A Data Management Perspective on Vehicular Networks

Sergio Ilarri, Thierry Delot, Raquel Trillo

This is a postprint version of the following article, published by IEEE (DOI: 10.1109/COMST.2015.2472395): S. Ilarri, T. Delot and R. Trillo-Lado, "A Data Management Perspective on Vehicular Networks", IEEE Communications Surveys and Tutorials, ISSN 1553-877X, volume 17, number 4, IEEE Computer Society, 2420-2460, Fourthquarter 2015. Changes were made to this version by the publisher prior to publication. The final version of record is available athttp://dx.doi.org/10.1109/COMST.2015.2472395.

***Abstract*—The interest of intelligent transportation systems and vehicular ad hoc networks has increased in the recent years. As a fundamental building block for the development of applications for vehicular networks, new techniques are needed to handle data appropriately in the vehicles. In this paper, we present a comprehensive overview of data management for vehicular networks, where the vehicle-to-vehicle communications play a key role. We describe the technological context of vehicular networks along with the different types of data managed in that environment, and we analyze several challenges, such as the evaluation of the relevance of data regarding the occurrence of events on the roads (e.g., accidents), the design of appropriate (effective and efficient) content-based data dissemination protocols, the competition in the access to physical resources (e.g., parking spaces), the development of suitable data aggregation techniques specifically adapted to the context of vehicular networks, and query processing. The paper provides an in-depth coverage of data management for vehicular networks, but keeps at the same time a didactic orientation. Supported by an extensive collection of relevant references, we analyze the state of the art, identify some must-read references, outline research problems, and extract conclusions and lessons learnt.**

***Index Terms*—Vehicular networks, data management, data dissemination, data sharing, data aggregation, query processing, scarce physical resources on the roads.**

I. INTRODUCTION

Advances in mobile computing technologies and the increased interest in the development of *Intelligent Transportation Systems* (*ITS*) [1], [2] have led to an intensive research effort concerning the concepts of *intelligent vehicles* (assisted by technologies that enhance the driver's experience by improving the safety and/or performance) and *connected cars* (cars equipped with network access), as well as to the so-called *Vehicular Ad Hoc Networks* (*VANETs*) [3], [4], [5]. VANETs are highly-dynamic ad hoc networks where the vehicles carry a short-range wireless communication device, such as an OBU (On-Board Unit), that they can use to directly and quickly exchange data with other vehicles (e.g., using IEEE 802.11p and IEEE 1609.x protocols, or WAVE) and even to communicate them queries (i.e., requests of data), directly in a peer-to-peer (P2P) way (without the need to deploy a communication infrastructure) or with the help of supporting fixed nodes on the roads.

Thanks to these technologies, vehicles can exchange different types of data relevant to drivers, such as information about available parking spaces, accidents, an emergency braking, obstacles in the road, real-time traffic information, or information relative to the coordination of vehicles in emergency situations. The data exchanged can be generated by sensors embedded in the vehicles (e.g., for data such as the current speed and location, or the status of brakes and airbags), by other external data sources (e.g., sensors deployed along the roadside), etc. In some cases, they could even be introduced by the driver himself/herself (crowdsourcing) by using an appropriate interface, for example by pushing a button in a specific smartphone application (e.g., creating reports in Waze[1]).

This scenario opens up a number of opportunities for the development of interesting applications and services; for example, the data received by a vehicle enable the driver to become aware of events located far away [6]. However, several difficulties also arise. Most of them are related to the fact that an inter-vehicle ad hoc network is a highly-dynamic network subject to continuous changes in its topology. For example, two vehicles within range of each other can move at high speeds in opposite directions, which leaves a small time window available for data exchange. This creates truly interesting challenges, which must be addressed to propose suitable driver assistance systems. Data management in vehicular networks concerns the application of techniques to manage data that are of interest to drivers, including suitable mechanisms to retrieve and exchange data, filter the relevant data, process queries on the data, aggregate data, and exploit data effectively while avoiding potential competition problems; according to [7], data management is one of the four performance cornerstones for ITS.

In this paper, we present a comprehensive overview of data management for vehicular networks. Several related surveys and tutorials on vehicular networks have been published previously, related to requirements and architectures [8], inter-vehicle communications [9], [10] and information dissemination [11], mobility models [12], information management for safety applications [13], applications [14], routing protocols [15], [16], [17], [18], [19], encouraging participation in vehicular networks [20], security [21], [22], and vehicular *Delay-/Disruption-Tolerant Networking* (*vehicular DTN*) [23], [24]. However, up to the authors' knowledge, no survey or tutorial has focused so far on data management in vehicular networks offering the extensive coverage of the different topics that we provide in this study, despite the interest of recent proposals and special issues (e.g., [25], [26]). According to

Sergio Ilarri is with the University of Zaragoza, Spain, e-mail: silarri@unizar.es. Corresponding author.

Thierry Delot is with the University of Valenciennes, France, e-mail: tdelot@univ-valenciennes.fr.

Raquel Trillo is with the University of Zaragoza, Spain, e-mail: raquel@unizar.es.

[1]https://www.waze.com

a recent survey by ABI Research, the availability of vehicle-to-vehicle communications in new vehicles will reach 61.8% by 2027[2], which emphasizes the importance of data management for vehicular networks. Even though this paper is data-oriented, many issues obviously lie in the intersection between the communications and the data management fields, as they are strongly related, and therefore this study is complementary to other papers focused on communications (e.g., [9], [10]).

The structure of the rest of this paper is as follows. In Section II we provide an overview of the data management challenges. In Section III we describe the general context of vehicular networks. In Section IV we focus on the different types of data that can be managed in a vehicular network and their representation. In Section V we tackle the query processing (push-based approaches, pull-based approaches, and hybrid approaches). In Section VI we concentrate on the data dissemination protocols that are needed to carry a message to the potentially interested targets. In Section VII, we consider the problem of relevance evaluation. In Section VIII, we describe the problem of scarce resources on the roads that may involve a competition among vehicles. In Section IX, we explain the techniques proposed for data aggregation in vehicular networks. In Section X, we summarize some lessons learned. In Section XI, we collect some must-read references. Finally, in Section XII, we present some conclusions and lines for future research.

II. Overview of Data Management Challenges

We could highlight the need of suitable techniques to perform several data-related tasks [27], such as:

- *Determining the relevance of the information received.* When a data item is received by a vehicle, the data management system in the vehicle should be able to determine whether that information is interesting or not, according to the context of the vehicle. In other words, there should be some mechanism to assess the relevance of the data (e.g., see [28]). The relevance of the data can be seen from a double perspective. On the one hand, it should be determined whether it is convenient to show the information received to the driver or if, on the contrary, this could be unnecessary or disturbing for him/her. On the other hand, it has to be decided if the information received should be broadcasted to other vehicles. Several factors can affect the concept of relevance, including both temporal and spatial aspects. For example, in the case of information about an available parking space, an interested car must determine: 1) whether it is close enough to the reported parking space (spatial relevance), and 2) whether the parking space has been released recently and therefore it is probably still available (temporal relevance). These spatial and temporal relevance factors also appear for other types of events. For example, an accident will be relevant to a driver if he/she is driving towards the accident in a specific direction (unless it is an accident that disturbs both driving directions). As another example, an emergency braking usually has a quite short spatial relevance (the event is only relevant to nearby vehicles driving behind) and a short lifetime (i.e., the event may have a critical impact but only for a short time, requiring a quick real-time processing).
- *Disseminating the data efficiently in the network.* An efficient and effective approach is needed to make the information available to the interested vehicles with a minimum network overhead (e.g., see [29], [30]). The idea of relevance plays again a major role [31]: an event should be propagated to neighboring vehicles while the event is considered relevant in the area, thus leading to a dynamic dissemination area that evolves according to the relevance of the event. The dissemination protocol should also attempt to minimize the number of messages diffused. So, approaches such as traditional flooding [32], that lead to the well-known *broadcast storm problem* [33], [34], are not appropriate in this context. Therefore, other schemes are necessary.
- *Managing competitive resources on the roads.* The interest of peer-to-peer systems relies on the willingness of the participating nodes to cooperate and exchange information among them. However, providing all the interesting information to all the interested nodes may lead to problems in the case of information about scarce resources for drivers. So, vehicles could compete for spatio-temporal resources [35]. For example, if a parking space has been released and this information is communicated to many nearby vehicles that are searching for parking, then they will engage in a fierce competition and all but one (the one eventually occupying the space successfully) will end up disappointed with the use of such a data sharing system. Similarly, if there exists a fast route and all the vehicles are informed about it, a traffic congestion could appear in that route, making it slow instead of fast. Therefore, the evaluation of the relevance of the data items is not enough, and some mechanism is needed to decide which information should be communicated to which drivers. In a way, this will allow "allocating" the scarce spatio-temporal resources wisely (e.g., see [36], [37]).
- *Aggregating data.* By transmitting aggregated data instead of fine-grained data items, it is possible to reduce the communication overhead significantly. Moreover, obviously, not all the information received by a vehicle can be stored indefinitely by the vehicle and, even if this could be possible, it would probably be useless due to the limited temporal relevance of the events. Nevertheless, the data management system in a vehicle could summarize the information received, applying some spatio-temporal data aggregation technique (e.g., see [38], [39]), and then use the aggregated data to try to extract some extra knowledge that it could use in the future. For example, by receiving information about available parking spaces, a vehicle could be able to learn (given enough time) information about areas where available parking spaces are frequent. Similarly, by exchanging information about accidents it is possible to automatically detect dangerous areas. Each vehicle could also exchange (parts of) its aggregates with

[2]http://www.abiresearch.com/press (Research News, 19 March, 2013).

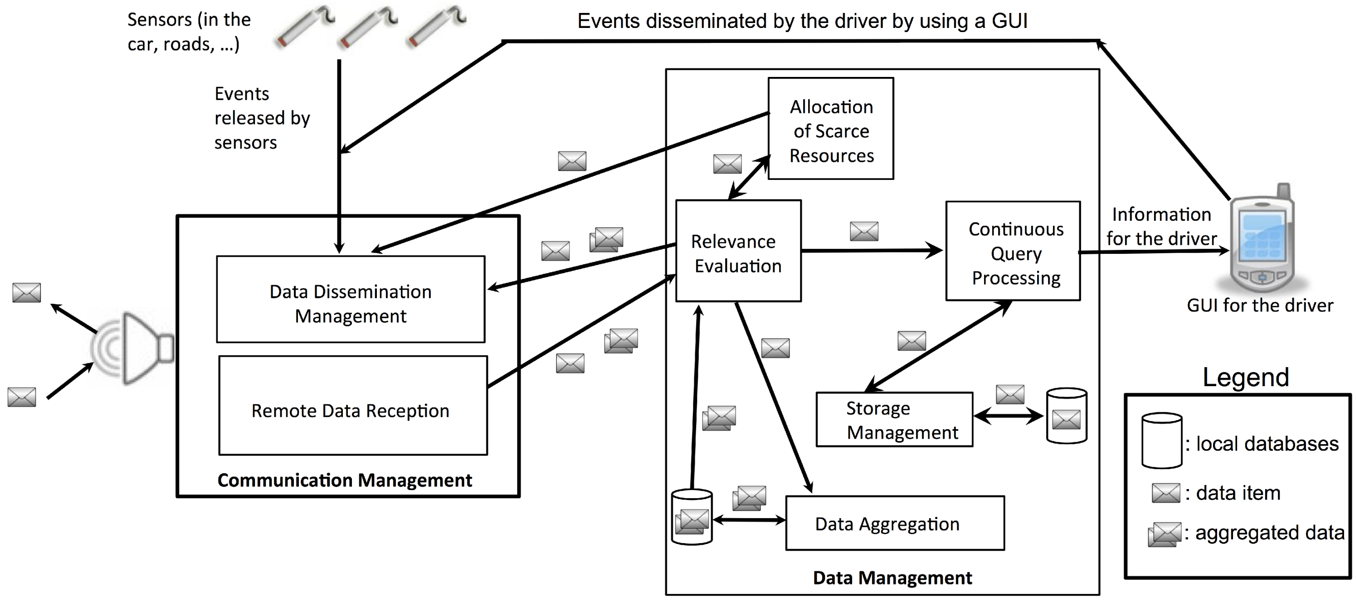

Fig. 1. General overview of data-related tasks in vehicular networks

other vehicles to help them increase their knowledge too.

Figure 1 shows a high-level summary of the data management tasks commented above. Figure 2 presents a concept map that shows the main topics covered in this paper and their relations. The different topics are supported by several technologies and encouraged by the interest of developing applications for drivers (box 1 "Context"). We focus on aspects related to the management of different types of data that are of interest in vehicular networks (box 2 "Data managed in vehicular networks"). A driver can access the information that he/she needs through queries, which are evaluated by a query processor executing in the vehicle (box 3 "Query processing"), which exploits data received by the vehicles implicitly (push-based approach) or retrieved as needed from other vehicles (pull-based approach). These data are communicated to the vehicles by using different data sharing approaches (box 4 "Data dissemination"), which are usually not data-agnostic but affected by the type and contents of the data transmitted (content-based data dissemination). A key element for both data dissemination and query processing is the estimation of the pertinence and potential interest of the data (box 5 "Data relevance evaluation"), as data should be considered in the queries and/or disseminated to other vehicles depending on their significance. However, the indiscriminate dissemination of the same data to many vehicles could lead to competition problems if these data represent information about scarce resources on the roads (e.g., parking spaces), which requires the use of techniques to manage that problem (box 6 "Managing competitive resources"). Finally, the data received by the vehicles can be aggregated due to several reasons (box 7 "Data aggregation"), being knowledge extraction and bandwidth efficiency of prominent interest. It is interesting to highlight how the data communication task (box 4 "Data dissemination") interacts with other data management tasks, such as query processing, data relevance evaluation, data aggregation, and management of competitive road resources.

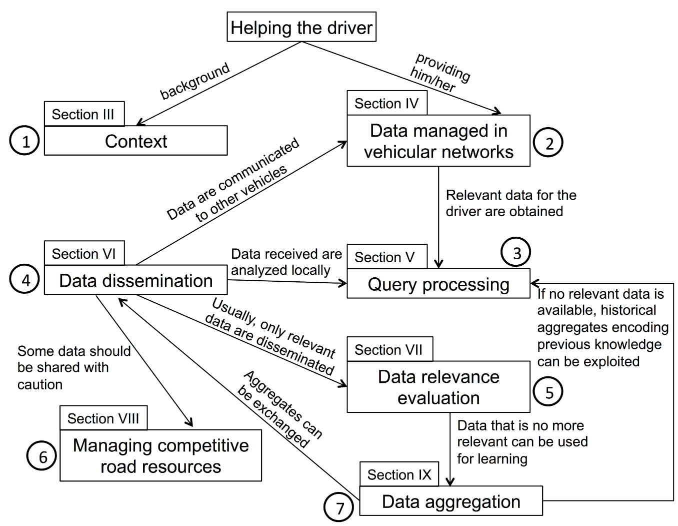

Fig. 2. Concept map showing the main data management topics covered

The circled numbers in Figure 2 indicate the logical sequence in which we tackle the different issues in this paper. In our description, we start by describing the context of vehicular networks (*1*) as it represents the technological basis of the study. Then, we consider the data that needs to be managed (*2*), as data is the key element in this work. Afterwards, we move on to query processing (*3*), as it represents the exploitation of the data to provide interesting information to the driver. We continue with data dissemination (*4*), as data collection is a fundamental need for query processing. The next element considered is data relevance evaluation (*5*), as it is important both for the query processing and for the data dissemination. Later, we focus on the problem of competition management (*6*), as it is also important for data dissemination in the case of certain types of data (data about scarce spatio-temporal resources). Finally, we tackle data aggregation (*7*), as an optional but interesting data management technique that can improve the performance and also extract knowledge that can be used in a variety of situations, such as when up-to-date precise data are not available for query processing.

III. General Context

The continuous development of computing and mobile communication technologies has led to the popularity of a wide range of small-sized computers and devices with increasing performance, storage, and communication capabilities. The joint use of these technologies in a mobile scenario opens up the opportunity for new applications for drivers and even passengers. In this section, we describe some aspects of the general context that provides the background for this study (see Figure 3). First, we describe the basic features of VANETs. Then, we focus on interesting applications for VANETs. Afterwards, we analyze the use of ad hoc communications and infrastructure-based communications. Finally, we discuss the role of sensors. Additional information about communication technologies for VANETs can be found in Appendix I.

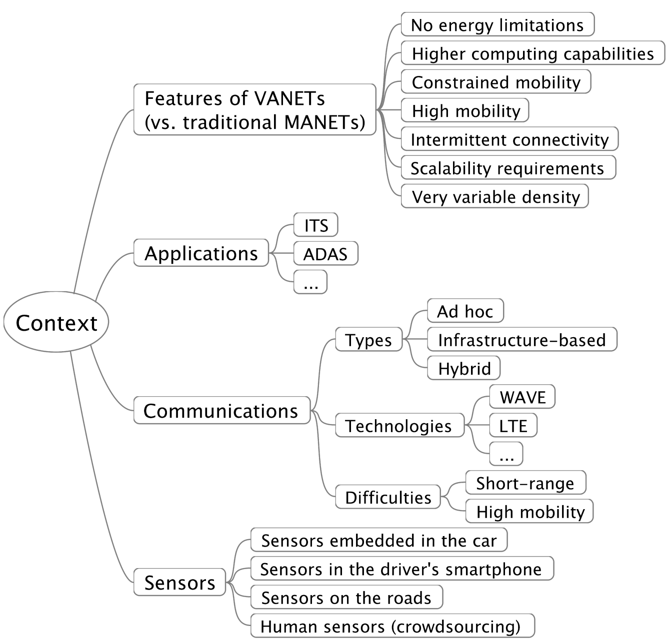

Fig. 3. Overview of the topics related to the general context of this study

A. Features of Vehicular Networks

Communication technologies can be helpful for sharing information among vehicles moving along the roads in a certain geographic area. Vehicles can carry a small computing device (e.g., a smartphone, a laptop, or an embedded OBU) with wireless communication capabilities to exchange data and queries with nearby vehicles, composing a vehicular ad hoc network [3], [4], [5] (see Figure 4). In a VANET, the vehicles can establish connections with other nearby vehicles in a peer-to-peer way [40] using short-range wireless communications, which avoids the need to deploy a wide-area communication infrastructure. These exchanges among vehicles are called *vehicle-to-vehicle* (*V2V*) communications, *car-to-car* (*C2C*) communications, or *inter-vehicle communications* (*IVC*). The term *vehicle-to-passenger/pedestrian* (*V2P*) communication has also been proposed to denote interactions with players other than the driver [13], [41]. Finally, other types of communications in VANETs where an infrastructure participates are also important and are discussed at the end of Section III-C.

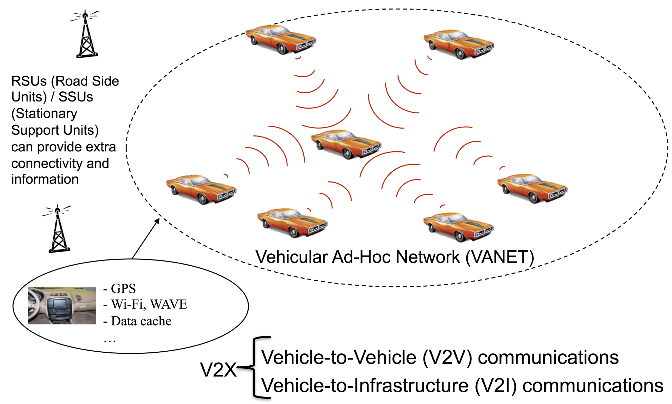

Fig. 4. Basic elements in a VANET

To fully exploit the potential of vehicular networks, several challenges arise, and many difficulties are due to the use of short-range wireless communications in an environment where the nodes are constantly moving and can appear/disappear in/from the communication network at any time. In this context, two vehicles can communicate directly only if they are near each other. The range of the wireless communication devices is limited to a few meters, depending on factors such as the specific technology used or the existence of obstacles; in the literature, typical values used are between 100 and 250 meters, but they sometimes vary more widely (as mentioned in Section X). As the vehicles are constantly moving, the maximum duration for a communication may be very short (a few seconds), especially when two nearby vehicles move quickly in opposite directions. Moreover, it is possible that no direct connection exists between two vehicles in the network, which would require the use of some multi-hop communication protocol (e.g., see [42], [43] and the example in Figure 5). These protocols are usually complex and it is difficult to guarantee an upper bound on the amount of time needed to deliver a message to a recipient, as the conditions and potential links change constantly; for example, each vehicle follows its own route and the driver may take dynamic navigation decisions, the density of vehicles can vary widely depending on the place and/or the time of the day, etc. So, in a vehicular network it is not easy to process a query that must retrieve relevant data from mobile nodes (i.e., the moving vehicles) within a certain geographic area and then return the result to the query originator, which is probably also a moving vehicle.

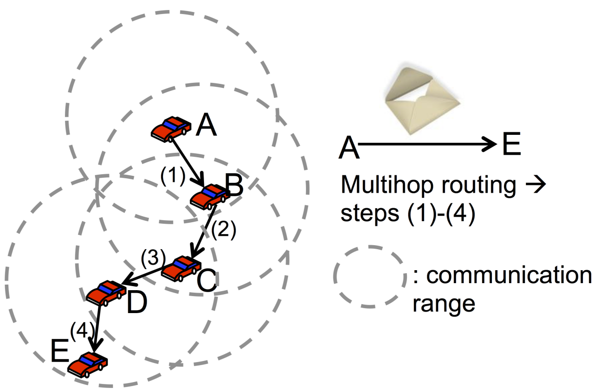

Fig. 5. Multihop routing to transmit a message outside the communication range of the sending vehicle

Although a VANET is a type of *MANET* (*Mobile Ad Hoc Network*) [44], there are some key differentiating features:

- *No energy limitations*. The vehicle itself can provide virtually unlimited energy to its processing and communication devices, thanks to its onboard batteries.
- *Higher computing capabilities*. The vehicle can accommodate quite powerful processing devices and sensors, as well as larger storage systems.
- *Constrained mobility*. Vehicles move through roadways rather than freely in the full geographic space. Besides, roads are usually characterized by typical features that affect the mobility of vehicles, such as speed limitations, different traffic densities along the day and time periods, etc. All these elements make the future positions or the direction of a vehicle more predictable, which could be exploited for example by routing protocols (e.g., see [45]).
- *High mobility*. VANETs are highly-dynamic mobile ad hoc networks, as the vehicles usually move at high speeds (especially, when moving on a highway).
- *Intermittent connectivity*. As a consequence of the high mobility of vehicles and the use of short-range wireless communications, the network topology changes very frequently. This is one of the main reasons for potential network partitioning/fragmentation and disconnections, as well as connectivity failures. So, it is frequent to have isolated groups of vehicles that cannot communicate among them because their distance exceeds the communication range. This also increases the communication delay, as additional time (called *rehealing time* in [46]) is needed to transmit a message across a region of disconnection.
- *Scalability requirements*. Potentially, a VANET could include a very high number of vehicles moving in the road network. All the vehicles with the appropriate hardware are potential nodes that can participate in a VANET.
- *Very variable density*. The number of vehicles in a VANET could vary significantly depending on the area, the time of the day, the existence of specific events encouraging the use of vehicles (e.g., rain, a concert in the area), etc. So, for example, depending on the situation, we could have light traffic, regular or medium traffic, and heavy or congested traffic. Sparse and dense traffic scenarios will likely co-exist in a VANET.

Besides, according to [47], a VANET can be considered as a case of DTN[3], where routing paths must be found opportunistically taking into account the existence of intermittently-connected hops. This is enough for some VANET applications. However, safety applications for VANETs do not exhibit delay-tolerance, as they require quick data propagation. The overview provided in [23] distinguishes between VANETs and *Vehicular Delay-Tolerant Networking* (*VDTN*) by indicating that VANETs assume end-to-end connectivity through some path (this assumption may be suitable in the case of a dense network) whereas VDTN does not make that assumption and instead exploits the storage capabilities of vehicles and opportunistic communications that can take place when a vehicle happens to enter the communication range of another one (more suitable for sparse networks). In this paper, we use the term VANET in general, for both cases, as it is usual in the literature.

B. Applications for VANETs

VANETs offer many opportunities for the development of interesting applications for drivers (and even other passengers) [9], [48], [49]. For example, exchanged data can be gathered and stored locally by the vehicles, in order to be queried later by the driver or by other vehicles to obtain interesting information, such as the number of free parking slots in the neighborhood, the existence of a traffic jam in the center of the city, the presence of a car crash ahead, etc. A variety of projects and working groups have invested efforts in the development of *VC* (*Vehicular Communication*) systems and related technology; [23], [50], [51] provide a good overview of these efforts.

The most popular applications for vehicular networks are related to driving safety. Thus, to reduce the number of accidents, a variety of programs, generally involving Intelligent Transportation Systems [1], [2], have been initiated in places such as Japan, Europe, and the United States, attracting the interest of researchers both in academia and in industry. Thanks to the resulting research, *Advanced Driver Assistance Systems* (*ADAS*) [52] were born. Some ADAS are already available in the market (e.g., navigation systems, warning systems to alert the driver when he/she is about to fall asleep in order to prevent him/her from crossing the center line), and many others are under development. For these safety applications, it is essential that vehicles be able to detect dangerous situations (e.g., by using embedded sensors) and communicate them to other nearby vehicles quickly. Numerous examples of vehicular safety applications could be mentioned (e.g., see [53]), such as: *Emergency Electronic Brake Light* (*EEBL*) warning, *Blind Spot Warning* (*BSW*), *Forward Collision Warning* (*FCW*) or simply

[3]DTN is an overlay networking architecture that tackles the problem of lack of continuous network connectivity. Networks employing the DTN architecture are *Intermittently Connected Networks* (*ICNs*).

Collision Warning Systems (*CWSs*) [54], *Do Not Pass Warning* (*DNPW*), *Intersection Movement Assist* (*IMA*), *Lane Keeping Assistance* (*LKA*), *Adaptive Cruise Control* (*ACC*), *Left Turn Assist* (*LTA*), *lane change assistant*, and *merge assistance* [55]. The collective term *Local Danger Warning* (*LDW*) is also very popular (e.g., see [56]).

Besides safety-related applications, there are other applications concerning the increase of transportation efficiency and traffic management [57], the provision of useful information to drivers (e.g., to inform drivers about the availability of parking spaces), and even entertainment. For example, the work presented in [9] provides a taxonomy of IVC applications considering four types:

- *General Information Services* (type 1), which include advertisements, entertainment feeds, data services, and queries disseminated in the VANET to obtain data from other peers. According to the authors of [9], these services generally require low communication overhead and a high delivery ratio.
- *Safety Information Services* (type 2), which provide warning messages, road awareness, information about road conditions, and traffic alerts. For these applications, latency is a key performance metric, as keeping a low delay of message transmission is sometimes critical to guarantee road safety.
- *Individual Motion Control Applications* (type 3) imply the exchange of movement information (e.g., position, velocity, acceleration, direction) to support vehicles that control their movements based on the information received from other vehicles, enabling collision detection and avoidance, motion regulation and adaptive cruise control, etc. Again, latency requirements for these types of applications are very strict.
- *Group Motion Control Applications* (type 4) focus on the case of vehicles organized in groups and that may adjust their movement (e.g., their speed and direction) depending on the behavior of each other (shared planning). These types of applications can help to make an optimal use of intersections, optimize the movements of platoons of vehicles, etc. They are more diverse regarding their requirements. For example, for intersection collision avoidance the authors of [9] identify soft real-time requirements, but for platooning maneuvers they indicate hard real-time requirements.

The classification indicated above is just one possible way to categorize applications for VANETs, but there are others. For example, [58] provides a classification based on the role of the vehicle regarding the management of data: as a data source, as a data consumer, or as both a data producer and a data consumer. As another example, [50] divides applications in three categories: transportation safety, transportation efficiency, and services that enhance comfort or enable (business or personal) transactions in the vehicle. The work in [59] classifies applications according to three primary directions: transportation safety, traffic efficiency, and *infotainment* (i.e., information and entertainment). The study in [60] distinguishes between comfort applications (traffic information systems, weather information, information about gas stations or restaurants, Internet access, music downloads, digital map downloads, etc.) and safety applications. The doctoral dissertation presented in [61] mentions safety, informational, and entertainment. Finally, [62] considers three categories: cooperative driver-assistance applications (safety applications), local *floating data* applications, and user communication and information services. It is also interesting to indicate that the survey presented in [63] examines VANETs from the perspective of their potential to lead to ecological solutions (e.g., avoid congested routes, follow optimal speed advisories), proposing *green performance measures* such as fuel consumption and emission, power consumption, and battery energy. We have provided here a summary of alternative classifications, for the sake of completeness, but it should be noted that all the classifications are actually very similar, even if they use (in some cases, slightly) different names for the categories.

To conclude this section, we mention some other potential applications for vehicular networks that have been proposed, such as traffic information systems [64], [65], [66] and/or congestion assistance [67], [68], [69], location-based message boards [70], post-collision assistance in the case of accidents [71], [72], [73], *vehicular social networks* [74], [75], [76], [77], [78], [79], cooperative downloading and content distribution/sharing [80], [81], [82], [83], [84], [85], [86], [87], file sharing [88], media services [89], transmission of multimedia data [90], [91], [92], [93], [94], [95], [96] (e.g., to provide live videos of traffic jams or emergency situations, to enable inter-vehicle video conversations, video-on-demand [97]), drive-thru Internet access (opportunistic content-delivery from Wi-Fi access points) [98], [99], [100], [101], monitoring and surveillance [102], [103], [104], advertising [62], [105], [106], [107], car-pooling (also called car-sharing or ride-sharing) [108], [109], [110], taxi sharing [111], the "driving office" [52], virtual flea markets [112], or even games played by occupants of different vehicles [113], [114].

C. Ad Hoc vs. Infrastructure-based Communications

In the following, we first analyze the benefits of ad hoc communications. Then, we describe the role of fixed support nodes. Finally, we mention the possibility to use mobile telephony networks.

1) Benefits of Ad Hoc Communications: Although *pure* vehicular networks imply only ad hoc communications, other communication schemes could also be considered, based on a fixed infrastructure or on mobile telephony networks (e.g., 3G/4G or the future 5G, UMTS, GPRS). However, the use of ad hoc networks can bring some important benefits:

- *They are free, favoring the cooperation among vehicles*. They can facilitate a quick exchange of data with neighboring nodes at no cost, which will encourage the cooperation among nearby vehicles. On the contrary, the use of telephony networks usually implies subscription or service charges for the users. As an example, according to [86], the cost of LTE (Long Term Evolution) connections would encourage users to try to "get a free ride" (i.e., benefit from other peers without collaborating).

- *They support quick interactions*. They allow a very quick and direct (i.e., without intermediate proxies or routers) exchange of information between two vehicles that are within range of each other, which may be critical for safety applications for vehicular networks. Thus, for example, a situation where the information about an emergency braking must be communicated to the vehicles behind by sending it first to a centralized computer (instead of sending it directly to the interested vehicles) would be impractical. As mentioned in [115], centralized solutions may imply outdated data and difficulties to meet the real-time requirements. Time-critical applications cannot afford the large *RTT* (*Round-Trip Time*) implied by centralized solutions based on traditional mobile telephony networks (e.g., see [62], [65], [108], [116]).
- *They fit well with geographic or location-based routing* [17], [117], [118]. They naturally support applications that require communicating with all the vehicles in a certain target area (rather than communicating with a specific target vehicle), which is a common goal in vehicular networks. Geographic routing can be effectively used by exploiting the mobility of the vehicles (*carry-and-forward*) and using variants of *greedy forwarding approaches* that progressively try to get the message geographically closer to the target area.
- *They do not require any infrastructure*. There is no need of a dedicated centralized support infrastructure, which would be possibly expensive to deploy and maintain. Even though mobile telephony networks are available in many areas, there also exist areas without coverage (e.g., in forests or rural areas), where the vehicles could act as carriers of information. As mentioned in [115], the infrastructure required to cover a large area may be quite expensive. Moreover, in the case of natural disasters, centralized architectures based on cellular networks may fail [108].
- *They offer better scalability*. They can support growing data volumes and clients thanks to their decentralized structure. On the contrary, centralized solutions may exhibit poor scalability. As an example, [119] indicates that the detailed and continuously updated data required in city environments may overload centralized solutions.
- *They are supported by market perspectives and prospective regulations*. We already mentioned in Section I that the outlook is that a large percentage of new vehicles will be equipped with V2V communication technologies. We could also mention other initiatives like the *Car 2 Car Communication Consortium*[4] and the *Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010 on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport Text with EEA relevance*[5]. In the United States, the Department of Transportation's (DOT) National Highway Traffic Safety Administration (NHTSA) is also taking steps to enable V2V communications [120].
- *They might facilitate privacy*. Due to the distributed nature of vehicular networks, vehicles do not have to report their geographic location or other data to a central server to benefit from a service. Besides, data are usually disseminated in a local area around the vehicle. This could improve data privacy because, for example, no actor in the network holds the whole set of trajectories for each vehicle. However, this does not mean that privacy problems do not arise in a vehicular network, as for example intermediate nodes forwarding data could inspect data packets if additional measures are not taken.

2) The Important Role of Road Side Units: Although pure ad hoc interactions among vehicles offer advantages, it should be noted that the use of fixed infrastructure support nodes (if available) could be beneficial in some cases, and they can even play a key role in some scenarios. Therefore, a fixed infrastructure can also be a component of a VANET. Thus, some static relaying devices deployed along the roads could provide wide-coverage network access to nearby vehicles (e.g., see [98]), acting as *static gateways*, and aiding in the data exchange process and supporting the access to remote data sources as well as data access in areas with low density of vehicles [121], [122], [123], [124], where using them may be not only convenient but also necessary. These devices are usually called *Road Side Units* (*RSUs*) or *roadside units*, *Stationary Supporting Units* (*SSUs*), or simply *Supporting Units* (*SUs*) [125], *roadside access points* or *APs*, or *infostations*. RSUs can improve the connectivity in vehicular networks [126] and routing protocols can benefit from them (e.g., see [118]). According to [119], a few RSUs improve considerably the performance of data dissemination; however, according to [46], the RSUs need to be interconnected in order to achieve significant benefits.

Indeed, some studies consider RSUs an essential part of a vehicular network; for example, the surveys on routing protocols presented in [15] and [16] indicate that the best results are obtained when combining pure vehicular communications and communications with an infrastructure, according to [115] "Vehicular networks are hybrid mobile ad hoc networks where infostations and vehicles are present", according to [127] *hybrid vehicular networks* are those that are partially structureless, and [5] mentions the existence of a debate "about redefining the acronym VANET to deemphasize ad hoc networking". Terms such as *vehicle-to-infrastructure (V2I)* communications (and *infrastructure-to-vehicle* or *I2V* communications), *car-to-infrastructure* (*C2I*) communications, *car-to-roadside* (*C2R*) communications, or *vehicle-to-roadside* or *vehicle-to-road* (*V2R*) communications, are used to denote these interactions with a fixed infrastructure. *V2X* (*vehicular-to-X*) or *C2X* (*car-to-X*) is a collective term used for both V2V and V2I communications.

3) The Use of Mobile Telephony Networks: Moreover, a GPRS/UMTS communication device could also be installed in a vehicle as an auxiliary communication mechanism, for example for the transmission of special or not popular data, for accessing remote data that are not easily reachable by using

[4]http://www.car-to-car.org

[5]http://ec.europa.eu/transport/themes/its/road/action_plan

ad hoc communications, or for cases where the latency and cost is not a problem. The term *vehicle-to-backoffice* (*V2B*) is used in [66] to denote the communication with central entities using standards such as GSM or UMTS. In [128] the idea is to inject some messages to specific vehicles using cellular-based communications and then exploit vehicular communications to disseminate them. Some authors also considered centralized mobile telephony networks but emphasized the potential of V2V communications as future work (e.g., [75]). In [96] the term *hybrid vehicular network* is used to define a VANET where cellular communications are also available.

D. The Key Role of Sensors

The data to be exchanged with other vehicles can be obtained by the vehicle itself, using its embedded sensors, or from other sources. Thus, for example, among the on-board sensors we could mention sensors to obtain the current speed and location of the vehicle, sensors to obtain information regarding the functioning of brakes and airbags, humidity sensors, etc. Similarly, the data exchanged could be obtained from external sources, such as sensors deployed along the roads (e.g., to detect the occupancy of parking spaces or to estimate the amount of traffic), or from other vehicles that may carry information relevant to certain geographic areas. Moreover, the driver himself/herself could provide the data; for example, he/she could push a button in the graphical user interface of a specific data-sharing application to indicate his/her intention to release a parking space or to notify an existing accident.

In general, a wide variety of existing sensors can provide useful data from which some context information can be inferred [129]. A few examples follow: a speedometer would be needed to detect a sudden decrease of speed, which could mean a danger of collision for the vehicles driving behind; when several vehicles detect that their average speeds are very low for a long time, it probably means that they are in a traffic jam; a substantial difference among the spinning of wheels could be due to the existence of sliding pavement; a deployed airbag could mean that the vehicle has crashed; and the lack of vigilance (hypovigilance) of a driver can be detected, for example, with oculometers using techniques that monitor the driver's eye blinks (e.g., see [130]).

According to [131], luxury cars have more than 100 sensors. Sensors play such a key role in vehicular networks that the term *Vehicular Sensor Networks* (*VSNs*) [116], [132] has been popularized. However, there are two important differences with traditional mobile wireless sensor networks and cooperative sensing using mobile devices: 1) in vehicular networks energy consumption is not usually a problem (onboard batteries can be used), and 2) the large size of a car (in comparison to a traditional mobile device) facilitates the integration of heavy processing and sensorial components [116]. A recent study of collaborative sensing for urban transportation is presented in [133].

IV. Data Managed in Vehicular Networks

There is a lot of information that drivers may find relevant, such as information about accidents, traffic congestion, emergency braking situations, fuel prices, available parking spaces, emergency vehicles (e.g., ambulances or police cars), obstacles in the road, or the behavior of drivers (e.g., strange maneuvers due to intoxication or lack of vigilance). We can consider that each interesting piece of information represents an *event* of a certain type. So, numerous types of events are possible in the context of inter-vehicle communications.

In this section, we focus on the features of the typical data managed in vehicular networks and the representation of these data (see Figure 6). First, we explain different types of events that drivers may find interesting. Then, we analyze the main attributes that can be used to represent such events.

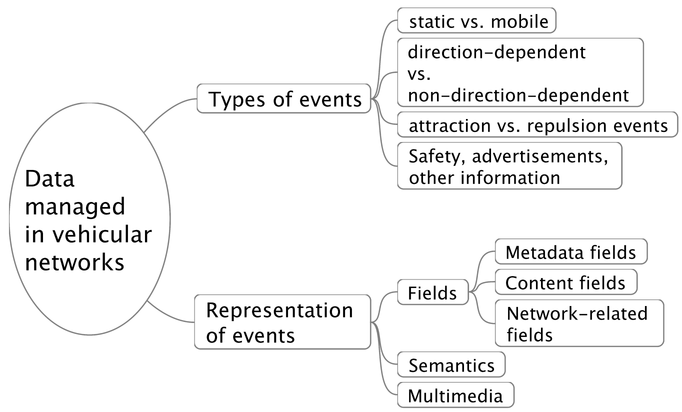

Fig. 6. Overview of the topics related to data managed in vehicular networks

A. Types of Events

We can classify the events of interest in vehicular networks based on two complementary criteria: mobility features and the attractiveness of reaching the event for the driver (see Table I). Based on *mobility features*, we can distinguish [134]:

- Stationary vs. mobile events. A *static event* (e.g., an available parking space) has a fixed location whereas the location of a *mobile event* (e.g., an emergency vehicle or a slowly-moving vehicle) changes along time.
- Direction-dependent vs. non-direction-dependent events. A *direction-dependent event* is only relevant to the vehicles traveling in a particular direction towards the event, whereas the relevance of a *non-direction-dependent event* for a driver is independent of the direction of the vehicle.

Obviously, both dimensions are orthogonal. Therefore, based on mobility features we can consider four different types of events: *stationary non-direction-dependent events*, *stationary direction-dependent events*, *mobile non-direction-dependent events*, and *mobile direction-dependent events*. Thus, for example, an available parking space is a stationary non-direction-dependent event, since it is static and may interest vehicles close to that resource independently of their current direction. A warning about an accident or an obstacle on the road is a stationary direction-dependent event because its location is fixed and only those vehicles that are going towards the accident or obstacle will find the message relevant, not the vehicles close to its location but moving

TABLE I
EXAMPLES OF TYPES OF EVENTS INTERESTING IN A VEHICULAR NETWORK

	Mobility features				Attractiveness		Other features		
Event	**Mobile**	**Stationary**	**Direction-dependent**	**Non-direction-dependent**	**Attraction event**	**Repulsion event**	**Resource**	**Safety**	**Informative**
Available parking space		√		√	√		√		
Emergency vehicle	√		√			√		√	
Accident		√	√			√			√
Driver behaving strangely	√			√		√		√	
Traffic jam		√	√			√			√
Fire on the road		√	√			√		√	
Road blocked		√	√			√			√
Petrol station		√		√	√		√		

in the opposite direction. Messages warning vehicles of a driver behaving strangely on a two-way road are mobile non-direction-dependent events: they concern all the vehicles that are likely to meet that driver, regardless of their direction of movement. As a final example, an emergency vehicle broadcasting a message for other vehicles to yield the right of way is a mobile direction-dependent event.

Moreover, based on the potential *attractiveness of reaching the event* for the driver, we can distinguish two types of events [135]:

- *Attraction events*, which are events that the driver would like to meet based on his/her current interests/goals and/or preferences. In some cases, reaching the event may imply changes in the current route of the vehicle, but the driver is probably willing to make the effort. Attraction events are usually related to physical *resources* on the roads, such as parking spaces, petrol stations, charging stations for electric vehicles, etc. As an example, a driver approaching downtown for a business meeting would be interested in parking spaces in the surrounding areas even if they were not very close to the meeting place. As another example, an unavailable taxi driver could release an event reporting other taxis about a person looking for a taxi, and any taxi nearby could be willing to change its direction to reach the potential passenger. Scarce resources for drivers may lead to competition among drivers (see Section VIII).
- *Repulsion events*, which are events that should be avoided whenever possible because they imply dangerous or difficult driving conditions. Classical examples are accidents, traffic jams, a slippery road, fire on the road, a vehicle that is driving in the wrong direction, a driver exhibiting strange behavior, a road blocked, etc.

It should be noted that the two classifications provided in this section are not the only options. For example, we could also classify events according to whether they are informative, warnings, or hazards, or according to the attributes under the heading “Other features” on the right of Table I.

B. Representation of Events

For simplicity, we assume that events could be represented as *records* with several *fields*. In general, three different subsets of fields can be distinguished:

- *Metadata fields*. These are fields that are used only for internal characterization of the event. They help to support the processing of the event but they are usually irrelevant (at least in raw form) to the driver. For example, in [134] the following metadata fields are proposed:
  - *Key*. It is used to identify the event unambiguously. It is a unique value generated by combining the current time plus the *GPS* (*Global Positioning System*) location of the event with a randomly-generated sequence. In general, this identifier is used to distinguish among similar events.
  - *Version*. It is a number used to distinguish between different updates of the same event. The motivation for this field is double. Firstly, the information associated to the event may change along time (e.g., its location in the case of a mobile event). Secondly, it may need to be refreshed; for example, if an event was expected to exist for a short time but it keeps active, new versions of the event will need to be generated to inform new arriving vehicles that may be interested in the event.
  - *Importance*. It is a value that helps to determine the urgency of presenting the information to the driver. An event with a high value for this field (e.g., an accident or an emergency braking) has priority in the sense that it is expected to be relevant to any driver that may encounter the event. So, the driver should always be informed about events with high importance that he/she may meet. On the contrary, events with a low importance (e.g., available parking spaces) are reported to the driver only if he/she has requested such information. The use of this field is also proposed in [136], which also uses the terms *severity* and *risk* as synonymous and distinguishes three levels: *high* (for messages such as accidents), *medium* (for information and advertisements), and *low* (for the rest of messages).
  - *DirectionRefPosition* and *MobilityRefPosition*. They are two preceding positions that provide each vehicle receiving the event with information needed to compute the direction and mobility vectors of the event, which are vectors that estimate its motion in the short and in the long term, respectively. In the approach presented in [134] (see Section VII-B), these vectors are necessary to estimate the relevance of the event (likelihood that the vehicle will meet the event).
- *Content fields*. These are fields that have clear informative value for the driver. For example, in [134] the following content fields are proposed:
  - *Description*. In [134], this field textually describes

the represented event, so it allows transmitting concrete information to drivers when they need to be warned. Alternatively, a simple identifier of the type of event could be provided instead.
  - *CurrentPosition*. It is the location where the data was generated (i.e., the location of the event). It is a GPS statement, and therefore includes three-dimensional coordinates as well the GPS time. Using the GPS time avoids synchronization problems between the clocks of the different vehicles. Although the driver can find the value of this field interesting, and therefore it is considered a content field, it will usually be also very helpful to estimate the relevance of the event for the driver; for example, if the event is far from the vehicle or too old, then it will probably be irrelevant. The current location of the events received could be used, for example, to show them to the driver on a map.

  Some additional content fields could be considered to encode other *information*. For example, when a vehicle receives information about an accident it may be very useful to show some *pictures or videos* to the driver, so that he/she can more easily assess the importance of the accident. Similarly, if the driver has received information about an available parking space, a picture would help him/her determine whether that parking space is suitable for him/her (e.g., if there is enough space for the vehicle and if the surroundings look nice). As another example, the use of multimedia clips to provide drivers with information about real-time traffic conditions on road segments ahead was proposed in [96]. In [70], the authors advocate a body message that can include *links* to attachments, in order to avoid the transmission of that additional information in case the driver is not interested.
- *Network-related fields*. These are fields related to the data dissemination protocol used (see Section VI), which will be usually content-based [30], [137], [127]. The goal of these fields is to encode some information that helps to increase the efficiency and effectiveness of the data dissemination protocol, by minimizing the number of transmissions, defining an appropriate spatio-temporal *dissemination area* where the messages should be diffused, etc. For example, in [30] the following network-related fields are considered: *HopNumber* and *LastDiffuserPosition*, which encode the number of transmissions of the message and the location of the last vehicle that diffused it, respectively. In [70], the use of a *lifespan* field and a *target area* field is proposed. In [138] there is a *TTL* (*Time-to-Live*) field, which controls how long the data item will be kept in the vehicular network. As a final example, [139] defines (among others) a *seq* field as a sequence number (to identify the most recent information) and a *expire* field to define the time interval during which the information contained is valid.

With the data representation approach proposed in [134], the category of the event (stationary or mobile, direction-dependent or non-direction-dependent, etc.) does not need to be explicitly represented as an attribute of the event, as it can usually be inferred from other fields. Nevertheless, when a data item representing an event is generated, the type of the event may need to be considered to fill the right values for some event's attributes. For example, for a stationary event the fields encoding the mobility information of the event (e.g., *DirectionRefPosition*, *MobilityRefPosition*) should have a consistent value. It should also be noted that, although it is not proposed in [134], an additional interesting metadata field would be the *type* of the event. Types of events could also be organized in a hierarchy; for example, as indicated in [140] we could have an event of type "warning" and subtype "traffic jam".

Despite the record-based representation described, which clearly shows the different types of attributes that could be considered, the use of *semantic techniques* (such as *ontologies* [141]) to represent information about events would be very interesting. This could enable the interoperability between different data management systems for vehicular networks and enable the possibility of automatic reasoning on the available data about events. Moreover, in general, the interest of semantic technologies for any type of location-based service has been emphasized in [142]. However, even though there exist some proposals for the use of ontologies in the field of Intelligent Transportation Systems (e.g., [143]), a complete approach to represent events of any type using ontologies to ease interoperability and enable inferences is still missing.

V. Query processing

When accessing data in a vehicular network, several access modes can be considered: push model, pull model, and hybrid model (see Figure 7).

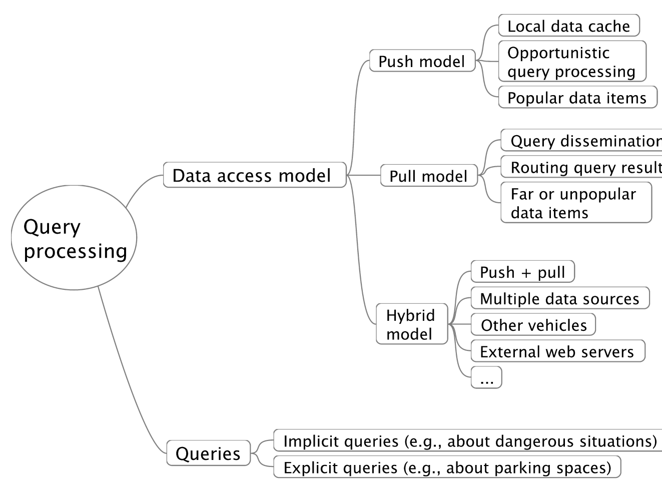

Fig. 7. Overview of the topics related to query processing

A. Push Model

In the *push model* (or *data-to-query* model), data are communicated to the vehicles even if they have not requested them explicitly (see Figure 8), which is the reason why the work presented in [144] calls this a *proactive model*. The data received by a vehicle are filtered out based on certain criteria (e.g., spatio-temporal criteria), as will be explained in Section VII, and then stored in a local database, data cache, or knowledge base. Then, based on the interests of the driver, several queries could be processed against the data stored locally. There may be some (predefined) *implicit queries*, that are continuously running even if the driver does not explicitly submit any query (e.g., *continuous queries* [145] asking about emergency events such as accidents, that may be interesting at any time) and also *explicit queries* submitted by the driver at a specific moment (e.g., queries asking about available parking spaces).

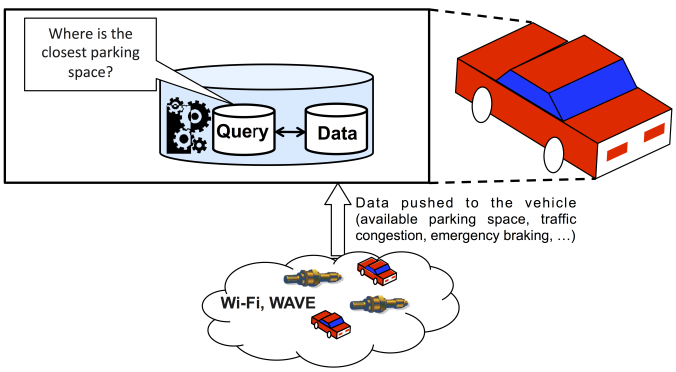

Fig. 8. Using a push model

With this approach, the query processing is *opportunistic*, in the sense that data become available only when another vehicle with relevant data passes nearby and transmits them. A challenge for push-based data dissemination models is how to perform the data dissemination efficiently (minimizing the latency and avoiding unnecessary overheads) and effectively (maximizing the percentage of interested vehicles reached).

This push-based model, which is the most popular option in vehicular networks, is used in proposals such as [134], [135], [146].

B. Pull Model

In the *pull model* (*on-demand* model or *query-to-data* model), a query is transmitted to other vehicles in the vehicular network in order to explicitly request data that may be relevant to such a query (see Figure 9), which is the reason why the work presented in [144] calls this a *reactive model* (data are not transmitted if not requested). This avoids the main shortcoming of push-based approaches, which is that they only support queries on the data stored locally, which are usually only data estimated as relevant to a high number of vehicles and concerning only nearby regions. A pull-based model enables access to specific data that may not be required by a large amount of vehicles [147], such as large files (e.g., videos) that are only of interest to a few users [88]. So, more types of queries can be supported, as they could potentially be diffused far away, if needed, to retrieve remote data. An example application scenario is that of vehicular sensing, surveyed in [116], where data provided by vehicle sensors are

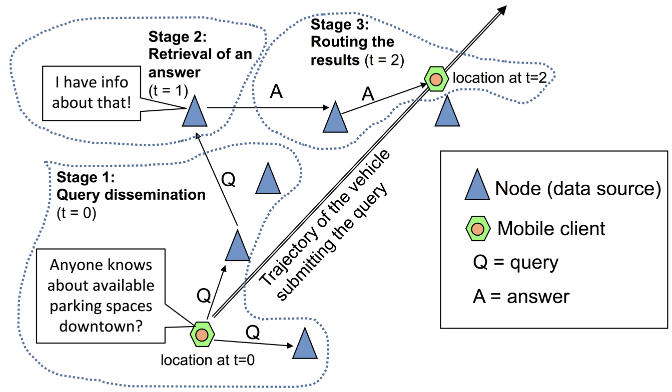

Fig. 9. Using a pull model

stored in an area (*geographic storage*) and can be retrieved by sending a query (i.e., by pulling).

Pull-based approaches face two main challenges: 1) some mechanism is needed to route the queries to the vehicles that could potentially store relevant information (e.g., based on spatio-temporal criteria); and 2) routing the query results back to the query originator (that may have moved in the meanwhile) is a challenge, even if the trajectory of the vehicle could be estimated. A potential solution for the second problem is to use some kind of *location service* [50], [148], [149], such as the *Geo Location Service* (*GLS*) proposed in [150], which maps identifiers of vehicles to their most recent location, or the *Region-based Location Service Management Protocol* (*RLSMP*) presented in [151], which exploits aggregation techniques. Opportunistic approaches such as *last-encounter-based routing protocols* [152] have also been proposed. Finally, it is also interesting to mention the *Breadcrumb Geocast Routing* (*BGR*) approach, described in [144], which implies leaving a trace of "breadcrumbs" that indicate the trajectory followed by the vehicle that submitted the query. In any case, it is difficult to collect and keep the needed information up-to-date. According to [15], the design of appropriate location servers for VANETs is an open issue. Due to the delays usually incurred by query processing strategies in this context, the term *delay-tolerant data query* is used in [45] to emphasize the importance of queries that are not time-critical.

As an example of pull-based approach, the *Vehicular Information Transfer Protocol* (*VITP*) [153] supports sending queries to remote areas in vehicular networks, but it does not focus on routing aspects beyond suggesting that the query could be enriched with information about the speed of the vehicle submitting the query (useful to try to estimate its location in the future). Similarly, [45] suggests as future work the possibility of encapsulating the querying vehicle's trajectory within the query packet, in order to facilitate the return of the query results. As another example, the work presented in [154] focuses on the problem of routing the query results: it proposes the use of *mailboxes* (fixed nodes) that are able to store the results of queries.

C. Hybrid Model

Of course, both approaches can be combined: it is possible to rely on push-based dissemination for popular data items that are relevant in nearby areas, and use a pull-based approach when disseminating a specific query is needed in order to retrieve relevant data that may be more specific or located in farther areas. Thus, according to [147], both models are necessary.

The study presented in [96] shows that the best approach to query *blobs* in vehicular networks is to push metadata and pull blob reports. The approach presented in [155] tries to adapt the size of the area where a message is disseminated based on the needs expressed by the vehicles inside, thus proposing a kind of hybrid approach between push and pull. Moreover, in some cases it may be necessary to complement the information available in the vehicular network with data stored in external servers, leading to a *multi-scale query processing* [156] (see Figure 10), where multiple data sources (other vehicles, external web servers, etc.) must be considered and exploited by using hybrid access modes.

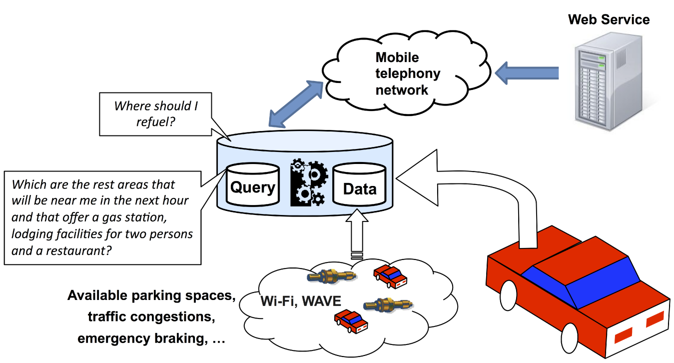

Fig. 10. Using a multi-scale query processing (multiple data sources)

D. Additional Comments About Query Processing

To finish this section, it is interesting to mention that *mobile agent technology* could be useful in the context of query processing for vehicular networks (see [157]). Mobile agents are "programs" that have the ability to move from one computer/device to another and resume their execution at the destination [158]. Therefore, they can bring a processing task wherever it is needed, the behavior of agents could be changed or upgraded at any time by deploying new versions of the agents, they could move to the data sources and perform there a local data aggregation and filtering (thus reducing the network load), and they could adapt themselves to changing environmental conditions in order to improve the data retrieval process. The benefits that mobile agents can bring to traffic management systems have been highlighted in [159]. However, the use of this technology in vehicular networks is quite unexplored so far. Although we mention it for completeness, the potential application of mobile agents (or even standard agents [160]) in the field of vehicular networks still requires further research.

It is also interesting to mention that a query language, called *TranQuyl*, has been proposed for the context of transportation systems [161].

VI. Data Dissemination

A data dissemination protocol is needed to enable the exchange of information among vehicles. So, when a vehicle receives a data item, it has to decide whether that item should be retransmitted to other vehicles or not. Several strategies can be applied to guarantee an effective and cost-efficient data dissemination. Usually, these strategies are adapted to the specific case of vehicular networks, which are highly dynamic, as approaches for general MANETs are usually considered inappropriate for VANETs [162].

In many cases, geographic or location-based routing protocols [17], [117], [118] are proposed. When the destination of the message is a single vehicle we have *geographical unicast* (*geounicast*), whereas *geographical broadcast* (*geocast*) implies sending a message to all the nodes within a certain geographic area. Unicast routing in VANETs is significantly complex and, according to [163], applications for VANETs that require unicast routing remain unclear. For our purposes, geounicast could be viewed as a specific case of geocast where the broadcasting aims at a single target node. To be effective, routing protocols should consider the existence of a suitable vehicle density to ensure a good connectivity (e.g., see [45], [164]). Some routing protocols, such as [42], [45], assume that vehicles are equipped with digital road maps, which are exploited to perform a better routing.

The potential sparsity of the vehicular network has to be considered when designing a dissemination protocol. For example, in some occasions some vehicles (acting as *data mules*) will need to carry data to areas where they can be disseminated (*data transportation via locomotion* vs. *data transportation via wireless communications*) [119], which is usually called *carry-and-forward*, *store-carry-and-forward*, *store-carry-forward* [165], *store-and-forward* [166], *vehicle-assisted data delivery* [45], *mobility-aided routing* [167], or *mobility-assisted data dissemination* [116]. In [168], two processes are distinguished: the *forward process*, where a message propagates using multi-hop forwarding; and the *catch-up* process, where the message propagates by using a carrying vehicle until it enters the communication range of the last uninformed vehicle within the next partition of vehicles.

It should be noted that data dissemination protocols for vehicular networks usually leverage the concepts of *location*, *contention*, and *content*, at the same time. For example, a suitable way to avoid contention is by limiting data forwarding based on the content of the messages transmitted and the locations of the vehicles involved.

In the rest of this section, we review different aspects related to data dissemination in VANETs (see Figure 11): we indicate some metrics used for data dissemination, we explain the importance of contention-based forwarding and content-based dissemination, and we present some proposed data dissemination strategies. Pure location-based routing protocols, whose purpose is to deliver a message to a specific target vehicle (i.e., geographical unicast, as commented above), are more related to communication rather than data management; nevertheless, we also discuss some popular approaches in Section VI-B.

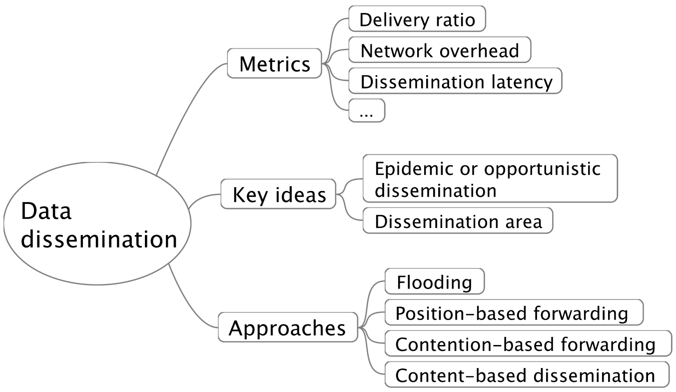

Fig. 11. Overview of the topics related to data dissemination

A. Metrics for Data Dissemination

A dissemination strategy should attempt to optimize metrics such as:

- The *data traffic overhead* [45], *network overhead*, *network load* [162], *bandwidth usage* [79], or *total number of transmissions* [169] (number of messages transmitted and/or received by the vehicles).
- The *broadcast utilization* [29], which is the percentage of new area covered by a broadcast.
- The number of vehicles not informed about important events, called *ignorance* in [170]. Alternatively, in [171] the concept of *network reachability* is defined, which represents the percentage of vehicles in the *zone of relevance* that receive the message. In other words, the *coverage* of the data dissemination protocol should be large enough.
- The number of vehicles receiving irrelevant information (called *redundancy* in [170]) or information similar to the one previously known (called *difference in knowledge* in [172]).
- The *utilization rate* [29], which is the proportion of useful information received by the vehicles.
- The percentage of messages that are successfully propagated, called *delivery ratio* in [162], [173], *reliability* or *packet reception ratio* in [174], *data-delivery ratio* in [45], or simply *delivery ratio* in [79]. This metric is highly dependent on the *robustness* of the protocol, which is defined in [162] as its ability to handle abrupt changes in the network topology.
- The time needed to propagate data between two vehicles located at a certain distance from one another, called *dissemination latency* in [29], *data-delivery delay* in [45], *end-to-end delay* in [175], *delivery delay* [79], or simply *delay* [162], [173]. In other words, *timeliness* is an important goal for a data dissemination protocol.
- The *efficiency* [173], which is the ratio of the total number of successfully transmitted packets to the total transmission cost.

Some proposals also try to maximize a *fairness index* [176], which indicates how well the utility (relevance) gains are distributed among the vehicles. It is also possible to consider *application-level metrics*, such as the amount of timed saved by a driver when using a particular data sharing approach [119]; we could also consider a more generic metric of *user satisfaction* [79]. The measurement of metrics for a given protocol is highly influenced by the specific scenario considered; for example, the work presented in [177] indicates that the most important factors affecting the dissemination of warning messages are the density of vehicles and the layout of the road map considered.

B. Position-Based Forwarding

The positions of the vehicles are usually an essential factor to consider for data forwarding. With position-based forwarding, a node forwards the packet being transmitted to a direct neighbor that is closer to the destination. So, the forwarding decisions are applied locally, without the need to apply a route discovery mechanism before initiating a data transmission (i.e., without *source routing*). In many proposals, usually focused on geounicast, vehicles keep a neighbor table (with information such as the location, speed, and direction of the neighbors) that is built by periodically exchanging information with the vehicles nearby. The survey presented in [15] distinguishes between (basic) *greedy forwarding* (data forwarding based on the known positions of the neighboring vehicles), *improved greedy forwarding* (based on the predicted current positions of the neighboring vehicles), and *predictive directional greedy forwarding* (that considers the 2-hop neighbors and not only the impact of the location but also the direction of movement).

For position-based vehicle-to-vehicle routing, several approaches could be mentioned, such as:

- The *Greedy Perimeter Stateless Routing* (*GPSR*) protocol [178] was proposed for the general case of wireless datagram networks and it selects a forwarding node that is the closest one to the destination. A recovery strategy, called *perimeter forwarding*, is applied when there is no neighbor closer to the destination than the current forwarding node (i.e., when a local maximum has been found). GPSR determines the geographic position of the neighbors through beaconing. The experimental results presented in [178] compare GPSR with *Dynamic Source Routing* (*DSR*) [179], which is a topology-based approach for mobile ad hoc networks, concluding that: GPSR offers a slightly better packet delivery success rate, it may reduce the routing protocol overhead (especially as the mobility increases), and it is more likely to select optimal-length paths for data delivery. However, this protocol has not been designed for the special case of vehicular networks.
- The *Geographic Source Routing* (*GSR*) protocol [42] was especially designed for vehicular ad hoc networks in cities. By exploiting information available on digital road maps, the sender node determines a sequence of junctions that a data packet should traverse to reach its destination,

based on a shortest-path calculation. The experimental evaluation presented in [42] shows that GSR can achieve a higher delivery rate and a lower latency than topology-based approaches for mobile ad hoc networks such as DSR and *Ad Hoc On-Demand Distance Vector Routing* (*AODV*) [180].

- The *Greedy Perimeter Coordinator Routing* (*GPCR*) protocol [181] was proposed later by the authors of GSR. It supports position-based routing in cities without the need of digital road maps in the vehicles and without using source routing. In this protocol, nodes that are located in the area of a junction are called *coordinators*. Coordinator nodes are preferred over non-coordinator nodes, and once a packet reaches a coordinator it has to decide the street that the packet has to follow. A challenge for this protocol is how to detect if a vehicle is located on a junction without using any road map information; two alternative approaches to deal with that problem are proposed in [181]. The experimental results presented compare GPSR with GPCR, showing that GPCR improves the delivery rate.
- The *Anchor-based Street and Traffic Aware Routing* (*A-STAR*) protocol [182] is also conceived for cities (like GSR), but it considers the density of vehicles in order to determine the optimal path, rather than just the shortest path; the motivation for this is that the shortest path could exhibit a low number of vehicles for routing. Specifically, A-STAR exploits information about city bus routes to identify a path with high connectivity. The experimental results presented in [182] show that A-STAR outperforms GPSR and GSR in urban environments.
- The *MUltihop Routing protocol for Urban vehicular ad hoc networks* (*MURU*) protocol [183] defines an *Expected Disconnection Degree* (*EDD*) metric in order to select a robust forwarding path between the source node and the destination. The authors experimentally compare MURU with DSR, GPSR, and *AODV-LL* [184] (*AODV Link Layer*[6]). The results show that MURU outperforms the other alternatives in terms of packet delivery ratio, data packet delay, and control overhead.
- The *improved Greedy Traffic Aware Routing* (*GyTAR*) protocol [185], for city environments, dynamically selects intermediate junctions one by one, considering both the existing vehicular traffic and the distance to the destination. This approach contrasts with the one used in GSR and A-STAR, where the sender node computes in advance a sequence of junctions for packet delivery. The experimental evaluation presented in [185] compares the packet delivery ratio, end-to-end delay, and routing overhead, of GyTAR, GSR, *LAR* (*Location Aided Routing*) [186], and *B-GyTAR* (*Basic GyTAR*, without local recovery, which implies that a packet is dropped when a local maximum is found): the results show that GyTAR outperforms the other approaches. In [187], the authors present *IFTIS* (*Infrastructure-Free Traffic Information System*), a decentralized mechanism for the estimation of traffic density in city roads, which can be used by GyTAR to estimate the traffic along the different roads.
- The *Enhanced GyTAR* (*E-GyTAR*) protocol [188] is a variation of GyTAR that considers the directions of the vehicles for junction selection: the selected junction has a high traffic density in the direction of the destination. The simulation results presented show that E-GyTAR achieves a higher packet delivery ratio and a lower end-to-end delay than GyTAR. Other routing protocols are also mobility-aware, such as *MAGF* (*Movement Aware Greedy Forwarding*) [189] or *GeoOpps* [190]; for example, GeoOpps exploits the information provided by the navigation systems in the vehicles in order to opportunistically route the data to the intended location.
- The *Hybrid Traffic-Aware Routing Protocol* (*HTAR*) [191] collects information regarding both the density of vehicles and the network traffic load, in such a way that each forwarding node can determine a robust and efficient forwarding path (succession of road junctions towards the destination node) for data delivery. According to the authors, considering only the vehicle density would not be enough as, whereas it is true that the possibility of transmission disconnection decreases with the number of nodes, the data network congestion can increase when there are many vehicles forwarding packets in an area. The experimental results presented in [191] show that HTAR outperforms GSR and GyTAR in terms of data delivery ratio and transmission throughput.
- The *Intersection-based Geographical Routing Protocol* (*IGRP*) [192] composes the forwarding path by selecting road intersections in a way that it maximizes the connectivity probability and at the same time satisfies quality-of-service (QoS) constraints relative to the delay, bandwidth usage, and bit error rate. The routing problem is formulated as a constrained optimization problem, which is tackled by using a genetic algorithm. The IGRP protocol is compared experimentally with GPSR, GPCR, and *OLSR* (*Optimized Link State Routing Protocol*) [193], showing that IGRP achieves better performance.
- The *Multiobjective Routing Protocol* (*MO-RP*) [194] is an interference-aware routing mechanism for vehicular networks where the vehicles are equipped with multi-channel radio interfaces. A new multi-objective metric proposed takes into account the co-channel interference, the link duration probability, and the end-to-end delay. The authors claim that their proposal can be integrated with the majority of the existing routing protocols. The experimental evaluation presented compares MO-RP with AODV, A-STAR, and DSR. MO-RP outperforms the other approaches regarding the packet delivery rate and the throughput, but it has a slightly higher overhead because it introduces new signaling packets for the construction of alternative paths.
- The *Directional Greedy Routing* (*DGR*) protocol [195] focuses on highway environments and applies directional greedy forwarding to move a data packet towards its destination. The *Predictive Directional Greedy Routing*

[6]AODV-LL is a variant of AODV that reduces its overhead by eliminating the use of periodical *hello messages*.

(*PDGR*) protocol (presented in the same paper) is a predictive extension of DGR that exploits a prediction of the possible future neighbors of the carrier of a packet to make routing more efficient. The experimental evaluation presented in [195] compares DGR, PDGR, GPSR, and GSR, using the following metrics: the packet delivery ratio, the end-to-end delay, and the routing overhead. In all the cases, considering open environments (city scenarios are not considered), DGR and PDGR outperform GPSR and GSR, and PDGR outperforms DGR thanks to the use of the prediction.

- The *Routing Protocol using Partial accurate routing Information* (*RPPI*) [196] exploits fine-grained traffic information in the local area and statistical traffic information in further areas to estimate the expected end-to-end delay. This two-level mechanism, that considers lower-precision information in remote areas, exploits the fact that more detailed information can be obtained as the transmitted packet gets closer to a previously-remote area. With this information, a next-hop intersection is selected at each intersection based on the expected delays of the routes and the final destination of the message. In the delay estimation, vehicles moving in both directions are considered, which according to the authors is one of the novelties of their work.

The list above is not exhaustive, but it is a good representative of the efforts performed in relation to position-based routing in vehicular networks. There are also proposals that advocate the use of a fixed infrastructure to support the routing process. For example, [139] uses the GSR protocol but extending the road graph with information about the available RSUs; RSUs are assumed to be interconnected through a reliable and fast backbone network, and so the distance between any two RSUs can be ignored. The proposal in [197] assumes the existence of RSUs at each intersection and proposes an adaptive QoS-aware routing protocol called *VACO* (*Vehicular routing protocol based on Ant Colony Optimization*). Some other protocols have proposed the introduction of *mobile gateways* (i.e., moving vehicles playing the role of RSUs), which can provide wide-range connectivity even if static RSUs are not available in the area. For example, [198] presents *MIBR* (*Mobile Infrastructure Based VANET Routing Protocol*), which considers buses as mobile gateways, since they have fixed routes and they could be equipped with larger-range transmission devices. The *Mobile-Gateway Routing Protocol* (*MGRP*) [199] considers the use of vehicles with a 3G connection (such as taxis) as mobile gateways: each mobile gateway connects with a base station using 3G and with other vehicles using Wi-Fi.

It should be noted that the position-based forwarding approaches mentioned in this section could also be potentially used or adapted to deliver a message to a target geographic area rather than to a specific vehicle.

C. Contention-Based Forwarding

In this section, we focus on the problem of constraining the indiscriminate rediffusion of data, by considering techniques that limit the number of data relays. A trivial data dissemination strategy is *flooding* [32], which implies that every vehicle simply retransmits everything that it receives. This strategy leads to a widespread propagation of messages, which usually ends up "flooding" the network and causing a major overhead. As it can easily overload the communication network and lead to the transmission of a large number of duplicate messages, it should be avoided.

Instead, *contention-based forwarding* [200] is usually advocated. These approaches try to limit the number of rediffusions of a message by applying *broadcast suppression techniques* [33], [34], [169]. Moreover, they achieve self-organization by assigning the forwarding decision to the potentially forwarding nodes rather than to the message originator [201]. The selection of the forwarder is achieved by desynchronizing the rediffusions:

- Usually, the selection is based on *the locations of the neighboring nodes*. So, when a node is selected as a forwarder, it suppresses transmissions of the same message from other nodes in the vicinity. An instantiation of this protocol for unicast messages is presented in [200]. For broadcasting in vehicular networks, we could reference, for example, [30], [114], [202]. In these approaches, in order to favor longer hops in the dissemination process, more distant vehicles are more likely to re-disseminate a message. So, the farthest vehicle from the previous sender is chosen to rebroadcast the message (or at least it has the highest probability to do so): such a vehicle may have the greatest number of neighbors not yet informed about the message being transmitted, and therefore it could be considered a good candidate to quickly rebroadcast the message to inform other vehicles. They are usually based on the use of *backoff timers* (also called *contention windows* or *defer timers*) that depend on the distance. The waiting time before transmitting decreases with the distance to the previous sender. Moreover, if a redundant message is received by the vehicle before the timer expires, then the retransmission of the message is cancelled (i.e., the forwarder is suppressed). So, there is a distance-based selection of the relay.
- Some proposals advocate a selection based on *the expected relevance of the message* computed by each vehicle. These proposals introduce traffic differentiation at the MAC (Medium Access Control) layer, in such a way that messages with a higher expected relevance are transmitted first. For example, in [201], the relevance is computed based on factors such as the context of the message (age of the message, its last broadcast time, its last reception time), the vehicle context (speed, road type), and the information context (distance to the information source, time of the day, etc.).
- The *Tall Vehicle Relaying* (*TVR*) approach presented in [203] proposes to consider also the height of the vehicles during the relay selection process. With this approach, a tall vehicle will be preferred as a relay as long as its distance to a potential short vehicle which is better positioned (e.g., the farthest one) does not exceed

a certain threshold. The motivation of the authors is that tall vehicles can considerably increase the communication range, as elevated antennas can find fewer obstacles for communication; specifically, they report an increase of the effective communication range of up to 50% depending on the scenario.

Contention-based forwarding approaches usually select a single node to forward a message, but this is not always the case. For example, the work in [175] identifies *clusters* of vehicles, and within each cluster a *cluster-head* (or *group leader* [204]) is selected to forward the message (the furthest vehicle inside the cluster); so, there are actually several forwarders (one per cluster), which could help propagate the message faster at the expense of additional network overhead.

D. Content-Based Dissemination

In this section, we focus on the problem of deciding how a message should be propagated in a controlled way, based on its contents. Besides keeping the network overhead under control, it is also very important to decide when the broadcasting should be stopped. Thus, it seems natural that the message transmitted will be relevant only for a certain time interval and within a certain geographic area. So, the message should not be transmitted outside that area or after that time interval. The term *content-based dissemination* [30], [137], [127] (or *content-centric* or *content-aware* communication [205]), also called *relevance-based data dissemination* in [31], is used to emphasize the interest of transmitting a message based on the data contained rather than on any other routing information attached to the message. The idea is that the message should be routed in such a way that it will reach the vehicles interested in those data. So, the data relevance (see Section VII) plays a key role in the dissemination process. For example, in [146], [206] the relevance is defined by spatial and temporal criteria that are used to decide whether an event should be stored and/or broadcasted. The work presented in [201] distinguishes between the *utility* (effective benefit of a message for a vehicle) and the *relevance* (overall expected benefit or utility for all the nodes that receive the message). Finally, [56] emphasizes the importance of prioritizing messages that have a higher expected benefit for their recipients.

In relation to this idea of relevance, [170] highlights some elements that should be taken into account in a dissemination strategy: the time elapsed since new data are available until the network stabilizes, the best distribution area around the event originator, and the lifetime of the data. The concept of *dissemination area* (e.g., see [30]), *persistence area* [127], *distribution area* [167], *region of interest* (*ROI*) [63], [108], *area of interest* (AoI) [165], or *zone-of-relevance* (ZOR) [51], [207], is used to denote the spatial area where a message should be broadcasted (because it is relevant within that area); the work presented in [108] sees it as a form of *VANET storage*. As commented before, this dissemination area is usually coupled with some *temporal validity* or *message lifetime*, which represents the time interval during which the message should be kept alive in the network because it is still relevant. A possible approach would be to try to define in advance the appropriate dissemination area for a certain type of data; for example, in [208] the authors define an algorithm to determine the locations where an event such as a traffic jam could have an impact on the choice of route by a driver. However, in [201], [209] it is claimed that the size and shape of the dissemination area, as well as the message lifetime, should not be set by the vehicle that generates the information about the event, as it is very hard to define them in advance. On the contrary, they should be adaptively determined (e.g., based on the current traffic conditions) using a distributed approach.

E. Some Illustrative Data Dissemination Approaches

Based on the previous considerations, several specific dissemination protocols have been proposed. In this section, we describe the basic aspects of some of them, in order to provide an overall picture of the typical issues and the proposed solutions.

1) Opportunistic Exchange: The work in [146] develops an *opportunistic exchange* mechanism, inspired by the field of epidemiology, where vehicles with a certain piece of information act as "disease carriers" by "contaminating" (i.e., transmitting that information to) the nearby vehicles along their routes (see Figure 12). This is an *epidemic-based protocol*, also called *gossip-based protocol* [210] (as rumors in society are spread in a similar way).

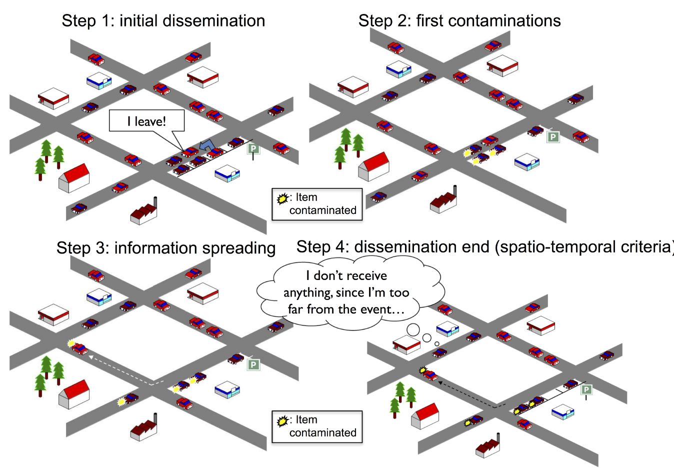

Fig. 12. Epidemic dissemination of data about an event based on spatio-temporal criteria

In the simulations performed, the authors analyze several aspects related to the dissemination process. They study how the number of copies of a data item evolves along time: it increases quickly until a maximum value is reached and then it decreases slowly until it becomes 0. They also analyze their spatial distribution: the number of copies decreases with the distance to the location where the data item was generated. Moreover, they examine the dissemination boundary radius as a function of time: the area where the data item is disseminated first expands until a maximum value is reached and then it shrinks until the data item eventually disappears. The authors also study the impact of the amount of space available for storing data items in the vehicles; they indicate that higher values lead to a larger dissemination area and lifetime of the data item. Finally, they analyze the impact of the transmission range and traffic speed: in both cases, higher values lead to a faster data dissemination and to a smaller lifetime of the event, due to a higher number of data item receptions that compete for the same amount of storage space.

2) Flooding, Epidemic, Proximity: In [170], three dissemination strategies for geospatial information are evaluated: the *flooding* strategy (introduced in Section VI-C), the *epidemic* strategy, and the *proximity* strategy. The epidemic strategy implies informing only a certain number of peers, whereas the proximity strategy leads to informing only the peers within a certain distance of the location of the event. This last strategy seems to achieve a good trade-off, but the need of more experiments is emphasized in [170].

In the simulations performed, the authors show that the flooding strategy minimizes the ignorance metric and the proximity strategy has a similar behavior; however, the epidemic strategy performs initially well but cannot lead to more than about 50% of the interested vehicles informed. Vehicles receive a high number of irrelevant messages (redundancy) with the three strategies, but particularly with the flooding and epidemic strategies. Flooding is the strategy that causes the larger network overhead, followed by the proximity strategy first and then by the epidemic strategy. The proximity strategy is the most sensitive to connectivity changes (density of vehicles, communication range), with a performance similar to that of flooding in high-connectivity scenarios. As a conclusion, they determine that the proximity strategy achieves a good trade-off in terms of the effectiveness and efficiency of the data dissemination.

3) Same-dir, Opp-Dir, Bi-Dir: Three dissemination protocols for highway scenarios are considered and compared in [29], within the *TrafficView* project [211]: dissemination by vehicles circulating in the same direction (*same-dir*), in the opposite direction (*opp-dir*), and in both directions (*bi-dir*).

As opposed to flooding, where re-broadcasting is immediate upon reception of a message, these dissemination strategies imply broadcasting information according to a specific *broadcast period*. All the data stored in a vehicle, both generated by the vehicle itself and received from other vehicles, are transmitted in a single packet, applying data aggregation if necessary. In the bi-dir protocol, vehicles in the opposite direction propagate only relayed data. The opp-dir model is usually the most efficient; intuitively, it can transmit relevant data to upcoming vehicles very quickly, thanks to the physical mobility of the vehicles that move in the opposite direction. However, if the traffic in the opposite direction is sparse, then it is better to exploit also the vehicles moving in the same direction (i.e., the bi-dir model).

In the simulations performed, the authors show how data disseminated in the opposite direction propagate faster, helped by the physical mobility of the vehicles. The same-dir model leads to the highest latency, followed by bi-dir first and then by opp-dir. The highest utilization rate is achieved by opp-dir, followed by same-dir and then by bi-dir. Nevertheless, the performance of the protocols proposed depends on the traffic density in each road direction: when traffic in the opposite direction is not sparse, opp-dir is more efficient than bi-dir and same-dir; however, when it is sparse, then bi-dir is the best protocol.

The importance of using vehicles moving in the opposite direction in the dissemination protocol (and also in routing) has also been indicated in other studies, such as [61], [69], [162], [166], [174], [196], [206], [212], [213], [214], [215]. So, those vehicles could be required to collaborate in the data dissemination even if they are not really concerned about a particular message/event (see Figure 13). The work presented in [166] distinguishes between longitudinal hopping and transversal hopping. *Longitudinal hopping* means propagating the message in the travel direction, whereas *transversal hopping* implies transferring the message to a relay vehicle driving in the opposite direction and forwarding it later to a vehicle moving in the original direction.

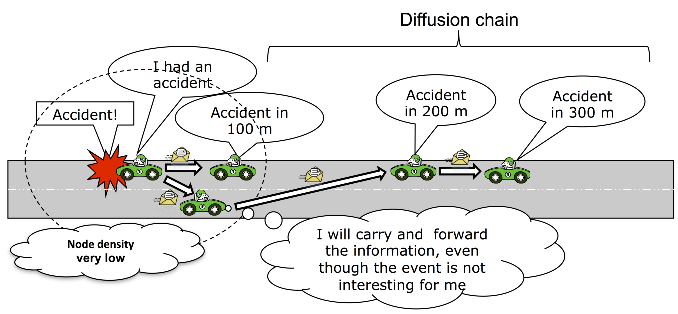

Fig. 13. Disseminating data with the help of vehicles moving in the opposite direction

4) Content Dissemination Based on the Relevance of the Events for the Vehicles: The content-based dissemination approach presented in [30] dynamically adapts the dissemination area as needed by considering the relevance of the events for the vehicles (see Section VII-B). As in other approaches such as [202], it applies *contention-based forwarding* (explained in Section VI-C). To minimize the number of redundant transmissions, each vehicle waits for a certain time period before rediffusing a message. The waiting period is inversely proportional to the distance between the receiving vehicle and the vehicle that sent the message, in order to favor retransmissions from vehicles located within the communication range but as far from the previous sender as possible.

In the simulations performed, the authors consider different types of events (explained in Section IV-A): stationary non-direction-dependent events, stationary direction-dependent events, mobile non-direction-dependent events, and mobile direction-dependent events. Unless the dissemination area is very small, the vehicles receive information about events with enough time to react, although for mobile events the reaction time decreases due to the difficulty to estimate the relevance well in advance. The network overhead is strongly reduced with the proposed approach, in comparison to traditional flooding and periodic flooding. The latency of the proposed protocol is slightly higher than in the case of both traditional flooding and periodic flooding, as it introduces waiting times at each hop of the dissemination process, to reduce network overloading. Nevertheless, the extra cost is limited and there is enough time for the driver to react according to the information received. The impact of the different penalty coefficients used in the computation of the relevance is also analyzed, providing some strategies to fine-tune them.

5) SODAD Approach: As a final example, [60], [65] proposes a *Segment-Oriented Data Abstraction and Dissemination (SODAD)* approach for comfort applications, using the *Self-Organizing Traffic Information System* (*SOTIS*) [64] as an example application. A basic broadcasting scheme is extended with a heuristic approach (*provoked broadcast*) that dynamically adapts the broadcast interval to avoid the network overload and at the same time favor the propagation of relevant changes. The default interval is chosen based on the minimum time interval needed to detect a vehicle moving at the maximum relative speed. Then, two events are considered to adapt the default interval: provocation events and mollification events. *Provocation events* lead to a decrease in the time interval and *mollification events* to an increase of the time interval. Typical examples of provocation events are the reception of out-of-date information (as they indicate that the number of transmissions is probably not high enough) and the reception of information from a vehicle located further than a certain distance (to favor long hops during the transmissions). An example of mollification event is the reception of information very similar to the one previously known by the vehicle.

In the simulations performed, the authors show that the proposed heuristic approach reduces the number of collisions in the communication channel and that the performance improvement achieved by the adaptive dissemination interval is beneficial.

6) Other Data Dissemination Approaches: We have seen a representative set of data dissemination protocols with some detail. The interested reader may also find useful the survey on data dissemination for vehicular networks presented in [11]. Besides, it is also relevant to briefly mention some additional approaches:

- A *publish/subscribe model for data dissemination* has also been proposed [115], [147]. With this approach, a certain number of replicas of each data item are created. Before broadcasting a data item, the replica owner broadcasts a message indicating its topic. Vehicles within communication range reply with a message containing their subscription status (*Informed*, *Interested*, or *Not Interested* in the data item), location, and direction. To select the next carrier of that replica, the replica owner uses this information to detect the cluster with the highest number of interested vehicles, and selects as the next replica carrier a random vehicle in a cluster that is moving in the opposite direction. The idea is to send a replica towards the area where the interested, but yet uninformed, vehicles are coming from. So, subscriptions are not only used as implicit queries executed locally in the vehicle (as described in Section V-A for the classical push model), but they also play a key role in the data dissemination process.
- The *Adaptive Warning Dissemination Scheme* (*PAWDS*) [216] is an adaptive technique that tries to adapt some parameters of the dissemination process depending on the road map profile and the density of vehicles. Specifically, the parameters considered are the time interval between two consecutive messages, the minimum distance for rebroadcasting, and the broadcast scheme used. Three broadcast schemes can be selected, depending on the situation: a *full dissemination* or *counter-based scheme*, where the rebroadcast of a message is inhibited when the number of times it has been received exceeds a certain threshold [33]; a *reduced dissemination* or *distance-based scheme*, where a retransmission is allowed only when the distance from the previous sender of the message is large enough [33]; and a *standard dissemination* or *enhanced Street Broadcast Reduction* (*eSBR*) scheme [217], which requires a minimum distance to enable forwarding, unless the vehicle is close to an intersection.
- The *enhanced Message Dissemination based on Roadmaps* (*eMDR*) scheme [47] focuses on warning messages in urban environments and exploits street map information in the dissemination process. The motivation behind this work is that purely-geographic approaches could fail due to the presence of obstacles that may prevent the propagation of the wireless signal (e.g., buildings), which could imply that some areas remain hidden during the dissemination process. In eMDR, a receiver is allowed to rebroadcast a message when it is able to reach new streets that were unreachable by the previous sender, and when it is near a junction and it is the closest vehicle near its center.
- The *Adaptive Multi-directional data Dissemination* (*AMD*) protocol proposed in [169] implies defining multiple directional sectors for simultaneous transmission, based on the road map and the presence of neighbors in each road direction. For example, in a highway a message is usually disseminated in both directions, and in an urban scenario it is disseminated in each possible direction in the road grid. This adaptive multi-directional dissemination is combined with a time slot density control (a suppression scheme is applied to select the furthest vehicles in each dissemination direction) and carry-and-forward to cope with sparse networks. Its authors claimed that the approach is appropriate for both urban scenarios and highway scenarios, as well as for both sparse networks and dense networks.
- The content diffusion protocol considered in [218] adopts a *credit-based system* to favor fair access to all the vehicles within range: the available number of credits is estimated as one half of the number of packets per second allowed by the current link divided by the number of neighbors. The concern about fairness in the data dissemination process is also considered in other proposals, such as [132], [176], [202], [219]. The approach in [132] considers the problem of data exchange between pairs of vehicles and presents a protocol to select the order in which messages should be disseminated and the vehicles that should disseminate them. The proposal in [202] (*FairDD*: *Fair Data Dissemination*) extends [132] by

considering a fully distributed approach (not only pairs of vehicles). This last work is, in turn, improved in [219] (*FairAD*: *Fair and Adaptive data Dissemination*), which combines [202] with an adaptive transmission rate to control the network overhead.

- The *Urban Multi-hop Broadcast* (*UMB*) protocol proposed in [220] focuses on urban environments. The dissemination process consists of two phases: directional broadcast and intersection broadcast. During the *directional broadcast* the protocol tries to select for rebroadcasting the furthest node in the broadcast direction. During the *intersection broadcast* the protocol relies on fixed *repeaters* installed at intersections, which re-diffuse each incoming message to all the road segments connected to that intersection (except to the road segment the message was coming from); so, these repeaters initiate new directional broadcasts. In a subsequent work [221], the authors conclude that those repeaters are not needed unless the line-of-sight between road segments connected to intersections is blocked by obstacles. Therefore, besides UMB, the authors also introduce in [221] a fully ad hoc approach for intersection broadcasting, called *AMB* (*Ad hoc Multihop Broadcast*), where vehicles (and not repeaters) broadcast messages to other road segments. In AMB, the protocol tries to select for this task a vehicle that is close to the intersection, as it is expected to have a good visibility of the other road segments. The final proposal of the authors is to use both protocols (UMB and AMB) in conjunction, depending on whether a certain intersection is equipped or not with a repeater.
- The *SmartGeocast* protocol [6] for information dissemination to multiple regions consists of two procedures: geocasting initialization and geocasting maintenance. The *geocasting initialization* procedure allows disseminating the information to several regions by using path sharing and path splitting schemes. The *geocasting maintenance* procedure is in charge of continuously informing new arriving vehicles. The authors argue that their approach can help to minimize the probability of receiving redundant messages and at the same time to avoid missing relevant information.
- In *MDDV* (*Mobility-centric Data Dissemination for Vehicular networks*) [222], messages are disseminated in an opportunistic manner, following a forwarding trajectory computed towards the destination region. The closest vehicle to the target area along the forwarding trajectory, called *the message head*, is selected for re-broadcasting the message during the forwarding phase. Then, once the target area is reached, a propagation phase within the area takes place.
- The *DV-CAST* protocol [223] focuses on highway scenarios and incorporates mechanisms to deal with both the broadcast storm problem and the disconnected network problem. A neighbor detection mechanism estimates the local topology by tracking periodic *hello messages* that are communicated by the direct neighbors. DV-CAST uses a broadcast suppression technique when the density of vehicles is high. Besides, it deals with network disconnection in sparse networks through store-carry-and-forward mechanisms.
- The *OppCast* (*opportunistic broadcast*) protocol presented in [174] tackles the problem of how to reliably broadcast emergency warning messages in vehicular networks where both the network layer and the link layer may be lossy. It uses controlled redundant broadcast at the network layer in order to ensure a certain packet delivery ratio, and at the link layer it uses an underlying MAC protocol called *opportunistic broadcast coordination function* (*OBCF*), that incorporates an explicit *broadcast acknowledgment* (*BACK*) mechanism. This BACK mechanism suppresses redundant rebroadcasts and also clears the channel for rebroadcast. OppCast can handle both sparse and dense vehicular networks by exploiting both the store-carry-and-forward paradigm and opportunistic forwarding, through an extension called *OppCast-Ext*, which is able to handle network partitions.
- The *PREemptive algorithm for DAta Transmission* (*PREDAT*) [165] attempts to tackle both the network congestion and the network partitioning problem, as according to its authors very few proposals tackle both problems simultaneously. PREDAT considers both urban and highway scenarios and adapts the transmission process, depending on the detected situation (dense or sparse area, city or highway), by using three elements: a preemptive mechanism, broadcast suppression, and store-carry-and-forward.
- *R-OB-VAN* [224] is a reliable opportunistic broadcast protocol that, by exploiting information about neighboring vehicles, tries to minimize the *shadowing effect* that may occur on the road; for example, obstacles such as a large vehicle or a platoon of trucks could block transmission to other vehicles.
- The data dissemination *DOVE* protocol is proposed in [214] to control the dissemination to a specific number of receivers in a certain area. The authors motivate the interest of controlling the number of receivers through several examples: collecting feedback from drivers passing an area prone to accidents and congestion, the dissemination of vouchers from a museum or store, and the ad hoc dissemination of advertisements on the road.
- A scheduling-based data dissemination approach supported by a fixed infrastructure is presented in [225]. It exploits the use of a *control node* that, by using knowledge about the topology of vehicles, appropriately selects relay nodes and schedules their transmissions. Each RSU could be a control node, which would minimize the number of potential transmission collisions but would not avoid them completely. Alternatively, the use of a central server as a control node would eliminate all the collisions.
- An approach for data dissemination from data centers (static information sources) is proposed in [226]. The authors present a basic scheme that is later improved in an extended version called *DP-IB* (*DP with intersection buffering*). DB-IB implies buffering and rebroadcasting data at the intersections, minimizing the amount of data directly poured from the data centers, thanks to a device

called *relay and broadcast station* (e.g., a roadside unit) used to improve the dissemination capacity (amount of data that can be disseminated in a given area).

As shown above, some protocols, such as PAWDS [216] and DV-CAST [223], consider information about the traffic density to adapt their behavior. So, techniques to estimate the vehicular density, such as the infrastructureless approaches presented in [227], [228], could be applied as a support to data dissemination protocols.

Moreover, some studies emphasize the importance of considering the priority of different types of messages (e.g., information about an accident, information about a traffic jam) in the data dissemination approach; for example, [229] proposes a distributed prioritized gossip algorithm for the scheduling of packets with different priorities, and [215] focuses on the dissemination of high-priority time-critical emergency messages.

Finally, according to [173], [230], [231], [232], [233] trajectories of vehicles can be exploited to improve data delivery; for example, [233] proposes the *Context-Aware Geocast* (*CAG*) protocol, which exploits the direct coverage provided by the trajectory of a vehicle and the indirect coverage provided by the trajectories of the vehicles that it encounters.

F. Final Notes and Conclusions About Data Dissemination

It should be noted that some dissemination protocols and studies related to data dissemination focus on the case of specific types of events for certain use cases and scenarios. For example, [146] tackles parking spaces, [206] road hazards, [60] comfort applications, [47], [119] urban environments, [29], [162] highways, [65] traffic information such as the average speed on certain road segments, [95] videos (where *Quality of Experience* metrics are important), etc. On the contrary, other proposals such as [30] claim to be able to accommodate the transmission of different types of events seamlessly in the vehicular network: the relevance is computed by considering several factors that are weighted with *penalty coefficients* that can be defined differently for different types of events, as explained in Section VII-B.

It is also interesting to highlight that data sharing approaches for vehicular ad hoc networks rely on the cooperation among vehicles [20]. Like other peer-to-peer approaches, they may require a certain percentage of participating nodes (i.e., appropriately equipped vehicles) to work. Therefore, several proposals have explicitly studied and considered the impact of *market penetration*. As mentioned in Section III-C, the use of RSUs/SSUs can lead to important benefits in areas where the density of vehicles is low. For example, [234] proposes adding static nodes at intersections to assist data delivery.

Finally, to conclude this section, we would like to mention that some data dissemination approaches for vehicular networks (e.g., see [175], [235] and the end of Section VI-C) are based on the concept of *vehicle clusters* (groups of vehicles located near each other): one vehicle within the cluster (the *cluster head*) is in charge of re-broadcasting. *Intra-cluster communication* (i.e., communication between vehicles belonging to the same cluster) and *inter-cluster communication* (i.e., communication between different clusters) are usually distinguished.

VII. ESTIMATING THE RELEVANCE OF THE DATA

Once certain data are produced, they are diffused in the vehicular network and thus received by many vehicles. The relevance of a data item is a measure of the interest of that data item considering a specific driver; for example, a traffic report is relevant to a driver if its reception affects his/her travel path [236]. The work presented in [172] considers that the relevance of a data item increases with the demand and decreases with the supply: the *demand* represents the potential impact on the driver's decision-making (for example, for route planning) and the *supply* how many vehicles have already the data item.

On the one hand, the estimation of the relevance will be used to decide whether the driver should be informed or not about the events, that is, for data presentation purposes. On the other hand, it could also have an impact on the data dissemination protocol if a content-based data dissemination protocol is used (see Section VI); the intuitive idea is that an event should be disseminated while it can be considered relevant to the vehicles in the area.

So, a core element for data management in vehicular networks is a module that computes a *relevance score* for each data item received. This score is usually based on spatio-temporal criteria, as a given event is usually relevant only within a specific spatial region and for a certain time interval. For example, in the case of information about an available parking space, an interested vehicle must determine if it is close enough to the reported parking space and if the parking space was liberated recently enough; this is because the relevance of the parking space is a measure of the likelihood that the space will still be available when the vehicle arrives there. In most cases, such as in the example of the parking space provided, exact optimal values defining the relevant spatial region and temporal interval cannot be precisely determined, and so they are estimated. The computation of the relevance of an event has to consider also the type of the event; for example, in the case of direction-dependent events the direction is an important factor, but not for non-direction-dependent events (see Section IV-A).

Based on the relevance score computed, the data management system in the vehicle decides if the event should be stored, reported to the driver, and/or disseminated to other vehicles. For this purpose, the relevance score can be compared with several thresholds (see Figure 14):

- If the relevance is higher than a certain *storage threshold*, then the event can be considered to be *potentially relevant to the vehicle*. Therefore, it is stored in its local data cache. The vehicle can act as a carrier of the event and watch it closely, as the relevance could change in the near future (e.g., it could increase considerably if the vehicle approaches the event), making it relevant enough to be reported to the driver and/or disseminated to other vehicles. As an example, [237] indicates that estimating the relevance can be a useful way to determine which

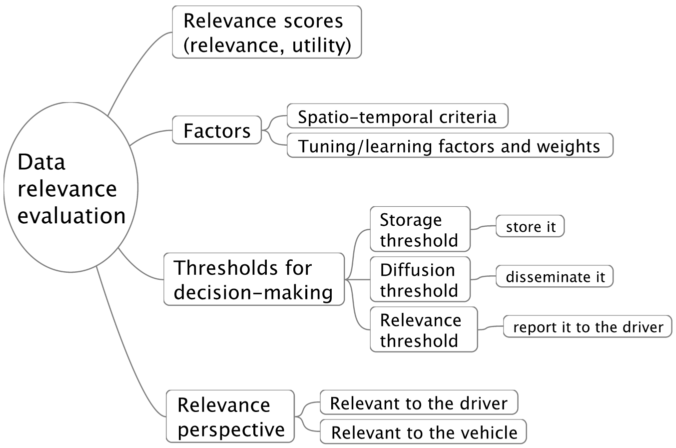

Fig. 14. Overview of the topics related to data relevance evaluation

exchanged traffic reports should be kept in a database of limited size.

- If the event is also higher than a certain *relevance threshold*, then it can be considered to be *relevant to the driver* as long as at least one of the following two conditions also holds: 1) the driver is interested in that kind of event (this interest could be part of the driver's profile or represented as a query), or 2) the event is assumed to be relevant to every driver (e.g., it has a high value for the *importance* field, as in the case of accidents). In this case, the event should be reported to the driver. As an example, in [238] a $T_{warning}$ threshold is defined to explain the trade-off between safety and the number of false warnings shown to the driver.
- Finally, if the relevance of the event is higher than a certain *diffusion threshold*, then the vehicle should consider re-disseminating the information about the event. As an example, in [56] the use of a *benefit threshold* is proposed to avoid redundant broadcasts.

As indicated above, a distinction between events *relevant to the vehicle* and events *relevant to the driver* can be made. Decisions about storing and disseminating events are based on the relevance for the vehicle, without considering the interests of the driver. In this way, the cooperation among vehicles is highlighted, which is a key issue in vehicular networks. Incentive mechanisms such as those presented in [20], [239], [240] can be used to encourage participation in the peer-to-peer network.

As we briefly mentioned before, it should be noted that the relevance of an event is a dynamic value that has to be re-computed periodically, as it will change with the movements of the vehicles. Thus, the vehicle could either get closer to the relevant area or further from it, which will affect the relevance of the event for that vehicle. Besides, in general, the relevance of an event will decrease along time, as the likelihood that the event will have disappeared increases. In the rest of this section, we review some examples of relevance functions that have been proposed in the literature.

A. Space-Time Relevance Function

In [146] the relevance function proposed is a weighted combination of the distance to the event and the age of the event:

$$F(R) = -\alpha * t - \beta * d \ (\alpha, \beta \geq 0) \quad (1)$$

where R represents a resource whose relevance has to be computed (e.g., a parking space), t is the age of the resource, d is the distance to the resource, and α and β are positive constants that weigh the importance of the age and the distance, respectively. According to the previous formula, the relevance decays linearly with the time and the distance.

Although the authors of [146] propose that specific relevance function, they also acknowledge that there are other types of relevance functions possible, possibly including additional factors such as the travel direction. The experimental evaluation included in the paper studies the evolution of the number of copies of a resource depending on the time and distance factors.

B. Geographic-Based Encounter Probability

In [30], [134] the concept of *Encounter Probability* (*EP*) between a vehicle and an event, which is an estimation of the likelihood that the vehicle will meet the event, is proposed as a measure of the relevance of events. The technique proposed to obtain the EP (a value in the range of 0% to 100%) is based on the computation of geographic vectors to estimate the direction of the vehicle and the event, and it also considers temporal aspects. Specifically, the computation of the EP between a vehicle and an event using geographic vectors is given by:

$$EP = \frac{100}{\alpha \times \Delta d + \beta \times \Delta t + \gamma \times \Delta g + \zeta \times c + 1} \quad (2)$$

As can be seen in the previous formula, several parameters (the *penalty coefficients* α, β, γ, and ζ) are used to weigh the importance of different factors: the geographical distance between the vehicle and the event when the vehicle is expected to be at the closest distance (Δd), the difference between the current time and the time when the vehicle will be closest to the event (Δt), the difference between the time when the event is generated and the moment when the vehicle will be closest to the event (Δg), and the angle between the vehicle's direction vector and the event's direction vector (represented by a collinearity coefficient c). This allows the definition of a spatio-temporal relevance area in a dynamic way. The work in [30] shows that dissemination areas that may appear in a typical practical scenario can be defined by setting appropriate penalty coefficients.

It should be noted that, by appropriately weighting the importance of the age of the event for the computation of the relevance, the use of *revocation/invalidation messages* (i.e., messages indicating that an event has disappeared) is not needed. Instead, each vehicle can estimate when the event becomes irrelevant. Invalidation messages could also be used, especially in circumstances when the conditions have changed significantly, such as in the case of an important accident that has been cleared up earlier than expected, but the problem is that it is very difficult to guarantee that all the vehicles previously informed of an event are reached by the corresponding event revocation message. When revocation messages are not used, the number of messages exchanged in the vehicular network is also minimized. Nevertheless, the use of invalidation messages could be convenient for some applications; for example, in car-pooling applications, to avoid trying to satisfy the same request more than once [108].

C. Map-Based Encounter Probability

In [135] the previous geographic-based computation of the EP is compared with a novel complementary approach that exploits information available in digital road maps to estimate the movements within the road network. This last technique is based on the distinction between attraction events and repulsion events (see Section IV-A). It estimates whether a driver could reach a certain attraction event within the expected TTL of the event, or escape from a repulsion event (by taking an alternative route) only if the event is reported now and not later.

For attraction events, the EP is computed as the *Reachability Probability* (*ReachP*), which is the probability that the vehicle will be able to reach the event in time (i.e., before it disappears):

$$ReachP = \begin{cases} 100 & if \quad TTL > TTR \\ 0 & otherwise \end{cases} \tag{3}$$

where the TTR (*Time To Reach*) is the time needed for the vehicle to reach the event by taking the shortest path. As there may be several attraction events relevant to the driver (i.e., with $ReachP = 100\%$), extra information is used to compute a *score* for each event and provide the driver with events of the same type ordered in a *ranked list*.

For repulsion events, the EP is computed as the *Need to Escape Probability* (*NeedEsP*), which indicates the probability that the driver needs to perform some specific action if he/she wants to avoid the event (e.g., taking a detour):

$$NeedEsP = \begin{cases} 100 & if \quad TTL > TTE \\ 0 & otherwise \end{cases} \tag{4}$$

where the *TTE* (*Time To Escape*) is the amount of time needed by the vehicle to reach the last intersection that offers the vehicle an alternative route to avoid the repulsion event, or the *TTR* if there is no such intersection (i.e., if it is not possible to avoid the repulsion event).

D. Learning-Based Relevance Estimation

Most relevance estimation techniques, such as those presented in Sections VII-A and VII-B, are based on the identification of relevance factors that are combined by applying certain weights to each of them. However, the problem with these approaches is that it is challenging to set appropriate weights and even to determine the factors that should be considered for a certain scenario. To overcome this problem, the use of supervised machine learning has been suggested (e.g., see [238]). The goal is to learn the relevant factors and also the best way to combine them (the weights), that is, to *learn the relevance function*. For that purpose, there is first a *learning step* (*training*), usually based on simulations representing sample cases [241], and then a *usage step*.

Specifically, the proposal in [238] focuses on the Emergency Electronic Brake Light application, which alerts drivers in the case of an emergency braking performed by a nearby vehicle. The goal is to try to estimate the relevance of emergency braking alerts in order to avoid false warnings, that could lead to unnecessary decelerations (that may additionally cause collisions) and to the driver's desensitization to alerts. For that purpose, it identifies four attributes that affect a driver's decision to initiate an emergency deceleration upon receiving an emergency braking alert from another vehicle:

- The time that the vehicle receiving the alert would need, traveling at its current speed, to reach its location.
- The density of vehicles: as the density of vehicles increases, the likelihood of emergency deceleration also increases.
- The difference between the speed of the vehicle that generates the alert and the speed of the vehicle that receives it: if the receiving vehicle travels faster, then the likelihood of emergency deceleration increases.
- The number of lanes separating the vehicle that generates the alert and the vehicle that receives it: a lower value implies a higher likelihood of emergency deceleration.

Moreover, it is acknowledged that other factors could be considered (attributes related to the weather or the road conditions, the age of the alert, etc.), but considering the previous factors led to a good performance in the simulation experiments carried out. As another example, [236] also considers, for a travel time dissemination application, the potential use of information about the road type and the percentage of shortest paths going through the affected road segment.

In [238], the machine learning techniques evaluated were Naïve Bayes and logistic regression, being Naïve Bayes the method that had the best overall performance. The proposal in [238] extends [242] (e.g., by considering the impact of lanes); although the focus was on the Emergency Electronic Brake Light application, these techniques based on machine learning could be applied to other transportation safety applications.

Moreover, the authors of the previous works have also studied the application of machine learning in the context of *travel time dissemination* [237], [243]. In [237] they compare the following machine learning algorithms: Naïve Bayes, logistic regression, Support Vector Machines (SVMs), artificial neural networks, and decision trees. All the approaches exhibited a similar performance, with decision trees having the highest accuracy but at the expense of high complexity, and it was concluded that logistic regression was the most understandable and intuitive approach. In [243], the authors focus on Naïve Bayes and develop an online learning approach based on [237], which supports the dynamic adaptation of the model to the existing circumstances. In [236] the authors study two different applications: parking availability dissemination and travel time dissemination.

Finally, they have also presented a platform that helps in the definition and evaluation of relevance functions [241], also based on machine learning. The platform applies the *Observe-Driver-and-Learn* (*ODaLe*) method, which implies observing the reaction of a driver upon receiving an event and using such information as an input to the machine learning algorithm. So, the method benefits from the implicit feedback that the drivers' actions represent. Besides, the platform includes a feature selection step that tries to choose a set of features that are highly predictive but with low correlation among them. Three safety applications are studied: Emergency Electronic Brake Light, Highway Merge Warning, and Control Loss Warning. For each application, a different set of features is chosen by the proposed feature selection algorithm. As in [238], Naïve Bayes and logistic regression are considered in the experimental evaluation; both exhibited a similar performance and helped to minimize the number of false warnings.

VIII. Managing Competitive Resources for Drivers

Access to information, in general, provides an advantage to the driver. Therefore, data sharing approaches for vehicular networks can enhance the driver's experience. However, the data exchanged can be of very different nature and not all of them should be treated equally. When the data represent scarce resources for drivers (physical resources available on the roads [146], rather than hardware or network resources), disseminating and communicating the same information to many drivers could lead to a competition between the vehicles to reach those resources (see Figure 15). In that case, sharing data without control could even be worse than not sharing data at all.

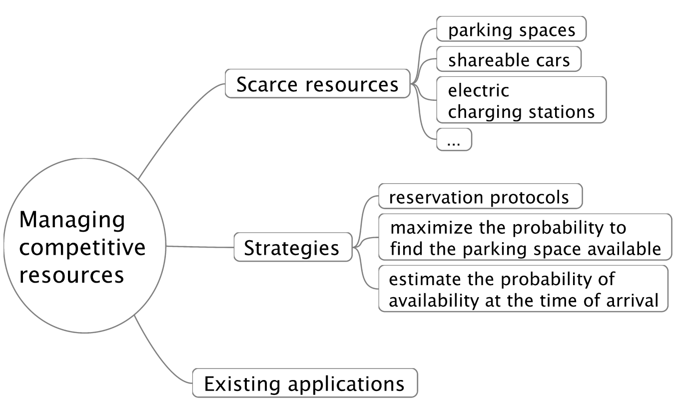

Fig. 15. Overview of the topics related to the management of competitive resources for drivers

A typical example of scarce resources for drivers are the available parking spaces in the vicinity, including on-street parking / curbside parking, parking garages (car parks or off-street parking facilities), slotted and unslotted parking spots, etc. If a data sharing approach presents the same information about an available parking space to several nearby interested drivers, those drivers will try to reach the same parking space. As only one of them will succeed in taking that available parking space, the others will be frustrated with the use of the system: as they were directed towards a parking space that was finally occupied by another vehicle, the final amount of time spent by those vehicles to park could actually increase with respect to the time that they would have needed if they had simply performed a *blind search* (i.e., just looking around without using any data sharing system at all). This intuitive idea has been experimentally observed in studies such as [244]. According to [245], "the possession of less accurate information on the parking demand alleviates competition" leading to better performance than in situations with complete knowledge, and therefore certain policies should be applied for information dissemination. Several data management strategies for vehicular networks have acknowledged this competition problem that appears when data about available parking spaces are freely disseminated in the network. The different existing proposals to tackle this problem could be classified in three categories (see Figure 16), that we describe in the rest of this section.

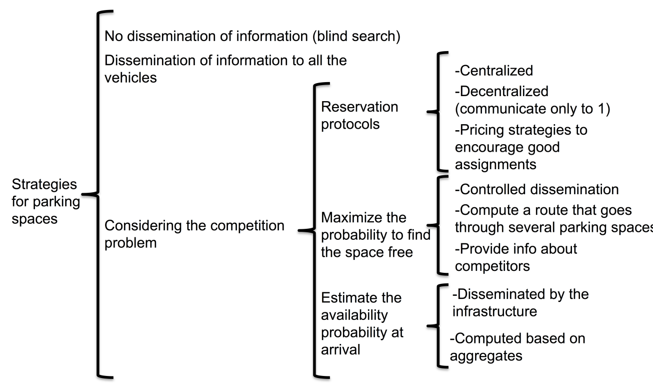

Fig. 16. Strategies to deal with parking spaces

Other examples of resources different from parking spaces could be considered. For example, charging stations for electric vehicles may become an important scarce resource in the future, as charging the battery of an electric vehicle takes considerably more time than refueling a gas-based car; therefore, it may be important to develop strategies to distribute the vehicles over the different charging stations in order to minimize the potential concurrency problems [246], [247]. Another example arises if we consider a hybrid mobile ad hoc network with both vehicles and mobile users, where taxi cabs in a crowded area could be scarce resources for the mobile users [248]. Similarly, in a car-sharing scenario a shareable car can be seen as a limited resource with some specific features (e.g., in terms of its capacity and availability). A competition problem similar to the one described for parking spaces may also arise if many vehicles share a similar destination and use a GPS-based navigation system that provides them with the same shortest-path routes [249]: a traffic congestion may move from one place to another due to common re-routing. As a final example, public bicycle sharing systems can also lead to competition regarding the availability of bikes and parking slots at the different bike stations [250].

It should be noted that we focus on data sharing, rather than on the problem of identifying the existence and occupancy of the parking spaces. For the detection of parking spaces, several techniques could be applied (e.g., see [133]), such as: the driver provides the information, fixed sensors on the parking spots provide their status, the vehicles themselves act as mobile sensor nodes that detect surrounding parking spaces, or sensors in the vehicle or in the driver's phone provide information used to detect parking and/or unparking events.

A. Reservation Protocols for Parking Spaces

A first potential solution to the competition problem is to use a reservation protocol that allows drivers to choose and be assigned a parking space. These proposals are usually restricted to specific scenarios where a support infrastructure is exploited to explicitly control the way the parking spaces are occupied, such as pay parking facilities [251], parking spots in a campus [252], or on-street parking spots with devices to prevent unauthorized parking [253].

Most reservation approaches are centralized. For example, the *Centrally Assisted Parking Search* (*CAPS*) approach [244] relies on a centralized server that has global knowledge about the availability of parking spaces in a city and can provide (through reservation) a parking space close to the driver's destination. As another example, the approach presented in [253] emphasizes the importance of reserving an optimal parking space, rather than any parking space, and presents a centralized approach to allocate and reserve both off-street and on-street parking spaces.

A general and completely decentralized reservation protocol for VANETs is proposed in [36]. The term *reservation* is used in this last work to denote the fact that, thanks to the protocol used, the information about an available parking space is disclosed to a single driver (physically preventing other vehicles from taking a public parking space is not possible). Figure 17 shows a simplified scenario with the main steps in that protocol, without considering the case where no interested vehicle is within the communication range of the vehicle releasing the parking space, which requires additional steps in order to extend the range of the announcement.

A crowdsourcing approach for on-street parking that does not assume a fixed sensor infrastructure is also presented in [254]. The idea is to monitor the available parking capacity of street segments and provide driving directions to reach segments with available capacity, to try to avoid the competition problem. It is interesting that the paper indicates the possibility to suggest directions that lead drivers to unexplored areas in order to improve the system's knowledge about the availability of parking in those areas. As in [36], the proposal cannot ensure the availability of a parking space because other drivers not following the expected protocol may reduce the available capacity by taking any parking space on their way.

A distributed approach is also proposed in [255]. However, in this case ad hoc communications are not used. Instead, technological advances in the emerging *Web of Things* are exploited. Specifically, each parking spot is equipped with a Web Server, as well as a Wi-Fi module, and represents an independent web resource. In this way, it is possible to query the status (occupied, free, or reserved) of a so-called *Smart Parking Spot* and reserve it through any web browser, as these capabilities are exposed as web services. The authors argue that their approach improves the scalability and interoperability.

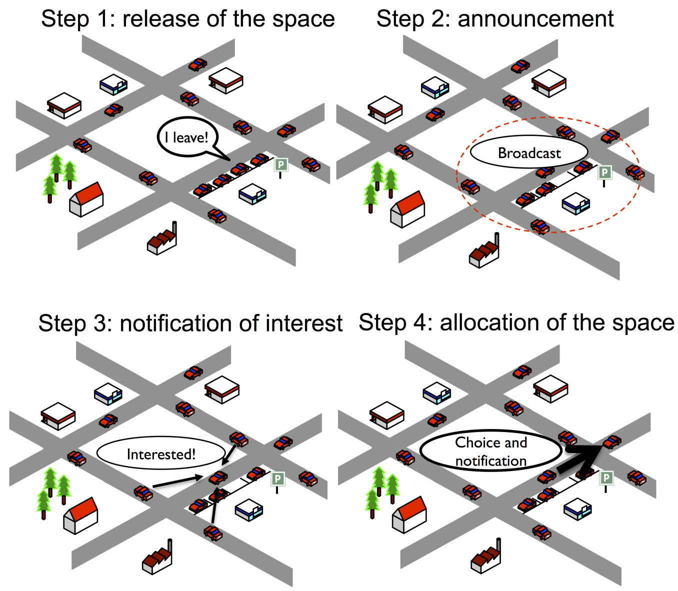

Fig. 17. Decentralized allocation of a parking space: basic scenario

Finally, it is interesting to mention the proposal in [256]. Even if it does not propose a real reservation protocol and no central authority decides in which slot a driver should park, it tries to encourage an assignment of parking slots to drivers that maximizes the system and environment optimality. It does so by dynamically determining pricing strategies for the parking spots in such a way that it makes the Nash equilibrium assignment equal to the system optimal assignment. In other words, the selfish vehicles are incentivized to behave in a way that benefits the welfare, bridging the gap between the System Optimum (SO) and the Nash Equilibrium (NE) regarding the matching between vehicles and parking spaces. Another approach to achieve this is to set payments among drivers looking to park [256], [257]. The interest of using pricing strategies to encourage drivers to go to specific car parks is also mentioned in [258]. Studying the impact of the selfishness of drivers in the context of parking is the focus of [259].

B. Protocols that Try to Maximize the Probability to Find the Parking Space Available

Several other proposals apply strategies to try to maximize the chances of successfully occupying a certain parking space. Thus, in [260] the idea is to exchange information about available and occupied parking spaces in a city in such a way that when an appropriate parking space is selected locally by a vehicle (based on the preferences of the driver), it also stops diffusing information about that available parking space. Another solution is presented in [261], which computes a route that goes through all the parking spaces considered available, based on the *Time-Varying TSP* (*Traveling Salesman Problem*). In [262], [263] several approaches are studied, such as a heuristic *gravitational model* (the *Gravity-based Parking Algorithm*, or *GPA*), where parking spaces attract searching vehicles towards them in a way that the vehicles will move towards areas with higher density of parking spaces, even if there are closer parking spaces but with less gravitational pull. As a final example, [264] proposes the use of a multi-hop wireless parking meter network (PMNET), where parking meters exchange information about the availability of their parking spaces; the authors of that work consider that the competition between drivers can be managed by enhancing the information provided about available parking spaces with information about potential competitors (e.g., their location).

C. Protocols that Try to Estimate the Availability Probability in an Area at the Time of Arrival

These proposals consider that the key element to manage is the probability to find an available parking space in a certain area, rather than the current occupancy status of specific parking spaces. There are proposals for parking lots (e.g., [258], [265], [266], [267], [268]) and for parking spaces in general (e.g., [269]).

For example, in [266] parking lots periodically disseminate certain status parameters (their capacity, the number of occupied spaces, the arrival rate, and the parking rate), which the vehicles can use to estimate the probability to find there an available parking space at the time of arrival. The proposal in [265] divides the city area in zones and assigns an RSU to each zone to keep track of the parking availability in the parking lots in that zone. The proposal presented in [268] to estimate the probability that there are available parking spots in a parking lot at a future time, according to its authors, would support the development of a system that provides a recommendation sequence of parking lots. The study provided in [258] models the decision of the driver to go to a certain car park as a stochastic process with a probability that depends on the expected occupancy of the car park; as future research, the authors of that work intend to determine the best way to communicate the information to the drivers (indicating the number of places available, the probability of parking, or just an assigned car park).

Whereas the previous proposals focus on estimating probabilities for parking lots, other proposals consider parking spaces in general. For example, the proposal in [269] emphasizes the interest of considering aggregate information to guide drivers towards areas where the probability to find an available parking space is high, instead of towards a specific parking space (that may be available now but could be occupied soon). In [39] the idea is to aggregate information about available parking spaces to extract general knowledge about their overall availability in certain areas and time periods. Finally, the work presented in [270] includes algorithms to compute a historical parking availability profile for streets and to estimate the parking availability in real-time.

D. Existing Applications for Parking Spaces

To finish this section, it is relevant to mention that some applications for smartphones appeared to try to facilitate the exchange of information about available parking spaces among drivers (e.g., *SpotScout*, *Apila*, *Placelib*, or *Google's Open Spot*). However, all these solutions were centralized and did not use ad hoc networks but mobile telephony networks (e.g., 3G/4G). Moreover, most of these types of applications do not stay in the market for a long time; for example, Google's Open Spot was released in 2010 and was deprecated in June 2012.

As an example, *Placelib* worked as follows. First a driver can announce that he/she is going to release a parking space, then the system finds (among the vehicles searching for parking spaces) an ideal candidate vehicle to take that spot, and finally the driver waits a few minutes until this candidate arrives to occupy the space, receiving a virtual payment in exchange. With such an approach, resources advertised are lost if no potential client is located in the vicinity. Moreover, the driver releasing the parking space has to wait for the arrival of the other vehicle, as a way of "reserving" the parking space for that vehicle; this not only may be inconvenient for the driver releasing the space but it may also lead to disputes with other drivers searching for a parking space.

It is also interesting to mention that there also exist some web-based applications that allow users to monitor the status of parking spaces in some cities. A notable example is *SFPark* [271] in San Francisco, which uses fixed sensors on the streets to detect the occupancy of on-street parking spots. An important problem with approaches like this one is the installation and maintenance cost of the infrastructure required, which has been criticized in a number of papers (e.g., [272], [273], [274], [275]).

According to [276], it would be interesting to have a parking application that offers the following advantages: 1) consider the final target location when deciding an appropriate parking space; 2) consider multimodality, as parking a car could be just one component of a trip using different transportation modes; 3) exploit real-time constraints such as parking restrictions during specific time periods; 4) accommodate a variety of methods to capture information about available parking spaces, both sensor-based and human-based; and 5) support different types of parking spaces, such as on-street parking, private parking spaces and garages, home parking available for rental at certain moments during the day, etc. The application should compute the likelihood of parking at the estimated time of arrival and offer real-time recommendations based on the learned user's preferences and the optimization goals (minimize the time to park, the distance to the final destination, the fuel consumption, etc.). The paper also indicates the possibility to reserve and pay for certain parking spots, highlighting the interest of a dynamic pricing schema; the reader interested in parking pricing can see [245], [277], and the references [256], [257], commented in Section VIII-A.

IX. Data Aggregation

In-network data aggregation (or, simply, data aggregation) has been the focus of significant research in the field of

Wireless Sensor Networks (*WSNs*) [278], which are energy-constrained; for example, see [279]. However, there are several differences regarding data aggregation in vehicular networks, such as:

- Data aggregation proposals for wireless sensor networks usually assume that a query is initiated from a single node (*base station*), which acts as a data sink for data collection (pull-based model). Based on this, it is possible to propose a tree-based aggregation scheme where the base station is the root of the tree. This is not applicable in vehicular networks, where all the vehicles would usually play the role of data sink (push-based model).
- In traditional wireless sensor networks, nodes are usually assumed to be static. This can be exploited to define structure-based aggregation schemes, which set up a routing structure in advance. However, topology-based routing approaches exploited in wireless sensor networks are not suitable for vehicular networks, due to the high mobility of vehicles.
- In wireless sensor networks, the final goal is to reduce energy consumption (by minimizing the communication overhead), which is not usually a limiting resource in vehicular networks.

Regarding data aggregation in VANETs, it is relevant to mention the work presented in [213], which proposes a generic modeling approach to support the characterization and comparison of different aggregation schemes; the motivation to develop a generic model is that existing aggregation schemes focus on specific applications and types of information. Besides, there is a distinction between syntactic and semantic data aggregation [280]: *syntactic data aggregation* implies a lossless data compression (mainly based on reducing the header overhead) and *semantic data aggregation* is an approximation of the original data based on the meaning of the information being aggregated; data aggregation that is not semantics-based is simply called *data compression* in [211]. Furthermore, [281] studies to what extent an aggregation scheme should reduce the original data to achieve scalability: the bandwidth usage regarding aggregated data about an area should be reduced asymptotically faster than $1/d^2$, where d is the distance to the area. Some approaches rely on predefined aggregation structures (e.g., [39], [282]), but others avoid them based on the argument that it is not appropriate to group data according to fixed structures with independence of the existing data correlation (e.g., [283], [284]).

In this section, we review the work performed in the field of data aggregation for the specific case of VANETs (see Figure 18). We classify the proposals according to their main purpose: reduce bandwidth usage, represent data at the appropriate level of abstraction, or learn from the environment. Besides, we present approaches that focus on secure data aggregation. It should be noted that the proposed classification is not the only possible one, as we acknowledge other benefits of data aggregation, like the reduction of energy consumption or the reduction of the message processing overhead due to a smaller number of disseminated messages [213].

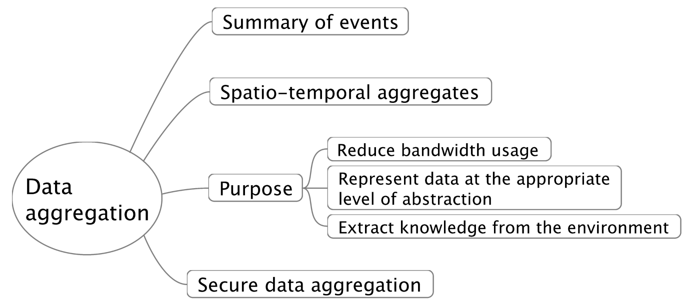

Fig. 18. Overview of the topics related to data aggregation

A. Data Aggregation to Reduce Bandwidth Usage

Data aggregation has been widely investigated in vehicular networks mainly as a means to compress information and reduce bandwidth usage (e.g., [69], [151], [285]). Communicating aggregated data, instead of information about specific events, can help to reduce the network congestion and consequently the occurrence of collisions. Thus, several studies emphasize that data aggregation can be a solution to achieve scalability in vehicular networks (e.g., [61], [286]).

In the data aggregation approach proposed in *TrafficView* [211], focused on traffic applications, the goal is to reduce the size of the information that needs to be transmitted to fit it into a single broadcast packet. There is an *aggregation module* in charge of aggregating individual traffic reports and replacing old records with new versions. The authors propose several approaches to select records for aggregation. On the one hand, the *ratio-based algorithm* divides the road ahead in regions and assigns a certain *aggregation ratio* to each region: based on the importance of that region and the need of accuracy for its data, fine-grained information is not required for regions located farther away from the vehicle. On the other hand, the *cost-based algorithm* considers a cost for aggregating each pair of records, which increases for vehicles located nearby and with the difference in the values included in both records, as well as with the number of vehicles that the aggregation affects. When two records have to be merged, the two records with the minimum aggregation cost are merged, as long as the merging cost does not exceed a certain *cost threshold*.

In [69], the system *TrafficFilter* is presented, which collects information for congestion assistance. The idea is to use V2V communications to build a speed profile of the road ahead in a distributed way. This speed profile, called *TrafficMap*, enlarges the traffic awareness of a vehicle up to a certain *virtual horizon*, so leading to an *over-the-horizon awareness* of traffic jams ahead. A vehicle can add a speed sample to the TrafficMap when it is considered a good representative of the average speed in its vicinity. So, TrafficFilter exploits the fact that there is certain correlation among the speeds of nearby vehicles, in order to aggregate traffic information. The protocol presented in [69] assumes single-lane highway scenarios, and an improved protocol is proposed in [287] to deal with multiple-lane highway scenarios.

CASCADE (*Cluster-based Accurate Syntactic Compression* *of Aggregated Data in VANETs*) [212] focuses also on the aggregation of traffic data. The road ahead a vehicle is divided into clusters of fixed size. Each vehicle broadcasts a *primary frame* containing its mobility data (location, speed, acceleration, and direction) every 300-400 ms; the primary frames received from vehicles nearby compose the *local view* of each vehicle. Besides, every four seconds each vehicle compresses, aggregates, and broadcasts its local view as an *aggregated frame*. CASCADE performs a cluster-based compression where only the differences between a vehicle's data (location and speed) and the overall data of its cluster (location of the center of the cluster and median speed of the vehicles inside it) are represented. It was reported that the scheme used in CASCADE leads to a compression rate of at least 86%. According to the experimental evaluation presented, the compression mechanism of CASCADE obtains at least a 45% higher reception rate, as compression allows smaller data frames, which reduces the likelihood of packet collisions. Finally, CASCADE succeeds in increasing the *visibility* of a vehicle. However, the proposal relies on the assumption of a four-lane highway. Initially, the cluster size considered was one lane wide (four meters) and 63 meters long. An analysis of the optimal cluster size to achieve a good trade-off between the aggregated frame size and the local view length is provided in [61], [288], concluding that the optimal cluster size is actually four lanes wide and 126 meters long. Besides CASCADE, the study in [289], which focuses on average speed forecasting, also proposes the use of clusters as the basis for data aggregation of traffic information: the cluster head (the closest vehicle to the center of the cluster) is the only one that broadcasts the average speed and the number of vehicles; this broadcast is directed towards other cluster members and to other cluster heads nearby. As another example, [283] also proposes a cluster-based data aggregation approach.

The method proposed in [282] is a hierarchical-based approach that uses *soft-state sketches* as a probabilistic approximation for data aggregation. They are a variation of Flajolet-Martin sketches (FM sketches). The basic idea behind the soft-state sketches is to set a TTL for the elements inserted into the sketch, in such a way that they will eventually die unless their TTL is refreshed by a new observation. The proposed data representation is duplicate-insensitive, and therefore it is possible to combine multiple aggregates for the same spatial area as well as to integrate lower-level aggregates into higher-level aggregates without over-counting event occurrences. In the experimental evaluation presented in the paper, the authors assume a hierarchy based on a grid composed by squared cells, but they acknowledge that an aggregation hierarchy should be predefined in a way that best fits the environment; for example, the interesting events (traffic situation, available parking spaces, etc.) may vary greatly depending on the specific road segment.

To conclude this subsection, we will briefly mention some other relevant approaches. In [125], a hierarchical aggregation approach is proposed; in this case, the structure is defined by landmarks and connecting roads at several hierarchical levels. A non-hierarchical aggregation scheme is indirectly suggested in the context of the SOTIS system [60], [64], [65], in the sense that the traffic condition of a road segment is estimated by computing the average velocity of the vehicles in that segment. *Catch-Up* [38], [290] is a data aggregation scheme based on the use of Bloom filters and an adaptive delay control policy for data dissemination; the basic idea is to intelligently inject delays before forwarding reports, in order to favor the aggregation of similar reports that are temporarily close (within a certain time-window of each other), thus striking a balance between communication overhead and propagation delay; [38] also highlights the interest of using data aggregation to improve the quality of the individual observations (the sensor readings of a single vehicle may be inaccurate). The study presented in [291] suggests combining the use of aggregated messages with revocation messages in order to improve the quality of the aggregates and keep them up-to-day. The *QoI-based Data Gathering Protocol* (*QoI-DG*) presented in [292] focuses on dynamic route guidance and proposes an aggregation approach that considers the application requirements, through the idea of *Quality of Information* (*QoI*) of the aggregated data. As a final example, it is interesting to mention [151], which aggregates location queries and location updates in the context of a location service protocol (RLSMP, see Section V-B), to minimize the network overhead.

B. Data Aggregation to Represent Data at the Appropriate Level of Abstraction

The *Aggregating Data Dissemination* (*ADD*) algorithm presented in [293] is based on the use of a hierarchical grid structure composed of cells for data aggregation at different resolutions. Each cell has at least a roadside unit which is selected as responsible for data aggregation regarding that spatial cell. Cells at a certain level are grouped into larger cells in higher levels to support aggregation regarding larger geographic areas. The idea behind the proposal is to provide data structures that can be queried at the appropriate granularity required. So, the assumption is that a driver will usually need detailed information about a small area but summarized information about larger areas.

In the *TrafficFilter* system described in Section IX-A, reduction operations can be performed to further reduce the size of the TrafficMap. This reduction process is based on the idea that a vehicle needs a more precise representation of the speed information when it is close to the corresponding area, but traffic information of further areas can be summarized.

As a final example, the method based on soft-state sketches described in [282] (see Section IX-A) also indicates that detailed data is kept in the vicinity and coarser aggregates are made available at larger distances.

C. Data Aggregation to Learn from the Environment

Another possibility is to consider data aggregation as a way to store in the vehicles a summary of previously-observed events, either directly observed by the vehicle or received from other neighboring vehicles. This approach is quite different from most proposals, which usually consider a piece of data received as an element to store in a local data cache temporarily, processed locally and possibly used to notify the driver and/or be transmitted to other vehicles, and deleted once used. Instead of just using the data received for query processing and discarding them later once they are out of date, it is possible to exploit these deprecated data to extract some *additional knowledge* that can then be exploited in the future. Obviously, it is not realistic to store in a vehicle all the information received about events, due to both the required storage capacity and the underlying processing time needed to query such data. However, spatio-temporal aggregates can be built and stored, since they provide a good compromise between data accuracy and the required storage and processing capacity. Then, those spatio-temporal aggregates or summaries can be exploited to estimate the probability of occurrence of a certain event even in the absence of relevant real-time observations.

As an example of the interest of using data aggregation techniques, by aggregating information about available parking spaces it should be possible to estimate the frequency with which parking spaces are released, and thus to determine the probability of finding an available parking space in a certain area, even if no recent information about parking spaces in that area has been received (see Figure 19). This knowledge could then be exploited by the drivers, for example to decide moving towards an area with potentially available parking spaces. Similarly, it can be used by the data management system when evaluating the relevance of the events, for example by strongly penalizing the time elapsed since a parking space was released if it is located in an area where many vehicles usually search for parking, or by estimating the probability of finding an available parking space at the time of arrival [28], [267]. As another example, by aggregating data about accidents it is possible to detect areas that are particularly dangerous at certain times.

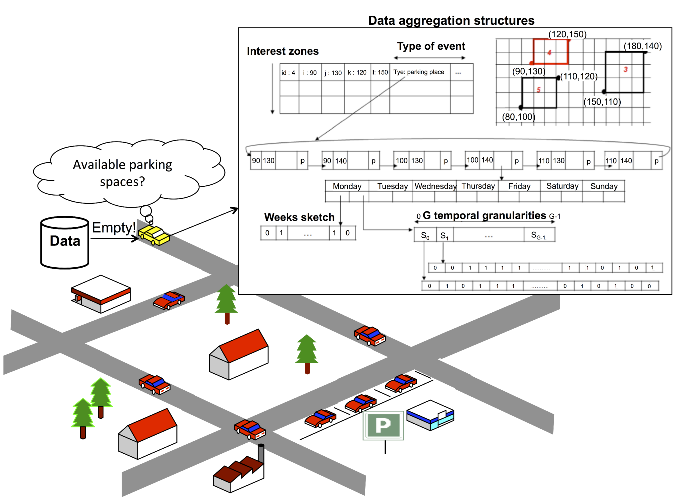

Fig. 19. Exploiting aggregated data in the absence of current data in the local cache

Based on this idea, in [39] the authors identify two main challenges for spatio-temporal data aggregation: how to deal with duplicate information about the same event in order to avoid over-counting (data about the same event can be received by several vehicles), and how to determine a good trade-off between the size of the summaries and their accuracy. A two-level spatio-temporal model is used: the *physical level* performs a fixed fragmentation of space and time, and the *logical level* is a logical splitting on top of the physical level and based on the user preferences. By considering both a spatial and a temporal dimension, it is possible to build knowledge that is relevant in specific spatial regions and time intervals, used to define specific areas of interest to the drivers. Duplicate counts are avoided thanks to the use of FM sketches, along with the assumption that each event has a unique identifier; this last assumption is actually not easy to guarantee for the case of events that are observed by several vehicles. Different temporal and spatial granularities can be managed in the model.

Moreover, the work presented in [39] also describes an exchange protocol allowing vehicles to share and merge (parts of) their respective aggregates according to a publish/subscribe process. As the connection duration may be insufficient to allow a complete exchange of summaries, a mechanism based on priorities (depending on the type of event, the areas of interest, and the time granularity) is used. Besides, a vehicle avoids exchanging summaries with the same vehicle in a short time by keeping a list of the N latest vehicles with which it exchanged summaries. Thanks to this exchange, vehicles can increase the quality and coverage of the data collected for the areas they want to monitor (i.e., the areas of interest).

The authors of [39] evaluated their strategy by considering the problem of searching for an available parking space. The results obtained showed the benefits of keeping and exploiting summaries of data, as well as the benefits of exchanging those summaries. Thus, the proposal leads to an increase of about 10% in the number of vehicles finding an available parking space. Moreover, the experiments also show that benefits can be obtained even without a complete aggregation process (i.e., with vehicles building summaries based on a reduced observation range).

D. Secure Data Aggregation

With data aggregation, atomic reports generated by several vehicles are combined. As commented before, this is an important advantage due to the reduction of data size. Besides, it could also help to increase privacy, as individual reports usually "disappear" into the aggregates. However, the aggregation itself implies important difficulties from a security point of view, due to the difficulty to verify the integrity of the aggregated information. According to [280], data aggregation "aggravates the security problem". Thus, several attacks can take place [286]:

- *Forging of atomic reports*: generation of false individual reports by a vehicle.
- *Suppression of aggregates*: maliciously dropping aggregates received during the dissemination process.
- *Forging of aggregates*: generation of aggregates with fabricated data, thus claiming that certain data are true and supported by observations from a certain number of vehicles.

Nevertheless, the study presented in [204] indicates that data aggregation not only increases the efficiency but also "contributes to better data correctness and, in some sense, a higher level of security". Similarly, [294] mentions that "data aggregation can also be used to increase reliability of disseminated information". Thus, by grouping several messages the receiver could see that the same event is supported by evidence provided by several contributing vehicles.

The *CASCADE* method [61], [212], [288] presented in Section IX-A also proposes exploiting data aggregation to detect malicious attacks. In particular, the idea is to compare the intersection between the traffic view of a vehicle and a received traffic view to detect vehicles that may be injecting false traffic views in the vehicular network.

FM sketches are used in *SAS* [295], a secure data aggregation scheme for vehicular sensing networks. The authors emphasize that a malicious attacker could modify the aggregated structures. Two types of attacks are considered: *inflation attacks* and *deflation attacks*, depending on whether a 0-bit in an FM sketch is turned into a 1-bit, or vice versa. Therefore, *sketch proof* techniques based on authentication are proposed to detect those attacks.

The solution proposed in [286] is based on the addition of *attestation metadata* to the aggregates. The idea is to choose, and add to the aggregate, an appropriate subset of the underlying atomic reports to enable a probabilistic verification. Besides the *clues* included in the attestation metadata, there may be application-specific clues (e.g., the expected range of values for the application). This solution is not attached to a specific data aggregation scheme. As future work, the authors plan to "bridge the gap between security and privacy" by avoiding revealing details about the individuals who contributed with their reports to an aggregate.

Related to the TrafficView project, [280] presents a probabilistic validation approach based on the use of a tamper-proof device that should be available in each car. This device would perform several secure operations, such as signing records, generating timestamps, and generating random numbers. The basic idea of the proposal is "to challenge" the vehicle that aggregates data by asking a proof that can be used to probabilistically validate the aggregate provided. The proof is a certain original valid record, whose number is selected randomly by the challenger. To increase the probability of detecting malicious cars, the challenger could request more than one original record. These random checks enable a probabilistic detection of malicious vehicles, which are so discouraged from attacking the vehicular network by diffusing false information.

The proposal in [296] also considers a probabilistic verification process, but in this case to reduce the time needed for signature verification. The idea is that all the vehicles that agree with an aggregated message sign it (the number of signatures stored in a message can be limited, as indicated in [294]), but only a subset of the signatures included in the message are verified by a receiving vehicle. The minimum number of signatures to check depends on the *intimacy level*, which is defined according to the average number of authenticated vehicles and the distance to the event reported in the aggregated packet. Besides, the authors propose to use fuzzy logic rules (representing spatial and temporal criteria) to decide if two individual reports should be aggregated (they refer to the same event) or not. Another approach that is based on fuzzy logic to decide if two data items should be aggregated is presented in [297]; the use of fuzzy reasoning avoids the need of relying on predefined aggregation structures such as hierarchical tree structures, grids, or road segments.

Other proposals that consider the security aspect of data aggregation in VANETs could be mentioned, such as the study in [204], which proposes mechanisms related to the use of combined signatures[7], overlapping groups of vehicles, and dynamic group creation; [298], based on secret and public keys and on the aggregation of signatures into *multisignatures*; and *AEMA* (*Aggregated Emergency Message Authentication*) [299], which uses a syntactic and cryptographic aggregation with *aggregate signatures* along with batch verification.

X. Some Lessons Learned

This study presents an extensive overview of vehicular networks from a data management perspective. A few lessons could be highlighted:

- *The complexity of the environment makes experimental evaluation very difficult*. Due to economic, scalability, and ease of testing reasons, simulators are used to evaluate protocols and applications for vehicular networks. In some cases, field trials are also performed, but the types of real-world tests that are affordable usually provide only a proof-of-concept in controlled scenarios and with a very small number of vehicles. Overall, performing an experimental evaluation in this context is a very difficult task: there are a good number of simulators available, many scenarios and parameter settings that could be studied, simulations are very time-consuming, etc. Furthermore, due to existing difficulties, most proposals do not explicitly include human studies in the evaluations, even though determining the way the protocols and applications affect human behavior should probably be the ultimate goal of an evaluation. The use of analytical models [300] and even games [301] could help alleviate the cost of simulations, but developing and applying them effectively are also a challenge.
- *The complexity of the environment makes comparisons very difficult*. Even if we just focus on a specific data management challenge (such as data relevance evaluation, data dissemination, or data aggregation), comparing different proposals is really difficult. Two main reasons explain this. First, the results of a certain experimental evaluation depend on a high number of experimental parameters, such as the road map considered, the scenario (urban scenario, highway, rural scenario, etc.), the density of vehicles, the types of events simulated, the network communication parameters, etc. As an example, even with a simple parameter such as the communication range for V2V communications we can find large discrepancy in the typical/maximum values considered in different studies (e.g., 200 meters in [302], 350-500 meters in [206],

[7]Concatenated signatures, onion signatures or message oversigning, and hybrid signatures.

1000 meters in [65]). The second reason is the large amount of simulators that can be used to simulate both the network communications and the mobility of vehicles, each one offering different functions and exhibiting different simulation capabilities. Moreover, there are no benchmarks. The overall effect is that trying to reproduce a given experimental setup described in a study, as well as comparing the results of two different experimental evaluations, would be really arduous.

- *The complexity of the environment challenges the development of generic solutions*. As we have highlighted along this paper, many proposals focus on specific use cases and scenarios or make some assumptions that limit their use to certain contexts. For example, according to [15] most routing protocols can only be applied to either rural or urban environments, [16] indicates that most routing protocols were proposed considering only city environments, [230] focuses on light-traffic road networks such as rural areas, and [213] indicates that domain-specific assumptions guide the use of data aggregation strategies for vehicular networks. The reason is that the conditions and environmental factors may change widely, and therefore it is not easy to propose a generic solution able to provide optimal or good results in all the situations, applications, and requirements. For example, quite different data dissemination decisions should be applied in a sparse vehicular network and in a dense vehicular network: carry-and-forward would play a key role in a sparse vehicular network, whereas minimizing the number of data rediffusions should be a goal in a very dense vehicular network (to ensure scalability and avoid overloading). As another example, the evaluation of the relevance of events depends on a number of factors, context elements, and user preferences. Even supposedly general solutions for relevance evaluation depend on a number of factor weights that are not easy to fine-tune (e.g., see [30]). The application of machine learning techniques (e.g., see [238], as explained in Section VII-D), could be an interesting research path to continue exploring.
- *The complexity of the environment requires interdisciplinary approaches*. To start with, as emphasized in this paper, the frontier between data management and communications for vehicular networks is not well-defined, given the interdependence and complementarity of these two fields. Moreover, security is another important ingredient to add to the mix, as we would like to guarantee properties such as data authenticity, reliability, trust, and privacy, even if some properties such as trust and privacy are in conflict with each other [303]. Besides, social studies and economics could provide insights to favor cooperation, by providing incentives or applying suitable billing schemes (e.g., see [20], [239], [240]); this is a critical issue for the eventual success of vehicular networks, as vehicles need to cooperate for tasks such as multihop forwarding and data sharing. The development of appropriate and non-intrusive user interfaces is also a key element that deserves careful study, as it is important not to distract the driver [304]. Finally, we not only need interdisciplinary research teams, but also approaches that take all these elements into account to propose a solution that can accommodate and exploit the existing variety of communication technologies (Wi-Fi, mobile telephony networks, etc.), interaction schemes (peer-to-peer, centralized), heterogeneous data sources, and other services that may available (e.g., see [156]).

Finally, we would also like to stress that it is also important to watch technological advances and regulations very closely, as the potential success of a proposal may depend on an inter-weaved combination of factors, including technological, industrial, and event political support.

XI. Must-Read References

This survey collects a rich set of relevant references that provide in-depth knowledge of the state of the art. In this section, we highlight a very limited selection of must-read references that are representative of the different main topics covered in this study:

- *Background knowledge*. Concerning the general topic of vehicular networks, we can highlight references such as the survey on data-driven ITS provided in [2], the tutorial survey on vehicular networks presented in [5], and studies regarding applications for vehicular networks [9]. Other interesting surveys are provided along the paper, and particularly in Sections I to III.
- *Query processing* (Section V). Regarding the push model for query processing, [146] presents the idea of opportunistic resource spreading in vehicular networks as a form of epidemics (vehicles spread information when entering in contact with other vehicles, like a disease), and [135] describes two alternative approaches for pushing data to vehicles (one approach based on pure geographic computations and another one exploiting the information available in digital road maps). Concerning the pull-based model, the VITP approach, described in [153], tackles the problem of processing location-sensitive requests that need to retrieve information about specific target areas; the problem of routing the query results back to a query originator is studied in works such as [154] (approach based on the use of fixed nodes called mailboxes) and [144] (approach that exploits a trace of "breadcrumbs" left by the vehicle that submitted the query). As a representative example of an approach that uses both the push-based and the pull-based model, [96] focuses on the problem of querying blobs in vehicular networks. Finally, it is also interesting to highlight the idea of multi-scale query processing [156], which exploits hybrid access models and several data sources.
- *Data dissemination* (Section VI). Among the existing data dissemination approaches for vehicular networks, we could highlight [170], which focuses on highway scenarios and compares three approaches that differ in the direction of the vehicles participating in the process, and [30], which adapts the dissemination area based on the relevance of the events for the vehicles. For a good

overview of the general problem of routing in vehicular networks, the interested reader is referred to surveys such as [15], [18]. A review of information dissemination in vehicular networks can be found in [11].
- *Estimating the relevance of the data* (Section VII). As a basic starting point, an intuitive spatio-temporal relevance function is presented in [146]. Estimating the relevance of information about an event based on the probability that the vehicle will meet the event is proposed in [134] (using basic geographic computations) and [135] (computing routes in a digital road map). The use of supervised machine learning to automatically infer the significant factors affecting the relevance of data is proposed in [238].
- *Managing competitive resources for drivers* (Section VIII). Our selection of references related to the competition problem focuses on parking spaces. Among the reservation protocols we highlight the centralized approach presented in [244] (CAPS) and the ad hoc approach described in [36]. As good examples of solutions that try to maximize the probability of availability of the parking space at the time of arrival, the reader is advised to read [261] (computing a route through parking spaces) and [262] (parking slot assignment games, gravitational model). The approach presented in [39] is interesting because it exploits data aggregation to learn the availability of parking spaces in different areas and time periods. Finally, we must reference SFPark [271] as a very popular infrastructure-based solution for parking spaces.
- *Data aggregation* (Section IX). The aggregation approach presented in the context of the TrafficView project [211] aims at reducing the size of the data communicated. Similarly, a hierarchical-based probabilistic data aggregation is presented in [282]. Aggregating data as a way to build knowledge about the environment is explored in [39].

The reader who is mainly interested in obtaining a general overview of a specific topic could just read the selected references provided above and the text of this paper covering that topic. Nevertheless, it should be noted that the additional references provided in this study are considered also very relevant and particularly useful to acquire in-depth knowledge about specific proposals.

XII. Conclusions and Open Challenges

In this paper, we have presented a comprehensive study on data management for vehicular networks. We have analyzed several topics that are relevant from the point of view of data management: types of interesting events that can be considered, query processing, data dissemination approaches, strategies to estimate the relevance of data, techniques to manage data about scarce resources for drivers, and data aggregation. In this final section, we summarize some lessons learned and open challenges. The data management challenges that appear in the context of vehicular networks have recently attracted significant research attention. However, as mentioned along the paper, there are still open problems, such as:

- As an example, as mentioned in Section IV-B, the exchange of multimedia data in a vehicular network (e.g., see [90], [94], [96]) is challenging but could also provide much richer information about events happening on the roads. For example, a picture of an available parking space would be useful for the driver to better assess if its size is suitable for his/her vehicle and if the surrounding area is nice or not. Similarly, a short video of an accident would help to evaluate its impact. As a final example, we can imagine the collaboration of vehicles in surveillance tasks, potentially capturing images of suspicious activities in a city. Two vehicles could be within the communication range of each other only during a short time window, which could pose major difficulties for the exchange of large amounts of data. The transmission of multimedia data could also imply a high network overhead.
- The use of ontologies [141] to represent events (see Section IV-B) could also facilitate an unambiguous interpretation of events. As an example, we can mention the *SSN* (*Semantic Sensor Network*) ontology [305], which represents the capabilities, measurement processes, observations, and deployments, of sensors. Similarly, we can expect the future definition of ontologies to represent data relevant in the context of vehicular networks. Moreover, this could enable the interoperability among different data management systems for vehicles. Thus, we can imagine the co-existence of different information systems and applications in the context of vehicular networks, developed by different companies, that could exchange data among them thanks to the use of ontologies that precisely define the meaning of those data. Beyond the simple interpretation of the data exchanged, ontologies can also support reasoning, leading to inferring information that has not been explicitly stated; for example, an accident is a potential cause of a traffic jam, and therefore if the driver is interested in avoiding traffic jams he/she will also probably be interested in nearby accidents that can slow down traffic. Despite the potential of using ontologies in vehicular networks, their real application and the possibilities they offer are yet to be explored.
- Another interesting challenge is how to route queries and results in a highly-dynamic network using only wireless short-range ad hoc communications. This could be solved in the future by the underlying network protocols (e.g., [306] studies the feasibility of IP communications on top of WAVE), but at least in the meanwhile the data transmitted could play a role in the routing process. Thus, for example, we could consider the possibility of encapsulating the expected trajectory of the vehicle that submits the query and keeping this trajectory along with the results to try to take appropriate routing decisions at each intermediate vehicle. However, it is not clear which strategies could be applied when there are significant changes in the expected trajectory.
- The development of middleware to facilitate data management in vehicular networks could also be beneficial. This middleware could encapsulate functionalities such as geo-routing and typical data management techniques required in the context of vehicular networks (data relevance evaluation, data aggregation, etc.), enabling an

extensible and adaptable software architecture on top of which different applications and information systems could be developed. As an example, the use of mobile agent technology [158] has been indicated as a potential facilitator for data management and query processing in vehicular networks and ITS [157], [159], but there is no evidence yet about its real utility.
- Security issues (such as those briefly pointed out in Section IX-D) are not easy to solve in vehicular networks, given the special characteristics of such a dynamic peer-to-peer environment, where vehicles can join and leave the network at any time and where short-range wireless communications are usually used. Moreover, the critical impact of a security attack in this environment makes security concerns particularly relevant. Thus, for example, the dissemination of false information could be used to gain a competitive advantage, for example to minimize traffic on the route or the number of competitors searching for a parking space, by encouraging other vehicles to move to distant areas. Moreover, it could also lead to accidents or potential harm to human lives. Some interesting studies on security for vehicular networks can be found in [307], [308], [309].

The previous list is not exhaustive. For example, some other recent trends consider the interest of sharing underutilized hardware resources in vehicular networks to build *vehicular clouds* (*VCs*) [310], [311], [312], [313], that enable cloud computing services such as *Network as a Service* (*NaaS*), *Storage as a Service* (*STaaS*), and *Cooperation as a Service* (*CaaS*). Similarly, several proposals also advocate exploiting parked vehicles as stationary nodes that can participate in multi-hop communications [314], [315], [316], [317], [318]. Some studies also highlight other specific problems; for example, [15] indicates that routing protocols usually consider either rural or urban environments but not both.

We look forward to the interesting opportunities and challenges brought by vehicular networks and we hope that this paper will encourage further research and multi-disciplinary efforts involving both the data management and the communications research communities.

ACKNOWLEDGMENTS

This work was supported by the CICYT project TIN2013-46238-C4-4-R and DGA-FSE. Thanks also to the French International Campus on Safety and Intermodality in Transportation, the Nord-Pas-de-Calais Region, the European Union, the Regional Delegation for Research and Technology, the Ministry of Higher Education and Research, and the National Center for Scientific Research. Last but not least, we also sincerely thank the anonymous reviewers for their useful and insightful comments.

REFERENCES

[1] G. Dimitrakopoulos and P. Demestichas, "Intelligent transportation systems," *IEEE Vehicular Technology Magazine*, vol. 5, no. 1, pp. 77–84, 2010.

[2] J. Zhang, F.-Y. Wang, K. Wang, W.-H. Lin, X. Xu, and C. Chen, "Data-driven intelligent transportation systems: A survey," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 4, pp. 1624–1639, 2011.

[3] S. Olariu and M. C. Weigle, Eds., *Vehicular Networks: From Theory to Practice*. CRC Press, 2009.

[4] J. J. Blum, A. Eskandarian, and L. J. Hoffman, "Challenges of intervehicle ad hoc networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 5, no. 4, pp. 347–351, 2004.

[5] H. Hartenstein and K. P. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *IEEE Communications Magazine*, vol. 46, no. 6, pp. 164–171, 2008.

[6] L. Zhang, D. Gao, S. Gao, and V. Leung, "SmartGeocast: Dynamic abnormal traffic information dissemination to multiple regions in VANET," in *Ninth International Wireless Communications and Mobile Computing Conference (IWCMC 2013)*. IEEE Computer Society, 2013, pp. 1750–1755.

[7] B. W. Kolosz and S. M. Grant-Muller, "Appraisal and evaluation of interurban ITS: A European survey," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 3, pp. 1070–1087, 2014.

[8] G. Karagiannis, O. Altintas, E. Ekici, G. J. Heijenk, B. Jarupan, K. Lin, and T. Weil, "Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 4, pp. 584–616, 2011.

[9] T. L. Willke, P. Tientrakool, and N. F. Maxemchuk, "A survey of inter-vehicle communication protocols and their applications," *IEEE Communications Surveys & Tutorials*, vol. 11, no. 2, pp. 3–20, 2009.

[10] M. L. Sichitiu and M. Kihl, "Inter-vehicle communication systems: A survey," *IEEE Communications Surveys & Tutorials*, vol. 10, no. 2, pp. 88–105, 2008.

[11] S. Panichpapiboon and W. Pattara-Atikom, "A review of information dissemination protocols for vehicular ad hoc networks," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 3, pp. 784–798, 2012.

[12] J. Härri, F. Filali, and C. Bonnet, "Mobility models for vehicular ad hoc networks: A survey and taxonomy," *IEEE Communications Surveys & Tutorials*, vol. 11, no. 4, pp. 19–41, 2009.

[13] M. Kakkasageri and S. Manvi, "Information management in vehicular ad hoc networks: A review," *Journal of Network and Computer Applications*, vol. 39, pp. 334–350, 2013.

[14] Y. Toor, P. Mühlethaler, A. Laouiti, and A. de La Fortelle, "Vehicle ad hoc networks: Applications and related technical issues," *IEEE Communications Surveys & Tutorials*, vol. 10, no. 3, pp. 74–88, 2008.

[15] S. M. Bilal, C. J. Bernardos, and C. Guerrero, "Position-based routing in vehicular networks: A survey," *Journal of Network and Computer Applications*, vol. 36, no. 2, pp. 685–697, 2013.

[16] B. T. Sharef, R. A. Alsaqour, and M. Ismail, "Vehicular communication ad hoc routing protocols: A survey," *Journal of Network and Computer Applications*, vol. 40, pp. 363–396, 2014.

[17] S. Allal and S. Boudjit, "Geocast routing protocols for VANETs: Survey and guidelines," in *Sixth International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS 2012)*. IEEE Computer Society, 2012, pp. 323–328.

[18] F. Li and Y. Wang, "Routing in vehicular ad hoc networks: A survey," *IEEE Vehicular Technology Magazine*, vol. 2, no. 2, pp. 12–22, 2007.

[19] A. Dua, N. Kumar, and S. Bawa, "A systematic review on routing protocols for vehicular ad hoc networks," *Vehicular Communications*, vol. 1, no. 1, pp. 33–52, 2014.

[20] J. A. Dias, J. J. Rodrigues, and L. Zhou, "Cooperation advances on vehicular communications: A survey," *Vehicular Communications*, vol. 1, no. 1, pp. 22–32, 2014.

[21] S. Gillani, F. Shahzad, A. Qayyum, and R. Mehmood, "A survey on security in vehicular ad hoc networks," in *Communication Technologies for Vehicles*, ser. Lecture Notes in Computer Science (LNCS), vol. 7865. Springer, 2013, pp. 59–74.

[22] J. M. de Fuentes, L. González-Manzano, A. I. González-Tablas, and J. Blasco, "Security models in vehicular ad-hoc networks: A survey," *IETE Technical Review*, vol. 31, no. 1, pp. 47–64, 2014.

[23] P. R. Pereira, A. Casaca, J. J. P. C. Rodrigues, V. N. G. J. Soares, J. Triay, and C. Cervelló-Pastor, "From delay-tolerant networks to vehicular delay-tolerant networks," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 4, pp. 1166–1182, 2012.

[24] J. N. Isento, J. J. Rodrigues, J. A. Dias, M. C. Paula, and A. Vinel, "Vehicular delay-tolerant networks – a novel solution for vehicular communications," *IEEE Intelligent Transportation Systems Magazine*, vol. 5, no. 4, pp. 10–19, 2013.

[25] T. Delot and S. Ilarri, "Introduction to the special issue on data management in vehicular networks," *Transportation Research Part C: Emerging Technologies*, vol. 23, pp. 1–2, 2012.
[26] S. Ukkusuri, Y. Wang, and T. Chigan, "Introduction to the special issue on exploiting wireless communication technologies in vehicular transportation networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 3, pp. 633–634, 2011.
[27] T. Delot and S. Ilarri, "Data gathering in vehicular networks: The VESPA experience (invited paper)," in *Fifth IEEE Workshop On User MObility and VEhicular Networks (LCN ON-MOVE 2011)*. IEEE Computer Society, 2011, pp. 801–808.
[28] P. Szczurek, B. Xu, O. Wolfson, J. Lin, and N. Rishe, "Learning the relevance of parking information in VANETs," in *Seventh ACM International Workshop on Vehicular Ad Hoc Networks (VANET 2010)*. ACM, 2010, pp. 81–82.
[29] T. Nadeem, P. Shankar, and L. Iftode, "A comparative study of data dissemination models for VANETs," in *Third Annual International Conference on Mobile and Ubiquitous Systems (MobiQuitous'06) Workshops*. IEEE Computer Society, 2006, pp. 1–10.
[30] N. Cenerario, T. Delot, and S. Ilarri, "A content-based dissemination protocol for VANETs: Exploiting the encounter probability," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 3, pp. 771–782, 2011, special issue on Exploiting Wireless Communication Technologies in Vehicular Transportation Networks.
[31] T. Kosch, C. J. Adler, S. Eichler, C. Schroth, and M. Strassberger, "The scalability problem of vehicular ad hoc networks and how to solve it," *IEEE Wireless Communications*, vol. 13, no. 5, pp. 22–28, 2006.
[32] H. Lim and C. Kim, "Flooding in wireless ad hoc networks," *Computer Communications*, vol. 24, no. 3-4, pp. 353–363, 2001.
[33] Y.-C. Tseng, S.-Y. Ni, Y.-S. Chen, and J.-P. Sheu, "The broadcast storm problem in a mobile ad hoc network," *Wireless Networks*, vol. 8, no. 2/3, pp. 153–167, 2002.
[34] N. Wisitpongphan, O. K. Tonguz, J. S. Parikh, P. Mudalige, F. Bai, and V. Sadekar, "Broadcast storm mitigation techniques in vehicular ad hoc networks," *IEEE Wireless Communications*, vol. 14, no. 6, pp. 84–94, 2007.
[35] O. Wolfson, "Spatio-temporal competition for transportation resources," in *20th International Symposium on Temporal Representation and Reasoning (TIME 2013)*, 2013, pp. 7–8.
[36] T. Delot, S. Ilarri, S. Lecomte, and N. Cenerario, "Sharing with caution: Managing parking spaces in vehicular networks," *Mobile Information Systems*, vol. 9, no. 1, pp. 69–98, 2013.
[37] G. Yan, M. C. Weigle, and S. Olariu, "A novel parking service using wireless networks," in *IEEE International Conference on Service Operations, Logistics and Informatics (SOLI'09)*. IEEE Computer Society, 2009, pp. 406–411.
[38] B. Yu, C.-Z. Xu, and M. Guo, "Adaptive forwarding delay control for VANET data aggregation," *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 1, pp. 11–18, 2012.
[39] D. Zekri, B. Defude, and T. Delot, "Building, sharing and exploiting spatio-temporal aggregates in vehicular networks," *Mobile Information Systems*, vol. 10, no. 3, pp. 259–285, 2014.
[40] J. Luo and J.-P. Hubaux, "A survey of research in inter-vehicle communications," in *Embedded Security in Cars – Securing Current and Future Automotive IT Applications*. Springer, 2005, pp. 111–122.
[41] N. Liu, M. Liu, J. Cao, G. Chen, and W. Lou, "When transportation meets communication: V2P over VANETs," in *30th International Conference on Distributed Computing Systems (ICDCS 2010)*. IEEE Computer Society, 2010, pp. 567–576.
[42] C. Lochert, H. Hartenstein, J. Tian, H. Füβler, D. Hermann, and M. Mauve, "A routing strategy for vehicular ad hoc networks in city environments," in *Intelligent Vehicles Symposium (IV'03)*. IEEE Computer Society, 2003, pp. 156–161.
[43] M. Conti and S. Giordano, "Multihop ad hoc networking: The theory," *IEEE Communications Magazine*, vol. 45, no. 4, pp. 78–86, 2007.
[44] I. Chlamtac, M. Conti, and J. J.-N. Liu, "Mobile ad hoc networking: Imperatives and challenges," *Ad Hoc Networks*, vol. 1, no. 1, pp. 13–64, 2003.
[45] J. Zhao and G. Cao, "VADD: Vehicle-assisted data delivery in vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 3, pp. 1910–1922, 2008.
[46] A. B. Reis, S. Sargento, F. Neves, and O. K. Tonguz, "Deploying roadside units in sparse vehicular networks: What really works and what does not," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 6, pp. 2794–2806, 2014.
[47] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Evaluating the impact of a novel message dissemination scheme for vehicular networks using real maps," *Transportation Research Part C: Emerging Technologies*, vol. 25, pp. 61–80, 2012.
[48] M. Gerla and L. Kleinrock, "Vehicular networks and the future of the mobile Internet," *Computer Networks*, vol. 55, no. 2, pp. 457–469, 2011.
[49] S. Al-Sultan, M. M. Al-Doori, A. H. Al-Bayatti, and H. Zedan, "A comprehensive survey on vehicular ad hoc network," *Journal of Network and Computer Applications*, vol. 37, pp. 380–392, 2014.
[50] P. Papadimitratos, A. de La Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 84–95, 2009.
[51] S. Zeadally, R. Hunt, Y.-S. Chen, A. Irwin, and A. Hassan, "Vehicular ad hoc networks (VANETS): Status, results, and challenges," *Telecommunication Systems*, vol. 50, no. 4, pp. 217–241, 2012.
[52] K. Bengler, K. Dietmayer, B. Färber, M. Maurer, C. Stiller, and H. Winner, "Three decades of driver assistance systems: Review and future perspectives," *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 4, pp. 6–22, 2014.
[53] D. Bowman, S. Baker, S. Stone, Z. Doerzaph, and R. Hanowski, "Development of performance requirements for commercial vehicle safety applications," Report No. DOT HS 811 772, 2013, U.S. Department of Transportation, National Highway Traffic Safety Administration.
[54] T. ElBatt, S. K. Goel, G. Holland, H. Krishnan, and J. Parikh, "Cooperative collision warning using dedicated short range wireless communications," in *Third ACM International Workshop on Vehicular Ad Hoc Networks (VANET'06)*. ACM, 2006, pp. 1–9.
[55] Z. Wang, L. Kulik, and K. Ramamohanarao, "Proactive traffic merging strategies for sensor-enabled cars," in *Fourth ACM International Workshop on Vehicular Ad Hoc Networks (VANET'07)*. ACM, 2007, pp. 39–48.
[56] S. Eichler, C. Schroth, T. Kosch, and M. Strassberger, "Strategies for context-adaptive message dissemination in vehicular ad hoc networks," in *Second International Workshop on Vehicle-to-Vehicle Communications (V2VCOM'06)*. IEEE Computer Society, 2006, pp. 1–9.
[57] S. Djahel, R. Doolan, G.-M. Muntean, and J. Murphy, "A communications-oriented perspective on traffic management systems for smart cities: Challenges and innovative approaches," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 1, pp. 125–151, 2014.
[58] U. Lee, R. Cheung, and M. Gerla, *Vehicular Networks: From Theory to Practice*. CRC Press, 2009, ch. 6 "Emerging Vehicular Applications", pp. 6:1–6:30.
[59] C. T. Barba, "Contribution to design a communication framework for vehicular ad hoc networks in urban scenarios," Ph.D. dissertation, Universitat Politècnica de Catalunya (UPC BarcelonaTech), Barcelona, Spain, 2013.
[60] L. Wischhof, A. Ebner, and H. Rohling, "Information dissemination in self-organizing intervehicle networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 6, no. 1, pp. 90–101, 2005.
[61] K. Ibrahim, "Data aggregation and dissemination in vehicular adhoc networks," Ph.D. dissertation, Old Dominion University, Norfolk, Virginia, USA, 2011.
[62] W. Enkelmann, *InterVehicle-Communications Based on Ad Hoc Networking Principles: The FleetNet Project*. Universitätsverlag Karlsruhe, 2005, ch. 7 "Applications for Inter-Vehicle Communication", pp. 213–231.
[63] M. Alsabaan, W. Alasmary, A. Albasir, and K. Naik, "Vehicular networks for a greener environment: A survey," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 3, pp. 1372–1388, 2013.
[64] L. Wischhof, A. Ebner, H. Rohling, M. Lott, and R. Halfmann, "SOTIS – A self-organizing traffic information system," in *57th IEEE Vehicular Technology Conference-Spring (VTC'03 – Spring)*, vol. 4. IEEE Computer Society, 2003, pp. 2442–2446.
[65] ——, *InterVehicle-Communications Based on Ad Hoc Networking Principles: The FleetNet Project*. Universitätsverlag Karlsruhe, 2005, ch. 8 "Self-Organizing Traffic Information System", pp. 233–257.
[66] M. Seredynski and P. Bouvry, "A survey of vehicular-based cooperative traffic information systems," in *14th International IEEE Conference on Intelligent Transportation Systems (ITSC 2011)*. IEEE Computer Society, 2011, pp. 163–168.
[67] S. Dornbush and A. Joshi, "StreetSmart traffic: Discovering and disseminating automobile congestion using VANET's," in *IEEE 65th Vehicular Technology Conference-Spring (VTC'07 – Spring)*. IEEE Computer Society, 2007, pp. 11–15.
[68] C. van Driel, "Driver support in congestion: An assessment of user needs and impacts on driver and traffic flow," Ph.D. dissertation, University of Twente, The Netherlands, 2007.

[69] M. van Eenennaam and G. Heijenk, "Providing over-the-horizon awareness to driver support systems," in *Fourth IEEE Workshop on Vehicle to Vehicle Communications (V2VCOM'08)*. University of Twente (The Netherlands), 2008, pp. 19–25.

[70] J. Cheambe, J.-J. Tchouto, and C. Tittel, *InterVehicle-Communications Based on Ad Hoc Networking Principles: The FleetNet Project*. Universitätsverlag Karlsruhe, 2005, ch. 9 "The Pinboard Application", pp. 259–287.

[71] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Automatic accident detection: Assistance through communication technologies and vehicles," *IEEE Vehicular Technology Magazine*, vol. 7, no. 3, pp. 90–100, 2012.

[72] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Reducing emergency services arrival time by using vehicular communications and evolution strategies," *Expert Systems with Applications*, vol. 41, no. 4, Part 1, pp. 1206–1217, 2014.

[73] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "A system for automatic notification and severity estimation of automotive accidents," *IEEE Transactions on Mobile Computing*, vol. 13, no. 5, pp. 948–963, 2014.

[74] S. Smaldone, L. Han, P. Shankar, and L. Iftode, "RoadSpeak: Enabling voice chat on roadways using vehicular social networks," in *First Workshop on Social Network Systems (SocialNets'08)*. ACM, 2008, pp. 43–48.

[75] I. Lequerica, M. G. Longaron, and P. M. Ruiz, "Drive and share: Efficient provisioning of social networks in vehicular scenarios," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 90–97, 2010.

[76] A.-U.-H. Yasar, N. Mahmud, D. Preuveneers, K. Luyten, K. Coninx, and Y. Berbers, "Where people and cars meet: Social interactions to improve information sharing in large scale vehicular networks," in *Symposium on Applied Computing (SAC 2010)*. ACM, 2010, pp. 1188–1194.

[77] M. Knobel, M. Hassenzahl, M. Lamara, T. Sattler, J. Schumann, K. Eckoldt, and A. Butz, "Clique trip: Feeling related in different cars," in *Designing Interactive Systems Conference (DIS 2012)*. ACM, 2012, pp. 29–37.

[78] A. M. Vegni and T. D. Little, *VANETs as an Opportunistic Mobile Social Network*. CRC Press, 2014, ch. 15, pp. 437–465.

[79] F. Mezghani, R. Dhaou, M. Nogueira, and A.-L. Beylot, "Content dissemination in vehicular social networks: Taxonomy and user satisfaction," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 34–40, 2014.

[80] A. Nandan, S. Das, G. Pau, M. Gerla, and M. Y. Sanadidi, "Co-operative downloading in vehicular ad-hoc wireless networks," in *Second Annual Conference on Wireless On-demand Network Systems and Services (WONS'05)*. IEEE Computer Society, 2005, pp. 32–41.

[81] U. Lee, J.-S. Park, J. Yeh, G. Pau, and M. Gerla, "Code Torrent: Content distribution using network coding in VANET," in *First International Workshop on Decentralized Resource Sharing in Mobile Computing and Networking (MobiShare'06)*. ACM, 2006, pp. 1–5.

[82] S. Ahmed and S. S. Kanhere, "VANETCODE: Network coding to enhance cooperative downloading in vehicular ad-hoc networks," in *International Conference on Wireless Communications and Mobile Computing (IWCMC'06)*. ACM, 2006, pp. 527–532.

[83] K. C. Lee, S.-H. Lee, R. Cheung, U. Lee, and M. Gerla, "First experience with CarTorrent in a real vehicular ad hoc network testbed," in *Mobile Networking for Vehicular Environments (MOVE'07)*. IEEE Computer Society, 2007, pp. 109–114.

[84] Y. Zhang, J. Zhao, and G. Cao, "Roadcast: A popularity aware content sharing scheme in VANETs," in *29th International Conference on Distributed Computing Systems (ICDCS'09)*. IEEE Computer Society, 2009, pp. 223–230.

[85] M. Li, Z. Yang, and W. Lou, "CodeOn: Cooperative popular content distribution for vehicular networks using symbol level network coding," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 1, pp. 223–235, 2011.

[86] M. Gerla, C. Wu, G. Pau, and X. Zhu, "Content distribution in VANETs," *Vehicular Communications*, vol. 1, no. 1, pp. 3–12, 2014.

[87] F. Malandrino, C. Casetti, C.-F. Chiasserini, and M. Fiore, "Content download in vehicular networks in presence of noisy mobility prediction," *IEEE Transactions on Mobile Computing*, vol. 13, no. 5, pp. 1007–1021, 2014.

[88] M. Sathiamoorthy, A. G. Dimakis, B. Krishnamachari, and F. B. Member, "Distributed storage codes reduce latency in vehicular networks," *IEEE Transactions on Mobile Computing*, vol. 13, no. 9, pp. 2016–2027, 2014.

[89] L. Zhou, Y. Zhang, K. Song, W. Jing, and A. V. Vasilakos, "Distributed media services in P2P-based vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 2, pp. 692–703, 2011.

[90] J.-S. Park, U. Lee, S. Y. Oh, M. Gerla, and D. S. Lun, "Emergency related video streaming in VANET using network coding," in *Third ACM International Workshop on Vehicular Ad Hoc Networks (VANET'06)*. ACM, 2006, pp. 102–103.

[91] M. A. Bonuccelli, G. Giunta, F. Lonetti, and F. Martelli, "Real-time video transmission in vehicular networks," in *2007 Mobile Networking for Vehicular Environments (MOVE'07)*. IEEE Computer Society, 2007, pp. 115–120.

[92] M. Guo, M. H. Ammar, and E. W. Zegura, "V3: A vehicle-to-vehicle live video streaming architecture," *Pervasive and Mobile Computing*, vol. 1, no. 4, pp. 404–424, 2005.

[93] F. Xie, K. A. Hua, W. Wang, and Y. H. Ho, "Performance study of live video streaming over highway vehicular ad hoc networks," in *66th IEEE Vehicular Technology Conference (VTC'07 – Fall)*. IEEE Computer Society, 2007, pp. 2121–2125.

[94] N. N. Qadri, M. Fleury, B. R. Rofoee, M. Altaf, and M. Ghanbari, "Robust P2P multimedia exchange within a VANET," *Wireless Personal Communications*, vol. 63, no. 3, pp. 561–577, 2012.

[95] M. D. Felice, E. Cerqueira, A. Melo, M. Gerla, F. Cuomo, and A. Baiocchi, "A distributed backbone-based framework for live video sharing in VANETs," in *11th ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks (PE-WASUN 2014)*. ACM, 2014, pp. 33–40.

[96] O. Wolfson and B. Xu, "A new paradigm for querying blobs in vehicular networks," *IEEE Multimedia*, vol. 21, no. 1, pp. 48–58, 2014.

[97] C. Xu, F. Zhao, J. Guan, H. Zhang, and G.-M. Muntean, "QoE-driven user-centric VoD services in urban multihomed P2P-based vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 5, pp. 2273–2289, 2013.

[98] J. Ott and D. Kutscher, "Drive-thru Internet: IEEE 802.11b for automobile users," in *23rd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'04)*. IEEE Computer Society, 2004, pp. 362–373.

[99] J. Zhao, T. Arnold, Y. Zhang, and G. Cao, "Extending drive-thru data access by vehicle-to-vehicle relay," in *Fifth ACM International Workshop on Vehicular Ad Hoc Networks (VANET'08)*. ACM, 2008, pp. 66–75.

[100] J. Eriksson, H. Balakrishnan, and S. Madden, "Cabernet: Vehicular content delivery using WiFi," in *14th International Conference on Mobile Computing and Networking (MobiCom'08)*. ACM, 2008, pp. 199–210.

[101] N. Cheng, N. Lu, N. Zhang, X. S. Shen, and J. W. Mark, "Vehicular WiFi offloading: Challenges and solutions," *Vehicular Communications*, vol. 1, no. 1, pp. 13–21, 2014.

[102] U. Lee, B. Zhou, M. Gerla, E. Magistretti, P. Bellavista, and A. Corradi, "MobEyes: Smart mobs for urban monitoring with a vehicular sensor network," *IEEE Wireless Communications*, vol. 13, no. 5, pp. 52–57, 2006.

[103] O. Urra, S. Ilarri, E. Mena, and T. Delot, "Using hitchhiker mobile agents for environment monitoring," in *Seventh International Conference on Practical Applications of Agents and Multi-Agent Systems (PAAMS'09)*, ser. Advances in Intelligent and Soft Computing, vol. 55. Springer, 2009, pp. 557–566.

[104] X. Li, H. Huang, X. Yu, W. Shu, M. Li, and M.-Y. Wu, "A new paradigm for urban surveillance with vehicular sensor networks," *Computer Communications*, vol. 34, no. 10, pp. 1159–1168, 2011.

[105] Z. Li, C. Liu, and C. Chigan, "On secure VANET-based ad dissemination with pragmatic cost and effect control," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 1, pp. 124–135, 2013.

[106] S.-B. Lee, J.-S. Park, M. Gerla, and S. Lu, "Secure incentives for commercial ad dissemination in vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 6, pp. 2715–2728, 2012.

[107] A. Nandan, S. Tewari, S. Das, M. Gerla, and L. Kleinrock, "AdTorrent: Delivering location cognizant advertisements to car networks," in *Third International Conference on Wireless On Demand Network Systems and Services (WONS'06)*, 2006, pp. 203–2012.

[108] B. Liu, B. Khorashadi, D. Ghosal, C.-N. Chuah, and H. M. Zhang, "Analysis of the information storage capability of VANET for highway and city traffic," *Transportation Research Part C: Emerging Technologies*, vol. 23, pp. 68–84, 2012.

[109] J. Zhu, Y. Feng, and B. Liu, "PASS: Parking-lot-assisted carpool over vehicular ad hoc networks," *International Journal of Distributed Sensor Networks*, pp. 1–9, 2013.

[110] A. G. Bianchessi, G. Cugola, S. Formentin, A. C. Morzenti, C. Ongini, E. Panigati, M. Rossi, S. M. Savaresi, F. A. Schreiber, L. Tanca, and E. G. V. Depoli, "Green move: A platform for highly configurable, heterogeneous electric vehicle sharing," *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 3, pp. 96–108, 2014.

[111] P.-Y. Chen, J.-W. Liu, and W.-T. Chen, "A fuel-saving and pollution-reducing dynamic taxi-sharing protocol in VANETs," in *72nd IEEE Vehicular Technology Conference (VTC 2010 – Fall)*, 2010, pp. 1–5.

[112] U. Lee, J. Lee, J.-S. Park, and M. Gerla, "FleaNet: A virtual market place on vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 1, pp. 344–355, 2010.

[113] M. Wellens, B. Westphal, and P. Mähönen, "Performance evaluation of IEEE 802.11-based WLANs in vehicular scenarios," in *65th Vehicular Technology Conference Spring (VTC'07 – Spring)*, 2007, pp. 1167–1171.

[114] C. E. Palazzi, M. Roccetti, and S. Ferretti, "An intervehicular communication architecture for safety and entertainment," *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 1, pp. 90–99, 2010.

[115] I. Leontiadis and C. Mascolo, "Opportunistic spatio-temporal dissemination system for vehicular networks," in *First International MobiSys Workshop on Mobile Opportunistic Networking (MobiOpp'07)*. ACM, 2007, pp. 39–46.

[116] U. Lee and M. Gerla, "A survey of urban vehicular sensing platforms," *Computer Networks*, vol. 54, no. 4, pp. 527–544, 2010.

[117] J. Bernsen and D. Manivannan, "RIVER: A reliable inter-vehicular routing protocol for vehicular ad hoc networks," *Computer Networks*, vol. 56, no. 17, pp. 3795–3807, 2012.

[118] A. O'Driscoll and D. Pesch, "Hybrid geo-routing in urban vehicular networks," in *IEEE Vehicular Networking Conference (VNC 2013)*. IEEE Computer Society, 2013, pp. 63–70.

[119] C. Lochert, B. Scheuermann, M. Caliskan, and M. Mauve, "The feasibility of information dissemination in vehicular ad-hoc networks," in *Fourth Annual Conference on Wireless On demand Network Systems and Services (WONS'07)*. IEEE Computer Society, 2007, pp. 92–99.

[120] National Highway Traffic Safety Administration (NHTSA), "U.S. department of transportation announces decision to move forward with vehicle-to-vehicle communication technology for light vehicles," NHTSA 05-14, 2014, U.S. Department of Transportation, National Highway Traffic Safety Administration, http://www.nhtsa.gov/About+NHTSA/Press+Releases/2014/USDOT+to+Move+Forward+with+Vehicle-to-Vehicle+Communication+Technology+for+Light+Vehicles [Last access: August 10, 2015].

[121] P. Li, X. Huang, Y. Fang, and P. Lin, "Optimal placement of gateways in vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 6, pp. 3421–3430, 2007.

[122] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. M. T. Calafate, and P. Manzoni, "Road side unit deployment: A density-based approach," *IEEE Intelligent Transportation Systems Magazine*, vol. 5, no. 3, pp. 30–39, 2013.

[123] E. S. Cavalcante, A. L. Aquino, G. L. Pappa, and A. A. Loureiro, "Roadside unit deployment for information dissemination in a VANET: An evolutionary approach," in *14th International Conference on Genetic and Evolutionary Computation Conference Companion (GECCO Companion 2012)*. ACM, 2012, pp. 27–34.

[124] O. Trullols, M. Fiore, C. Casetti, C. F. Chiasserini, and J. M. B. Ordinas, "Planning roadside infrastructure for information dissemination in intelligent transportation systems," *Computer Communications*, vol. 33, no. 4, pp. 432–442, 2010.

[125] C. Lochert, B. Scheuermann, C. Wewetzer, A. Luebke, and M. Mauve, "Data aggregation and roadside unit placement for a VANET traffic information system," in *Fifth ACM International Workshop on Vehicular Ad Hoc Networks (VANET'08)*. ACM, 2008, pp. 58–65.

[126] A. M. Vegni, C. Campolo, A. Molinaro, and T. D. C. Little, *Routing in Opportunistic Networks*. Springer, 2013, ch. 7 "Modeling of Intermittent Connectivity in Opportunistic Networks: The Case of Vehicular Ad hoc Networks", pp. 179–207.

[127] I. Leontiadis, P. Costa, and C. Mascolo, "A hybrid approach for content-based publish/subscribe in vehicular networks," *Pervasive and Mobile Computing*, vol. 5, no. 6, pp. 697–713, 2009.

[128] M. Rondinone, J. Gozalvez, J. Leguay, and V. Cona, "Exploiting context information for V2X dissemination in vehicular networks," in *14th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2013)*. IEEE Computer Society, 2013, pp. 1–9.

[129] Y. Lee, S. S. Iyengar, C. Min, Y. Ju, S. Kang, T. Park, J. Lee, Y. Rhee, and J. Song, "MobiCon: A mobile context-monitoring platform," *Communications of the ACM*, vol. 55, no. 3, pp. 54–65, 2012.

[130] A. Amditis, A. Polychronopoulos, E. Bekiaris, and P. Antonello, "System architecture of a driver's monitoring and hypovigilance warning system," in *IEEE Intelligent Vehicle Symposium (IV'02)*, vol. 2. IEEE Computer Society, 2002, pp. 527–532.

[131] B. Fleming, "Sensors – A forecast [automotive electronics]," *IEEE Vehicular Technology Magazine*, vol. 8, no. 3, pp. 4–12, 2013.

[132] R. S. Schwartz, A. E. Ohazulike, H. W. van Dijk, and H. Scholten, "Analysis of utility-based data dissemination approaches in VANETs," in *74th IEEE Vehicular Technology Conference (VTC 2011 – Fall)*. IEEE Computer Society, 2011, pp. 1–5.

[133] S. Ilarri, O. Wolfson, and T. Delot, "Collaborative sensing for urban transportation," *IEEE Data Engineering Bulletin*, vol. 37, no. 4, pp. 3–14, 2014.

[134] T. Delot, N. Cenerario, and S. Ilarri, "Vehicular event sharing with a mobile peer-to-peer architecture," *Transportation Research Part C: Emerging Technologies*, vol. 18, no. 4, pp. 584–598, 2010.

[135] T. Delot, S. Ilarri, N. Cenerario, and T. Hien, "Event sharing in vehicular networks using geographic vectors and maps," *Mobile Information Systems*, vol. 7, no. 1, pp. 21–44, 2011.

[136] F. G. Mármol and G. M. Pérez, "TRIP, a trust and reputation infrastructure-based proposal for vehicular ad hoc networks," *Journal of Network and Computer Applications*, vol. 35, no. 3, pp. 934–941, 2012.

[137] F. Guidec and Y. Maheo, "Opportunistic content-based dissemination in disconnected mobile ad hoc networks," in *International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies (UBICOMM'07)*. IEEE Computer Society, 2007, pp. 49–54.

[138] X. Lin, X. Sun, P.-H. Ho, and X. Shen, "GSIS: A secure and privacy-preserving protocol for vehicular communications," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 6, pp. 3442–3456, 2007.

[139] D. Borsetti and J. Gozalvez, "Infrastructure-assisted geo-routing for cooperative vehicular networks," in *Second IEEE Vehicular Networking Conference (VNC 2010)*. IEEE Computer Society, 2010, pp. 255–262.

[140] I. Leontiadis, "Publish/subscribe notification middleware for vehicular networks," in *Fourth Middleware Doctoral Symposium (MDS'07)*. ACM, 2007, pp. 12:1–12:6.

[141] O. Corcho, M. Fernández-López, and A. Gómez-Pérez, "Methodologies, tools and languages for building ontologies: Where is their meeting point?" *Data & Knowledge Engineering*, vol. 46, no. 1, pp. 41–64, 2003.

[142] S. Ilarri, A. Illarramendi, E. Mena, and A. Sheth, "Semantics in location-based services – guest editors' introduction for special issue," *IEEE Internet Computing*, vol. 15, no. 6, pp. 10–14, 2011.

[143] S. Fuchs, S. Rass, B. Lamprecht, and K. Kyamakya, "A model for ontology-based scene description for context-aware driver assistance systems," in *First International Conference on Ambient Media and Systems (Ambi-Sys'08)*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008, pp. 1–8.

[144] J. Timpner, M. Wozenilek, and L. Wolf, "Breadcrumb routing: Query-response geocast for mobile originators in vehicular networks," in *Fifth IEEE Vehicular Networking Conference (VNC 2014)*. IEEE Computer Society, 2014, pp. 45–52.

[145] D. Terry, D. Goldberg, D. Nichols, and B. Oki, "Continuous queries over append-only databases," *SIGMOD Record*, vol. 21, no. 2, pp. 321–330, 1992.

[146] B. Xu, A. M. Ouksel, and O. Wolfson, "Opportunistic resource exchange in inter-vehicle ad-hoc networks," in *Fifth International Conference on Mobile Data Management (MDM'04)*. IEEE Computer Society, 2004, pp. 4–12.

[147] I. Leontiadis, "A content dissemination framework for vehicular networking," Ph.D. dissertation, University College London, United Kingdom, 2009.

[148] M. Ayaida, M. Barhoumi, H. Fouchal, Y. Ghamri-Doudane, and L. Afilal, "Joint routing and location-based service in VANETs," *Journal of Parallel and Distributed Computing*, vol. 74, no. 2, pp. 2077–2087, 2014.

[149] S. M. Das, H. Pucha, and Y. C. Hu, "Performance comparison of scalable location services for geographic ad hoc routing," in *24th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'05)*, vol. 2. IEEE Computer Society, 2005, pp. 1228–1239.

[150] M. Gerla, B. Zhou, Y.-Z. Lee, F. Soldo, U. Lee, and G. Marfia, "Vehicular grid communications: The role of the internet infrastructure," in *Second Annual International Workshop on Wireless Internet (WICON'06)*. ACM, 2006, pp. 1–10.

[151] H. Saleet and O. A. Basir, "Location based message aggregation in vehicular ad hoc networks," in *IEEE Global Communications Workshops*. IEEE Computer Society, 2007, pp. 1–7.
[152] M. Grossglauser and M. Vetterli, "Locating mobile nodes with EASE: Learning efficient routes from encounter histories alone," *IEEE/ACM Transactions on Networking*, vol. 14, no. 3, pp. 457–469, 2006.
[153] M. D. Dikaiakos, S. Iqbal, T. Nadeem, and L. Iftode, "VITP: An information transfer protocol for vehicular computing," in *Second ACM International Workshop on Vehicular Ad Hoc Networks (VANET'05)*. ACM, 2005, pp. 30–39.
[154] T. Delot, N. Mitton, S. Ilarri, and T. Hien, "GeoVanet: A routing protocol for query processing in vehicular networks," *Mobile Information Systems*, vol. 7, no. 4, pp. 329–359, 2011.
[155] N. Nakamura, Y. Niimi, and S. Ishihara, "Live VANET CDN: Adaptive data dissemination scheme for location-dependent data in VANETs," in *IEEE Vehicular Networking Conference (VNC 2013)*. IEEE Computer Society, 2013, pp. 95–102.
[156] T. Delot, S. Ilarri, M. Thilliez, G. Vargas-Solar, and S. Lecomte, "Multi-scale query processing in vehicular networks," *Journal of Ambient Intelligence and Humanized Computing*, vol. 2, no. 3, pp. 213–226, 2011.
[157] O. Urra, S. Ilarri, T. Delot, and E. Mena, "Mobile agents in vehicular networks: Taking a first ride," in *Eighth International Conference on Practical Applications of Agents and Multi-Agent Systems (PAAMS 2010)*, ser. Advances in Intelligent and Soft Computing, vol. 70. Springer, 2010, pp. 119–124.
[158] R. Trillo, S. Ilarri, and E. Mena, "Comparison and performance evaluation of mobile agent platforms," in *Third International Conference on Autonomic and Autonomous Systems (ICAS'07)*. IEEE Computer Society, 2007, pp. 41–46.
[159] B. Chen and H. H. Cheng, "A review of the applications of agent technology in traffic and transportation systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 2, pp. 485–497, 2010.
[160] T. Delot, S. Ilarri, and M. del Carmen Rodríguez-Hernández, "Intelligent transportation systems – maybe, but where are my agents?" in *Sixth International Conference on Ad Hoc Networks (AdHocNets 2014)*, ser. LNICST (Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering), vol. 140. Springer, 2014, pp. 39–50.
[161] O. Wolfson, A. P. Sistla, and B. Xu, "The TranQuyl language for data management in intelligent transportation," *Transportation Research Part C: Emerging Technologies*, vol. 23, pp. 3–13, 2012, special issue on Data Management in Vehicular Networks.
[162] R. S. Schwartz, R. R. R. Barbosa, N. Meratnia, G. Heijenk, and H. Scholten, "A directional data dissemination protocol for vehicular environments," *Computer Communications*, vol. 34, no. 17, pp. 2057–2071, 2011.
[163] W. Chen, R. K. Guha, T. J. Kwon, J. Lee, and Y.-Y. Hsu, "A survey and challenges in routing and data dissemination in vehicular ad hoc networks," *Wireless Communications & Mobile Computing*, vol. 11, no. 7, pp. 787–795, 2011.
[164] D. Sormani, G. Turconi, P. Costa, D. Frey, M. Migliavacca, and L. Mottola, "Towards lightweight information dissemination in inter-vehicular networks," in *Third ACM International Workshop on Vehicular Ad Hoc Networks (VANET'06)*. ACM, 2006, pp. 20–29.
[165] R. I. Meneguette, A. Boukerche, G. Maia, A. A. Loureiro, and L. A. Villas, "A self-adaptive data dissemination solution for intelligent transportation systems," in *11th ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks (PE-WASUN 2014)*. ACM, 2014, pp. 69–76.
[166] A. Kesting, M. Treiber, and D. Helbing, "Connectivity statistics of store-and-forward intervehicle communication," *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 1, pp. 172–181, 2010.
[167] O. Wolfson, A. Ouksel, and B. Xu, "Resource discovery in disconnected mobile ad-hoc networks," in *International Workshop on Next Generation Geospatial Information*, 2003, pp. 1–3.
[168] H. Wu, R. Fujimoto, and G. Riley, "Analytical models for information propagation in vehicle-to-vehicle networks," in *60th Vehicular Technology Conference Fall (VTC'04 – Fall)*, vol. 6. IEEE Computer Society, 2004, pp. 4548–4552.
[169] R. S. Schwartz, H. Scholten, and P. J. M. Havinga, "A scalable data dissemination protocol for both highway and urban vehicular environments," *EURASIP Journal on Wireless Communications and Networking*, vol. 2013, pp. 257:1–257:19, 2013.
[170] S. Nittel, M. Duckham, and L. Kulik, "Information dissemination in mobile ad-hoc geosensor networks," in *Third International Conference on Geographic Information Science (GIScience'04)*, 2004, pp. 206–222.
[171] R. Kumar and M. Dave, "DDDRC: Decentralised data dissemination in VANET using raptor codes," *International Journal of Electronics*, vol. 102, no. 6, pp. 946–966, 2015.
[172] T. Zho, B. Xu, P. Szczurek, and O. Wolfson, "TrafficInfo: An algorithm for VANET dissemination of real-time traffic information," in *15th World Congress on Intelligent Transportation Systems (WCITS'08)*, 2008, pp. 1–12.
[173] Y. Zhu, Y. Wu, and B. Li, "Trajectory improves data delivery in urban vehicular networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 25, no. 4, pp. 1089–1100, 2014.
[174] M. Li, K. Zeng, and W. Lou, "Opportunistic broadcast of event-driven warning messages in vehicular ad hoc networks with lossy links," *Computer Networks*, vol. 55, no. 10, pp. 2443–2464, 2011.
[175] A. M. Vegni and E. Natalizio, "Forwarder smart selection protocol for limitation of broadcast storm problem," *Journal of Network and Computer Applications*, vol. 47, pp. 61–71, 2015.
[176] R. S. Schwartz, A. E. Ohazulike, C. Sommer, H. Scholten, F. Dressler, and P. Havinga, "On the applicability of fair and adaptive data dissemination in traffic information systems," *Ad Hoc Networks*, vol. 13, Part B, pp. 428 – 443, 2014.
[177] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Identifying the key factors affecting warning message dissemination in VANET real urban scenarios," *Sensors*, vol. 13, no. 4, pp. 5220–5250, 2013.
[178] B. Karp and H. T. Kung, "GPSR: Greedy Perimeter Stateless Routing for wireless networks," in *Sixth Annual International Conference on Mobile Computing and Networking (MobiCom 2000)*. ACM, 2000, pp. 243–254.
[179] D. Johnson, Y. Hu, and D. Maltz, "The Dynamic Source Routing Protocol (DSR) for mobile ad hoc networks for IPv4," Internet Engineering Task Force (IETF), Request for Comments (RFC) 4728, 2007.
[180] C. Perkins, E. Belding-Royer, and S. Das, "Ad hoc On-Demand Distance Vector (AODV) routing," Internet Engineering Task Force (IETF), Request for Comments (RFC) 3561, 2003.
[181] C. Lochert, M. Mauve, H. Füβler, and H. Hartenstein, "Geographic routing in city scenarios," *SIGMOBILE Mobile Computing and Communications Review*, vol. 9, no. 1, pp. 69–72, 2005.
[182] B.-C. Seet, G. Liu, B.-S. Lee, C.-H. Foh, K.-J. Wong, and K.-K. Lee, "A-STAR: A mobile ad hoc routing strategy for metropolis vehicular communications," in *Third International IFIP-TC6 Networking Conference (Networking 2004)*, ser. Lecture Notes in Computer Science (LNCS), vol. 3042. Springer, 2004, pp. 989–999.
[183] Z. Mo, H. Zhu, K. Makki, and N. Pissinou, "MURU: A multi-hop routing protocol for urban vehicular ad hoc networks," in *Third Annual International Conference on Mobile and Ubiquitous Systems (MobiQuitous'06)*. IEEE Computer Society, 2006, pp. 1–8.
[184] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," in *Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom'98)*. ACM, 1998, pp. 85–97.
[185] M. Jerbi, S.-M. Senouci, T. Rasheed, and Y. Ghamri-Doudane, "Towards efficient geographic routing in urban vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 9, pp. 5048–5059, 2009.
[186] Y.-B. Ko and N. H. Vaidya, "Location-aided Routing (LAR) in mobile ad hoc networks," *Wireless Networks*, vol. 6, no. 4, pp. 307–321, 2000.
[187] M. Jerbi, S.-M. Senouci, T. Rasheed, and Y. Ghamri-Doudane, "An infrastructure-free traffic information system for vehicular networks," in *66th IEEE Vehicular Technology Conference (VTC'07 – Fall)*. IEEE Computer Society, 2007, pp. 2086–2090.
[188] S. M. Bilal, S. Mustafa, and U. Saeed, "Impact of directional density on GyTAR routing protocol for VANETs in city environments," in *14th International Multitopic Conference (INMIC 2011)*. IEEE Computer Society, 2011, pp. 296–300.
[189] N. Brahmi, M. Boussedjra, J. Mouzna, and M. Bayart, "Adaptative movement aware routing for vehicular ad hoc networks," in *International Conference on Wireless Communications and Mobile Computing: Connecting the World Wirelessly (IWCMC'09)*. ACM, 2009, pp. 1310–1315.
[190] I. Leontiadis and C. Mascolo, "GeOpps: Geographical opportunistic routing for vehicular networks," in *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM'07)*. IEEE Computer Society, 2007, pp. 1–6.

[191] J.-W. Lee, C.-C. Lo, S.-P. Tang, M.-F. Horng, and Y.-H. Kuo, "A hybrid traffic geographic routing with cooperative traffic information collection scheme in VANET," in *13th International Conference on Advanced Communication Technology (ICACT 2011)*. IEEE Computer Society, 2011, pp. 1496–1501.

[192] H. Saleet, R. Langar, K. Naik, R. Boutaba, A. Nayak, and N. Goel, "Intersection-based geographical routing protocol for VANETs: A proposal and analysis," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 9, pp. 4560–4574, 2011.

[193] T. Clausen and P. Jacquet, "Optimized Link State Routing Protocol (OLSR)," Internet Engineering Task Force (IETF), Request for Comments (RFC), 2003.

[194] P. Fazio, F. D. Rango, C. Sottile, and A. F. Santamaria, "Routing optimization in vehicular networks: A new approach based on multiobjective metrics and minimum spanning tree," *International Journal of Distributed Sensor Networks*, pp. 1–13, 2013.

[195] J. Gong, C.-Z. Xu, and J. Holle, "Predictive directional greedy routing in vehicular ad hoc networks," in *27th International Conference on Distributed Computing Systems Workshops (ICDCSW'07)*. IEEE Computer Society, 2007, pp. 2:1–2:8.

[196] R. Tian, B. Zhang, J. Zheng, and J. Ma, "A new distributed routing protocol using partial traffic information for vehicular ad hoc networks," *Wireless Networks*, vol. 20, no. 6, pp. 1627–1637, 2014.

[197] G. Li and L. Boukhatem, "Adaptive vehicular routing protocol based on ant colony optimization," in *Tenth ACM International Workshop on Vehicular Ad Hoc Networks (VANET 2013)*. ACM, 2013, pp. 95–98.

[198] J. Luo, X. Gu, T. Zhao, and W. Yan, "A mobile infrastructure based VANET routing protocol in the urban environment," in *International Conference on Communications and Mobile Computing (CMC 2010)*, vol. 3. IEEE Computer Society, 2010, pp. 432–437.

[199] H.-Y. Pan, R.-H. Jan, A. A.-K. Jeng, and H.-R. Tseng, "Mobile-gateway routing for vehicular networks," in *Eighth IEEE VTS Asia-Pacific Conference on Wearable Computing Systems (APWCS 2011)*. IEEE Computer Society, 2011, pp. 1–5.

[200] H. Füβler, J. Widmer, M. Kasemann, M. Mauve, and H. Hartenstein, "Contention-based forwarding for mobile ad hoc networks," *Ad Hoc Networks*, vol. 1, no. 4, pp. 351–369, 2003.

[201] C. Adler, S. Eichler, T. Kosch, C. Schroth, and M. Strassberger, "Self-organized and context-adaptive information diffusion in vehicular ad hoc networks," in *Third International Symposium on Wireless Communication Systems (ISWCS'06)*. IEEE Computer Society, 2006, pp. 307–311.

[202] R. S. Schwartz, A. E. Ohazulike, and H. Scholten, "Achieving data utility fairness in periodic dissemination for VANETs," in *75th IEEE Vehicular Technology Conference Spring (VTC 2012 – Spring)*. IEEE Computer Society, 2012, pp. 1–5.

[203] M. Boban, R. Meireles, J. Barros, P. Steenkiste, and O. K. Tonguz, "TVR – tall vehicle relaying in vehicular networks," *IEEE Transactions on Mobile Computing*, vol. 13, no. 5, pp. 1118–1131, 2014.

[204] M. Raya, A. Aziz, and J.-P. Hubaux, "Efficient secure aggregation in VANETs," in *Third ACM International Workshop on Vehicular Ad Hoc Networks (VANET'06)*. ACM, 2006, pp. 67–75.

[205] X. Cheng, X. Hu, L. Yang, I. Husain, K. Inoue, P. Krein, R. Lefevre, Y. Li, H. Nishi, J. G. Taiber, F.-Y. Wang, Y. Zha, W. Gao, and Z. Li, "Electrified vehicles and the smart grid: The ITS perspective," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 4, pp. 1388–1404, 2014.

[206] G. K. Mitropoulos, I. S. Karanasiou, A. Hinsberger, F. Aguado-Agelet, H. Wieker, H.-J. Hilt, S. Mammar, and G. Noecker, "Wireless local danger warning: Cooperative foresighted driving using intervehicle communication," *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 3, pp. 539–553, 2010.

[207] L. Briesemeister, L. Schäfers, and G. Hommel, "Disseminating messages among highly mobile hosts based on inter-vehicle communication," in *IEEE Intelligent Vehicles Symposium (IV'00)*. IEEE Computer Society, 2000, pp. 522–527.

[208] A. Török, P. Laborczi, and G. Gerhath, "Spatially constrained dissemination of traffic information in vehicular ad hoc networks," in *68th Vehicular Technology Conference Fall (VTC'08 – Fall)*. IEEE Computer Society, 2008, pp. 1–5.

[209] C. Adler and M. Strassberger, "Putting together the pieces – A comprehensive view on cooperative local danger warning," in *13th ITS World Congress and Exhibition on Intelligent Transport Systems and Services (ITS'06)*, 2006.

[210] P. Costa, D. Gavidia, B. Koldehofe, H. Miranda, M. Musolesi, and O. Riva, "When cars start gossiping," in *Sixth Workshop on Middleware for Network Eccentric and Mobile Applications (MiNEMA'08)*. ACM, 2008, pp. 1–4.

[211] T. Nadeem, S. Dashtinezhad, C. Liao, and L. Iftode, "TrafficView: Traffic data dissemination using car-to-car communication," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 8, no. 3, pp. 6–19, 2004.

[212] K. A. Ibrahim and M. C. Weigle, "CASCADE: Cluster-based accurate syntactic compression of aggregated data in VANETs," in *IEEE Globecom Workshops*. IEEE Computer Society, 2008, pp. 1–10.

[213] S. Dietzel, F. Kargl, G. Heijenk, and F. Schaub, "Modeling in-network aggregation in VANETs," *IEEE Communications Magazine*, vol. 49, no. 11, pp. 142–148, 2011.

[214] T. Yan, W. Zhang, and G. Wang, "DOVE: Data dissemination to a desired number of receivers in VANET," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 4, pp. 1903–1916, 2014.

[215] C. Suthaputchakun, M. Dianati, and Z. Sun, "Trinary partitioned black-burst-based broadcast protocol for time-critical emergency message dissemination in VANETs," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 6, pp. 2926–2940, 2014.

[216] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "An adaptive system based on roadmap profiling to enhance warning message dissemination in VANETs," *IEEE/ACM Transactions on Networking*, vol. 21, no. 3, pp. 883–895, 2013.

[217] F. J. Martinez, M. Fogue, M. Coll, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Evaluating the impact of a novel warning message dissemination scheme for VANETs using real city maps," in *Ninth IFIP TC 6 international conference on Networking (NETWORKING 2010)*, ser. Lecture Notes in Computer Science (LNCS), vol. 6091. Springer, 2010, pp. 265–276.

[218] C. Barberis and G. Malnati, "Design and evaluation of a collaborative system for content diffusion and retrieval in vehicular networks," *IEEE Transactions on Consumer Electronics*, vol. 57, no. 1, pp. 105–112, 2011.

[219] R. S. Schwartz, A. E. Ohazulike, C. Sommer, H. Scholten, F. Dressler, and P. J. M. Havinga, "Fair and adaptive data dissemination for traffic information systems," in *IEEE Vehicular Networking Conference (VNC 2012)*. IEEE Computer Society, 2012, pp. 1–8.

[220] G. Korkmaz, E. Ekici, F. Özgüner, and Ü. Özgüner, "Urban multi-hop broadcast protocol for inter-vehicle communication systems," in *First ACM International Workshop on Vehicular Ad Hoc Networks (VANET'04)*. ACM, 2004, pp. 76–85.

[221] G. Korkmaz, E. Ekici, and F. Özgüner, "Black-burst-based multihop broadcast protocols for vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 5, pp. 3159–3167, 2007.

[222] H. Wu, R. Fujimoto, R. Guensler, and M. Hunter, "MDDV: A mobility-centric data dissemination algorithm for vehicular networks," in *First ACM International Workshop on Vehicular Ad Hoc Networks (VANET'04)*. ACM, 2004, pp. 47–56.

[223] O. K. Tonguz, N. Wisitpongphan, and F. Bai, "DV-CAST: A distributed vehicular broadcast protocol for vehicular ad hoc networks," *IEEE Wireless Communications*, vol. 17, no. 2, pp. 47–57, 2010.

[224] A. Laouiti, P. Mühlethaler, and Y. Toor, "Reliable opportunistic broadcast in VANETs (R-OB-VAN)," in *Ninth International Conference on Intelligent Transport Systems Telecommunications (ITST'09)*. IEEE Computer Society, 2009, pp. 382–387.

[225] X. Shen, X. Cheng, L. Yang, R. Zhang, and B. Jiao, "Data dissemination in VANETs: A scheduling approach," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 5, pp. 2213–2223, 2014.

[226] J. Zhao, Y. Zhang, and G. Cao, "Data pouring and buffering on the road: A new data dissemination paradigm for vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 6, pp. 3266–3277, 2007.

[227] M. Artimy, "Local density estimation and dynamic transmission-range assignment in vehicular ad hoc networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 8, no. 3, pp. 400–412, 2007.

[228] J. A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "An infrastructureless approach to estimate vehicular density in urban environments," *Sensors*, vol. 13, no. 2, pp. 2399–2418, 2013.

[229] A. Cornejo, C. Newport, S. Gollakota, J. Rao, and T. Giuli, "Prioritized gossip in vehicular networks," *Ad Hoc Networks*, vol. 11, no. 1, pp. 397–409, 2013.

[230] J. Jeong, S. Guo, Y. Gu, T. He, and D. Du, "TBD: Trajectory-based data forwarding for light-traffic vehicular networks," in *29th International Conference on Distributed Computing Systems (ICDCS'09)*. IEEE Computer Society, 2009, pp. 231–238.

[231] F. Xu, S. Guo, J. Jeong, Y. Gu, Q. Cao, M. Liu, and T. He, "Utilizing shared vehicle trajectories for data forwarding in vehicular networks," in *30th International Conference on Computer Communications (INFOCOM 2011)*. IEEE Computer Society, 2011, pp. 441–445.

[232] J. Jeong, S. Guo, Y. Gu, T. He, and D. H. Du, "Trajectory-based statistical forwarding for multihop infrastructure-to-vehicle data delivery," *IEEE Transactions on Mobile Computing*, vol. 11, no. 10, pp. 1523–1537, 2012.

[233] R. Jiang, Y. Zhu, T. He, Y. Liu, and L. M. Ni, "Exploiting trajectory-based coverage for geocast in vehicular networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 25, no. 12, pp. 3177–3189, 2014.

[234] Y. Ding and L. Xiao, "SADV: Static-node-assisted adaptive data dissemination in vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 5, pp. 2445–2455, 2010.

[235] L. Bononi and M. D. Felice, "A cross layered MAC and clustering scheme for efficient broadcast in VANETs," in *IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS'07)*, 2007, pp. 1–8.

[236] P. Szczurek, B. Xu, J. Lin, and O. Wolfson, "Spatio-temporal information ranking in VANET applications," *International Journal of Next-generation Computing*, vol. 1, no. 1, pp. 62–86, 2010.

[237] ——, "Machine learning approach to report prioritization with an application to travel time dissemination," in *Second SIGSPATIAL International Workshop on Computational Transportation Science (IWCTS'09)*. ACM, 2009, pp. 31–36.

[238] P. Szczurek, B. Xu, O. Wolfson, and J. Lin, "Estimating relevance for the emergency electronic brake light application," *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 4, pp. 1638–1656, 2012.

[239] O. Wolfson, B. Xu, and A. P. Sistla, "An economic model for resource exchange in mobile peer to peer networks," in *16th International Conference on Scientific and Statistical Database Management (SSDBM'04)*. IEEE Computer Society, 2004, pp. 235–244.

[240] L.-Y. Yeh and Y.-C. Lin, "A proxy-based authentication and billing scheme with incentive-aware multihop forwarding for vehicular networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 4, pp. 1607–1621, 2014.

[241] P. Szczurek, B. Xu, O. Wolfson, and J. Lin, "A platform for the development and evaluation of passive safety applications," in *IEEE Intelligent Vehicles Symposium (IV 2012)*. IEEE Computer Society, 2012, pp. 808–813.

[242] ——, "Intelligent Transportation Systems: When is safety information relevant?" in *12th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2011)*. IEEE Computer Society, 2011, pp. 1–6.

[243] P. Szczurek, B. Xu, O. Wolfson, J. Lin, and N. Rishe, "Prioritizing travel time reports in peer-to-peer traffic dissemination," in *Seventh International Symposium on Communication Systems Networks and Digital Signal Processing (CSNDSP 2010)*. IEEE Computer Society, 2010, pp. 454–458.

[244] E. Kokolaki, M. Karaliopoulos, and I. Stavrakakis, "Opportunistically assisted parking service discovery: Now it helps, now it does not," *Pervasive and Mobile Computing*, vol. 8, no. 2, pp. 210–227, 2012.

[245] ——, "Leveraging information in parking assistance systems," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 9, pp. 4309–4317, 2013.

[246] F. Alesiani and N. Maslekar, "Optimization of charging stops for fleet of electric vehicles: A genetic approach," *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 3, pp. 10–21, 2014.

[247] M. M. de Weerdt, E. H. Gerding, S. Stein, V. Robu, and N. R. Jennings, "Intention-aware routing to minimise delays at electric vehicle charging stations," in *23rd International Joint Conference on Artificial Intelligence (IJCAI 2013)*. AAAI Press / International Joint Conferences on Artificial Intelligence, 2013.

[248] P. Zhou, T. Nadeem, P. Kang, C. Borcea, and L. Iftode, "EZCab: A cab booking application using short-range wireless communication," in *Third IEEE International Conference on Pervasive Computing and Communications (PerCom'05)*, 2005, pp. 27–38.

[249] S. J. Pan, M. A. Khan, I. S. Popa, K. Zeitouni, and C. Borcea, "Proactive vehicle re-routing strategies for congestion avoidance," in *Eighth International Conference on Distributed Computing in Sensor Systems (DCOSS 2012)*. IEEE Computer Society, 2012, pp. 265–272.

[250] J. Pfrommer, J. Warrington, G. Schildbach, and M. Morari, "Dynamic vehicle redistribution and online price incentives in shared mobility systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 4, pp. 1567–1578, 2014.

[251] G. Yan, W. Yang, D. B. Rawat, and S. Olariu, "SmartParking: A secure and intelligent parking system," *IEEE Intelligent Transportation Systems Magazine*, vol. 3, no. 1, pp. 18–30, 2011.

[252] I. Ganchev, M. O'Droma, and D. Meere, "Intelligent car parking locator service," *International Journal on Information Technologies and Knowledge*, vol. 2, no. 2, pp. 166–173, 2008.

[253] Y. Geng and C. G. Cassandras, "New "smart parking" system based on resource allocation and reservations," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 3, pp. 1129–1139, 2013.

[254] X. Chen, E. Santos-Neto, and M. Ripeanu, "Crowdsourcing for on-street smart parking," in *Second ACM International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications (DIVANet 2012)*. ACM, 2012, pp. 1–8.

[255] S. S. Mathew, Y. Atif, Q. Z. Sheng, and Z. Maamar, "Building sustainable parking lots with the Web of Things," *Personal and Ubiquitous Computing*, vol. 18, no. 4, pp. 895–907, 2014.

[256] D. Ayala, O. Wolfson, B. Xu, B. DasGupta, and J. Lin, "Pricing of parking for congestion reduction," in *20th International Conference on Advances in Geographic Information Systems (SIGSPATIAL 2012)*. ACM, 2012, pp. 43–51.

[257] O. Wolfson and J. Lin, "A marketplace for spatio-temporal resources and truthfulness of its users," in *Seventh SIGSPATIAL International Workshop on Computational Transportation Science (IWCTS 2014)*. ACM, 2014, pp. 70–75.

[258] A. Schlote, C. King, E. Crisostomi, and R. Shorten, "Delay-tolerant stochastic algorithms for parking space assignment," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 5, pp. 1922–1935, 2014.

[259] E. Kokolaki, M. Karaliopoulos, G. Kollias, M. Papadaki, and I. Stavrakakis, "Vulnerability of opportunistic parking assistance systems to vehicular node selfishness," *Computer Communications*, vol. 48, no. 15, pp. 159–170, 2014.

[260] N. Bessghaier, M. Zargayouna, and F. Balbo, "An agent-based community to manage urban parking," in *Advances on Practical Applications of Agents and Multi-Agent Systems*, ser. Advances in Intelligent and Soft Computing, vol. 155. Springer, 2012, pp. 17–22.

[261] V. Verroios, V. Efstathiou, and A. Delis, "Reaching available public parking spaces in urban environments using ad-hoc networking," in *12th International Conference on Mobile Data Management (MDM 2011)*. IEEE Computer Society, 2011, pp. 141–151.

[262] D. Ayala, O. Wolfson, B. Xu, B. Dasgupta, and J. Lin, "Parking slot assignment games," in *19th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (GIS 2011)*. ACM, 2011, pp. 299–308.

[263] ——, "Parking in competitive settings: A gravitational approach," in *13th International Conference on Mobile Data Management (MDM 2012)*. IEEE Computer Society, 2012, pp. 27–32.

[264] P. Basu and T. D. C. Little, "Networked parking spaces: Architecture and applications," in *IEEE Vehicular Technology Conference Fall (VTC'02 – Fall)*. IEEE Computer Society, 2002, pp. 1153–1157.

[265] R. Panayappan, J. M. Trivedi, A. Studer, and A. Perrig, "VANET-based approach for parking space availability," in *Fourth ACM International Workshop on Vehicular Ad Hoc Networks (VANET'07)*. ACM, 2007, pp. 75–76.

[266] A. Klappenecker, H. Lee, and J. L. Welch, "Finding available parking spaces made easy," *Ad Hoc Networks*, vol. 12, pp. 243–249, 2012.

[267] M. Caliskan, A. Barthels, B. Scheuermann, and M. Mauve, "Predicting parking lot occupancy in vehicular ad hoc networks," in *65th IEEE Vehicular Technology Conference (VTC'07 – Spring)*. IEEE Computer Society, 2007, pp. 277–281.

[268] E. H.-K. Wu, C.-Y. Liu, J. Sahoo, M.-H. Jin, and S.-H. Lin, "Agile urban parking recommendation service for intelligent vehicular guiding system," *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 1, pp. 35–49, 2014.

[269] M. Caliskan, D. Graupner, and M. Mauve, "Decentralized discovery of free parking places," in *Third ACM International Workshop on Vehicular Ad Hoc Networks (VANET'06)*. ACM, 2006, pp. 30–39.

[270] B. Xu, O. Wolfson, J. Yang, L. Stenneth, P. S. Yu, and P. C. Nelson, "Real-time street parking availability estimation," in *14th International Conference on Mobile Data Management (MDM 2013)*, vol. 1. IEEE Computer Society, 2013, pp. 16–25.

[271] SFMTA, "SFpark," http://sfpark.org, San Francisco Municipal Transportation Agency (SFMTA), [Last access: August 10, 2015].

[272] S. Mathur, T. Jin, N. Kasturirangan, J. Chandrasekaran, W. Xue, M. Gruteser, and W. Trappe, "ParkNet: Drive-by sensing of road-side parking statistics," in *Eighth International Conference on Mobile*

Systems, Applications, and Services (MobiSys 2010). ACM, 2010, pp. 123–136.

[273] S. Nawaz, C. Efstratiou, and C. Mascolo, "ParkSense: A smartphone based sensing system for on-street parking," in *19th Annual International Conference on Mobile Computing & Networking (MobiCom 2013)*. ACM, 2013, pp. 75–86.

[274] K.-C. Lan and W.-Y. Shih, "An intelligent driver location system for smart parking," *Expert Systems with Applications*, vol. 41, no. 5, pp. 2443–2456, 2014.

[275] A. Nandugudi, T. Ki, C. Nuessle, and G. Challen, "PocketParker: Pocketsourcing parking lot availability," in *International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp 2014)*. ACM, 2014, pp. 963–973.

[276] S. di Martino, R. Fitzpatrick, S. Ilarri, and O. Wolfson, "HappyParking," *Dagstuhl Reports*, vol. 3, no. 12, pp. 120–121, 2014, section 5.2 of Social Issues in Computational Transportation Science (Dagstuhl Seminar 13512).

[277] E. Kokolaki, M. Karaliopoulos, and I. Stavrakakis, "Trading public parking space," in *15th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2014)*. IEEE Computer Society, 2014, pp. 1–6.

[278] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[279] E. Fasolo, M. Rossi, J. Widmer, and M. Zorzi, "In-network aggregation techniques for wireless sensor networks: A survey," *IEEE Wireless Communications*, vol. 14, no. 2, pp. 70–87, 2007.

[280] F. Picconi, N. Ravi, M. Gruteser, and L. Iftode, "Probabilistic validation of aggregated data in vehicular ad-hoc networks," in *Third ACM International Workshop on Vehicular Ad Hoc Networks (VANET'06)*. ACM, 2006, pp. 76–85.

[281] B. Scheuermann, C. Lochert, J. Rybicki, and M. Mauve, "A fundamental scalability criterion for data aggregation in VANETs," in *15th International Conference on Mobile Computing and Networking (MobiCom'09)*. ACM, 2009, pp. 285–296.

[282] C. Lochert, B. Scheuermann, and M. Mauve, "A probabilistic method for cooperative hierarchical aggregation of data in VANETs," *Ad Hoc Networks*, vol. 8, no. 5, pp. 518–530, 2010.

[283] M. Shoaib, W.-C. Song, and K. H. Kim, "Cluster based data aggregation in vehicular adhoc network," in *Fourth International Conference on Communication Technologies for Vehicles (Nets4Cars/Nets4Trains 2012)*, ser. Lecture Notes in Computer Science (LNCS), vol. 7266. Springer, 2012, pp. 91–102.

[284] S. Dietzel, E. Schoch, B. Bako, and F. Kargl, "A structure-free aggregation framework for vehicular ad hoc networks," in *Sixth International Workshop on Intelligent Transportation (WIT'09)*, 2009.

[285] L. Sun, Y. Wu, J. Xu, J. Li, and Y. Xu, "Data aggregation and information type in road probing," in *Internet of Things*, ser. Communications in Computer and Information Science, vol. 312. Springer, 2012, pp. 529–534.

[286] S. Dietzel, E. Schoch, B. Könings, M. Weber, and F. Kargl, "Resilient secure aggregation for vehicular networks," *IEEE Network*, vol. 24, no. 1, pp. 26–31, 2010.

[287] R. S. Schwartz, M. van Eenennaam, G. Karagiannis, G. J. Heijenk, W. K. Wolterink, and H. Scholten, "Using V2V communication to create over-the-horizon awareness in multiple-lane highway scenarios," in *Intelligent Vehicles Symposium (IV 2010)*. IEEE Computer Society, 2010, pp. 998–1005.

[288] K. A. Ibrahim and M. C. Weigle, "Optimizing CASCADE data aggregation for VANETs," in *Fifth IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS'08)*. IEEE Computer Society, 2008, pp. 724–729.

[289] J.-Y. Yang, L.-D. Chou, C.-F. Tung, S.-M. Huang, and T.-W. Wang, "Average-speed forecast and adjustment via VANETs," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 9, pp. 4318–4327, 2013.

[290] B. Yu, J. Gong, and C.-Z. Xu, "Catch-Up: A data aggregation scheme for VANETs," in *Fifth ACM International Workshop on Vehicular Ad Hoc Networks (VANET'08)*. ACM, 2008, pp. 49–57.

[291] S. Eichler, C. Merkle, and M. Strassberger, "Data aggregation system for distributing inter-vehicle warning messages," in *31st IEEE Conference on Local Computer Networks (LCN'06)*. IEEE Computer Society, 2006, pp. 543–544.

[292] C. Feng, Z. Li, S. Jiang, and R. Zhang, "Data aggregation and routing guidance with QoS guarantee in VANETs," *International Journal of Distributed Sensor Networks*, pp. 1–11, 2014.

[293] H.-W. Tsai, T.-S. Chen, and S.-K. Lin, "Dissemination of data aggregation in vehicular ad hoc networks," in *Tenth International Symposium on Pervasive Systems, Algorithms, and Networks (ISPAN'09)*. IEEE Computer Society, 2009, pp. 625–630.

[294] J. M. Molina-Gil, P. Caballero-Gil, C. Hernández-Goya, and C. Caballero-Gil, "Data aggregation for information authentication in VANETs," in *Sixth International Conference on Information Assurance and Security (IAS 2010)*. IEEE Computer Society, 2010, pp. 282–287.

[295] Q. Han, S. Du, D. Ren, and H. Zhu, "SAS: A secure data aggregation scheme in vehicular sensing networks," in *IEEE International Conference on Communications (ICC 2010)*. IEEE Computer Society, 2010, pp. 1–5.

[296] P. Caballero-Gil, J. Molina-Gil, and C. Caballero-Gil, "Data aggregation based on fuzzy logic for VANETs," in *Fourth International Conference on Computational Intelligence in Security for Information Systems (CISIS 2011)*. Springer, 2011, pp. 33–40.

[297] S. Dietzel, B. Bako, E. Schoch, and F. Kargl, "A fuzzy logic based approach for structure-free aggregation in vehicular ad-hoc networks," in *Sixth ACM International Workshop on Vehicular Ad Hoc Networks (VANET'09)*. ACM, 2009, pp. 79–88.

[298] A. Viejo, F. Sebé, and J. Domingo-Ferrer, "Aggregation of trustworthy announcement messages in vehicular ad hoc networks," in *69th IEEE Vehicular Technology Conference (VTC'09 – Spring)*. IEEE Computer Society, 2009, pp. 1–5.

[299] H. Zhu, X. Lin, R. Lu, P.-H. Ho, and X. Shen, "AEMA: An aggregated emergency message authentication scheme for enhancing the security of vehicular ad hoc networks," in *IEEE International Conference on Communications (ICC'08)*. IEEE Computer Society, 2008, pp. 1436–1440.

[300] W. Wang, S. S. Liao, X. Li, and J. S. Ren, "The process of information propagation along a traffic stream through intervehicle communication," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 1, pp. 345–354, 2014.

[301] S. Ilarri, E. Mena, and V. Rújula, "Vanet-X: A videogame to evaluate information management in vehicular networks," in *Third International Workshop on Information Management for Mobile Applications (IMMoA 2013)*, ser. CEUR Workshop Proceedings, vol. 1075. CEUR-WS.org, 2013, pp. 28–35.

[302] S. Demmel, A. Lambert, D. Gruyer, A. Rakotonirainy, and E. Monacelli, "Empirical IEEE 802.11p performance evaluation on test tracks," in *IEEE Intelligent Vehicles Symposium (IV 2012)*. IEEE Computer Society, 2012, pp. 837–842.

[303] Z. Li and C. Chigan, "On joint privacy and reputation assurance for vehicular ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 13, no. 10, pp. 2334–2344, 2014.

[304] K. M. Bach, M. G. Jæger, M. B. Skov, and N. G. Thomassen, "You can touch, but you can't look: Interacting with in-vehicle systems," in *26th SIGCHI Conference on Human Factors in Computing Systems (CHI'08)*. ACM, 2008, pp. 1139–1148.

[305] M. Compton, P. Barnaghi, L. Bermudez, R. García-Castro, Ó. Corcho, S. Cox, J. Graybeal, M. Hauswirth, C. Henson, A. Herzog, V. Huang, K. Janowicz, W. D. Kelsey, D. L. Phuoc, L. Lefort, M. Leggieri, H. Neuhaus, A. Nikolov, K. Page, A. Passant, A. Sheth, and K. Taylor, "The SSN ontology of the W3C Semantic Sensor Network Incubator Group," *Web Semantics: Science, Services and Agents on the World Wide Web*, vol. 17, pp. 25–32, 2012.

[306] S. Céspedes, N. Lu, and X. Shen, "VIP-WAVE: On the feasibility of IP communications in 802.11p vehicular networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 1, pp. 82–97, 2013.

[307] M. Raya, P. Papadimitratos, and J.-P. Hubaux, "Securing vehicular communications," *IEEE Wireless Communications*, vol. 13, no. 5, pp. 8–15, 2006.

[308] M. N. Mejri, J. Ben-Othman, and M. Hamdi, "Survey on VANET security challenges and possible cryptographic solutions," *Vehicular Communications*, vol. 1, no. 2, pp. 53–66, 2014.

[309] F. Qu, Z. Wu, F.-Y. Wang, and W. Cho, "A security and privacy review of VANETs," *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–12, 2015, to appear.

[310] H. Mousannif, I. Khalil, and S. Olariu, "Cooperation as a service in VANET: Implementation and simulation results," *Mobile Information Systems*, vol. 8, no. 2, pp. 153–172, 2012.

[311] S. Olariu, I. Khalil, and M. Abuelela, "Taking VANET to the clouds," *International Journal of Pervasive Computing and Communications*, vol. 7, no. 1, pp. 7–21, 2011.

[312] S. Olariu, T. Hristov, and G. Yan, *Mobile Ad Hoc Networking: Cutting Edge Directions, Second Edition*. John Wiley & Sons, 2013, ch. 19 "The Next Paradigm Shift: From Vehicular Networks to Vehicular Clouds", pp. 645–700.

[313] M. Whaiduzzaman, M. Sookhak, A. Gani, and R. Buyya, "A survey on vehicular cloud computing," *Journal of Network and Computer Applications*, vol. 40, pp. 325–344, 2013.

[314] N. Liu, M. Liu, W. Lou, G. Chen, and J. Cao, "PVA in VANETs: Stopped cars are not silent," in *30th IEEE International Conference on Computer Communications (INFOCOM 2011)*. IEEE Computer Society, 2011, pp. 431–435.

[315] J. Balen, G. Martinovic, K. Paridel, and Y. Berbers, "PVCM: Assisting multi-hop communication in vehicular networks using parked vehicles," in *Fourth International Congress on Ultra Modern Telecommunications and Control Systems (ICUMT 2012)*. IEEE Computer Society, 2012, pp. 119–122.

[316] N. Liu, M. Liu, G. Chen, and J. Cao, "The sharing at roadside: Vehicular content distribution using parked vehicles," in *31st IEEE International Conference on Computer Communications (INFOCOM 2012)*. IEEE Computer Society, 2012, pp. 2641–2645.

[317] F. Malandrino, C. Casetti, C.-F. Chiasserini, C. Sommer, and F. Dressler, "The role of parked cars in content downloading for vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 9, pp. 4606–4617, 2014.

[318] C. Sommer, D. Eckhoff, and F. Dressler, "IVC in cities: Signal attenuation by buildings and how parked cars can improve the situation," *IEEE Transactions on Mobile Computing*, vol. 13, no. 8, pp. 1733–1745, 2014.

Sergio Ilarri is an Associate Professor in the Department of Computer Science and Systems Engineering at the University of Zaragoza. He received his B.S. and his PhD in Computer Science from the University of Zaragoza in 2001 and 2006, respectively. For a year, he was a visiting researcher in the Mobile Computing Laboratory at the Department of Computer Science at the University of Illinois in Chicago, and he has also cooperated (through several research stays) with the University of Valenciennes and with IRIT in Toulouse. His research interests include data management issues for mobile computing, vehicular networks, mobile agents, and the Semantic Web. He authored a number of publications in relevant journals and conferences and participated as guest editor of special issues in Transportation Research Part-C, IEEE Internet Computing, IEEE Multimedia, the Journal of Systems and Software, and the Distributed and Parallel Databases journal.

Thierry Delot is an Associate Professor at the University of Valenciennes since 2002. He is a member of the LAMIH research center (UMR CNRS/UVHC 8201) and an associate researcher at INRIA Lille Nord Europe in the FUN research group. Thierry received the MSc and the PhD in Computer Science at the University of Versailles in 1998 and 2001, respectively. Thierry's research interests mainly concern mobile data management and query processing techniques. He is or has been involved in several projects related to data management in vehicular networks. He was guest editor of several special issues related to data management published in Transportation Research Part-C (Emerging Technologies), Pervasive and Mobile Computing or the Journal of Systems and Software. In the past five years, Thierry co-authored 2 books, 8 book chapters, 8 papers in international journals, and 11 articles in international conferences. Thierry has also been the (co-)organizer of several events of the database community such as the CNRS Summer School on Ambient Intelligence in 2009 and 2011, the EDBT Summer School in 2009, the DS2ME@ICDE workshop in 2008 or the IMMoA@VLDB workshop in 2012 and 2013.

Raquel Trillo-Lado is an Associate Professor (Profesora Colaboradora) in the Department of Computer Science and Systems Engineering at the University of Zaragoza. She received her B.S. and her PhD in Computer Science from the University of A Coruña in 2003 and 2012, respectively. She was a visiting researcher in the Databases Group (DBGroup) at the University of Modena and Reggio Emilia (Italy), and she has also cooperated with the Databases Laboratory (LBD) at the University of A Coruña. Her research interests include data management in different contexts, in particular keyword search on structured data sources. She authored several publications in relevant journals and conferences.

APPENDIX A
COMMUNICATION TECHNOLOGIES USED IN VANETS: WAVE AND OTHER EFFORTS

Several technologies have been considered as potential enablers of vehicular communications. For example, [1] identifies 802.11p WAVE, Wi-Fi, cellular, and infrared, as representative vehicular communication wireless data links. In the following, we provide an overview of the technologies considered, emphasizing the role of the standard WAVE:

- *Cellular networks*, such as *GSM* (*Global System for Mobile Communications*), *GPRS* (*General Packet Radio Service*), *3G/4G* or the future *5G* [2], *UMTS* (*Universal Mobile Telecommunications System*), or *LTE* (*Long Term Evolution*). These technologies could be used in vehicular environments, but they are infrastructure-based, centralized, and subject to consumer fees. They are not designed for ad hoc scenarios, where other short-range communication technologies are usually considered more appropriate (see Section III-C). Nevertheless, *Device-to-Device* (*D2D*) communications are also being studied as an underlay to cellular networks (e.g., see [3], [4]): they enable direct communication between mobile devices without using the support infrastructure (e.g., the base stations). At the moment, there is no standard for D2D communications [4].
  According to the study presented in [5], UMTS cannot guarantee a suitable warning message delivery delay. Besides, the maximum data rate that it offers is 20 times lower than that offered by a WLAN (*Wireless Local Area Network*). Nevertheless, within the FleetNet project, an adaptation of *UTRA TDD* (*UMTS Terrestrial Radio Access Time Division Duplex*) for VANETs is proposed [6], [7]: in [6] the authors compare UTRA TDD and the IEEE 802.11b standard in vehicular environments, and conclude that UTRA TDD outperforms IEEE 802.11b. A survey on the benefits and problems of LTE as an enabling technology for VANETs is available in [8].
- *Bluetooth* [9]. As an example, the potential use of Bluetooth for ad hoc connections between moving vehicles is studied in [10]. Through simulations, the authors study the service discovery and connection times required, as well as the impact of speed on the maximum time within communication range. They conclude that the results obtained do not preclude the use of Bluetooth in applications where the connecting devices will stay in range of each other only for a short time. Nevertheless, nowadays Bluetooth is not usually considered a key technology for vehicular networks.
- The term *DSRC* (*Dedicated Short-Range Communications*) [11], [12] refers to communications taking place in a dedicated, licensed, frequency band. Thus, for example, in the United States, DSRC communications operate over a dedicated 75 MHz spectrum band in the 5.9 GHz band, which was allocated by the US Federal Communications Commission (FCC) in October 1999. This avoids interference with other Wi-Fi devices using unlicensed frequencies. So, they are considered particularly appropriate as enablers of active safety systems, that can benefit from a controlled spectrum for reliability and/or efficiency reasons. They are expected to offer interesting advantages in vehicular communications, such as a suitable operation in scenarios with a high mobility of vehicles, communication ranges of up to 1 Km, and reliability in harsh environments with extreme weather conditions. Initially they were based on the standard IEEE 802.11a (ASTM-DSRC standard [13]), but later there was a shift to the WAVE standard (commented below) and the term DSRC/WAVE was popularized [14], which means that nowadays DSRC and WAVE are considered jointly.
- Amendments to the basic *IEEE 802.11* standard. The first version of IEEE 802.11 was released in 1997 and revised in 1999, 2007, and 2012 (e.g., the 2012 version is available in [15]). As an example of standard within the IEEE 802.11 family, IEEE 802.11n (released in 2009) offers up to 600 Mb/s [16].
  Several studies have analyzed the potential use of WLAN communication technologies in VANETs. For example, [17] considers IEEE 802.11a, IEEE 802.11b, and IEEE 802.11g. According to that work, "Overall, WLAN technology proved to work also at vehicular speed". In [18], the authors study the potential use of IEEE 802.11b for vehicular communications and conclude that it is suitable for high-mobility scenarios, but they also emphasize that it is significantly affected by the environment, due to the presence of buildings and the availability of *Line Of Sight*.
  IEEE 802.11p targets specifically vehicular networks [19]. It supports communications between vehicles moving at up to 200 Km/h, a theoretical maximum communication range of 1 Km, and data exchanges between moving devices of a few seconds before the connectivity is lost [16]. Besides, it is part of the WAVE framework (see below).
- *WAVE* (*Wireless Access in Vehicular Environments*) [20], [21] standards (IEEE 802.11p and IEEE 1609.x) have been more recently proposed, motivated by the important differences between VANETs and traditional WLANs. So, WAVE is designed to support a highly-dynamic network (vehicles moving at high speeds), extreme multipath environments (many signal reflections), long ranges of operation (up to 1 Km), priority control, removal of long connection establishment delays, etc.
  It is based on the standard IEEE 802.11 [16], but with some variations to adapt it to a vehicular environment, that conform the IEEE 802.11p standard (e.g., see [20]). A WAVE environment is composed of RSUs (see Section III-C) in static locations (e.g., traffic lights, road signs) and *OBUs* (*On-Board Units*) mounted on vehicles. WAVE supports two protocol stacks: IPv6 and also *WSMP* (*WAVE Short-Message Protocol*), thus enabling both time-critical communications and TCP/UDP delay-tolerant transmissions. The WSMP supports directly controlling physical layer characteristics (e.g., the channel number and the transmission power used). In WAVE there is a control channel (CCH) and service channels

(SCHs). WAVE short messages (WSMs) can be sent on any channel, whereas IP traffic is allowed only on SCHs. The WAVE communication stack is composed of IEEE 802.11p (the Physical and MAC layers, based on IEEE 802.11a), IEEE 1609.4 (multichannel operation, on top of the MAC layer), IEEE 1609.3 (networking services, related to the Logical Link Control, network, and transport layers of the OSI model, which allows incorporating IPv6, UDP, TCP, and WSMP), IEEE 1609.1 (resource management), and IEEE 1609.2 (security services). WAVE enables communications outside the context of a basic service set (BSS), with the WAVE units operating independently, in such a way that the initial overhead of association and authentication can be avoided. Nevertheless, WAVE basic service sets (WBSSs) are also supported, which can consist of OBUs or OBUs and RSUs. The WAVE standard supports configuring a portal function at an RSU, between the wireless network and a wired network.

Some studies have also evaluated the performance of WAVE. For example, based on simulations, [22] shows that the traffic prioritized schemes work well and the delay of highest-priority control messages remains very limited, but also suggests the need of more work to avoid higher delays when the network load is high.

From the aforementioned communication technologies, WAVE, as the standard specifically focused on vehicular networks, is considered the most promising one. However, studies such as [21] emphasize that the field is still open to additional research and development and several efforts are ongoing. As an example, the work presented in [23] studies several limitations of the IP communications supported in WAVE and proposes a new framework to address them, called *VIP-WAVE* (*Vehicular IP in WAVE*). An IPv6 communication stack providing network continuity for vehicular networks is presented in [24]. As another example, [25] proposes adaptations to the MAC protocol of IEEE 802.11p to support different access priorities based on mobility parameters of vehicles, in order to avoid unfairness problems. A service differentiation scheme is proposed as an enhancement of WAVE in [26], based on a fuzzy inference system that deduces a *context severity metric* of a vehicle in relation to its environment and the neighbor vehicles. Regarding MAC protocols, the work presented in [27] advocates the use of *TDMA* (*Time Division Multiple Access*) to avoid the indeterminacy of the IEEE 802.11p CSMA/CA (*Carrier Sense Multiple Access with Collision Avoidance*) protocol, and [28] presents a survey of MAC approaches proposed for VANETs and discusses existing challenges. The study in [29] argues that the current specification of IEEE 802.11p leads to performance degradation in harsh highly-dynamic vehicular environments, and proposes a new adaptive algorithm where vehicles modify their transmission parameters based on the density and average speed of vehicles in the road. As a final example, according to [30], it is possible to set up a smartphone-based vehicular network that, using cellular communications, can achieve a latency below one second.

Supporting the use of different communication technologies transparently has also been the subject of research [31]. The work presented in [32] indicates that vehicular communication solutions using different technologies are not uncommon. According to [33], [34], [35], the future trend is indeed to integrate different types of communication technologies, in order to better exploit the specific benefits of each one and their availability, as well as the specific needs.

On the other hand, the possibility of performing *Dynamic Spectrum Access* (*DSA*) in vehicular networks [36], and more specifically TV white space, is also attracting attention recently as a possible solution to the spectrum scarcity problem. For example, [37] presents the first trial of inter-vehicle communications using TV white space in a city, and there are other proposals to use the TV band (e.g., [38]). One technology for DSA is cognitive radio [36], which has given rise to the concept of *cognitive vehicular networks* (*CVNs*) [39], [40]. CVNs imply adapting the concept of cognitive radio [41] to the context of vehicular networks, in such a way that vehicles can opportunistically access radio channels allocated to licensed users. A framework for the coexistence of IEEE 802.22 networks and CVNs was recently presented in [42].

References Cited in the Appendix

[1] P. Papadimitratos, A. de La Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 84–95, 2009.

[2] E. Hossain and M. Hasan, "5G cellular: key enabling technologies and research challenges," *IEEE Instrumentation Measurement Magazine*, vol. 18, no. 3, pp. 11–21, 2015.

[3] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Communications Magazine*, vol. 47, no. 12, pp. 42–49, 2009.

[4] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1801–1819, 2014.

[5] C. Wewetzer, M. Caliskan, K. Meier, and A. Luebke, "Experimental evaluation of UMTS and Wireless LAN for inter-vehicle communication," in *Seventh International Conference on ITS Telecommunications (ITST'07)*. IEEE Computer Society, 2007, pp. 1–6.

[6] A. Ebner, H. Rohling, L. Wischhof, R. Halfmann, and M. Lott, "Performance of UTRA TDD ad hoc and IEEE 802.11b in vehicular environments," in *57th IEEE Vehicular Technology Conference-Spring (VTC'03 – Spring)*, vol. 2. IEEE Computer Society, 2003, pp. 960–964.

[7] M. Lott, R. Halfmann, E. Schulz, M. Meincke, M. D. P. Guirao, and K. Jobmann, *InterVehicle-Communications Based on Ad Hoc Networking Principles: The FleetNet Project*. Universitätsverlag Karlsruhe, 2005, ch. 2 "Data Link Control", pp. 29–81.

[8] G. Araniti, C. Campolo, M. Condoluci, A. Iera, , and A. Molinaro, "LTE for vehicular networking: A survey," *IEEE Communications Magazine*, vol. 51, no. 5, pp. 148–157, 2013.

[9] I. Bluetooth SIG, "Bluetooth technology website," http://www.bluetooth.com [Last access: August 10, 2015].

[10] P. Murphy, E. Welsh, and J. P. Frantz, "Using Bluetooth for short-term ad hoc connections between moving vehicles: A feasibility study," in *IEEE 55th Vehicular Technology Conference Spring (VTC'02 – Spring)*, vol. 1, 2002, pp. 414–418.

[11] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 GHz DSRC-based vehicular safety communication," *IEEE Wireless Communications*, vol. 13, no. 5, pp. 36–43, 2006.

[12] X. Wu, S. Subramanian, R. Guha, R. G. White, J. Li, K. W. Lu, A. Bucceri, and T. Zhang, "Vehicular communications using DSRC: Challenges, enhancements, and evolution," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 9, pp. 399–408, 2013.

[13] ASTM International, "Standard specification for telecommunications and information exchange between roadside and vehicle systems – 5GHz band Dedicated Short Range Communications (DSRC): Medium Access Control (MAC) and Physical Layer (PHY) Specifications," ASTM E2213-03, 2003.

[14] Y. J. Li, "An overview of the DSRC/WAVE technology," in *Quality, Reliability, Security and Robustness in Heterogeneous Networks*, ser. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol. 74. Springer, 2012, pp. 544–558.

[15] IEEE, "802.11-2012 – IEEE standard for information technology – telecommunications and information exchange between systems local and metropolitan area networks – specific requirements part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications," pp. 1–2793, 2012.

[16] G. R. Hiertz, D. Denteneer, L. Stibor, X. P. Costa, and B. Walke, "The IEEE 802.11 universe," *IEEE Communications Magazine*, vol. 48, no. 1, pp. 62–70, 2010.

[17] M. Wellens, B. Westphal, and P. Mähönen, "Performance evaluation of IEEE 802.11-based WLANs in vehicular scenarios," in *65th Vehicular Technology Conference Spring (VTC'07 – Spring)*, 2007, pp. 1167–1171.

[18] V. González, A. L. Santos, C. Pinart, and F. Milagro, "Experimental demonstration of the viability of IEEE 802.11b based inter-vehicle communications," in *Fourth International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities (TridentCom'08)*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008, pp. 1:1–1:7.

[19] S. Demmel, A. Lambert, D. Gruyer, A. Rakotonirainy, and E. Monacelli, "Empirical IEEE 802.11p performance evaluation on test tracks," in *IEEE Intelligent Vehicles Symposium (IV 2012)*. IEEE Computer Society, 2012, pp. 837–842.

[20] D. Jiang and L. Delgrossi, "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," in *IEEE Vehicular Technology Conference (VTC'08 – Spring)*. IEEE Computer Society, 2008, pp. 2036–2040.

[21] R. A. Uzcátegui and G. Acosta-Marum, "WAVE: A tutorial," *IEEE Communications Magazine*, vol. 47, no. 5, pp. 126–133, 2009.

[22] S. Gräfling, P. Mähönen, and J. Riihijärvi, "Performance evaluation of IEEE 1609 WAVE and IEEE 802.11p for vehicular communications," in *Second International Conference on Ubiquitous and Future Networks (ICUFN 2010)*. IEEE Computer Society, 2010, pp. 344–348.

[23] S. Céspedes, N. Lu, and X. Shen, "VIP-WAVE: On the feasibility of IP communications in 802.11p vehicular networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 1, pp. 82–97, 2013.

[24] J. Santa, F. Pereníguez, F. Bernal, P. J. Fernández, R. Marín, and A. F. Skarmeta, "A framework for supporting network continuity in vehicular IPv6 communications," *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 1, pp. 17–34, 2014.

[25] W. Alasmary and W. Zhuang, "Mobility impact in IEEE 802.11p infrastructureless vehicular networks," *Ad Hoc Networks*, vol. 10, no. 2, pp. 222–230, 2012.

[26] M. A. Salahuddin, A. Al-Fuqaha, and M. Guizani, "Exploiting context severity to achieve opportunistic service differentiation in vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 6, pp. 2901–2915, 2014.

[27] J. Sahoo, E. H.-K. Wu, P. K. Sahu, and M. Gerla, "Congestion-controlled-coordinator-based MAC for safety-critical message transmission in VANETs," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 3, pp. 1423–1437, 2013.

[28] M. Booysen, S. Zeadally, and G.-J. van Rooyen, "Survey of media access control protocols for vehicular ad hoc networks," *IET Communications*, vol. 5, no. 11, pp. 1619–1631, 2011.

[29] K. Hafeez, L. Zhao, B. Ma, and J. Mark, "Performance analysis and enhancement of the DSRC for VANET's safety applications," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 7, pp. 3069–3083, 2013.

[30] Y. Park, J. Ha, S. Kuk, H. Kim, C.-J. Liang, and J. Ko, "A feasibility study and development framework design for realizing smartphone-based vehicular networking systems," *IEEE Transactions on Mobile Computing*, vol. 13, no. 11, pp. 2431–2444, 2014.

[31] W. Kellerer, C. Bettstetter, C. Schwingenschlögl, P. Sties, K.-E. Steinberg, and H.-J. Vögel, "(Auto) mobile communication in a heterogeneous and converged world," *IEEE Personal Communications*, vol. 8, no. 6, pp. 41–47, 2001.

[32] O. Mehani, R. Boreli, and T. Ernst, "Context-adaptive vehicular network optimization," in *Ninth International Conference on Intelligent Transport Systems Telecommunications (ITST'09)*. IEEE Computer Society, 2009, pp. 186–191.

[33] F. Dressler, H. Hartenstein, O. Altintas, and O. K. Tonguz, "Inter-vehicle communication: Quo vadis," *IEEE Communications Magazine*, vol. 52, no. 6, pp. 170–177, 2014.

[34] X. Cheng, X. Hu, L. Yang, I. Husain, K. Inoue, P. Krein, R. Lefevre, Y. Li, H. Nishi, J. G. Taiber, F.-Y. Wang, Y. Zha, W. Gao, and Z. Li, "Electrified vehicles and the smart grid: The ITS perspective," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 4, pp. 1388–1404, 2014.

[35] S. Imadali, A. Kaiser, F. Sivrikaya, N. El Sayed, M. Boc, W. Klaudel, A. Petrescu, and V. Veque, "A review of network mobility protocols for fully electrical vehicles services," *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 3, pp. 80–95, 2014.

[36] S. Pagadarai, B. A. Lessard, A. M. Wyglinski, R. Vuyyuru, and O. Altintas, "Vehicular communication: Enhanced networking through dynamic spectrum access," *IEEE Vehicular Technology Magazine*, vol. 8, no. 3, pp. 93–103, 2013.

[37] O. Altintas, K. Seki, H. Kremo, M. Matsumoto, R. Onishi, and H. Tanaka, "Vehicles as information hubs during disasters: Glueing Wi-Fi to TV white space to cellular networks," *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 1, pp. 68–71, 2014.

[38] T. Jiang, Z. Wang, L. Zhang, D. Qu, and Y.-C. Liang, "Efficient spectrum utilization on TV band for cognitive radio based high speed vehicle network," *IEEE Transactions on Wireless Communications*, vol. 13, no. 10, pp. 5319–5329, 2014.

[39] D. Niyato, E. Hossain, and P. Wang, "Optimal channel access management with QoS support for cognitive vehicular networks," *IEEE Transactions on Mobile Computing*, vol. 10, no. 4, pp. 573–591, 2011.

[40] M. Di Felice, R. Doost-Mohammady, K. Chowdhury, and L. Bononi, "Smart radios for smart vehicles: Cognitive vehicular networks," *IEEE Vehicular Technology Magazine*, vol. 7, no. 2, pp. 26–33, 2012.

[41] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40–48, 2008.

[42] Y. Han, E. Ekici, H. Kremo, and O. Altintas, "Enabling coexistence of cognitive vehicular networks and IEEE 802.22 networks via optimal resource allocation," in *13th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt 2015)*. IEEE Computer Society, 2015, pp. 451–458.