Vehicular Networks: A New Challenge for Content Delivery-based Applications

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A significant number of promising applications for vehicular ad-hoc networks (VANETs) are becoming a reality. Most of these applications require a variety of heterogenous content to be delivered to vehicles and to their on-board users. However, the task of content delivery in such dynamic and large-scale networks is easier said than done. In this paper, we propose a classification of content delivery solutions applied to VANETs while highlighting their new characteristics and describing their underlying architectural design. First, the two fundamental building blocks that are part of an entire content delivery system are identified: replica allocation and content delivery. The related solutions are then classified according to their architectural definition. Within each category, solutions are described based on the techniques and strategies that have been adopted. As result, we present an in-depth discussion on architecture, techniques, and strategies adopted by studies in the literature that tackle problems related to vehicular content delivery networks.

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1. INTRODUCTION

Vehicular ad-hoc networks (VANETs) are migrating from theory to practice, due to the manufacturers' interest in providing new on-road services to their clients [Zeadally et al. 2012]. VANETs consist of vehicles with on-board wireless communication facilities that are able to establish ad-hoc communication with their peers, as well as with infrastructure stations. In addition to wireless communication capability, vehicles in a

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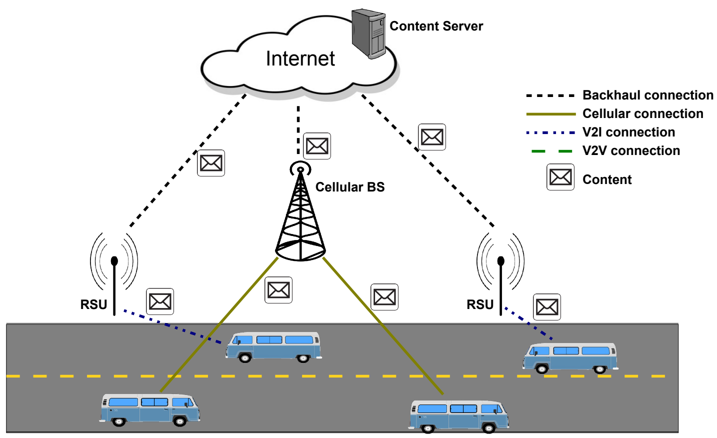
VANET are also equipped with processing, memory, storage, sensors, and visualization units.

The VANET paradigm is evolving from simple warning messages to advanced applications with content delivery requirements, such as those used for entertainment, information, and advertisement [Willke et al. 2009; Lee et al. 2014]. In entertainment applications, media content of various types, including video, music, and web page (to name a few) are delivered to on-board users during their journey. In information systems, the delivered content transmits news, weather and traffic reports, road conditions, and any other information that may be of interest to users. In advertisement applications, users receive advertisements from restaurants and hotels on their route, and regarding hotels, and parking at their final destination. The content sources of these applications are located outside the VANET, most likely somewhere on the Internet. In addition to externally-sourced applications, it is important to recognize another class of application with sources internal to the network. In the latter case, vehicles equipped with a variety of sensors are able to gather information and deliver it to other vehicles. For example, a vehicle that identifies the occurrence of an accident may deliver a real-time video showing the area of the accident to its peers.

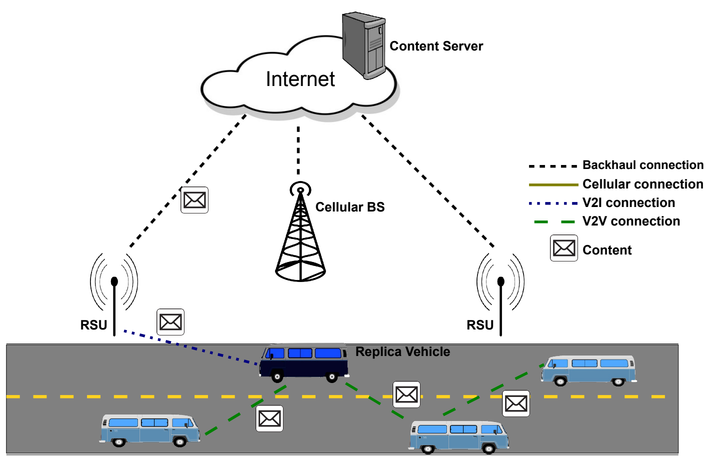
Several problems can arise in VANETs when content is shared only through infrastructure communication. First, the access network may be overloaded, as many vehicles will require a medium to receive their content. Furthermore, servers may also be overloaded, since they will have to respond to a large number of requests. The overloaded resources may result in longer response times, congestion, packet loss, and, consequently, low quality of experience for the user. Moreover, the stationary infrastructure stations must be strategically placed to cover the entire application area. Finally, a higher user cost may apply, since the infrastructure communication is more expensive than ad-hoc.

Given that content delivery is an important demand for VANET applications, and that it is not appropriate to use only the infrastructure communication, the idea do organize vehicles as a content delivery network (CDN) is promising [Pathan and Buyya 2007]. The objective of a CDN is to distribute content replicas to surrogate servers in order to keep content close to clients. In VANET scenarios, some vehicles can be selected to act as temporary content providers for delivering content to potential clients nearby using vehicle-to-vehicle (V2V) communication, a less expensive approach than using vehicle-to-infrastructure (V2I). Furthermore, this may lead to network access and server offload, as well as lower response time and bandwidth consumption. These benefits are illustrated in Figure 1. In the first part 1(a), infrastructure communication alone is used to deliver content to all vehicles, through both Road-side Units (RSUs) and cellular networks. In the second part 1(b), one vehicle is selected to keep a replica of the content, and to use V2V communication to deliver it to other vehicles. The replica allocation in 1(b) illustrates that it required only one message from the infrastructure, compared to the four that were required when V2V communication was not used (Figure 1(a)).

Content Delivery Networks will play an important role by allowing high quality and low-cost content delivery to VANET applications. Thus, researchers in this field should be aware of the state-of-the-art solutions in order to determine their research directions. In this paper, we propose a classification of content delivery solutions applied to VANETs while highlighting their new characteristics and describing their underlying architectural design. First, we identify two fundamental building blocks that are part of an entire CDN system: replica allocation and content delivery. We then classify the related solutions for each one, according to their architecture characteristics, as depicted in Figure 2. Within each category, we also categorize the solutions based on their input data, techniques, and strategies adopted. As a result, this article presents



(a) Infrastructure-Only Content Delivery



(b) Content Delivery by Selecting a Vehicle as Replica

Fig. 1. In infrastructure-only content delivery (a), the server uses V2I communication (cellular or RSUs), which may overload the network as well as the server. On the other hand, in the CDN approach (b), a vehicle is selected to act as a surrogate server, and uses V2V communication to deliver the content to its peers; consequently, it offloads the network and the server, as well as decreases cost and improves applications' performance.

an in-depth discussion on architecture, techniques, and strategies adopted by studies in the literature that tackle problems related to vehicular content delivery networks. Furthermore, the challenges faced when proposing vehicular content delivery network solutions are also presented.

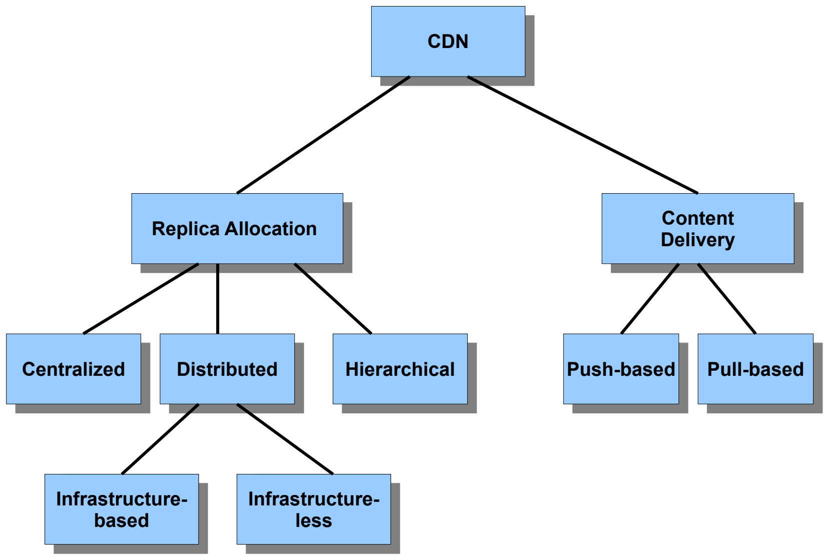


Fig. 2. CDN categories from the architecture perspective. Two fundamental building blocks are part of a CDN system: Replica Allocation and Content Delivery. There are different architecture approaches to implement these building blocks.

This article is organized as follows. Section 2 presents a brief description of traditional Content Delivery Networks, as well as how this concept is applied to VANET scenarios. This section also presents some important challenges that must be addressed in this field. In Section 3, we analyze the studies related to replica allocation in VANETs, which is one of the fundamental CDN building blocks. In Section 4, we analyze the studies that propose solutions to content delivery in VANETs, which is the other fundamental CDN building block. The studies described in Sections 3 and 4 are organized according to their architecture, as well as the techniques employed in their solutions. Finally, Section 5 concludes this survey and presents some future directions.

2. CONTENT DELIVERY NETWORK (CDN)

The increase in demand for Internet services, particularly in the context of the Web during the 1990s, has led to problems with network congestion and server overload [Hofmann and Beaumont 2005]. Due to the large demand, content provider servers began suffering from performance issues, and were unable to respond to all requests in a satisfactory way. To tackle this problem, a new concept called Content Delivery Network (CDN) was proposed in the late 1990s [Peng 2004; Vakali and Pallis 2003; Pathan and Buyya 2007; Pallis and Vakali 2006]. The basic idea behind CDN is to allocate content replicas in different, strategically placed servers, and to redirect a request to the most appropriate server that could better respond to it.

According to the CDN literature [Peng 2004; Pathan and Buyya 2007], there are two major challenges that arise when designing a CDN. The first is the issue of selecting good replica locations and replicating the content, thus keeping it up to date. The second challenge is related to the discovery of the most appropriate replica and the content delivery itself. These issues are the two fundamental building blocks that compose a CDN system, and are even more challenging in dynamic environments such as VANETs. In this article, we refer to these concepts as replica allocation and content delivery, respectively. Since CDN concepts and studies are well covered in the literature, we do not extend the discussion on this subject to our survey. Readers can refer to the articles [Peng 2004; Pathan and Buyya 2007; Vakali and Pallis 2003] and [Pallis and Vakali 2006] to find relevant details on this field.

2.1. Vehicular Content Delivery Networks

A significant number of promising applications for VANETs are becoming a reality [Willke et al. 2009; Lee et al. 2014]. Most of them require the delivery of a variety of content that may be provided by vehicles themselves, or by any other entities in the network. In the first case, the vehicles act as sensors and content sources. They will be equipped with GPS, cameras, weather sensors, and microphones, among other sensors. In addition to the physical sensors, vehicles may infer important information based on their knowledge, regarding accidents, hazards in the road, slick surfaces, and so on. Applications that can use these sensors include real-time accident video transmission, weather prediction, and alert indications. Another class of applications is one in which content originates from the infrastructure (e.g., Internet servers) and must be delivered to the vehicles. This class includes applications such as on-demand video, web page access, advertisements, file downloads, and information systems (e.g., traffic, weather, incidents), to name a few.

All of the applications mentioned above, and others that hold promise, require the delivery of some sort of content to vehicles. Thus, the deployment of a CDN in such environments seems to be a good solution to help provide more quality content, reduce end-to-end delay in content delivery, reduce bandwidth consumption, and offload the network infrastructure. This general idea has already been discussed in some studies [Lee et al. 2014; Gerla et al. 2014b; Amadeo et al. 2013]. However, there is no such study that analyzes the solutions of CDN applied to VANETs, which we achieve in this current work.

The studies described in this survey apply different terms to the same concepts. Thus, we organize the main CDN concepts applied to VANETs and their respective terms in Table I. This taxonomy table helps with the reading of our survey, as well as those of other related works. When describing and discussing specific studies, we use the same terms their authors have adopted to facilitate the comprehension of further references to the original study.

Table I. Taxonomy

Concept Description	**Related Terms**
Selection of specific nodes to act as temporary content providers	Replica allocation; Replica selection; Replica placement;
Nodes selected to act as temporary content providers	Replica keepers; Carriers; Surrogate servers; Mobile storage; Replica nodes; Bearers;
Fixed infrastructure station placed on the roads	Road-side unit (RSU); Base Station (BS); Access Point (AP); Infostation;
Node interested in some content	Client; User; Requester; Consumer; Subscriber; Downloader;
Node providing content	Server; Provider; Publisher;

2.2. Challenges

CDN is a well explored field in the area of traditional networks, including the Internet [Pathan and Buyya 2007; Peng 2004; Vakali and Pallis 2003; Pallis and Vakali 2006]. In the past few years, this concept began to be explored by the research community in the VANET field. This was due to the rapid increase in VANET development, also leveraged by vehicle manufacturers. However, it turns out that traditional CDN solutions, as originally proposed for the Internet, may not be applied to VANETs due to their differences when compared to traditional networks. As discussed in the following, the specific characteristics of VANETs make the development of CDN even more challenging, but it is still an open issue.

First, VANETs present a highly dynamic topology, posing increasing difficulties in selecting and maintaining the replicas. Vehicles are in constant movement at different speeds and acceleration. This leads to constant changes in the network topology, because contacts among vehicles are continually established and terminated. Thus, the most appropriate vehicles to act as replicas may also change over time. In contrast, surrogate servers in the Internet are stationary and strategically placed where they are expected to be useful, based on content demand, historical facts, and expectation. Therefore, there is no need to constantly change the replica places.

In addition, high vehicle mobility suggests that several different server replicas will be required to complete a delivery. Contact between vehicles may not last enough to deliver full content. In [Uppoor and Fiore 2012], the authors, during a large-scale mobility trace from the city of Cologne, in Germany, showed that most contact between vehicles lasts no longer than 15 seconds. This amount of time may not be sufficient for delivery, in which case a vehicle will require many providers to receive content. In fact, this makes the content delivery task even more difficult in such dynamic scenarios.

For some applications, content refers to specific locations, and must be delivered only to those vehicles that are passing by or travelling in the direction of those respective locations. Some content, such as video of an ongoing traffic jam, may only interest vehicles in specific regions. Thus, the delivery process may be aware of this situation and make decisions based on that. In addition, content may only be valid for a period of time (e.g., during a traffic jam). Outside this validity time frame, it has no utility at all. Two extra variables must then be added to the content delivery system: space and time. This poses even more challenges for content replication and delivery.

Another issue is the difference in network density over the duration of time and space, which increases the cost of selecting the replicas and delivering content to users. Network density may differ significantly, depending on the time of day (e.g., peak hours or late at night) and the region (e.g., downtown or rural regions). This requires content delivery to be aware of and adaptive to different network density scenarios. Some authors have been working on solutions to measure and predict the traffic intensity in the roads, and consequently the network density, such as [Younes and Boukerche 2015]. However, a lot of work should be done on this field. Therefore, the density variability issue increases the complexity of a content delivery system, particularly in large-scale environments.

Finally, VANET solutions are intended for deployment in large cities that have hundreds of thousands of vehicles on the roads. Furthermore, connected vehicles are expected to be integrated to the Internet of Things (IoT) [Piro et al. 2014; Borgia 2014; Gerla et al. 2014a]. In such complex scenarios, content may be provided by and to a number of entities other than vehicles (e.g., intelligent semaphores, smart cameras, mobile devices, drones) in a large-scale, heterogeneous architecture. Thus, vehicular content delivery systems must also be efficient, resilient, and scalable.

All of these issues imply that many challenges exist in the vehicular content delivery network field. To help address these challenges, it is important to have a background in the existing solutions and their characteristics. In this work, we survey the studies found in the literature that propose replica allocation (Section 3) and content delivery (Section 4) solutions applied to VANETs. Furthermore, we describe some issues that have yet to be tackled in this field, offering insight into future research directions.

3. REPLICA ALLOCATION SOLUTIONS

As described in Section 2, the idea behind CDNs is to keep content replicas in nodes close to the clients, and to then instruct them to use the replicas instead of the server itself. One of the most challenging issues for the deployment of a CDN to VANETs is the selection of appropriate vehicles to act as replica nodes. In this section, the studies proposing solutions to the replica allocation problem applied specifically to VANETs are described and analyzed. Some studies relating to MANETs or cellular networks, considered relevant to VANETs' scope, are also presented. The solutions are analyzed from the architecture perspective, which defines how the entities are organized and communicate among themselves. The decision of which architecture to use plays an important role on the performance of replica allocation.

One question that first arises is whether or not some vehicles are more appropriate than others for keeping replicas. Some studies found in the literature have focused on answering this question. In [Resta and Santi 2010], the authors demonstrated analytically that the full capacity of data dissemination in mobile networks can be achieved only when the best disseminators are selected. In the study described in [Zyba et al. 2011], the authors demonstrated that in different mobility scenarios (taxis and mobile users in a university campus), some mobile nodes in the network are more relevant to data dissemination than others; furthermore, they demonstrated that the dissemination capacity is expected to improve when those nodes are selected. This was also demonstrated in [Silva et al. 2014] for a vehicular large-scale scenario, in which the authors showed that some vehicles presented special characteristics regarding complex network aspects in addition to mobility behavior aspects. The vehicles that presented special characteristics were expected to be better content carriers.

Given that some vehicles are expected to be more appropriate replicas than others, another issue arises: the question of how those vehicles are selected. From the VANET architecture perspective, there are basically three approaches adopted to the replica allocation process: centralized, distributed (infrastructure-based or infrastructure-less), and hierarchical. The studies found in the literature for each of these categories are analyzed in the following section. At the end of this section, we present some meaningful remarks.

3.1. Centralized Approach

In the centralized approach, the decision regarding the selection of vehicles as replicas is made by a centralized entity (e.g., RSU, AP, and Internet server). The centralized entity is expected to have a high computational capacity in terms of memory and processing, a constant energy source, and a wide bandwidth. In addition, the centralized server may take advantage of a broader view of the network. However, care should be taken when allocating replicas in a large-scale scenario.

The centralized solutions usually require a significant amount of knowledge of network topology and status, as the studies described. In MobTorrent [Chen and Chan 2009], the replica nodes are selected for each content request. Based on the expected contact graph, the provider AP replicates chunks of the content to other APs, as well as to other vehicles, with the objective of maximizing the amount of data transferred to the requesting vehicle. The selection of carrier vehicles depends on the vehicles' movement direction and expected encounter time with the requesting vehicle and the APs. This solution requires a precise vehicle encounter prediction and APs position, which may not be accurately available in large-scale dynamic networks. Another study proposes Push-and-track [Whitbeck et al. 2012], which keeps track of the nodes that have already received content, and decides whether to re-inject new replicas into the network. Through exhaustive simulation in a realistic mobility scenario, the authors showed that random selection of replica nodes outperformed other strategies like entry time, position, and connectivity-based approaches. The major drawback of both solutions is the requirement for vehicle mobility behavior or for the network connectivity graph, which may be costly to obtain with acceptable accuracy. Finally, an optimization solution is described in [Bruno et al. 2014], where content is placed into RSUs based on its demand and popularity, with the objective of maximizing the content availability. In contrast to other existing solutions, this proposal assumes the adoption of the Information-Centric Network (ICN) model [Liu et al. 2014; Grassi et al. 2014; Amadeo et al. 2013; Bai and Krishnamachari 2010], in which the content search and delivery consider the content's name instead of its physical location.

Other studies propose solutions to deliver content from one fixed source station to a destination station. Thus, a vehicle is selected to be the content carrier from the source to the destination. On-Time [Acer et al. 2011] is a routing protocol for bus transportation systems. The objective is to deliver content from one point to another, using buses as carriers. Based on the scheduled stops of each bus, an algorithm that tries to maximize the delivery probability within a given period is used to select the best carrier bus. In a similar manner, but one that considers all vehicles in a highway scenario, OVS-OBRM [Khabbaz et al. 2012] selects a vehicle to be the carrier of content that must be delivered from one RSU to another. Thus, the authors propose the computation of the residual travel time (the time taken for each vehicle to reach the target RSU). The vehicle in the vicinity of the source with the smallest residual travel time is then selected as the carrier. The main drawback of these solutions is the assumption that both source and destination are fixed entities.

Other studies evaluate centralized approaches for selecting target nodes to adopt opportunistic communication in order to offload the cellular network. Although not directly applied to VANETs, they propose innovative and interesting solutions and are described in this survey, since they could be adapted to VANET scenarios. Opp-Off [Han et al. 2010; Han et al. 2012] selects an initial set of target users to exploit opportunistic communication for dissemination in cellular networks. The idea is to maximize the number of users reached and to minimize the amount of cellular communication. However, since this is a NP-hard problem, the authors propose and evaluate three algorithms: random, greedy, and heuristic. The heuristic takes into account the expected mobility pattern. The greedy approach achieves the best results, as it approximates the best case of target selection. However, it requires the user's mobility behavior, which may not be easy to obtain. Similarly, TOMP [Baier et al. 2012] is a cellular opportunistic offloading strategy that selects some mobile devices as the initial target set. This set of mobile devices is then responsible for opportunistically disseminating the information to its peers. The target set selection in TOMP takes into account the position and speed of each mobile device. The mobile devices that are expected to encounter a higher number of peers are selected as part of the target set. Both solutions, Opp-Off and TOMP, are lacking in the scalability area since they require a large amount of information and complex algorithms to run.

In general, the centralized solutions achieve good coverage results with respect to their purposes. However, they do not scale well due to their computational complexity. Additionally, they require a significant amount of up-to-date information to operate properly. In fact, most proposals for replica allocation applied to VANETs consider distributed algorithms that may or may not take advantage of infrastructure stations, as described in the following.

3.2. Distributed Approach

In the distributed approach, the replica selection uses distributed algorithms and protocols that only consider localized information. Some distributed solutions are infrastructure-less, with the decisions made only by the vehicles themselves. Others, on the other hand, are infrastructure-based, since they take advantage of infrastructure stations. We describe the infrastructure-based solutions next, followed by the infrastructure-less.

3.2.1. Infrastructure-based distributed solutions. In the infrastructure-based distributed approach, decisions are made in a distributed fashion with help from infrastructure stations. This can be considered a reasonable assumption. It is expected that VANET scenarios will be covered by infrastructure communication capabilities, for example, traditional cellular networks or even V2I dedicated short-range communication using recent standards like 802.11p [Department 2010]. The main advantage of the infrastructure-based distributed approach is the capability of using a computational system with a broader view of the network without having to organize a hierarchy among vehicles. Some studies in the literature have already exploited this advantage in their proposals on VANET replica allocation procedures, as described in the following.

In Figaro [Malandrino et al. 2012], content management is performed by brokers, which are entities running on infrastructure computational systems. Each broker is responsible for a set of users, and receives advertising of their local content from them. By having a complete view of the content availability and requests in its region, a broker is able to decide which content must be kept as a replica by the user that has received it. A broker also decides which content must be replicated and where, based on its popularity. The disadvantage of this solution is the overhead caused by content report messages, since vehicles move constantly and rapidly from one broker coverage to another. Similarly, VTube [Luan et al. 2014; 2011] explores the RSUs, described as Road-side Buffers by its authors, to replicate content where it is more likely to be requested. To this end, VTube takes advantage of the content popularity to draw a distributed solution for increasing the expected download rate.

Some proposals take advantage of the expected connectivity graph built by infrastructure stations to decide how to select carriers and schedule a content download. In TEG-PW [Malandrino et al. 2013a], RSUs keep track of content availability. Based on mobility predictions, an RSU formulates a linear programming optimization problem to schedule content delivery by selecting the carriers to pre-fetch content chunks. These carriers are selected based on the encounter time-expanded graph prediction, which is built by a traffic manager system using mobility information messages from vehicles. Each RSU updates its contact prediction map based on the local contacts it observes. Similarly, in [Trullols-Cruces et al. 2012], the APs maintain contact maps based on overhearing the messages exchanged among vehicles. The contact of two vehicles is predicted based on historical moments of contact that occurred between two vehicles that have moved in a similar pattern to the current ones. The contact map is exploited by an AP to select the vehicles required to carry content that should be downloaded by other vehicles, using an estimated encounter prediction. Several algorithms based on contact probability are evaluated through simulations. The main drawback of the described solutions is their requirement for the connectivity graph and the future contact prediction, which are costly to maintain in dynamic networks such as VANETs.

A hybrid approach is also explored in two studies [Leontiadis 2007] and [Leontiadis et al. 2009a], that focused on keeping replica content in the vicinity of a region of interest. The content is transmitted to a region by *Infostations* located in that region, as well as by vehicles passing by or expecting to pass by. Vehicles are selected as replicas according to their movement characteristics, which are used as input for utility function. This is done by a current content carrier that checks whether one of its neighbors may be a better carrier, and, in a positive case, transfers the content to its neighbor. One drawback of this solution is the overhead caused by periodic messages sent by vehicles containing their mobility status to be used as input for the utility function.

In general, infrastructure-based distributed approaches are scalable, since they take advantage of infrastructure stations as well as distributed algorithms. However, they require more complex solutions because of their distributed fashion. Furthermore, the infrastructure stations must be strategically placed to cover the application scenario.

3.2.2. Infrastructure-less distributed solutions. In this approach, the decision pertaining to which vehicle should keep a replica of content is made without the help of any infrastructure station, and is based only on local information. On one hand, solutions in this group tend to scale well to larger scenarios. On the other hand, the limited information used as input for the algorithms may lead to a poor replica allocation. Some solutions, as described in the following, follow the infrastructure-less distributed approach.

Some studies propose schemes similar to caches, in which content is stored for a period of time only in vehicles that have received it. Although caching schemes differ from replica allocation [Padmanabhan et al. 2008], some of them are worth mentioning in this survey since they may be used in conjunction with allocation schemes to improve content availability in vehicular content delivery networks. Furthermore, we can think of a cache as a replica self-allocation process, in which the vehicles themselves are able to apply a strategy to decide whether or not to act as a replica. Other caching schemes are omitted here and can be found in specific surveys, such as [Padmanabhan et al. 2008].

In InfoShare [Fiore et al. 2005], replicas are kept by vehicles for a period of time after they receive requested content. All content received is cached, and no further information is used to help with the decision of caching. Similarly, InfoCast [Sardari et al. 2009] proposes that vehicles are selected as carriers when they successfully receive content. After that, the vehicle periodically broadcasts the content to its neighbors. On the other hand, Hamlet [Fiore et al. 2011; Fiore et al. 2009] is a cooperative caching scheme in which nodes estimate their neighbors' caching to decide which content to keep in their own cache, and for how long. This is done through query and response message overhearing, which allows nodes to be aware of content belonging to their neighbors. In this way, a diversity of content is expected in the vicinity, increasing data availability. In general, the disadvantage of the caching schemes is that a large number of unnecessary replicas may be created. This makes schemes difficult to maintain, and may cause overhead and congestion on the network. However, together with replica allocation schemes, caches may help increase content availability.

Another strategy for VANETs is the adoption of peer-to-peer (P2P) swarming protocols such as BitTorrent [Cohen 2003]. In SPAWN [Nandan et al. 2005], the vehicles retain their downloaded content, and cooperate among themselves to improve data availability. Unlike the traditional centralized approach, peer discovery in SPAWN is done in a distributed manner by gossip messages exchanged among neighbors. The disadvantage of this solution is that it may not be possible to find a content replica close to the requester; also, depending on the delay in time it takes for a request to reach a provider, the network topology may have changed significantly, which increases delivery cost.

In the approach presented in [La et al. 2012], each node retaining content decides, based on its capacity and workload, whether the content should be dropped or replicated to other nodes. The replication is performed when the node decides it cannot sufficiently attend to all demands in its neighborhood. The placement of replicas is based on the random walk diffusion mechanism, in which content moves randomly from one replicated node to another, considering only 1-hop communication. The replica content movement occurs after a period of storage time. A similar strategy is used in [Khaitiyakun and Sanguankotchakorn 2014], in which vehicles are selected to keep content replicas based on lower-layer information. More specifically, a subset with higher coverage areas of the Multi-Point Relay (MPR) nodes, identified by the routing protocol, are selected as replica vehicles.

An interesting research focus is related to *geocast* delivery. In *geocast* applications, each content is specific to certain regions of interest, and only vehicles occupying or moving into that region must receive it. The pure distributed approach for replica allocation fits well with the *geocast* demand because the decision may be based only on information local to the region of interest. When it comes to replica allocation for such *geocast* demands, the idea is to select vehicles to which content can be transmitted, in the region of interest; thus, the majority of vehicles passing by will receive the content. Basically, what distinguishes the studies in this field is the practice of selecting vehicles in the best and least costly way possible. In the following, the main *geocast* solutions are presented.

In [Maihöfer et al. 2005], a *geocast* dissemination strategy elects a node to keep replicas of data inside a region of interest. The election process is based on the length of time each vehicle will stay inside the region. To make the election process less costly, more than one vehicle may be elected as replica keeper. A new election process begins when the previously selected node is no longer appropriate because it has left the region. In RADD [Kumar et al. 2015], the vehicles in a region decide on the best replica, based on their number of connections, velocity, communication range, and the number of replicas in the vicinity. They exchange messages containing their parameters, and the one with the highest index is selected as the replica.

Another *geocast* solution is ARM [Borsetti et al. 2011], a framework that also elects good content carriers in a distributed way. This process of selection is based on the following information: carrier distance from the target central point, the angle between vehicle direction and the target central point, vehicle speed, and the target area size. Only one node is elected for each instance of content, and a new election round is begun when the node is no longer deemed appropriate to act as a carrier. The main drawback of this solution is the overhead caused by messages exchanged in the selection process, as well as by monitoring when a new election must take place. Finally, LINGER [Fiore et al. 2013] is a protocol used to transmit information in a geographic region of interest. To this end, the authors propose an index that is computed locally by vehicles and that takes into account the distance to the center point of the region of interest, the angle of vehicles (relative to the center point), and speed. This solution, in contrast to the others, does not require the knowledge of vehicle trajectory. However, an overhead is created by the message exchanges required to compute the index values and to select the carriers.

The pure distributed (i.e., infrastructure-less) solutions for replica allocation use local information to decide which vehicles are more appropriate to act as content carriers. Some of the studies follow a cache-based approach, while others consider vehicle trajectory knowledge or current mobility patterns. Another approach is to let the vehicles themselves compute the local index and decide which are more appropriate to act as carriers. In general, these indices are computed based on vehicles' information, such as position, speed, and direction. The distributed infrastructure-less solutions are scalable, as they require only local information. However, they are more complex and require more message exchanges among neighbors, which may cause network overhead. This kind of solution also tends to be fault tolerant, as failures may be locally identified, and can then be solved as soon as possible.

3.3. Hierarchical Approach

Most studies proposing cluster-based replica allocation algorithms have their focus on MANETs [Sharma et al. 2010]. Despite being proposed specifically for MANETs, some of these studies are discussed in this survey because they describe innovative solutions. When it comes to VANET scenarios, hierarchical architectures are not well explored due to their highly dynamic vehicular topology; this may lead to a high cost for the maintenance of a hierarchical structure. However, it is important to describe how MANET solutions work, which will give insight into their applicability for VANETs.

In [Huang et al. 2003], the authors explore the use of mobility behavior to organize groups. Based on the motion behavior of nodes, they propose DRAM, a decentralized algorithm used to organize clusters in which nodes have similar motion behavior. Replicas of all content are then allocated based on their access frequencies and the derived allocation units. To avoid the overhead of flooding messages, the proposed solution does not require the knowledge of global network connectivity.

Distributed Hash Tables (DHTs) is a well-known data structure used to create indices for content search. In [Martin and Hassanein 2005], a Distributed Hash Table Replication (DHTR) system is proposed. In DHTR, the cluster heads keep information regarding the cluster node replica content in a local replica cache. Furthermore, a global replica cache keeps information regarding which content is maintained by each cluster member. The members of the cluster monitor their cluster head status and start a re-election process when the cluster head is no longer available.

When a group of mobile users intends to download the same content, they may cooperate to reduce bandwidth consumption and improve data availability. This problem is tackled in [Stiemerling and Kiesel 2009] and [Stiemerling and Kiesel 2010], in which mobile nodes in the proximity elect a node to be the central controller. The controller node is responsible for coordinating which chunks of data each mobile node should download from the Internet; this decision is based on local demands and throughput measurements. The idea is to increase the probability of fetching required content within the deadline.

FCD [Stanica et al. 2013] is one of the few content delivery solutions that focuses on content flowing from vehicles to infrastructure servers. The authors propose a scheme to select a small number of vehicles to receive the collected data from other vehicles in a region; this scheme then proposes to use cellular communication to deliver all data to the infrastructure. Topology metrics (i.e., node degree and assortative organization) computed locally by vehicles over time are used to decide which vehicle will be responsible for each region.

Slinky [Kawadia et al. 2011] is a content networking protocol that organizes the network into communities and keeps content replicas in each community. Slinky also defines a scheme to replicate content across the communities. Community formation is achieved by adopting a distributed version of the greedy approach for the minimum domination set solution; it requires only local knowledge (a small number of hops) of the network topology.

In VANETs, it is expected that the movement of some vehicles will follow the same behavior due to speed constraints, road capacity, and daily activity cycles in urban scenarios. For example, in [Uppoor and Fiore 2012], the authors showed, based on a realistic large-scale mobility scenario, that there are some patterns in mobility flows that operate according to different periods of the day. This group mobility behavior can be exploited through the proposal of hierarchical replica allocation schemes intended for VANETs.

When it comes to vehicular networks, hierarchical replica allocation solutions are not yet well explored. The main drawback of hierarchical solutions is high maintenance cost, which is not suitable for the large scale and highly dynamic topology of VANETs. However, based on the fact that vehicles may present a group mobility behavior, it is a good idea to exploit this issue when proposing hierarchical solutions. If the cost of organizing and maintaining clusters could be reduced, CDN may take advantage of the hierarchical organization in replica allocation and management.

3.4. Remarks

Based on the studies described above, we argue that each architectural approach has its advantages and disadvantages, as summarized in Table II. In general, it is possible to make some important observations that concern the architecture adopted thus far in VANET replica allocation solutions. The centralized approach takes advantage of a global view of the network, which enables the adoption of good allocation graph algorithms. However, it is lacking in terms of scalability, since it requires a large amount of up-to-date and accurate data to operate properly. In contrast, the pure distributed approach scales well. However, this approach is complex, since it requires a significant overhead on the network, and cannot take advantage of a broader view of the network. The distributed approach that requires help from infrastructure stations can balance those drawbacks by reducing the overhead, increasing the scalability, and taking advantage of a broader view of the network. However, this approach requires infrastructure stations placed in well-planned areas, which increases the deployment cost. The main drawback of the hierarchical approach is the cost needed to organize and maintain clusters; this is even more significant in highly dynamic networks, including VANETs. By the time the clusters are formed, the cluster heads can use a broader view of the network to operate.

Table II. Replica Allocation Architecture Approaches

Approach	Advantages	Disadvantages
Centralized	Global vision of the network Takes advantage of topology-aware algorithms Does not require complex distributed algorithms and protocols	Single point of failure Does not scale well Topology and other information may be out-of-date
Distributed	Does not require a global processing unit Easy access to up-to-date local information	Complexity of distributed algorithms and protocols Only partial vision of the network
Hierarchical	Can adopt topology-aware algorithms for each cluster There is a cluster head to coordinate the activities	Cost to organize and maintain the clusters

In addition to the architecture adopted, each solution can also be categorized according to its input data, which is the data it requires to operate and allocate replicas. The solutions' input data can be classified into four categories: *Network Topology*, *Expected Network Topology*, *Vehicle Information*, and *Content Demand*. The definitions of the first two are straightforward. *Network Topology* refers to the current graph representing the vehicles, the RSUs, and their contacts. On the other hand, the *Expected Network Topology* refers to the graph representing the network topology in the future; in other words, it represents the predicted topology graph. The *Vehicle Information* input data may refer to different aspects, depending on the solution. In general, it refers

Table III. Replica Allocation Solutions Summary

Solution	**Input**	**Solution Basis**	**Comments**
		Centralized	
MobTorrent [Chen and Chan 2009]	Expected Network Topology	Graph-based	Depends on prediction accuracy
Push-and-track [Whitbeck et al. 2012]	Network Topology	Graph-based	Cost to keep track of covered vehicles
On-Time [Acer et al. 2011]	Expected Network Topology	Graph-based	Assumes fixed source and target
OVS-OBRM [Khabbaz et al. 2012]	Vehicle Information	Index-based	Assumes fixed source and target
		Distributed Infrastructure-based	
Figaro [Malandrino et al. 2012]	Network Topology, Content Demand	Graph-based	Overhead caused by content advertisement messages
VTube [Luan et al. 2014]	Content Demand	Graph-based	Complexity
TEG-PW [Malandrino et al. 2013a]	Expected Network Topology	Graph-based	Depends on prediction accuracy
Cooperative [Trullols-Cruces et al. 2012]	Expected Network Topology	Graph-based	Depends on prediction accuracy
Hybrid P/S [Leontiadis et al. 2009a]	Vehicle Information	Index-based	Overhead caused by report messages
		Distributed Infrastructure-less	
InfoShare [Fiore et al. 2005]	Vehicle Information	Self-allocation based	Overhead caused by queries broadcast
Hamlet [Fiore et al. 2011]	Content Demand	Self-allocation based	Overhead caused by queries broadcast
InfoCast [Sardari et al. 2009]	Vehicle Information	Self-allocation based	Overhead caused by content broadcast
SPAWN [Nandan et al. 2005]	Vehicle Information	Self-allocation based	Overhead of replica discovery
Abiding Geocast [Maihöfer et al. 2005]	Vehicle Information	Index-based	Overhead caused by the selection process
RADD [Kumar et al. 2015]	Vehicle Information	Index-based	Overhead caused by the index calculation process
ARM [Borsetti et al. 2011]	Vehicle Information	Index-based	Overhead caused by the index calculation process
LINGER [Fiore et al. 2013]	Vehicle Information	Index-based	Overhead caused by the index calculation process
		Hiearchical	
DRAM [Huang et al. 2003]	Content Demand	Index-based	Overhead due to cluster management
DHTR [Martin and Hassanein 2005]	Vehicle Information	Index-based	Overhead due to cluster management
FCD [Stanica et al. 2013]	Network Topology	Graph-based algorithms	Assumes fixed target
Slinky [Kawadia et al. 2011]	Network Topology	Graph-based algorithms	Scalability issues

to the vehicle speed, position, and direction. Finally, *Content Demand* refers to the popularity of content, which may indicate the probability of a content to be requested.

Each solution can also be categorized according to its solution basis. The main solutions presented in this survey can be classified into three different solution basis: *Graph-based*, *Index-based*, and *Self-allocation-based*. Solutions in the *Graph-based* class adopt graph algorithms (e.g. maximum network flow, minimum domination set, among others) to select replica vehicles that are expected to achieve high coverage and high delivery rates. In general, the *Index-based* solutions use their input data to compute a comparable value that is used to select the most appropriate replica vehicles. Finally, *Self-allocation-based* refers to solutions in which a vehicle itself is responsible for deciding whether or not to keep a local replica. The most relevant solutions found in the literature and discussed previously are summarized in Table III. For each solution, this summary presents its input data required for operation, its solution basis, and some comments.

We also outline below some important characteristics regarding the solutions' foundational aspects. First, current and expected network topologies provide very useful insights; they enable the scheduling of delivery so that clients receive different parts of content from different replica sources, depending on their trajectory and expected encounters. However, they require a significant amount of up-to-date and predicted information regarding vehicles, traffic conditions, traffic light schedules, and so on. The acquisition of this information is a difficult and costly task, especially on highly dynamic networks such as VANETs. On the other hand, index-based solutions, in which vehicles compute indices based on local information, require less computational effort. Furthermore, if well-defined, the computed index may lead to good replica selection. However, these solutions require complex distributed protocols to control the replica allocation process; they also lack a broader view of the network. In general, the distributed solutions are scalable and may lead to good delivery performance. However, the content discovery when there is no control over content location is costly, and leads to high network overhead.

Each solution basis has advantages and disadvantages. Based on the solutions surveyed, Figure 3 depicts the input data, advantages and disadvantages of each of the three solution basis classes selected. In general, *Index-based* solutions include the following characteristics: scalable since they require only local information; robust to topology changes; and fault-tolerant, because new indices are computed as soon as changes take place. However, these solutions cause a high network overhead due to message exchange between vehicles to help with index computation. *Self-allocation* solutions are also scalable because vehicles make decisions autonomously, and fault-tolerant because many replicas of the same content may coexist. However, it is costly to keep current content. Finally, *Graph-based algorithms* lead to high delivery rates. On the other hand, they are computationally complex and require foreseen and accurate data to operate.

To conclude our discussion on replica allocation solutions, it is important to state that the great majority of solutions found in the literature only performed evaluations on low-scale mobility scenarios. In addition, some of them only presented analytical results. All evaluation results presented by the authors are extremely relevant for validating their proposals. However, we argue that before deploying a CDN solution to a real VANET, more realistic evaluations must be conducted. In fact, it is also important to note that there is a lack of realistic vehicular mobility scenarios available in the literature. Hence, another challenge when proposing a VANET CDN solution is determining a proper evaluation method.

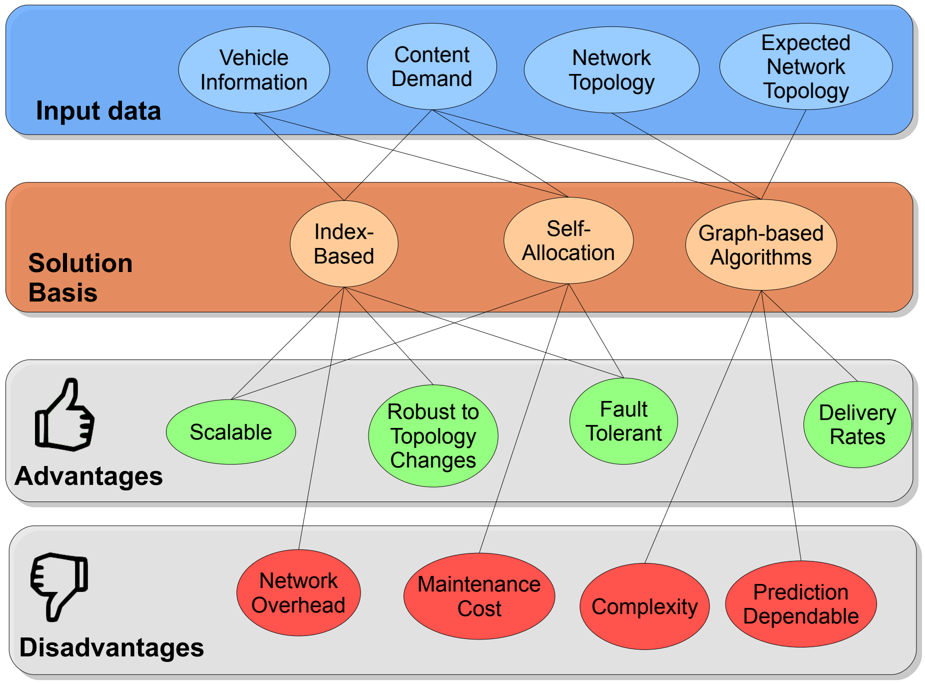


Fig. 3. Replica allocation solutions general aspects: input data, solution basis and main characteristics.

4. CONTENT DELIVERY SOLUTIONS

One of the most covered areas in the literature regarding VANETs is routing and forwarding strategies [Willke et al. 2009; Nadeem et al. 2006; Li and Wang 2007; Bujari 2012; Boukerche and Darehshoorzadeh 2014; Boukerche et al. 2011]. Most studies focus on deciding which vehicles should act as relays in the process of forwarding a message to its destination [Villas et al. 2013; Sung and Lee 2012; Ruiz et al. 2012; Rostamzadeh and Gopalakrishnan 2011; Viriyasitavat et al. 2011].

Video streaming over VANETs has received significant attention in the recent years, since many applications will benefit from such type of content. However, VANETs highly dynamic topology poses significant challenging issues to video streaming. One of these issues is related to routing and dissemination, since end-to-end delay and delivery rate impact directly on the video quality. Many studies in the literature have proposed solutions to this problem [Resende et al. 2015; Maia et al. 2013; Rezende et al. 2014; Li et al. 2014; Pazzi and Boukerche 2014; Sharma et al. 2015; Torres et al. 2015; Xu et al. 2015; Felice et al. 2015; Naeimipoor and Boukerche 2014; Maia et al. 2015]. Other studies focus on providing high Quality-of-Experience (QoE) videos [Jelassi et al. 2015; Pham et al. 2014; Yang Li 2014], which is a basic requirement for video streaming. The adoption of redundancy is also considered to increase the delivery rate [Rezende et al. 2015].

All these solutions are important for content delivery, as they are responsible for disseminating requests and responses through multi-hop communications. However, they are outside the scope of this survey, since they refer to message routing and forwarding instead of content delivery.

Content delivery in VANETs is classified as pull- or push-based. In a pull-based application, vehicles send requests to the content providers (or their replicas) and receive the requested content from a selected provider. One of the challenges of this approach is the replica discovery process, that decides which replica is most appropriate for responding to a specific request. Unlike pull-based approaches, push-based applications assume that vehicles with specific characteristics are interested in particular content; the objective is to then deliver content to all such vehicles. One of the challenges of this approach is to achieve high coverage where, in the best case, all target vehicles receive the content.

In this section, for each pull- and push-based approach, we describe and analyze solutions according to their architectural organization, as well as to their solution basis. Most solutions adopt distributed infrastructure-based or infrastructure-less strategies, while some of them propose hierarchical solutions for pull-based applications. Some of the studies presented were already described from the replica allocation perspective in Section 3. Hereafter, they are analyzed from the content delivery point of view.

4.1. Pull-based Solutions

One architectural approach adopted for content delivery is the hierarchical approach. In this strategy, the network is organized into clusters, and the cluster heads are responsible for receiving requests from their members and for determine the appropriate provider to whom they can send out a response. In [Gerla et al. 2014b], the authors propose that vehicles in the vicinity elect one of them to be connected to the Long Term Evolution (LTE) network and to then share content with the others. Since LTE technology involves a high cost, incentives to users and the round-robin scheme are adopted, so the cost would be shared among the involved vehicles.

Some approaches adopt hierarchical structures for content discovery and delivery in MANET scenarios. Due to the specific characteristics of VANETs, hierarchical solutions have not been applied extensively in these networks. The hierarchical approach is advantageous in terms of scalability issues. It should be noted that the cost of organizing and maintaining clusters may not be feasible in such dynamic networks with constant topology changes, such as VANETs. However, the ideas behind MANET solutions may be of interest to future solutions for VANETs. Hence, some of these solutions are analyzed.

In DHTR [Martin and Hassanein 2005], the cluster heads use a global replica cache to propagate a request to only those clusters that are supposed to keep the requested content, as opposed to all of them. This solution diminishes the overhead in the network when the content is not located on the same cluster as the requesting node. In [Derhab and Badache 2006] the authors also propose a hierarchical pull-based content distribution approach in which the requests are sent to the cluster heads. A cluster head tracks the content each of its cluster members are able to provide; based on this information, it decides which member can respond to a request. Nodes send update messages to their cluster heads informing them when their content has changed.

Another common approach to pull-based content delivery is to broadcast requests in multi-hop communications until they reach a provider. The provider then sends the content to the requesting node using the multi-hop reverse path in the direction of the requester. The main problem with one such approach is the flooding scheme used to propagate the request. Thus, efficient forwarding strategies that deal with the broadcast storm problem must be adopted to avoid a high overhead. In InfoShare [Fiore et al. 2005], a content request is broadcast in a flooding scheme until it reaches a source vehicle that can respond to it. Upon receiving the request, the carrier vehicle delivers the content by a unicast path to the requesting vehicle. The path between the content source and its destination is built during the requesting process; this includes the addresses of the relay nodes until the request reaches the carrier. Similarly, CRoWN [Amadeo et al. 2012] proposes new layers to the IEEE 802.11p protocol stack which are responsible for providing content-centric communication. Content requests are broadcast by the consumer until they reach a provider that can respond. To avoid broadcast storms, relay nodes adopt a contention time and only forward a request if they have not received the same request from one of their neighbors.

The broadcasting request approach is also used in CCVN [Amadeo et al. 2013], a pull-name-based content centric architecture in which vehicles broadcast requests to RSUs and nearby vehicles. Since more than one provider may exist, the most responsive one is selected to deliver the requested content following the reverse path to the requester. Finally, SPAWN [Nandan et al. 2005] adopts a P2P approach similar to traditional swarming protocols like BitTorrent [Cohen 2003]. However, unlike the traditional centralized approach, peer discovery is done in a distributed way through the broadcasting of gossip messages.

One problem encountered through the propagation of request messages in multi-hop communications is the generated overhead. Additionally, the reverse path to the requesting node may change as a result of the vehicle's movement, affecting the route of the response to the requester. To avoid such overhead costs, vehicles may inform their neighbors about their available contents. Interested nodes will then be able to send requests directly to one of the providers. In [Guidec and Maheo 2007], mobile hosts announce to their neighbors a list of documents they keep stored locally. When a mobile node is interested in a document, it sends a request to the document owner that, in the sequence, broadcasts the requested document content. According to the authors, broadcasting is used in the response because more than one host may be interested in the same document. Similarly, a file sharing solution is proposed in [Lu et al. 2011], which exploits opportunistic communications between mobile nodes to deliver files to interested nodes.

Some proposals make use of global information from infrastructure stations to schedule a delivery. In this case, request messages are sent to infrastructure stations that are aware of the expected vehicle trajectories, and are able to schedule from the points where the requesting vehicle must receive parts of the content along their route. In the work described in [Malandrino et al. 2013b], the authors perform evaluations on the content delivery in VANETs for such a system model. In this scenario, each vehicle may be interested in different content and may send a request to an AP that will schedule the delivery. These authors propose a time varying graph model and, based on realistic scenarios, discover important information, such as how the AP locations play a major role in the network capacity, and knowing how the user mobility can be advantageous in the application of the carry-and-forward communication paradigm.

In MobTorrent [Chen and Chan 2009], vehicles send their content requests to infrastructure stations, using either cellular communication or other WWAN methods. Based on the request and the expected mobility behavior represented by a predicted contact graph, the station performs a pre-fetch of the content and schedules the delivery by selecting the APs and the vehicles to assist, using opportunistic communications. The requester keep the APs up-to-date by sending information on which chunks have already been delivered.

Network coding is a scheme proposed to improve the overall network capacity [Gkantsidis and Rodriguez 2005]. Basically, the idea behind this mechanism is that packet forwarders combine several packets together before transmission. Given the broadcast characteristic of wireless links, network coding can help to increase the network throughput [Katti et al. 2008]. VANETCODE [Ahmed and Kanhere 2006] is a content distribution solution that takes advantage of network coding to help with peer selection and content discovery. Vehicles request content from an AP that encodes the content blocks and broadcasts them to all passing vehicles, including those that are requesting. When not under AP coverage, vehicles cooperate with one another by sending out the blocks they own. Unlike SPAWN [Nandan et al. 2005], vehicles do not have to request specific blocks, because the encoding scheme adopted makes all blocks relevant to vehicles.

Figaro [Malandrino et al. 2012] keeps content location information in the so-called brokers, located in infrastructure stations. Requests are sent to brokers that search for and indicate mobile nodes that could provide the content to the requesting node. Mobile nodes also keep the brokers informed of the content they are able to provide. A broker disseminates the request to other brokers through a proxy when it does not have an entry for requested content. In TEG-PW [Malandrino et al. 2013a], when a vehicle wants to download specific content, it sends a request to the query management server via an RSU or via cellular communications. The request is forwarded to RSUs in the area near the vehicle. The RSUs fetch portions of the content from the content server and deliver them to the vehicle. When appropriate, RSUs exploit V2V communication by selecting other vehicles as relays or to carry-and-forward the content.

In [Trullols-Cruces et al. 2012], vehicles send request messages to an AP that uses its contact map to organize a cooperative download scheme. The scheme is achieved by delivering the content to intermediate vehicles that have a high probability of encountering the requesting vehicle. Another similar proposal is CarTorrent [Lee et al. 2007], in which vehicles send their requests to APs that deliver the chunks available for the connection period. In addition, vehicles periodically generate gossip messages to inform others about their content; a V2V communication is then established among vehicles to co-operatively download the remaining chunks.

Some of the pull-based solutions found in the literature consider only infrastructure communication and do not take advantage of V2V opportunistic transmissions. The main drawback of these solutions is infrastructure overload. This is one drawback with MoPADS [Ha and Ngo 2009], which considers the integration of vehicular and cellular networks. Vehicles send their content requests using the cellular network. Then, MoPADS schedules the content delivery by selecting which APs will be part of the process. To cope with such a NP-hard problem, the authors propose a heuristic to select the delivering AP and determine the content to be delivered, with a focus on maximizing the throughput. This solution also takes into account the expected vehicle trajectory.

The work presented in [He et al. 2013] focuses on video delivery to vehicles in a scenario covered by both cellular and WiFi networks. Since WiFi networks are less expensive and provide higher bandwidth than cellular ones, the proposed algorithm uses this technology as its first option. The on-road video delivery problem tackled in the article was proven to be NP-complete, and the authors proposed heuristics to solve it. The APs enrolled in each delivery, and the period of time and location that the cellular communication will adopt, is obtained by the server that schedules the delivery. One difference in this work related to similar ones in the literature is the requirement that the video experience have good quality, which adds restricted delay constraints to the problem.

To conclude the pull-based content delivery analysis, we describe a solution in which the content is pulled by base stations from vehicles to collect their information. In DMND [Wang et al. 2010], the base stations are the interested parties of the model, and request information from vehicles using a named data approach. They periodically broadcast messages containing the content name that interests them to nearby vehicles. Upon receiving a request message, a vehicle decides if it must respond based on the information supplied by request message naming.

In the pull-based applications, content providers respond to specific requests to deliver the requested content. When infrastructure stations are available, the main challenge relates to the delivery scheduling process; this selects the vehicles and stations to act as providers, depending on their contact prevision with the requester. On the other hand, the content discovery process is the main challenge when no infrastructure stations are available. In this case, it is important to use efficient routing schemes and to select good replica keepers to perform content pre-fetching.

4.2. Push-based Solutions

In push-based applications [Willke et al. 2009], vehicles presenting particular properties are assumed to be interested in content, and must thus receive it. One strategy adopted is to allow RSUs to periodically broadcast their content to passer-by vehicles. The vehicles that receive the content may then act as disseminators to help with the propagating process. DP [Zhao et al. 2007] is a data dissemination scheme in which a data center selects specific roads on which to push the content, based on a disseminating zone. The content is propagated to the selected roads and vehicles passing by, which then use a broadcast contention scheme to disseminate the data to the desired dissemination zone. In addition, some vehicles passing by selected intersections that may lead to the dissemination zone are also selected to carry-and-forward the content. In InfoCast [Sardari et al. 2009], it is considered that all vehicles in a highway scenario are interested in all messages originating from the RSUs. The RSUs adopt a rate-less coding scheme and broadcast their messages to all vehicles passing by. When a vehicle receives a message in its entirety, it is considered to be a carrier and thus broadcasts the message to its neighbors to help increase coverage. In [Baiocchi and Cuomo 2013], the list of content available in the server-side stations is pushed to vehicles passing by, which disseminate this information to other vehicles using V2V communication. Vehicles interested in content use cellular communication to request and download it. In other words, the push-approach is used to inform vehicles about the availability of content. Type-Based Content Distribution (TBCD) [Cao et al. 2014] adopts a similar approach. The content is first pushed by a provider to the RSUs located close to the interested vehicles. Then, the RSUs periodically broadcast the content to the passing vehicles. In addition, some vehicles also rebroadcast the content, depending on the content type and on the number of interested clients.

When the content is already located in the vehicles, they may propagate this information to their neighbors using V2V communication. *PrefCast* [Lin et al. 2012] is a solution that considers a mobile social scenario in which nodes forward their content to their neighbors using opportunistic communications. The forwarding is performed considering user profile and preferences instead of relying on the proximity of the mobile nodes. Although proposed for MANETs, the idea of social preferences may be applied to VANETs to improve content distribution solutions. RTAD [Sanguesa et al. 2015] is a real-time adaptive dissemination system in which vehicles decide the broadcast scheme to use, among a set of schemes, based on the current network density and topology information on the road. Thus, this solution is expected to perform well under different network conditions. Push-and-Track [Whitbeck et al. 2012] is a framework that takes advantage of opportunistic ad-hoc communications to offload the network core infrastructure when disseminating content to various nodes. This solution was proposed for scenarios in which many nodes may be interested in the same content. Some nodes are selected to initially receive the content, which they then periodically disseminate to their neighbors. One strength of this solution is that the disseminators keep track of the nodes that have already received the content by adopting an acknowledgment scheme, which is very useful for increasing the dissemination coverage area.

In some scenarios, content should be pushed to a single vehicle. The TSF (trajectory-based statistical forwarding) [Jeong et al. 2010] solution uses the target vehicle trajectory to send the message to an RSU (target point); this RSU will in turn become the rendezvous point for the vehicle (i.e., an RSU that the vehicle is expected to encounter). RSUs are selected in the vehicle trajectory based on the time they are expected to pass the RSUs, and the expected delay. An encounter prediction map is used in [Xu et al. 2011] to schedule content delivery from source to destination. In this solution, APs are responsible for collecting and offering trajectory information pertaining to vehicles. Based on an encounter prediction graph, the delivery of a message is scheduled using multi-hop V2V communications. Existing push-based dissemination approaches take into account the direction and movement of vehicles to decide which vehicles to send a message to, as is proposed in [Nadeem et al. 2006]. In this study, vehicles disseminate traffic information to other vehicles depending on their movement direction.

An alternative to the pure push- and pull-based dissemination approaches is the adoption of the Publish/Subscribe (P/S) [Eugster et al. 2003] paradigm; in this paradigm, content is delivered only to subscribers that have shown interest in particular content. This approach was explored in [Leontiadis et al. 2009a; Leontiadis and Mascolo 2007; Leontiadis et al. 2010; 2009b]. Vehicles that have an interest in content send out a subscription message to express their interest. When content is available, the publishers push content only to those vehicles that have subscribed to it.

The hierarchical architecture is also adopted in push-based dissemination, as proposed by [Derhab and Badache 2006]; in this work, cluster heads are responsible for periodically propagating new data updates to their cluster components, and also to other cluster heads. Before disseminating updates, the cluster heads wait for a period of time to receive more updates from other nodes, reducing the message exchanges.

In [Maihöfer et al. 2005], the authors evaluate three *geocast* push-based dissemination approaches: server, election, and neighbor. In the first approach, a server sends a message to the destination region. It can then deliver the message either periodically or by notification. Depending on the distance from the server to the destination region, this solution may not perform well. In the election approach, a node in the destination region is elected to store and disseminate messages. Although efficient in terms of coverage, the election approach generates a high overhead in the network. Finally, in the neighbor approach, each node keeps the messages destined for its location, and shares them with a new neighbor in the destination region. As a drawback, we can mention the bandwidth required to deliver a message in the destination region.

4.3. Remarks

The decision of using a pull- or push-based approach depends on the application demands. If content must be delivered only to requesting vehicles, the pull-based approach is more appropriate. Otherwise, if the content providers must decide which vehicles need to receive content according to their properties, the push-based approach is more appropriate. However, both pull and push-based solutions may differ depending on the technique used to deliver the content.

Each solution may have different types of data as input. We classify the input data in five categories: *Network Topology*, *Expected Network Topology*, *Vehicle Information*, *Content Information*, and *Network Information*. The definitions of the first three (i.e., *Network Topology*, *Expected Network Topology*, *Vehicle Information*) are straightforward and are the same as described in Section 3.4. *Content Information* refers to content demand as well as content meta-data such as type and author. Finally, *Network Information* is used by some solutions as network measurements, for example, link quality, congestion, and capacity.

Table IV. Content Delivery Solutions Summary

Solution	Input	Solution Basis	Comments
		Pull-Based	
LTE Driven Cluster [Gerla et al. 2014b]	Network Information, Vehicle Information	Reverse Request Path	Clustering management
InfoShare [Fiore et al. 2005]	Network Information	Reverse Request Path	Overhead caused by requests
CroWN [Amadeo et al. 2012]	Network Information	Reverse Request Path	Overhead caused by requests
CCVN [Amadeo et al. 2013]	Network Information	Reverse Request Path	Overhead caused by request
SPAWN [Nandan et al. 2005]	Network Information	Content Announcements	Overhead caused by replica discovering
MobTorrent [Chen and Chan 2009]	Expected Network Topology	Delivery Scheduling	Depends on prediction accuracy
VANETCODE [Ahmed and Kanhere 2006]	Network Information	Periodic Broadcast	Overhead caused by periodic messages
Figaro [Malandrino et al. 2012]	Network Information, Content Information	Delivery Scheduling	Overhead caused by advertisements messages
TEG-PW [Malandrino et al. 2013a]	Expected Network Topology	Delivery Scheduling	Depends on prediction accuracy
CarTorrent [Lee et al. 2007]	Network Information	Content Announcements	Overhead caused by gossip messages
MoPADS [Ha and Ngo 2009]	Network Information	Delivery Scheduling	Depends on prediction accuracy
OVD [He et al. 2013]	Vehicle Trajectory	Delivery Scheduling	High computational complexity
DMND [Wang et al. 2010]	Content Information	Periodic Broadcast	Overhead caused by periodic messages
		Push-Based	
DP [Zhao et al. 2007]	Network Information, Vehicle Information	Periodic Broadcast	Overhead caused by periodic messages
Infocast [Sardari et al. 2009]	Content Information	Periodic Broadcast	Overhead caused by periodic messages
PrefCast [Lin et al. 2012]	Content Information	Delivery Scheduling	User profile requirement
RTAD [Sanguesa et al. 2015]	Vehicular Information	Periodic Broadcast	Overhead caused by beacon messages
Push-and-Track [Whitbeck et al. 2012]	Network Topology, Vehicular Information	Periodic Broadcast	Cost to track all vehicles covered
TBCD [Cao et al. 2014]	Vehicle Information	Periodic Broadcast	Content information requirement
TSF [Jeong et al. 2010]	Vehicle Trajectory	Delivery Scheduling	Overhead caused by beacon messages
STDFS [Xu et al. 2011]	Expected Network Topology	Delivery Scheduling	Overhead caused by beacon messages

In addition to the different types of input data, each content delivery solution can also be classified according to its solution basis. In this survey, we classify them in four categories: *Reverse Request Path*, *Delivery Scheduling*, *Periodic Broadcast*, and *Content Announcements*. In the *Reverse Request Path* solutions, request messages are disseminated until they reach a vehicle that can respond; in other words, a provider. The provider then responds to the requester using the reverse path (i.e., the path in the opposite direction) that the request message took to reach it. On the other hand, *Delivery Scheduling* solutions usually use the expected network topology to schedule

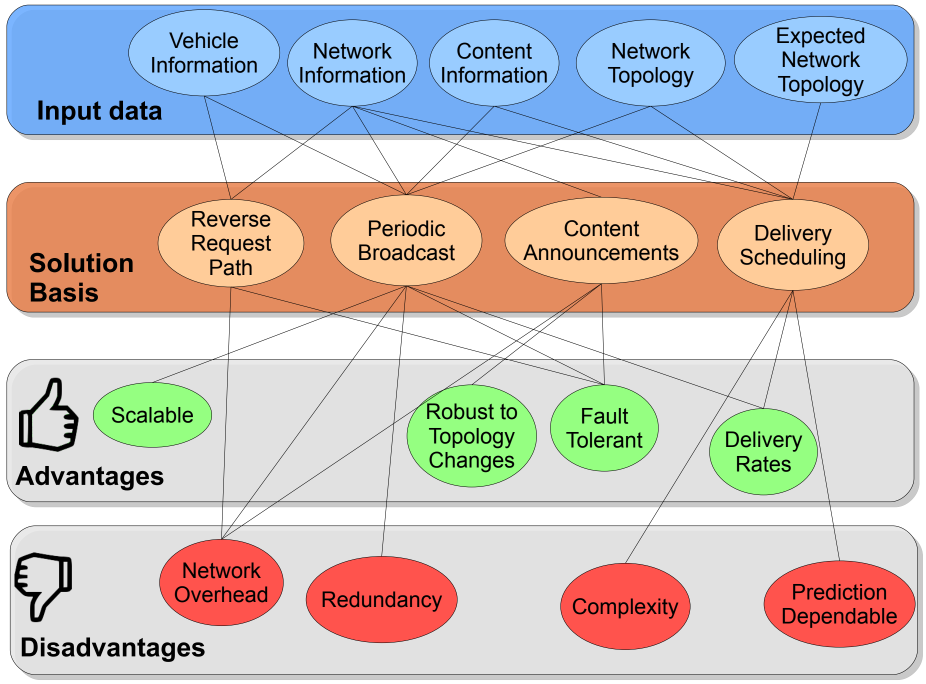


Fig. 4. Content delivery solutions general aspects: input data, solution basis and main characteristics.

a delivery based on the expected contacts that the requester will have in the future. In contrast, in *Periodic Broadcast* solutions, providers periodically broadcast content to vehicles passing by. Finally, *Content Announcements* refers to solutions in which content providers announce their content to their neighbors. A vehicle interested in certain content then requests it directly from a known provider.

The main solutions found and described in this survey are summarized in Table IV, which presents their input data, solution basis, and some comments. Each content delivery solution technique has its advantages and disadvantages as well. Figure 4 highlights each solution input, advantages, and disadvantages. Application designers should refer to these results before deciding on the best approach for their particular demands.

Reverse Request Path is one of the most frequently adopted techniques for content discovery and delivery, particularly in distributed architectures. In this method, the path that a request message travels in order to reach the provider is used following the reverse direction for the delivery of content. The main drawbacks of such an approach are the overhead caused by flooding requests in large-scale networks, such as VANETs, and the fact that the reverse path to the requester may not be the same due to high vehicle mobility. Thus, an efficient routing protocol that deals with the broadcast storm problem must be adopted. In addition, the replica allocation scheme plays an important role in its performance: when a replica is found quickly, fewer messages are exchanged, and fewer hops are required. On the other hand, this technique is scalable since only localized information is required; it is also fault-tolerant, since more than one path to the provider may exist.

Another scalable and fault-tolerant technique that leads to high delivery rates is the *Periodic Broadcast*. However, this solution also leads to a high number of redundant messages and, consequently, a high network overhead. In addition, good replica allocations will also impact positively on its performance. In *Content Announcements* solutions, content providers announce to their neighbors the list of content they are able to offer. This also leads to a high network overhead because of the announcement messages. However, the content discovery process is less complex and less expensive.

One option is to adopt a hybrid solution that supports distributed protocols and takes advantage of infrastructure information. In this case, vehicle trajectory and expected network topology are really helpful for content discovery and delivery. However, the *Delivery Scheduling* solutions require a significant amount of information concerning vehicles' movements, traffic conditions, road maps, traffic lights, etc. In addition, the adoption of such information most likely requires the execution of complex graph algorithms.

5. CONCLUSION AND FUTURE DIRECTIONS

A significant amount of promising applications for VANETs are becoming a reality, such as entertainment, information, and advertisement. CDN have been playing an important role in the performance of these applications. Many researchers have been working on proposing content delivery solutions for applications with different demands. Furthermore, many different strategies have been considered for VANET content delivery. In this work, we presented an in-depth view of content delivery solutions applied to VANETs. We conducted the discussion focusing on the solution strategies in terms of their architecture, inputs, and basic techniques.

Many problems must be tackled before having efficient, robust, and scalable vehicular content delivery solutions. In what follow, we outline some of the research directions one might pursue in the near future:

— *Efficient replica selection*: When appropriate vehicles are selected to keep content replicas, the overall content delivery performance increases. However, this is not a trivial task due to VANET's specific characteristics. Furthermore, the selection depends on several aspects, including the target vehicles, the target area, the content validity period, the content size, the content type, and the content constraints. Hence, it is important to propose new efficient, robust, and scalable replica allocation solutions, which will be fundamental to the performance of VANET applications;
— *Topology prediction*: When network topology can be predicted with high accuracy, well-known graph algorithms, such as maximum network flow and minimum dominating set, could be applied to orchestrate content delivery. Although these and other graph algorithms are NP, efficient heuristics that run on polynomial time could be used instead. However, to predict a vehicular network topology is easier said than done, due to a large number of variables that are involved: traffic lights, the behavior of pedestrians, hazards, and the subconscious aspects of drivers [Luo et al. 2015];
— *Efficient communication protocols*: Besides selecting replica vehicles accordingly, it is very important to propose efficient and large-scale delivery protocols. These protocols are used for content delivery in push- and pull-based applications, as well as for request propagation in pull-based applications. Because of VANETs' specific characteristics, the protocols may be aware of network topology changes and able to operate on different density scenarios;
— *Internet of Things (IoT) integration*: in the future, vehicles are expected to be part of an overall IoT scenario. Thus, vehicular content delivery solutions may take advantage of such integration to improve their services. In this case, a variety of devices with sensing capability (e.g., mobile smart devices, intelligent traffic lights, un-

manned aerial vehicles, monitoring cameras) will provide data to support the replication and delivery algorithms, andas well as content to be delivered to vehicles. Furthermore, in addition to vehicles, other IoT devices will also be considered as replica placements, with the objective of increasing content availability. However, such integration of VANETs and IoT is not trivial, and a substantial effort should be directed to protocol design, architecture, and standardization rules;

— *Delay-sensitive content*: The increase in demand for multimedia content consumed by users in recent years is notable. In vehicles, on-board users will also demand this type of content that, in general, is delay-sensitive (e.g.,video-on-demand). This constraint makes the content delivery process even more difficult. This issue will probably be among the top vehicular content network demands in the near future;

— *Incentive mechanisms*: The cooperative behavior of vehicles will play an important role for vehicular content delivery networks. Rational users will not offer their resources unless benefits are offered to them. In other words, vehicles will only agree to act as content replica and relay content to other vehicles if they receive some incentives. Thus, it is important to propose incentive mechanisms that will encourage selfish but rational vehicles to cooperate with their peers;

— *Vehicular cloud computing*: Vehicular networks are expected to evolve into a model in which vehicles form a cloud to extend their computational capabilities. This model is called Vehicular Cloud Computing (VCC) or Vehicular Cloud Network (VCN). By taking advantage of a cloud, more complex algorithms (e.g., graph-based replica allocation algorithms) could be adopted. Therefore, research efforts should also be directed to this field;

— *Integration into cellular networks*: Vehicular networks will benefit from the cellular infrastructure that already covers a significative part of most cities around the world. The adoption of this technology to perform infrastructure communication will save deployment money and will allow a rapid market penetration for VANET applications. In addition, the next version of Long Term Evolution (LTE) technology will implement the device-to-device (D2D) capability, that, together with WiFi Direct, will be able to provide more reliable data communication in VANETs [Asadi and Mancuso 2013]. The LTE-VANET integration is a hot topic that should advance in the next few years;

— *Security and privacy*: Malicious users will accompany the rise of advanced VANET applications. Denial-of-service attacks, malicious programs, private information access, and spam are some of the issues that network operators and users must remain aware of. Thus, security and privacy mechanisms to protect users from virtual attacks are also key issues.

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