation measures the delivery delay and packet loss. This algorithm places RSUs by dividing each geographical region into cells that are convex polygons. To create and define the shape of polygons, it considers the maximum tolerable packet delay, which represents how far data packets can travel from one RSU to another, considering a limited period. This approach was demonstrated to improve the reliability of communication and increase the logical coverage area of each RSU.

A Simple Network Management Protocol (SNMP) [137] framework was proposed in [138] to implement and control off-board communication through cellular technologies. This framework combines the characteristics of the SNMP protocol with mechanisms to access the territorial GSM network, allowing the creation of a monitoring system focused in the performance of the network. To collect information for the system, vehicles are equipped with several sensors that collect information on speed, acceleration, steering angle, and air temperature. The authors employed SNMP to take advantage of two classes of location based on (i) tracking and (ii) mobility control. GUERRILA Management Architecture (GMA) [139] is another SNMP-based solution. It uses a cluster-based management mechanism and a set of mobile agents to create an autonomous management environment. To accomplish this, nodes that share the same characteristics are aggregated into clusters managed by nomadic managers. These managers autonomously collaborate with network nodes to manage the entire network. Soo-Jin et al. [140] proposed an integrated wireless management system to monitor device status. It is based on SNMP and allows the owner of a device to manage it remotely. It requires an administrator to evaluate security vulnerabilities. Papalambrou et al. [141] presented a network monitoring implementation for DTNs that differs from the diagnostic interplanetary network gateway (DING) [142] by focusing on the bundle protocol deployment. It implements monitoring mechanisms in the bundle and lower layers, allowing assessment of DTN performance. MAN4VDTN [143] is an SNMP-based solution for VDTNs that provides support to push data from VDTN nodes. In this solution, the network management system handles the communication between the network nodes using SNMP messages. The Trap Coverage Area Protocol (TPAC) [144] was designed as a low-cost methodology to monitor vehicle communication in urban environments by taking advantage of traffic cameras, usually placed on road intersections. TPAC uses roadside routers to control the cameras, which seek the vehicle's license plate number for identification. It also combines the concept of the trap covering the area with newly proposed algorithms to maximize scalability in an attempt to overcome the recognized vehicle tracking problem. The results demonstrated the efficiency of TPAC in reducing communication overhead and latency. Chen et al. [145] proposed several fog computing methodologies to solve the problem of network load created by the growing number of vehicles. These methodologies are supported by two dynamic scheduling algorithms capable of handling constant network changes. To optimize communication latency and balance the cost and performance of communication, a new strategy was presented in [146]. It combines both vehicular and cellular networks, reducing the higher latency that characterizes ad hoc connections and the energy and budget costs associated with cellular networks. The bandwidth rebating problem was solved with a two-stage Stackelberg game.

5.2. Resources and Data Management

Usually, vehicular network nodes have several resource constraints, the most common of which are related to storage and power limitations. To optimize resource consumption of nodes and its overall performance, it is necessary to design solutions that fulfill the communication requirements in vehicular networks.

To deal with buffer constraints, a model that considers a semi-Markov distribution was designed to be deployed in wireless sensor vehicular networks [147]. It aims to solve the problem of data transportation between sensor nodes and sinks. This model bases its decision process on a buffer allocation policy where the buffer is divided into states according to its occupancy percentage. It also introduces a parameter that limits the buffer occupancy of each network node. This will allow packets to drop only if buffer saturation occurs. Yu et al. [148] proposed a cloud computing architecture in which mobile nodes can share their resources with others considering three distinct cloud types: (i) vehicular, (ii) roadside, and (iii) central. A vehicular cloud is established by a set of cooperative mobile nodes communicating with each other. A roadside cloud is established among a group of RSUs, allowing mobile nodes to access resources stored at cloud servers located at the RSUs. Finally, a central cloud is set up by a set of servers maintained outside the network. To solve node resource competition, the proposed architecture uses a game-theoretical framework. In [149], a joint resource management scheme was proposed to perform access network selection, helping in the handover decision process. This decision is taken considering the results obtained from an optimal algorithm that uses a semi-Markov decision method. An optimal algorithm is then derived via reinforcement learning whose objective is to minimize the blocking probability while maximizing the system total throughput.

Cordeschi et al. [150,151] designed and implemented a resource management controller that is capable of handling vehicles' energy and computation constraints. This controller deals with the resource management problem by dynamically controlling the access to time windows of RSUs as well as traffic flows. In [152], a cooperative resource management is proposed to deal with the bandwidth and computing resource-sharing problem. This problem was solved through a coalition game model implementation in cooperative service providers, based on two-sided matching theory. Following this approach, the mechanism aims to improve the QoS for users by reducing the number of consumed resources. Arani et al. [153] designed a resource management tool for self-organizing networks that aims to solve energy consumption problems in highly populated scenarios. This is achieved by combining the proposed tool with several mechanisms to manage joint channels and power allocation procedures. In [154], a resource search and management scheme was proposed. The goal of this work was to allow vehicular networks to perform management operations without the need for a fixed and centralized infrastructure. This is possible due to a proposed peer-to-peer protocol called SMART that discovers and manages resources, allowing vehicles to self-organize, creating connections with each other to manage and share resources. Kumar et al. [155] proposed an architecture that allows the integration of mobile edge computing with smart grid environments. Thus, vehicles are able to decide which charging stations are the best choice to perform charging and discharging operations. To minimize energy consumption, the authors proposed a virtual machine migration approach that is implemented at the data center side. In [156], two controllers were proposed to deal with energy constraints in vehicular environments. They consider the kinetic energy of vehicles and the fuel consumption of the engine to optimize vehicle velocity. Vehicles' engine, brake system, and transmission are managed by the controllers on the basis of a real-time road feedback approach. A trust management mechanism was proposed in [157] to efficiently use vehicles' physical resources (e.g., storage and power). This mechanism solves the trustworthiness problem that may lead to un-authorizing users consuming limited network resources without any intention of contributing to the proper operation of the network. This is achieved by implementing a three-manager cloud-based trust management framework. The first level, the Global Trust Manager (GTM), stores and manages all vehicle profiles. The Domain Trust Manager then obtains vehicle information from the GTM to assign a trust evaluation token to each vehicle that will be used by the Vehicular Trust Model to inform neighbors about the trustworthiness of a vehicle. In [158], a framework for performing monitoring and management activities in VDTNs was proposed. It takes advantage of the unique characteristics of VDTNs to gather real-time information regarding the network state. For example, it collects information on nodes' buffer space, power, and statistical data on communication performance. To improve the overall network performance, it implements two modules: monitoring and management. The monitoring module is always seeking nodes with buffer constraints or nodes diverging from the protocol. If either of these situations occurs, the management module takes actions against the misbehaving node and generates an alert informing other nodes to avoid contacts with the constrained node. Performance studies show that this framework reduces the waste of resources, increasing the overall network performance. Additionally, for the VDTNs, a resource management tool, called REMA [159], was proposed. Its main objective is to support and take advantage of different routing protocols to minimize the consumption of network resources. This is achieved through the development of new and advanced scheduling methodologies that forward data packets, always taking into account the best interests of a VDTN network. Performance evaluation studies conducted through simulation have shown that REMA significantly decreases the number of wasted resources, increases the packet delivery rate, and decreases the overhead rate when compared with scenarios where no additional action is taken to deal with resource consumption.

Patwardhan et al. [160] proposed a data management scheme where vehicles can help each other locate network resources. With this implementation, vehicles can rapidly adapt to local network changes. To enable data management, the authors consider vehicles' reputation and an epidemic data exchange protocol capable of establishing trust relationships. A node's reputation score is calculated based on a taxonomy of four device types (Encountered, Observed, Cooperative, and Malicious) followed by the level of cooperation. To classify nodes under this taxonomy, this scheme considers several metrics, such as frequently visited locations, mobility patterns, or information categories. In [161], a data management policy for vehicular networks was proposed. It aims to prevent the occurrence of scalability and congestion problems by managing bandwidth and preventing unnecessary duplication of data. This policy takes advantage of vehicle mobility and a context-aware service based on geographic location to estimate how important information is to end-users. It also considers a publisher/subscriber model and a cluster-based algorithm to disseminate data. Another data management framework was proposed in [162]. It tackles some data processing issues by transforming data into XML-based data, which allows in-vehicle infotainment to be easily accessed and processed. A proactive data dissemination scheme to manage critical data in vehicular data networks was proposed in [163]. In this scheme, each vehicle must broadcast packet requests to pull resources from the network. This request is then answered by the nearest producer. In the case of critical content, vehicles use a critical data forwarding scheme that gives them the ability to disseminate a special beacon message to their 1-hop neighbor.

Tayyaba et al. [164] proposed an architecture that uses machine learning mechanisms to handle the resource demands of modern vehicular network infrastructures, like 5G-enabled networks. By an approach that learns with the feedback gathered from resource classification and management, the authors manage to make a Long Short-Term Memory approach to outperform other techniques with promising results. In [165] a radio resource management scheme was proposed to decrease the impact of the transmission latency. This scheme relays its operation on two different stages that consider a prevalent road-traffic density to create a novel twin-timescale perspective for avoiding the frequent exchange or near-instantaneous channel state information. A resource allocation mechanism to deal with reliability and latency in vehicular-to-vehicular links was proposed in [166]. This mechanism uses a power allocation algorithm to optimize the spectrum reusing pattern and address a polynomial-time solvable bipartite matching problem.

5.3. Discussion and Open Issues

Dealing with communications, data, and resource management is a challenging topic because most network nodes have to operate under resource constraints, which severely compromise their network performance. Despite all the proposals presented in this section, there are still some challenging issues to overcome. For example, the exchange of large amounts of data (e.g., multimedia content such as photos and videos) in vehicular networks is a challenging task. However, it could help provide richer and more detailed information to travelers about road conditions. The exchange of this kind of data between vehicles may not be an easy task due to short contact durations, which limits the amount of data that can be exchanged. Transmitting this kind of data may also lead to high network overhead.

Regarding data management, a possible solution to facilitate data aggregation and data relevance evaluation is to develop some kind of middleware that could combine routing functionalities with data evaluation techniques. This approach can equip vehicular networks with extensible and adaptable software architectures that could be placed on top of different applications and information systems. Several proposals in this field have begun to appear; however, there is no evidence of its applicability in real scenarios. Table 4 highlights the most important contributions related to communications, data, and resource management. Moreover, this table presents the most important conceptual characteristics of, and remarks on, each method.

Table 4. Summary of different types of communication, data, and resource management approaches.

References	Main Conceptual Characteristics	Remarks
[131]	Uses two network-performance-reporting techniques that consider simple policy-based procedures and metrics.	Ensures that the deployed ITS services requirements are met by selecting the appropriate data dissemination method and the underlying heterogeneous communication network.
[132]	Employs distributed channel selection and cognitive radio technology to access the frequency spectrum. Uses information (e.g., speed and direction) gathered from moving vehicles frequency channels to predict the channel quality. To ensure optimal channel performance, MOCA employs the SNR and bit error rate.	Significant network connectivity improvement with decrease in throughput and jitter. Surpasses the TFRC-CR protocol [167] performance.
[133]	The network communications infrastructure is managed by an algorithm capable of discovering roadside units on the basis of the information collected by vehicles. It uses vehicles density and speed combined with migration ratios to handle traffic fluctuations.	To achieve optimized performance, knowledge of the full matrix of vehicles is not necessary.
[135]	Enhances mobile node communication by dynamically grouping them into regions according to their direction of motion. Each region has a fixed location server and a group leader. The group leader is responsible for collecting and maintaining the exact location information of nearby vehicles, while the location server maintains the reported information and replies to the location queries made by the group members.	This proposal was evaluated through simulation, which proved that it is able to contribute to the development of more accurate location discovery services.
[136]	Places roadside units considering as criteria the packet delay and loss. Geographic locations are divided into regions considering convex polygons.	It results in less packet delay and packet losses, improving the overall communication performance significantly.
[138]	Manages to combine the SNMP protocol with mechanisms to access the territorial GSM network. Vehicles are equipped with several sensors that allow them to collect speed, acceleration, steering angle, and air temperature.	By considering the use of SNMP, this method outperforms other methods in terms of throughput and jitter.

Table 4. *Cont.*

References	Main Conceptual Characteristics	Remarks
[139]	Nodes sharing similar characteristics are grouped into the same cluster, which is managed by a single nomadic manager. Nomadic managers collaborate with other nodes to perform network management functions.	Minimizes management traffic and conserves wireless bandwidth by using nomadic managers.
[140]	The status of each network device is managed by an integrated wireless system that uses the SNMP protocol to allow the owner of the device to implement different management functionalities.	Administrators are allowed to improve the security levels of their own vulnerability evaluation.
[141]	Implements a network monitoring approach for DTNs that differs from DING; Focuses its implementation on the bundle protocol; It implements monitoring strategies in the bundle and lower layers, allowing assessment of DTN performance.	Collects detailed information about network status that can be easily accessed and processed by data visualization tools.
[143]	Enables statistical data collection from network nodes through the SNMP protocol.	Proposal for a network management solution based on the standard SNMP for VDTNs.
[147]	This model bases its decision process on a buffer allocation policy where the buffer is divided into states according to the occupancy percentage. Introduces a parameter that limits the buffer occupancy of each network node, avoiding dropping unnecessary packets.	Solves the problem of data transportation between sensor nodes and sinks.
[148]	Vehicles may share resources with others considering three different kinds of cloud definitions: vehicular, roadside, and central. To deal with vehicle resource competition, this scheme uses a game-theoretical framework.	Solve an issue regarding virtual machine migration due to node mobility and speed. Service-dropping rate is attenuated.
[149]	Proposes an optimal algorithm to perform access network selection and assist the handover decision process. The handover decision process is formulated as a semi-Markov decision process.	Performance evaluation studies compare its performance with other three algorithms (Load Balance, Highet MCS, and RLwoHO) and show that it exceeds their performance.
[150,151]	Focuses its operation on energy and computational limitations of vehicles. Dynamically controls the roadside units' access time windows.	Helps minimize the impact of the resource management problem.
[152]	Implements in cooperative service providers a coalition game model based on two-sided matching theory.	Improves the QoS for users and decreases the amount of consumed resources. Solves the bandwidth and computing resource-sharing problem.
[160]	Vehicles help each other locate resources by implementing an approach that allow them to rapidly adapt to local network changes. Uses vehicle reputation and an epidemic data exchange protocol to establish trust relationships. Node reputation is calculated on the basis of a taxonomy that comprises four device types (Encountered, Observed, Cooperative, and Malicious) followed by the level of cooperation.	This approach increases resource availability by performing collaborative data exchanges between vehicles.
[161]	Uses vehicle mobility to determine how relevant and important information is to end users.	Prevents problems associated with scalability and congestion by managing bandwidth and preventing unnecessary duplication data.
[162]	A layer to perform management functionalities is implemented in the Java programming language.	Allows in-vehicle infotainment to be easily accessed and processed.

6. Conclusions

In the last decade, several vehicular network architectures have been proposed that use mobile nodes to enable communication in different types of scenarios. For example, vehicular networks may be considered as a solution when a fixed infrastructure with a path between source and destination nodes may not be available. Despite all the advances achieved in this type of networks, there are still challenging issues that must be overcome (e.g., short contact duration, storage capacity, limited power, latency, and energy consumption). Implementing network management or monitoring functionalities may help solve some of these issues. Several approaches have been proposed in the literature to detect network anomalies and manage network resources in order to improve the overall network performance.

This work summarized the most important projects, frameworks, and proposals on vehicular networks management and monitoring. Such proposals may employ wireless ad hoc and delay-tolerant networks. Studies based on the presented solutions have shown that vehicular networks offer significant performance gains when network management and monitoring solutions are deployed.

This work may be considered a starting point for studying and proposing more complex and efficient management and monitoring solutions that aim to increase confidence and reliability in the use of vehicular networks.

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