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Data Offloading Techniques Through Vehicular Ad Hoc Networks: A Survey

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ABSTRACT Recently, for satisfying users' various mobile Internet service requests for data exchange anytime and anywhere even in their moving vehicles, the generated mobile data traffic has been rapidly increasing and has become a serious burden on current cellular networks. To partially address such a serve challenge, vehicular ad hoc networks (VANETs) have emerged as an effective approach for enhancing vehicular services and applications by equipping vehicles with wireless and processing capabilities. In this paper, we survey the recent advances in the data offloading techniques through VANETs. Particularly, based on the communication patterns among vehicles and infrastructures, we classify these techniques into three categories, i.e., data offloading through vehicle-to-vehicle communications, vehicle-to-infrastructure communications, and vehicle-to-everything communications. Besides, we present a detailed taxonomy of the related techniques by discussing the pros and cons for various offloading techniques for different problems in VANETs. Finally, some opening research issues and challenges are outlined to provide guidelines for future research work.

INDEX TERMS Vehicle ad hoc network, data offloading, communication patterns, vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-everything.

I. INTRODUCTION

Recently, due to the rapid advancements of information and communication technology (ICT) especially on mobile communications, modern lifestyle has been greatly changed, and people expect to access the Internet in their online social life for exchanging data anytime and anywhere even in their moving vehicles [1]–[4]. Moreover, the data exchange in vehicles are also provided by cellular networks such as 3G and 4G. Particularly, in the vehicular data exchange, the requests for various content services from vehicular users are rapidly increasing, e.g., tourist/advertisement information, social media on roads, games, file downloads, and social applications (e.g., Twitter, Wechat and Facebook). However, without degrading the quality of service/experience (QoS/QoE), current cellular networks cannot effectively support the increasing service requests from vehicular users as well as the generated data traffic due to some practical factors such as increasing density of vehicles on roads, high mobility of vehicles, unreliable cellular coverage and limited cellular network resources. Thus, to address these serious challenges, revolutionary schemes regarding network architectures and data transmission techniques needs to be introduced towards future networks [5]–[8].

One emerging approach is to employ the network architecture of vehicular ad hoc networks (VANETs), which is a specific kind of mobile ad hoc networks (MANETs) by equipping vehicles with wireless and processing functionalities for forming a dynamic vehicular network when moving on roads [9], [10]. Besides, VANETs have drawn much attention in academia and industry and are expected to be realized in the near future, thereby achieving data exchange among vehicles and infrastructure that enable various mobile vehicular services and applications for such as road safety, traffic efficiency, urban sensing, driver assistance and entertainment of vehicular users [9], [49]. Particularly in such a VANET, vehicles can establish intra-vehicle, vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and even vehicle-to-everything (V2X) communications for partially

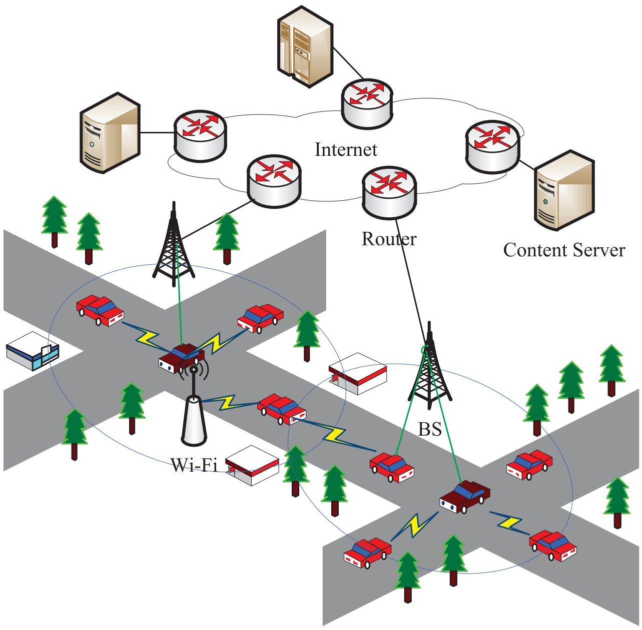

FIGURE 1. Illustration of data offloading system integrating cellular network and vehicular ad hoc networks.

alleviating the burden of data traffic on cellular networks while satisfying vehicular users' service requests locally.

Moreover, data offloading, also referred to traffic offloading, is another effective scheme for resolving the above challenges by employing complementary and revolutionary networking techniques to transfer data traffic originally from transmissions through cellular networks [11]–[13]. Due to the continuous and explosive growth in data traffic in the future, data offloading has become essential in mobile networks in order to decrease the capital expenditure (CPEX) and operational expenditure (OPEX) of mobile network operators (MNOs) while maintaining or enhancing the QoS/QoE of end users.

Consequently, it is potential to investigate the combination of the above two emerging networking techniques, i.e., data offloading through VANETs, as shown in Fig. 1. Particularly, based on the communication types among vehicles and infrastructures in VANETs, we classify the data offloading techniques into three types as: i) data offloading through V2V, ii) data offloading through V2I, and iii) data offloading through V2X. In particular, V2V communications are established directly for sharing data when a pair of vehicles are in close proximity, where fixed network infrastructure support is not required and cellular BSs can provide signaling control at most for their direct communications. However, data offloading through V2V is constrained by vehicles' limited resources (e.g., low transmit power), vehicle mobility and locations as well as their encounter time period. For data offloading through V2I, the roadside infrastructure including deploying cellular BSs or low-power road side units (RSUs) is a necessity for providing the data exchange services and applications based on V2I communications. However, the

TABLE 1. Abbreviations.

BS	Base station
CFC-IoV	Cooperative fog-computing-based Internet of vehicles
CPEX	Capital expenditure
D2D	Device-to-device
DSRC	Dedicated short-range communication
DTN	Delay tolerant networks
FCD	Floating car data
FITS	Wireless cellular system
ICT	Information and communication technology
ITS	Intelligent transportation system
LFSs	Local fog servers
LTE-A	Long Term Evolution Advanced
MANET	Mobile ad hoc network
MMCD	Minimum delay collaborative download
MNO	Mobile network operator
OPEX	Operational expenditure
POMDP	Partially observable Markov decision process
QoE	Quality of experience
QoS	Quality of service
RSU	Road side unit
SINR	Signal-to-interference-plus-noise ratio
SWIFT	Simultaneous wireless and information power transfer
V2V	Vehicle-to-vehicle
V2I	Vehicle-to-infrastructure
V2X	Vehicle-to-everything
VAO	Vehicle-mounted assisted offloading
VANET	Vehicular ad hoc network
VDTNs	Vehicular delay tolerant networks

practical deployment of cellular BSs or RSUs needs to address the issues such as limited coverage, high installation expense, and network maintenance. To make up the disadvantages of data offloading V2V communications and V2I communications, introducing V2X communications can be regarded as the last sort for data offloading in VANETs by combining them together, where a vehicle can communicate with either other vehicles in close proximity or the local RSU/BS depending on practical channel conditions. In this paper, we are motivated to present a comprehensive survey on the above classified three categories in terms of data offloading techniques through VANETs, and discuss the corresponding open research issues.

The abbreviations in this paper is shown in Table 1. The remainder of this paper is organized as follows. In Section II, we generally classify the existing techniques of data offloading through VANET into three categories. In Sections III, V, and IV, we review and discuss the current literature of each category, i.e., data offloading through V2V, V2X and V2I, respectively. Section VI concludes this paper and discusses future research areas.

II. CLASSIFICATION OF DATA OFFLOADING TECHNIQUES THROUGH VEHICULAR AD HOC NETWORKS

In this section, we review the main strategies and provide a comprehensive categorization of existing VANET-based data offloading technqiues. A lot of innovative technologies have emerged to offload data and reduce the load of cellular networks through VANETs. As shown in Fig. 2, according to the communication patterns among vehicles and

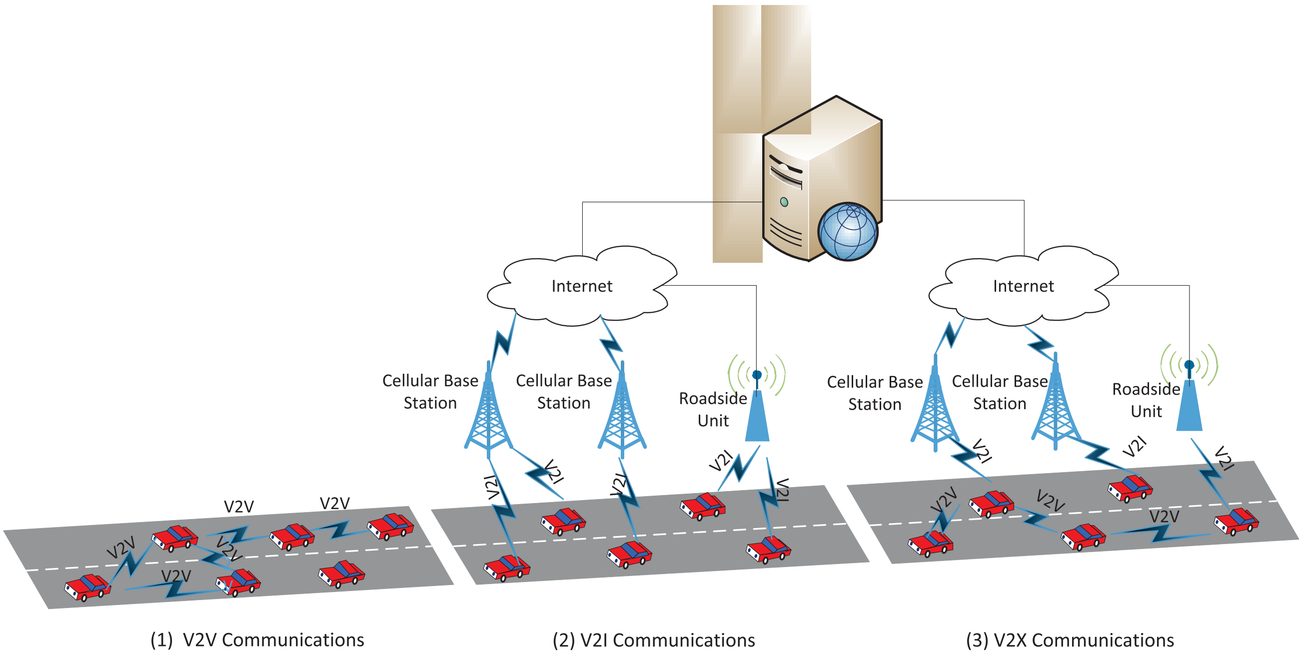

FIGURE 2. Illustration of data offloading techniques through vehicular ad hoc networks.

infrastructures, these techniques of data offloading can be classified into three categories: data offloading through V2V communications, data offloading through V2I communications, and data offloading through V2X communications (or hybrid data offloading). In the following, we give a brief introduction of the three data offloading techniques.

An idea and low-cost method for offloading vehicular cellular communications is to deliver data through V2V communications. By establishing a multi-hop V2V routing path between two vehicles, data can be transmitted directly between them through the established multi-hop V2V routing path without the help of cellular BSs. Data offloading through V2V communications has been applied in many fields, especially delay-tolerant services [14], [15], e.g., voice over IP, video on demand, instant messaging, online gaming, AR, and virtual reality, and so on.

Vehicles can also offload cellular data through RSUs, which refers to data offloading through V2I communications. Vehicles switch to connect with RSUs if vehicles move into the communication range of RSUs, and vehicles switch back to connect with BSs when they are moving out of RSUs' communication range. In order to alleviate the network congestion effectively, RSUs are used as the low-cost relay, which helps to reduce the resource consumption. V2I communication enables the vehicle to know the relevant information about its surroundings at any time, and provides all kinds of service information and data network access.

A growing number of vehicles are driving the combination of V2I and V2V communications, which share data between vehicles through V2X communications. Under the V2X scenario, data are offloaded from Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) and vice versa. V2X is one of the research hot-spots of vehicle-borne network. The function of timely warning of V2X vehicle networking has became a hot-spot to solve the road safety problems. It puts forward strict requirements for communication status, data limitation, safety and security, etc.

In the following sections, we will survey the current studies in terms of the above mentioned three categories of mobile data offloading techniques through VANETs respectively, which are briefly summarized in Table 2.

III. DATA OFFLOADING THROUGH V2V

There have been a number of studies focusing on data offloading techniques through V2V communications. Most of them aim to investigate V2V-based data offloading framework design, efficient data transmission algorithm design through V2V, optimization problem formulation and algorithm design, seed selection, and so on. In this section, we review the data offloading techniques through V2V.

Song *et al.* [16] investigated backward data delivery under the traffic hole problem for V2V data transmissions. When the backward data delivery with a traffic hole problem happens, no available vehicles can forward the data to the destination since the data moves in the direction opposite to that of vehicles' movement direction. In order to solve this problem, the authors proposed to utilize RSUs to assist the data transmission under traffic hole problem, which combines two data forwarding methods together. One method is forwarded by RSUs, and another is based on backward data forwarding among vehicles. In order to meet different data transmission requirements and reduce resource consumption,

TABLE 2. A Classification of data offloading techniques through vehicular Ad Hoc networks, together with their research issues and surveyed works.

Data Offloading through V2V	V2V-based data offloading framework or Architecture Design [19], [24] Efficient data transmission algorithm design through V2V [17], [18], [21], [25], [27] V2V-based data offloading optimization problem formulation and algorithm design [20], [22], [23], [26]
Data Offloading through V2I	V2I-based data offloading framework or Architecture Design [37] Efficient RSU-Assisted data transmission algorithm design [16], [31], [35] RSU-assisted data offloading optimization problem formulation and algorithm design [28]–[30], [32]–[34], [36]
Data Offloading through V2X	V2X-based data offloading framework or Architecture Design [40]–[42] Efficient V2X-based data transmission algorithm design [38], [39], [43], [47], [48] V2X-based data offloading optimization problem formulation and algorithm design [45], [46]

the authors extended the single-copy scheme and multiple copies scheme, and considered the trade-offs of these methods. Through extensive simulations, the authors verified the effectiveness of the proposed methods.

Hung *et al.* [17] proposed a control scheme for offloading vehicular traffic in a cellular network to V2V paths that exist in VANETs. The proposed scheme used a centralized management strategy for calculations and notifications to establish a VANET routing path for pair-wised vehicles, which are currently communicating with each other using cellular networks. Based on it, a software defined network (SDN) in a moving edge computing (MEC) architecture was designed. Using the proposed SDN_i - MEC architecture, vehicles send their contextual information to the SDN_i - MEC server's context database, and the SDN_i - MEC controller of the SDN_i - MEC server can calculate whether a V2V path exits between the two vehicles currently communicating with each other via cellular networks. The provided performance analysis showed that the proposed scheme outperforms other existing schemes in terms of throughput when the vehicles' density is neither very low nor very high.

Ancona *et al.* [18] exploited the utilization of V2V communications for relieving the burden of cellular networks from floating car data (FCD) traffic. FCD-based service is widely used in many practical applications, such as remote monitoring of vehicles, tracking and detection of vehicles, and real-time flow control. They investigated the performance margin of the V2V offloading method by considering both the best-case and worst-case data aggregation possibilities of vehicles. To enhance the offloading performance, a simple distributed heuristic algorithm was proposed, which has near-optimal performance under any FCD aggregation model.

Nshimiyimana *et al.* [19] provided a comprehensive survey about the requirements and advantages for V2V communications and offloading over 4G or 5G networks. Device to device (D2D) communication was also analyzed and surveyed in this study, especially on offloading cellular traffic. The V2V communication was reviewed and the importance of the relevant parameters of nodes was emphasized. First, various protocols and localization techniques utilized in VANETs were studied and summarized. Then, several clustering algorithms used in VANETs were introduced. Finally, several possible research topics in the future were given.

Kolios *et al.* [20] proposed an optimal forwarding decision strategy for V2V assisted offloading. A flexible network flow model was established, which captures the dynamic movement patterns of vehicles and the resulting communication interactions among vehicular terminals. Then, based on the proposed network flow model, a mathematical programming model with high computational efficiency was developed, and an optimized forwarding strategy that benefits from V2V communications was proposed. The authors also studied the limitations of inter-vehicle communication transmission, and derived the decision-making strategy for V2V assisted offloading to improve the data delivery performance. The performance of the proposed strategy was evaluated using realistic simulations and the results demonstrated the superior performance of the proposed framework.

Torres *et al.* [21] proposed a novel method to offload mobile data from or to VANETs based on a virtualization layer and a new routing protocol. The authors pointed out that VANET is expected to be an extension of the wired Internet and determine the three steps of the proposed mode of operation of the service. However, high mobility of vehicles poses a great challenge to opportunistic transmissions of mobile data due to the difficulty of establishing and maintaining multi-hop routing paths against highly varying network topology, sudden vehicle movements, a large number of packet losses caused by obstacles, and so on. They proposed a new data offloading algorithm, i.e., virtual node intersection-based routing (VNIBR) from scratch, and the data offloading performance of the proposed method was tested using the combination of network simulator NS3 and the SUMO simulator of urban mobility.

Zhioua *et al.* [22] studied an optimization problem formula named VOPP, which uses the intelligent transportation system (ITS) to offload cellular traffic. The goal of the optimization problem is to select the maximum number of data flows that can be routed to the downloader via VANETs. VOPP takes into account link availability, gateway capacity, and channel gain between the infrastructure and the downloader. Extensive numerical results showed that the proposed offloading model VOPP performs well, and the data offloading rate is closely related to the volume of the flow data, vehicle positions and topology.

Zhu *et al.* [23] studied a mobile data offloading system that combines cellular networks with opportunistic VANETs.

In such a system, a mathematical framework was developed to investigate the contact-aware optimal resource allocation problem for data offloading by considering the contact duration of vehicles. The corresponding data offloading optimization problem was formulated as utility maximization under limited storage conditions. Based on theoretical analysis, an optimal scheme for data offloading was proposed to allocate the limited buffer of the target vehicles. Extensive simulations were conducted to evaluate the performance of the proposed methods, and the results showed that the proposed contact duration-aware optimal data offloading method performs much better than other existing methods.

Lee *et al.* [24] studied the potential benefits of VANETs, and proposed a VANET-based data offloading framework based on space-time rendezvous, named DOVE. To enhance the data offloading performance of DOVE, the authors utilized the vehicle trajectories to select data offloading positions, and formulated the data offloading position selection problem as a space-time set coverage problem. Then, the authors proposed a novel algorithm based on time prediction and vehicle trajectory to solve the problem. Extensive simulation results showed that the proposed framework DOVE can significantly reduce 57% of cellular traffic by adopting data offloading through VANETs.

Yuan *et al.* [25] proposed a mathematical framework to investigate the space and time-constrained data offloading for location-related services through VANETs. A contact graph based on dynamic probability was constructed to quantitatively describe the delivery opportunities among vehicles. Then using the contact graph, a greedy algorithm was proposed to select proper offloading seeds to maximize the data offloading efficiency under the spatial and temporal constraints on data transmissions. To describe the offloading efficiency, a novel utility function was used. Extensive simulation results showed that the proposed method outperforms other existing methods, and can achieve high offloading efficiency.

Li *et al.* [26] established an erasure-coding-based optimization framework to investigate mobile data offload problem in opportunistic vehicular networks in realistic network scenarios. The authors formulated the data offloading problem as a maximization problem of users' interest satisfaction under multiple linear constraints of limited buffer size storage, and proposed an efficient scheme to decide when to use erasure coding and how to allocate network resources in terms of offloading helpers' buffer. It is worth noticing that the considered optimization problem considered realistic factors, e.g., different types of mobile data, two types of vehicular nodes in the system (e.g., helpers and subscribers), different interests in different data items, and different buffer sizes of helpers. Extensive realistic trace-driven simulations were conducted to evaluate the performance of the proposed algorithm, and the results showed that the proposed algorithm performs much better than other existing algorithms that are traditionally designed to solve this type of challenging problems.

Mezghani *et al.* [27] utilized V2V communications to offload cellular traffic, and presented an innovative seed selection method named SIEVE, which takes into account two key aspects, i.e., users' interest satisfaction and near-future contacts prediction. Actually, several seed selections methods have been designed for VANET-based data offloading, however, few of them consider the users interests for various content objects that can be generated. Therefore, the purpose of this study was to design an interest-aware seed selection method for VANET-based data offloading. Based on the above two aspects, SIEVE defines a content utility to describe the satisfaction of users' interests, and selects seeds which can maximize content utility. Extensive simulations were conducted to evaluate the performance of the proposed method, and the results showed that SIEVE can improve the content utility significantly compared with other existing solutions.

IV. DATA OFFLOADING THROUGH V2I

There have been also some studies focusing on data offloading techniques through V2I communications. Most of them aim to investigate V2I-based data offloading framework or architecture design, efficient RSU-assisted data transmission algorithm design, and RSU-assisted data offloading optimization problem formulation and algorithm design. In this section, we review the data offloading techniques through V2I communications.

Chen *et al.* [28] also studied the VANET-based data offloading problem, which aims to deal with the challenge of fleeting connection time between vehicles and RSUs. To solve this problem, they adopted a two-phase resource allocation process to utilize the pattern of wireless and backhaul links, e.g., link scheduling and bandwidth allocation. For link scheduling, the corresponding optimization problem was formulated as an integer linear programming (ILP) problem aiming to maximize the system throughput, and then a heuristic low-complexity algorithm was proposed to address this problem. For bandwidth allocation, they proposed a simple algorithm for implementation. Finally, extensive simulations were conducted to evaluate the performance of the proposed methods, and the results showed that the proposed methods are more effective and efficient in enhancing network performances compared with other existing methods.

El Mouna Zhioua *et al.* [29] studied the utilization of ITSs to offload cellular data traffic, and modeled the problem as an optimization problem which aims to select a maximum target set of flows to offload a portion of cellular data through VANETs. The authors considered both the VANET capacity and the V2I and V2V link quality on data offloading decisions, and proposed a cooperative traffic transmission problem formulation under the joint of 4G LTE Advanced (LTE-A) cellular network and VANETs. Extensive simulation results showed that the performance of data offloading is highly related to the data volume, path quality of the traffic, and channel load. Furthermore, under certain circumstances, the offloaded data traffic can reach 100%.

Similarly, el Mouna Zhioua *et al.* [30] also considered utilizing VAENTs to offload cellular data traffic, and modeled the problem as an optimization problem which aims to select a maximum target set of flows to offload data to the destination down-loader through VANETs. However, different from the above proposed optimization problem in [29], the authors in this study took into account the constraints of link availability, channel load by considering medium contention. Simulation results showed that the channel load, traffic data volume and link quality have a significant impact on the data offloading performance, and for low data volume, data offloading rate can reach 100%.

Yu *et al.* [31] investigated the potential of using both cellular networks and RSUs to improve data transmission performance. The authors proposed a deduplication hybrid cellular and RSU-based method, in which moving vehicles can exploit the advantages of both cellular networks and RSUs. Here, popular data items can be disseminated by RSUs, and unpopular data items can be disseminated by cellular networks. Considering the mobility of vehicles, they proposed three global data broadcast scheduling algorithms, i.e., independent RSU scheduling algorithm, collaborative RSU scheduling algorithm and collaborative RSU scheduling with lookahead algorithm. Extensive simulations were conducted to evaluate the performance of the proposed algorithms in terms of cellular usage and download speed. The results showed that compared with other existing methods, the proposed algorithms can effectively reduce the use of cellular data and increase the download speed.

Malandrino *et al.* [32], [33] studied the effectiveness of using VANETs to offload cellular data. The authors assumed that RSUs can exploit mobility prediction to decide which data they should fetch from the cellular network and to schedule delivery to vehicles. To predict the mobility of vehicles on the road, they proposed fog-of-war model, a simple but effective way to express and interpret different degrees of prediction accuracy. In the fog-of-war model, the uncertainty of the influencing mobility prediction was modeled by the probability of contact between nodes, which can reproduce the Markov prediction accuracy. Then, they used this time-expanded graph created by the fog-of-war model to formulate the optimization problem as a non-integer linear programming optimization problem. Finally, analysis and simulation results showed that the prediction-based method performs much better than the content popularity-based solution in term of offloading efficiency, and the proposed VANET-based offloading method can offload 70% cellular data.

Sun *et al.* [34] introduced a cooperative downloading scheme to offload traffic from cellular networks through VANETs. In the scheme, each RSU acts as a traffic manager, obtains appropriate data from the cellular network and distributes the data to vehicles in an approximately optimal way. Specifically, a storage time aggregated graph for planning data transmission was designed based on vehicle mobility prediction and throughput estimation of vehicles, and the downloading scheme was modeled as an optimization problem with multiple constraints. To solve the optimization problem, the authors proposed an iterative greedy driving algorithm for achieving a suboptimal solution with a polynomial time complexity. Extensive simulations were conducted to evaluate the performance of the proposed scheme. The results showed that compared with the existing maximum throughput and minimum delay collaborative download (MMCD), the proposed scheme can achieve 5%-25% improvements.

Feng and Feng used field measurement data to prove the non-uniformity of wireless data traffic along the streets of big cities, and observed that the load of BSs at street intersections was much higher than that of neighboring BSs. Hence, BSs at street intersections are often overloaded and become bottlenecks in cellular networks. To solve this problem, the authors proposed a vehicle-assisted offloading (VAO) scheme to use vehicles stopping at the red light to offload large amounts of data traffic at street intersections. In this scenario, the vehicle receives delay insensitive data from the lightly loaded BSs along the street and then sends the data to the roadside users after entering the intersection area and stopping at a red light. The authors proposed a novel architecture to enable such offloading scheme. Extensive simulation results showed that the proposed VAO scheme can achieve a significant performance gain.

Wang and Wu [36] investigated the trade-off between the downloading delay and the downloading cost to decide whether to download the data from the cellular network directly or from RSUs. They defined the downloading cost and downloading delay as users' satisfaction, and formulated an optimization problem for maximizing the satisfaction of users. To solve the optimization problem, they proposed an adaptive algorithm, which can dynamically adjust the estimation and the current strategy. The proposed algorithm studied the interface scheduling problem between VANETs and cellular networks, and developed download strategies based on historical encounters between vehicles and multiple RSUs. Extensive real-trace driven simulations were conducted to evaluate the performance of the proposed algorithm, and the results showed that compared with other existing methods, the proposed algorithm can achieve better performance in terms of data offloading.

Si *et al.* [37] introduced a new architecture, named DaVe, with the goal of effectively utilizing the potential resources from VANETs (including vehicles and Roadside Units) to alleviate congestion problems in cellular networks. With the Dave architecture, a QoS-aware traffic off-line solution was proposed to offload delay tolerant data through VANETs regardless of the data coming from or to VANTEs. Based on this, the authors proposed an optimized distributed data hopping scheme in which the next hop decision optimization problem was considered as a partially observable Markov decision process (POMDP) to achieve delay tolerance in VANETs. Moreover, in order to reduce the computational complexity, the authors also proposed a heuristic algorithm.

Extensive simulations were conducted to evaluate the performance of the propose scheme, and the results showed that the proposed scheme has a significant improvement of the performance, compared with other existing schemes.

V. DATA OFFLOADING THROUGH V2X

There have been also some studies focusing on data offloading techniques through V2X communications. Most of them aim to investigate V2X-based data offloading framework or architecture design, efficient V2X-based data transmission algorithm design, and V2X-based data offloading optimization problem formulation and algorithm design. In this section, we review the data offloading techniques through V2X communications.

Otsuki and Miwa [38] studied effectively utilizing the way of V2X communications, which combines V2V communications and V2I communications together, to offload cellular data traffic. To efficiently share contents within a certain period of time, the authors proposed an effective content delivery controlling algorithm for vehicular real-time content generation. The proposed algorithm used route prediction method to enable vehicles to efficiently share contents through V2X communications. Extensive simulations were conducted to evaluate the effectiveness of the proposed method, and the results showed that the proposed method can achieve a good data offloading performance in terms of communication count, loss count, and reduction rate.

Besides, there are also some studies about offloading floating car data. An important example of FCD is urban remote sensing, in which vehicles collect environmental information around them and upload that data to the control center of the Internet. This is an important part of the intelligent city of the future. Stanica *et al.* [39] were the first to explore the scenario of offloading FCD problem. The authors considered a large-scale vehicle scene and described it with a time-varying model, and formulated the corresponding FCD offloading problem. To solve the optimization problem, they proposed three distributed FCD offloading schemes based on the considered principles. Extensive simulation results showed that the proposed schemes were extremely efficient and can reduce the access network's demand for FCD capacity by up to 95% of the data.

Zhang *et al.* [40] studied the challenges and opportunities of applying collaborative fog computing for handling big data in VANETs. The authors proposed an architecture of regional cooperative fog-computing-based Internet of vehicles (CFC-IoV) to handle big data in smart cities. Then, potential applications of the proposed CFC-IoV architecture were discussed, i.e., mobile control, multi-source data acquisition, distributed computing and storage, multi-path data transmission, etc. To optimize the performance of CFC-IoV, they proposed a hierarchical resource management model including intra-fog energy-aware resource management and inter-fog QoS-aware resource management. Extensive simulations were conducted to evaluate the performance of the proposed CFC-IoV architecture, and the results showed that the proposed model can achieved excellent performance in terms of energy efficiency and packet dropping rates.

Aujla *et al.* [41] proposed a new 5G SDN-based data offloading method to offload 5G cellular traffic through VANETs. The evolution of 5G technology is happening, and intelligent control needs to design so as to make decisions in a restricted and congested network. In this method, the authors designed a SDN-based controller which manages and controls data offloading by using a priority manager and a load balancer. Using these two managers in SDN-based controllers, even if the network is overloaded, the proposed method still performs well. Furthermore, they also proposed a single-leader multi-follower Stackelberg game for network selection so as to increase the data offloading performance. To evaluate the performance of the proposed method, they selected different network parameter evaluation effects, i.e., interferences, number of channels, and safety issues of loading vehicle data. Extensive simulation results showed that the proposed method performs much better than existing solutions.

Vigneri *et al.* [42] proposed an alternative architecture based on two main ideas: 1) they used vehicles as mobile small cells and data caches to offload cellular traffic; 2) they exploited the mobility of vehicles to serve more data requests from users with mobile devices, by vehicles' local caches. When vehicles are used as mobile caches to serve data requests, these vehicles are more widespread and require lower costs, compared with small cells. Based on the proposed architecture, the authors proposed an analysis framework to calculate the optimal number of content copies that each vehicle should cache, and analyzed how to optimally refresh vehicles' caches to publish new contents and how to react to the temporal variability of content popularity, so as to increase the data offloading performance. Extensive simulation results showed that the proposed method can greatly reduce the infrastructure load in the urban environment with moderate penetration rates and tolerable content access delays.

Adiththan *et al.* [43] proposed an adaptive data offloading technology that is suitable for cloud computing control calculations. The purpose is to provide a computing offloading technology that is suitable for vehicle safety and stability requirements in the presence of unreliable communication networks. The proposed method considered current network conditions and control application requirements to determine the feasibility of using remote computing and storage resources. At the same time, the authors described a case of a cloud-based path using crowdsourced data for path planning. Based on this, the authors proposed an adaptive offloading controller architecture, which determines when to offload control calculations into the cloud so that additional data and computing resources can be used to implement cloud computing. The authors proved the feasibility of the proposed method by using the cloud-based path controller case using Matlab.

Amani *et al.* [44] proposed a policy-based data offloading framework to efficiently offload data traffic in heterogeneous wireless networks. The authors considered user centric, network centric and hybrid policies in the framework design, which shares the decision making between the user and the network. They proposed a novel scheme for the hybrid decision making between the user and the network based on the autonomic networking principle, and chose policies dynamically on the basis of the variation of network conditions and the operator strategies. Extensive simulations were conducted to evaluate the effectiveness of the proposed policies in real networks, and the results showed that the proposed hybrid policies can achieve a significant Offloading Efficiency (OE) of up to 40%.

Wang *et al.* [45] proposed a computing offloading solution that combines fog computing with decentralized traffic management systems to achieve real-time traffic management in fog-based IoV systems with the goal of minimizing the average response time of vehicle reporting events. To solve this problem, the authors first built a distributed urban traffic management system in which vehicles close to RSUs can be used as fog nodes. Then, according to the queuing theory, the authors modeled the parking and moving vehicle-based fog nodes, and concluded that the mobile vehicular fog nodes can be modeled as $M/M/1$ queues. Finally, the authors proposed an approximate method to solve the offloading optimization problem by decomposing the optimization problem into two sub-problems and scheduling traffic flows among different fog nodes. Extensive simulations were conducted to evaluate the performance of the proposed method using the real-world tax trajectory dataset, and the results showed that the proposed method outperforms other existing methods.

Baron *et al.* [46] proposed to use traditional vehicles for daily routine journeys equipped with storage devices to offload delay-tolerant cellular traffic onto the road infrastructure network. The proposed services utilizes the stops drivers make at charging/swapping stations to opportunistically offload contents on vehicles. The authors focused on dealing with the allocation of data to vehicles while addressing the complexity of the road network. To solve this problem, they proposed an embedding algorithm that calculates the offloading coverage where each logical link spans multiple road segments from the underlying road infrastructure. Then, the data transmission allocation problem was formulated as a linear programming model, through which to determine the best logical path that meets the data transmission performance requirements. To evaluate the performance of the proposed method, they used the actual road traffic counts in France, and the simulation results showed that the proposed method have the potential to help operators offload big data.

Luoto *et al.* [47] utilized V2X communications to offload cellular traffic in a scenario with multi-lane freeway covered by the LTE-A RSUs. To ensure reliable communications, the authors proposed a scheme to offload data to vehicles with low signal-to-interference-plus-noise ratio (SINR), which have higher link quality to the RSUs. These vehicles with higher link quality are also known as cluster leaders. Extensive simulations were conducted to evaluate the performance of the proposed scheme, and the results showed that the proposed scheme tried to offload data from low quality V2I links to high quality V2V links, and increased the successful delivery probability from 93% to 99.4%.

Feng *et al.* [48] proposed a vehicle assisted offloading (VAO) scheme that uses vehicle queue stopping for the red light to offload cellular data traffic from a busy street intersection cell to its largely idle neighboring cells. A considerable proportion of the mobile cellular traffic is insensitive to delay. As a benefit of using the VAO, the free resources of the roadside cell can be utilized to ease the congestion of the cross-cell, which substantially improves the wireless resources. The authors theoretically analyzed the performance of the proposed VAO scheme by considering the road traffic conditions and the communications between vehicles and pedestrians. They used fluid theory to simulate road traffic, and analyze the theoretical performance of the VAO scheme. Extensive simulation results verified the authors' analysis results, and proved that VAO can achieve significant performance gains.

VI. CONCLUSIONS AND FUTURE RESEARCH AREAS

Data offloading through VANETs is an emerging approach for alleviating the burden on current cellular networks when satisfying vehicular users' various services and applications. It can provide effective solutions for mobile data traffic management to MNOs for enhancing networking performances, e.g., reducing network congestions and improving users' QoS/QoE. Considering the rapid growth of mobile data traffic from vehicles, it is very urgent to investigate the corresponding data offloading techniques through VANETs. In this paper, we have investigated the technical concept of data offloading techniques through VANETs. Besides, according to the communication types among vehicles and infrastructures in VANETs, we have classified the related existing data offloading techniques into three categories, i.e., data offloading through V2V, data offloading through V2I, and data offloading through V2X. Then, we have introduced a detailed taxonomy of the existing studies on data offloading techniques in these three categories respectively.

Data offloading through VANETs is still a very new and hot research and application area. In spite of the above existing studies that we have surveyed, there are still many open research challenges when the data offloading techniques through VANETs are practically implemented. Among the main challenges, effective global/local network information, e.g., geographical locations, vehicle mobility, social relationships, link connections, congestion situations, buffer states, traffic rates and so on, needs to be collected and predicted timely, which is important for the involved network devices (e.g., vehicles and BSs/RSUs) to design online/offline data offloading schemes in VANETs. However, during the network information collection, security and privacy in VANETs are also important issues for consideration since some network devices are not willing to share their own information to others [6], [50]–[52]. As a result, new secure communication schemes involving data transmissions and network protocols need to be well investigated. Moreover, due to the rapid increase of vehicles on roads as well as service requests from vehicular users, VANETs are generally large-scale in the real world, and thus are required to provide network scalability for supporting larger traffic load while maintaining consistent and acceptable network performances (e.g., vehicular users' QoS/QoE). In particular, three research areas in terms of network scalability need to be exploited, i.e., clustering, symmetric multiprocessing and load balancing for satisfying vehicular users' services and applications effectively.

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