Offloading Mobile Data Traffic for QoS-aware Service Provision in Vehicular Cyber-Physical Systems

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***Abstract*—**Owing to the increasing number of vehicles in vehicular cyber-physical systems (VCPSs) and the growing popularity of various services or applications for vehicles, cellular networks are being severely overloaded. Offloading mobile data traffic through Wi-Fi or a vehicular ad hoc network (VANET) is a promising solution for partially solving this problem because it involves almost no monetary cost. We propose combination optimization to facilitate mobile data traffic offloading in emerging VCPSs to reduce the amount of mobile data traffic for the QoS-aware service provision. We investigate mobile data traffic offloading models for Wi-Fi and VANET. In particular, we model mobile data traffic offloading as a multi-objective optimization problem for the simultaneous minimization of mobile data traffic and QoS-aware service provision; we use mixed-integer programming to obtain the optimal solutions with the global QoS guarantee. Our simulation results confirm that our scheme can offload mobile data traffic by up to 84.3% while satisfying the global QoS guarantee by more than 70% for cellular networks in VCPSs.

Keywords—***mobile service; traffic offloading; vehicular cyber-physical system; vehicular ad hoc network; Wi-Fi; service provision; QoS***

1. INTRODUCTION

In recent years, vehicular cyber-physical systems (VCPSs) have been proposed to exploit the latest advances in sensing, computing, communications, and networking technologies to improve the intelligence, safety, efficiency, resiliency, and environmental compatibility of transportation systems [1, 2].

With the rapid development of VCPSs, an increasing number of vehicles with wireless communication capabilities can connect to Wi-Fi or cellular networks, thereby gaining access to various mobile services or applications such as safety applications, driving assistance, and multimedia content sharing. Owing to the widespread use of vehicles and growing service demands, mobile data traffic is increasing at an unexpected rate in VCPSs. According to the latest Cisco forecasts [3], global mobile traffic will increase tenfold between 2014 and 2019, and monthly global mobile data traffic will surpass 24.3 exabytes by 2019. Because of this exponential growth in mobile data traffic, cellular networks will be overloaded. In particular, during peak-hour traffic in urban areas, service provision will suffer from extreme performance hits in terms of limited network bandwidth, dropped calls, and unreliable coverage.

Rapid growth in mobile data traffic leads to a sharp drop in the quality of service provision [4]. To provide effective quality of service (QoS), the most straightforward solution is to increase the cellular network capacity by adding more base stations with a smaller cell size, such as picocells and femtocells, or by deploying 4G networks [5]. Hence, service providers around the world are busy rolling out 4G networks to meet the growing end-user demand for better QoS such as higher bandwidth and faster connectivity on the go. However, although 4G or LTE networks provide better QoS, when vehicular capabilities are combined with these networks, the widespread adoption of advanced vehicular applications, such as video sharing, cloud applications, and big data services, will further increase mobile data traffic. For example, in 2013, a 4G connection generated 14.5 times more traffic on average than a non-4G connection [3]. Therefore, even if the capacity of existing networks is enhanced, the future demands of users and applications will quickly exceed the network capacity. Simply using cellular networks for vehicular Internet access may aggravate the overload problem and degrade the service performance of both non-vehicular and vehicular users [6]. Thus, rapid growth in mobile data traffic leads to a growing need for offloading solutions, and it becomes essential for operators to provide various offloading schemes in VCPSs.

There are two types of schemes for achieving mobile data traffic offloading: Wi-Fi offloading [5-7] and vehicular ad hoc network (VANET) offloading [8-10]. Cellular network congestion can be alleviated by delivering data originally targeted for cellular networks by Wi-Fi (*i.e.*, Wi-Fi offloading) [6]. It has been shown that approximately 65% of cellular traffic can be offloaded by merely switching from cellular networks to Wi-Fi when Wi-Fi connectivity is available [5, 6, 11]. In urban environments, vehicles with low mobility signal nearby Wi-Fi access points (APs) when traveling along a road so that cellular traffic can be delivered to the vehicles through the drive-thru Internet [12] in an opportunistic manner. This opportunistic Wi-Fi offloading offers unique features in VCPSs. At present, vehicles are ranked third, behind homes and offices, in terms of places where people spend the most time daily [13]. Moreover, vehicles are becoming increasingly intelligent and connected, as they are equipped with on-board units (OBUs). According to forecasts of the European Telecommunications Standards Institute [14], by 2027,nearly all vehicles will be equipped with OBUs. OBUs are devices that provide vehicle-to-vehicle (V2V) links and vehicle-to-infrastructure (V2I) communications, where Wi-Fi APs and base stations of cellular networks belong to the infrastructure. Moreover, a dedicated frequency band, 5.86 to 5.92 GHz, has been allocated for IEEE 802.11p vehicular communications. Therefore, considering VANET for offloading cellular traffic (*i.e.*, VANET offloading) represents an attractive solution.

Using the above-mentioned technology as a foundation, some notable studies [5-10] have focused on offloading mobile data traffic. Although these offloading schemes can significantly reduce the mobile data traffic in cellular networks, they are not sufficiently efficient for VCPS sowing to two factors. First, most current studies focus on Wi-Fi offloading or VANET offloading and assume homogeneous offloading capacity for each Wi-Fi AP and vehicle in VCPSs. At first glance, this assumption appears to be reasonable, but it is unreasonable in a VCPS environment because different vehicles or newly deployed Wi-Fi APs are usually added to VCPSs to provide services; thus, different vehicular and Wi-Fi configurations form a heterogeneous mobile data traffic offloading environment. Second, an excellent mobile data traffic-offloading scheme satisfies the maximum traffic offloading requirements for service provision and also guarantees QoS. Therefore, QoS also plays an important role in determining the success or failure of offloading schemes. However, traditional offloading schemes mainly focus on the local QoS guarantee of mobile data traffic offloading and rarely consider the global QoS guarantee of service provision. The local QoS guarantee of mobile data traffic offloading is to offload traffic from a node with its QoS requirements independently on the other nodes. Even if the local QoS guarantee approach is useful in Wi-Fi environments, it is not suitable for mobile data traffic offloading with end-to-end QoS constraints (*e.g.*, maximum total response time) because such global constraints cannot be verified locally. The global QoS guarantee approach aims at solving the problem on the composite mobile data traffic offloading level. The aggregated QoS values of all possible nodes from Wi-Fi or VANET are computed and the node combination that maximizes mobile data traffic offloading while satisfying global constraints is selected. Hence, finding a tradeoff between mobile data traffic offloading and the global QoS guarantee is very important for VCPSs.

In this paper, we propose an alternative mobile data traffic offloading approach for VCPSs. In contrast to the previous studies described above, our study removes the assumption of offloading capacity homogeneity and considers the global QoS guarantee of QoS-aware service provision. First, we establish the Wi-Fi and VANET offloading models and quantify the offloading capacity of each Wi-Fi AP or vehicle. Then, mobile data traffic offloading is formulated as a multi-objective combinatorial optimization problem that aims to simultaneously optimize possibly conflicting objectives. The objectives include making efficient use of multidimensional resources, satisfying the global QoS guarantee, and reducing mobile data traffic. A mixed-integer programming search method is used to efficiently search for global optimal solutions within a reasonable runtime. We implement our approach and compare it with the other approaches using the QualNet simulator[1].The simulation results indicate that our approach significantly reduces mobile data traffic while satisfying the global QoS guarantee in VCPSs.

The remainder of this paper is organized as follows. Section 2 reviews related studies. Section 3 establishes the Wi-Fi and VANET offloading models for VCPSs, quantifies their offloading capacity, and presents the problem statement. Section 4 describes the proposed approach to mobile data traffic offloading for QoS-aware service provision in VCPSs. Section 5 presents performance evaluations for comparing our solution against existing solutions. Finally, Section 6summarizes our findings and concludes the paper.

2. RELATED WORK

Some notable schemes have been proposed to provide efficient mobile data traffic offloading for VCPSs.

From the Wi-Fi offloading perspective, Wi-Fi is recognized as one of the primary offloading technologies [11]. P. Deshpande *et al.* [15] proposed a prefetching mechanism motivated by the effective prediction of the mobility and connectivity of vehicles; the data can be redundantly prefetched by subsequent Wi-Fi APs. Subsequently, L. Kyunghan *et al.* [16] presented a delayed offloading framework, whereby users specify a deadline for each application or data, and each delay tolerant data is served in a shortest remaining time first manner through Wi-Fi networks. If the delay deadline of the data expires, the data are transmitted through 3G networks. A. Balasubramanian *et al.* [17] proposed an offloading framework for vehicular networks that supports fast switching between 3G and Wi-Fi and avoids bursty Wi-Fi losses. C. Nan *et al.* [6] presented an analytical framework for offloading cellular traffic through outdoor Wi-Fi networks in the vehicular environment and then modeled the arrivals and fulfillments of data services of a vehicular user as an M/G/1/K queue, derived the probability distribution of the effective service time, and analyzed the average service delay and offloading effectiveness via queuing analysis. P. Lv *et al.* [18] proposed an approach to support seamless and efficient Wi-Fi-based Internet access for moving vehicles. It consists of innovative protocols for both uplink and downlink. Seamless roaming of clients was achieved, while the channel utilization efficiency was improved considerably. H. Xiaoxiao *et al.* [19] developed a transport layer protocol to move bits from expensive cellular data networks to relatively cheaper Wi-Fi networks while supporting vehicular mobility and then designed a scheduling system to deliver optimal benefits to the user based on the selected utility and cost models. Although these Wi-Fi offloading schemes can significantly reduce the mobile data traffic, they are not sufficiently efficient for VCPSs because the Wi-Fi APs are heterogeneous. Moreover, these schemes cannot support the QoS constraints for traffic offloading; they deviate from the global QoS guarantee of QoS-aware service provision in VCPSs.

[1]http://web.scalable-networks.com/content/qualnet

From the VANET offloading perspective, L. Yong *et al.* [8] proposed an efficient algorithm to allocate network resources to mobile data that are waiting for offloading and then provided a decision as to which content should use the erasure coding and the coding policy for each set of mobile data. Based on this result, a data replication algorithm was proposed to distribute the coding packets or mobile data into the buffers of offloading helpers. G. Mouna Zhioua *et al.* [20] presented a max-flow optimization problem formulation to evaluate the capacity of VANET networks to route a fraction of the cellular traffic for the purpose of cellular infrastructure offloading and then selected data flows that could be routed to the downloader by considering the V2I and V2V link availability and quality, contention, flow volume, and flow service class. H. Labiod *et al.* [13] presented an analytical study by evaluating the extent to which a VANET could offload mobile data traffic while considering the constraints related to mobile node connectivity and the infrastructure features. L. Yong *et al.* [21] proved that this generic optimal disruption-tolerant network offloading problem is NP-complete and provided three suboptimal algorithms to tackle this challenging offloading problem. The first algorithm is designed for the generic offloading scenario, the second algorithm is suitable for the offloading scenario wherein content lifetimes are short, and the third algorithm provides the optimal solution for the special homogeneous offloading scenario with homogeneous contact rates and data items. Although these VANET offloading schemes can reduce the mobile data traffic with a QoS guarantee, they only provide a local QoS guarantee and cannot satisfy the global QoS guarantee of QoS-aware service provision in VCPSs.

In contrast to existing schemes that suffer from poor performance due to heterogeneous offloading capacity and global QoS guarantee in VCPSs, our approach can minimize mobile data traffic while satisfying the global QoS guarantee by modeling mobile data traffic offloading as a multi-objective combinatorial optimization problem.

3. WI-FI AND VANET OFFLOADING MODELS

Unlike traditional approaches, our approach takes QoS into consideration, *i.e.*, QoS as a constraint should be guaranteed when we use Wi-Fi and VANET to offload mobile data traffic.

Recently, as an increasing number of Wi-Fi APs are deployed over roads in VCPSs, vehicles have greater opportunities to access mobile services via Wi-Fi on the go. The communication region of a Wi-Fi AP is the geographical region where vehicles can send and receive service from the Wi-Fi. In the communication region, QoS is affected by the distance from the AP. Therefore, the appropriate region to offload mobile data traffic based on Wi-Fi should be computed accurately.

Note that building a VANET among vehicles is a very common technology in VCPSs. As vehicles have high dynamicity, numerous clustering methods have been proposed for grouping homogeneous vehicles into stable sets, which are called clusters. In fact, a cluster can form a VANET, and the VANET ensures stable communication viaV2Vlinks. Furthermore, owing to the high dynamicity of vehicles, not all services required in a VANET can guarantee QoS, which is related to the region. Therefore, the appropriate region to offload mobile data traffic with the global QoS guarantee in a VANET should also be calculated.

In this paper, we refer to vehicles that wish to access mobile services as "interest vehicles," and the interest vehicles receive services and download data from VCPSs. In our approach, interest vehicles obtain services in multiple ways: 1) receiving services via Wi-Fi if the interest vehicle is in the appropriate region of a Wi-Fi AP; 2) obtaining services from a VANET if they are available in the VANET; and 3) requesting cellular networks to provide services otherwise.

Table 1. Notations

Symbol	Meaning
q_{plr}	The packet loss rate of Wi-Fi
q_{de}	The network delay of Wi-Fi
d	The distance between a vehicle and a Wi-Fi AP
p	The received power at distance d from a Wi-Fi AP
bw	The bandwidth of Wi-Fi
m	Supporting the maximization number of vehicles in a Wi-Fi AP
q	The transmission probability of Wi-Fi
f_{WiFi}	The offloading mobile data traffic for an interest vehicle via Wi-Fi
ρ	The vehicle density of VANET
f_{plr}	The packet loss rate function of VANET
f_{de}	The delay function of VANET
B_{VANET}	The transfer rate among vehicles
P_{VA}	The probability of a vehicle engaging in a VANET
P_{ve}	The probability of an interest vehicle obtaining services from other vehicles
f_{VANET}	The degree of mobile data traffic offloading via VANET
V	A mobile data traffic-offloading task in a VCPS.
V	The candidate vehicle
l	The number of candidate vehicles in a VCPS
R	The number of QoS attributes of an offloading task in a VCPS
$q(V)$	The aggregated QoS attribute values from all of the selected candidate vehicles
$f(v)$	The mobile data traffic function for a moving vehicle v
$F(V)$	The mobile data traffic function for the offloading task V
C	The global QoS constraint set
m	The number of global QoS constraints

The primary objective is to calculate the amount of mobile data traffic that can be offloaded using Wi-Fi and VANET. To guarantee global QoS, we should determine the appropriate region to offload traffic in Wi-Fi and VANET. The QoS of

Wi-Fi or VANET includes many attributes, such as reputation, reliability, throughput, delay, and availability. In general, it can be divided into two categories: positive QoS attributes and negative QoS attributes. For the positive QoS attributes (*e.g.*, *reputation*, *availability*), the larger the attribute value is, the better the performance is of the server running the service. Conversely, the negative QoS attributes (*e.g.*, *packet loss rate*, *delay*) should be as low as possible. Without loss of generality, in this paper, we consider only negative QoS attributes, *i.e.*, packet loss rate and delay. Note that the notations in Table 1 will be used throughout the paper.

3.1 Wi-Fi Offloading Model

As this paper focuses on packet loss rate and delay, in this section, we discuss how these two QoS attributes $qos = \{q_{plr}, q_{de}\}$ affect mobile data traffic offloading and provide the Wi-Fi offloading mode in VCPS.

Generally, the packet loss rate decreases with the receive power increase. Additionally, distance is always one of the most important factors for receive power, *i.e.*, we can use the distance to measure the packet loss rate. Therefore, it is very important to keep vehicles in the appropriate region for guaranteeing the packet loss rate. According to the distance-loss model [22], we can calculate the received power p at distance d from a Wi-Fi AP as

$$p = p_0 - 10n_p \log(\frac{d}{d_0}) + \xi \tag{1}$$

where p_0 is the received power at reference distance d_0, n_p is the path loss exponent, and ξ is a Gaussian variable [22].

Assuming that the received power is p with the constraint of packet loss rate q_{plr}, we can obtain the effective distance d according to (1) as follows:

$$d = d_0 10^{\frac{p_0 + \xi - p}{10n_p}} \tag{2}$$

According to (2), we know that Wi-Fi can guarantee the QoS of the packet loss rate with an effective distance of $2d$. In other words, each vehicle has the opportunity to receive mobile data from a Wi-Fi network at a distance of 0 to $2d$. In reality, the effective distance of the vehicles is restrained by roads, and we can always compute an effective distance on each road. In urban areas, road density is always very high, and the effective distance of each road is different. For convenient calculation, we assume that the effective distance of the vehicle is a uniform distribution, *i.e.*, *l-U[0, 2d]*, where *l* denotes the effective distance of the vehicle. According to the uniform distribution, we can obtain the expectation of *l*, *i.e.*, *d*.

Delay also affects the appropriate Wi-Fi region. As is well known, bandwidth is the key factor that determines delay. For Wi-Fi, as the bandwidth is fixed, all vehicles share the fixed bandwidth, *i.e.*, the greater the number of vehicles that use Wi-Fi, the smaller the bandwidth availability is for each vehicle. We assume that the fixed bandwidth of Wi-Fi is *bw* and set the number of vehicles as *m*. We know that the vehicles connect to Wi-Fi by following a Poisson arrival process $\{X(t), t \ge 0\}$ with parameter $\lambda (>0)$ [8]. In practice, the traffic is different for various intervals in a day, but we can divide a day into several intervals according to the vehicle traffic such as rush hour. In addition, the number of vehicles for different intervals follows the Poisson distribution with different parameter λ. Assuming that there are n intervals $(T_1, T_2, ..., T_n)$ with parameters $(\lambda_1, \lambda_2, ..., \lambda_n)$, for the time t belonging to each interval, the probability of the number of vehicles in the Wi-Fi network can be obtained as

$$P\{X(t+s) - X(s) = m\} = e^{-\lambda t} \frac{(\lambda t)^m}{m!} \tag{3}$$

where s denotes the start time, $(s+t) \in (T_1, T_2, ..., T_n)$, $\lambda \in (\lambda_1, \lambda_2, ..., \lambda_n)$.

According to the delay, assuming that the overall bandwidth of a Wi-Fi AP is BW and the bandwidth of a service demand is bw, the upper bound of the number of vehicles, m, can be obtained as follows:

$$m = \left\lfloor \frac{BW}{bw} \right\rfloor \tag{4}$$

where $\lfloor \; \rfloor$ denotes rounding down. The probability of satisfying the bandwidth for the service is known as the transmission probability and is given by

$$q = \sum_{i=1}^{m} (e^{-\lambda t} \frac{(\lambda t)^i}{i\,!}) \tag{5}$$

According to (2), (3), and (5), offloading mobile data traffic f_{WiFi} for an interest vehicle via Wi-Fi can be calculated as

$$f_{WiFi} = B_{WiFi} q \frac{d}{v} \tag{6}$$

where v denotes the vehicle speed and B_{WiFi} denotes the Wi-Fi transfer rate.

3.2 VANET Offloading Model

VANET plays an important role in communication and service provision in VCPSs, and it can be used to offload mobile data traffic because vehicles can transfer services and data to the interest vehicle. As in the case of Wi−Fi, offloading mobile data traffic via VANET also requires a QoS guarantee.

In VCPSs, several environmental factors affect packet loss rate and delay, and one of the most important factors is the vehicle density of VANET. On the one hand, if the vehicle density is too high (traffic jams) and the vehicles are too crowded in the VANET, hops between vehicles would lead to data redundancy, which increases network overhead and also leads to the possibility of load imbalance. On the other hand, low vehicle density could make it difficult to establish a VANET. Therefore, the packet loss rate and delay can be represented by a quadratic function in a variable representing the vehicle density. To help us judge whether the present density of vehicles satisfies the QoS directly, we model them as regular quadratic functions (Although the functions of packet loss rate and delay are not regular quadratic functions, anon-increasing range and non-decreasing range exist for the value of QoS. Hence, we can model them as regular quadratic functions).

Let ρ denote vehicle density. The packet loss rate function f_{plr} and the delay function f_{de} can be described as follows:

$$f_{plr}(\rho) = a_{plr}\rho^2 + b_{plr}\rho + c_{plr} \tag{7}$$

$$f_{de}(\rho) = a_{de}\rho^2 + b_{de}\rho + c_{de} \tag{8}$$

where $a_{plr} \in R(a_{plr} \neq 0)$, $b_{plr} \in R$, and $c_{plr} \in R$ denote the coefficients of the quadratic functions with packet loss rate and $a_{de} \in R(a_{de} \neq 0)$, $b_{de} \in R$, and $c_{de} \in R$ denote the coefficients of the quadratic functions with delay.

Obviously, the transfer rate B_{VANET} among vehicles can be represented by the quadratic function with the vehicle density according to (7) and (8). We assume that $f_{BW}(\rho)$ denotes the transfer rate function with vehicle density as follows:

$$f_{BW}(\rho) = a_{BW}\rho^2 + b_{BW}\rho + c_{BW} \tag{9}$$

where $a_{BW} \in R(a_{BW} \neq 0)$, $b_{BW} \in R$, and $c_{BW} \in R$ denote the coefficients of the quadratic function of the transfer rate.

For the QoS guarantee of one service, when a VANET satisfies its packet loss rate and delay, *i.e.*, $f_{plr}(\rho) \leq q_{plr}$ and $f_{delay}(\rho) \leq q_{de}$, the interest vehicles can obtain service from the VANET. As vehicles accessing the Wi-Fi network follow a Poisson arrival process with parameter $\lambda(>0)$, the vehicle density ρ can be calculated from λ and the effective distance d as follows:

$$\rho = \frac{\lambda}{\pi v d} \tag{10}$$

In a VCPS environment, vehicles exhibit high dynamicity and the vehicle density varies in each area; thus, some vehicles are unable to form a VANET. Therefore, we set a VANET rate, denoted by p_{VA}, which represents the probability of a vehicle engaging in a VANET. Obviously, as the vehicle density ρ is higher, the rate p_{VA} is larger; thus, p_{VA} can be calculated using the vehicle density ρ as follows:

$$p_{VA} = f_{VA}(\rho) \tag{11}$$

where $f_{VA}(\rho)$ denotes a non-decreasing function with the variable ρ.

Moreover, vehicles in VCPSs may not have the service required by the interest vehicle. To describe this case, we set another parameter, which is referred to as the service probability p_{ve}, to represent the probability of an interest vehicle obtaining a service from other vehicles. Furthermore, the vehicles are constrained by road conditions and traffic rules when running on the road, and an interest vehicle may exit from a VANET at anytime owing to its high dynamicity. Therefore, we can obtain the duration t_{VA} for which a vehicle engages in a VANET according to the vehicle speed and road condition. Then, the degree of mobile data traffic offloading via VANET for one vehicle during t_{VA} can be calculated as follows:

$$f_{VANET}(\text{qos}) = \begin{cases} B_{VA} \cdot t_{VA} \cdot p_{VA} \cdot p_{ve}, & f_{plr}(\rho) \leq q_{plr} \text{ and } f_{de}(\rho) \leq q_{de} \\ 0, & \text{otherwise} \end{cases}$$

(12)

where B_{VA} denotes the transfer rate between vehicles in VANET.

4. OUR OFFLOADING APPROACH

4.1 System Model

As shown in Fig. 1, the system model is based on a VCPS architecture that consists of three systems: Wi-Fi APs, an LTE Advanced infrastructure, and a VANET network. The architecture includes a VANET network that consists of vehicles moving on a road where Wi-Fi APs are deployed. The geographical region of a Wi-Fi AP in which vehicles are moving and exchanging information with this Wi-Fi AP is referred to as ROW. The geographical region of a base station in which vehicles are moving and exchanging information with this base station is referred to as ROB vehicles that have three interfaces: an IEEE 802.11p interface, an IEEE 802.11n interface, and an LTE interface. Each vehicle uses the IEEE802.11p interface to communicate with its neighboring vehicles, the IEEE 802.11n interface to communicate with Wi-Fi APs, and the LTE interface to communicate with a base station of a cellular network.

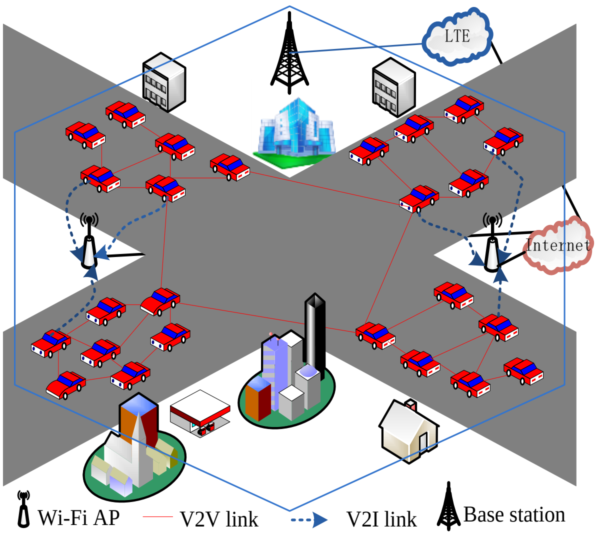

Fig. 1 System model

In VCPSs, vehicles periodically send their identity and position/velocity to the base station and Wi-Fi network so that they can keep track of vehicles in ROB and ROW. Thus, using position/velocity information received periodically from vehicles, snapshots of the vehicles are built to determine the V2I and V2V connectivity graph and the link stability in VCPSs. A graph connectivity manager (GCM) module is installed in each ROB. AROB can build and update the connectivity graph of vehicles using location information collected from the vehicles. The graph consists of vertices and edges, where a vertex represents a vehicular node. An edge joins two vertices, and it is assigned a weight related to the link quality fraction, *i.e.*, QoS will be affected. QoS is computed on the basis of the distance from the Wi-Fi AP and the vehicle density of the VANET. The vehicle connectivity graph is periodically updated at each base station using its GCM module with centralized control of VCPSs.

The interest vehicles of VCPSs obtain services/content from the infrastructure in multiple ways: 1) it could be a direct I2V transfer from Wi-Fi APs, *i.e.*, I2V link; 2) services could also be obtained from other vehicular nodes that relay it to the destination through multi-hop V2V links to the interest vehicle, *i.e.*, V2V link; and 3) the interest vehicle uses the direct link to the LTE infrastructure to obtain its service from the base station otherwise. Therefore, mobile data traffic has different QoS values when the vehicles belong to Wi-Fi or VANET. The remaining traffic is sent through the cellular network with a stable QoS value. Then, for the interest vehicles, the selection of vehicles according to QoS values based on the GCM module becomes very important for maximum mobile data traffic offloading in VCPSs; this is known as the vehicle selection problem.

4.2 Vehicle Selection

To clarify the process of vehicle selection, we provide some preliminary information in this section. Some basic concepts are listed below.

1) $V=\{\mathrm{v}_1, v_2, ..., v_n\}(n=1,2,3,...)$ denotes a mobile data traffic-offloading task that can satisfy the QoS guarantee. It is constructed by combining multiple candidate vehicles selected from each ROW. A ROW $v_i \in V\left(i=1,2,3,...\right)(1\le i\le n)$ often contains a number of candidate vehicles $v_i=\{v_{i1}, \mathrm{v}_{i2}, ..., \mathrm{v}_{il}\}$ where $l(l=1,2,3,...)$ is the number of candidate vehicles with the same offloading/communication function but different QoS values.

2) $QV=\{q_1(\mathrm{V}), q_2(\mathrm{V}), ..., q_r(\mathrm{V})\}$ denotes the attribute vector of an offloading task where the value of $q_r(\mathrm{V})$ is aggregated for $r\,(r=1,2,3,...)$ attribute values from all of the selected candidate vehicles using QoS aggregation functions.

3) $Qv_{ij}=\{q_1(\mathrm{v}_{ij}), q_2(\mathrm{v}_{ij}), ..., q_r(\mathrm{v}_{ij})\}$ denotes the QoS values of the vehicle v_{ij}. Then, the QoS aggregation function with the delay and packet loss rate of the vehicles is given by

$$q(\mathrm{V})=\sum_{i=1}^{n} q(\mathrm{v}_i) \tag{13}$$

4) Note that the greater the mobile data traffic is, the higher the QoS values of services are from vehicles. Hence, in this paper, we use a QoS aggregation value to represent the mobile data traffic. Mobile data traffic functions for a moving vehicle $v_{ij}\in v_i$ and offloading task V are defined as follows:

$$f(\mathrm{v}_{ij})=\sum_{k=1}^{r}\frac{Q_{i,k}^{max}-q_k(\mathrm{v}_{ij})}{Q_{i,k}^{max}-Q_{i,k}^{min}}\cdot tr \tag{14}$$

$$F(\mathrm{V})=\sum_{k=1}^{r}\frac{Q_{k}^{max}-q_k(\mathrm{V})}{Q_{k}^{max}-Q_{k}^{min}}\cdot tr \tag{15}$$

with

$$\begin{cases} Q_k^{max}=\sum_{i=1}^{r} Q_{i,k}^{max}\,(Q_{i,k}^{max}=\max_{\forall \mathrm{v}_{ij}\in v_i} q_k(\mathrm{v}_{ij})) \\ Q_k^{min}=\sum_{i=1}^{r} Q_{i,k}^{min}\,(Q_{i,k}^{min}=\min_{\forall \mathrm{v}_{ij}\in v_i} q_k(\mathrm{v}_{ij})) \end{cases} \tag{16}$$

where tr denotes the relation between QoS and traffic. $Q_{i,k}^{max}$ ($0<k<r$) is the maximum value of the k-th attribute of all of the candidate vehicles of the VCPS v_i. Similarly, $Q_{i,k}^{min}$ is the minimum value of the VCPS v_i, Q_k^{max} is the sum of all $Q_{i,k}^{max}$ in the offloading task *V*, and Q_k^{min} is the sum of all $Q_{i,k}^{min}$.

Using the mobile data traffic function, we can calculate the traffic of each candidate vehicle by mapping the vector of QoS values Qv_{ij} into a single global QoS aggregated value $f(\mathrm{v}_{ij})$. We can then sort and rank all candidate vehicles in VCPSs.

5) $C=\{C_1, C_2, ..., C_m\}$ denotes the global QoS guarantee in VCPSs, where $m\,(0<m<r)$ represents the number of QoS constraints.

Fig. 2 shows a conceptual overview of the vehicle selection problem for mobile data traffic offloading in VCPSs. Given an abstract offloading task request, which can be stated in a VCPS, the VCPS uses the existing infrastructure (*e.g.*, Wi-Fi, VANET, LTE) to locate available vehicles in each ROW using the Wi-Fi offloading model or VANET offloading model. As a result, a list of candidate vehicles is obtained for each task. The goal of vehicle selection is to select one component vehicle from each list such that mobile data traffic offloading of the VCPS is maximized while the aggregated QoS values satisfy the global QoS guarantee. This paper focuses on the selection of vehicles based on their traffic offloading and QoS attributes.

We present an example from a mobile data traffic-offloading task to illustrate our approach. As shown in Fig. 2, an offloading task involves three stages: 1) a vehicle requests video from some transfer vehicle in VANET; 2) the transfer vehicle transfers the request to Wi-Fi and LTE; and 3) a Wi-Fi AP or LTE provides the requested video content from the Internet. The video request is usually associated with a set of global QoS guarantees C, *e.g.*, delay ≤1 s. Hence, the running offloading process can be divided into three stages as shown in Fig. 2. First, a set of concrete vehicles, *i.e.*, $v_i=\{\mathrm{v}_{i1}, \mathrm{v}_{i2}, ..., \mathrm{v}_{il}\}$, is obtained to ensure that the candidate vehicles can meet the functional requirements of task

$V=\{v_1,v_2,...,v_n\}(n=3)$ (VANET, LTE, and Wi-Fi). Then, using the global QoS guarantee set C, the composite solutions that satisfy the global QoS guarantee are recorded. Finally, an optimal vehicle selection that achieves the maximum traffic offloading (*i.e.*, the traffic from LTE is the least) with the global QoS guarantee is determined.

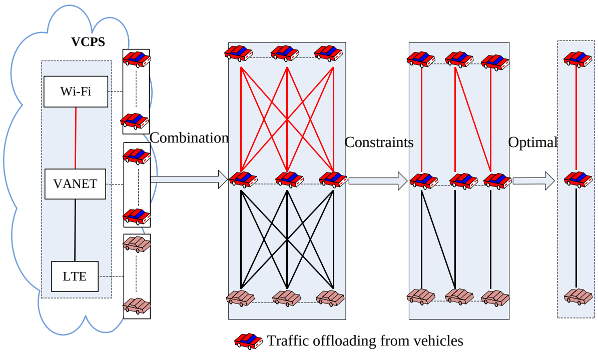

Fig. 2 Example of vehicle selection problem

4.3 Mobile Data Traffic Offloading Approach

Mobile data traffic offloading with global QoS guarantee is a multi-objective optimization problem. The optimal selection for a given offloading task V must meet the following two conditions:

1) For a given vector of global QoS guarantee $C=\{C_1,\cdots,C_m\}$ ($0\le m\le r$), $q(\mathrm{V})\le C$ ($\forall C_k\in C$), where $q(\mathrm{V})$ is the aggregated QoS value of the offloading task;

2) The maximum overall offloaded traffic in the offloading task from Wi-Fi and VANET.

Then, a vehicle selection algorithm should be designed to find the optimal VCPS vehicle under the global QoS constraint. Mixed-integer programming (MIP) is used to solve the multi-objective optimization problem. In our study, binary decision variables are used to represent the candidate vehicles. A candidate vehicle v_{ij} is selected in the optimal composition if its corresponding variable x_{ij} is set to one in the solution and discarded otherwise. By rewriting (15) to include the decision variables, the problem can be formulated as a maximization problem of the overall utility *F'(V)* value given by

$$\sum_{k=1}^{r}\frac{Q_k^{\max}-\sum_{i=1}^{n'}\sum_{j=1}^{l}x_{ij}\cdot q_k(\mathrm{v}_{ij})}{Q_k^{\max}-Q_k^{\min}}.\mathrm{tr} \tag{17}$$

subject to the global QoS guarantee and satisfying the allocation guarantee on the decision as

$$\begin{cases}\sum_{j=1}^{n}\sum_{i=1}^{l}q_k(\mathrm{v}_{ji})\cdot x_{ji}\ge C_k, 1\le k\le m\\ \sum_{j=1}^{l}x_{ji}=1, 1\le j\le n\end{cases} \tag{18}$$

where $n'(n'\le n)$ denotes the number of vehicles from the geographical region of Wi-Fi and VANET.

By solving (17) and (18) using any MIP solver method, a list of candidate vehicles is obtained and returned to the VCPS service broker, which provides services for the interest vehicle.

5. PERFORMANCE EVALUATION

We evaluated our Wi-Fi and VANET offloading models via numerical analysis and verified their effectiveness. We also implemented our offloading approach and compared it with other approaches based on the QualNet simulator.

5.1 Numerical Analysis

5.1.1 Parameter setting

First, we analyzed the effective distance and transmission probability in Wi-Fi. Then, the vehicle density and transfer rate in VANET were analyzed on the basis of the analysis results for the effective distance. Finally, we analyzed the degree of mobile data offloading with different types of services using our offloading models.

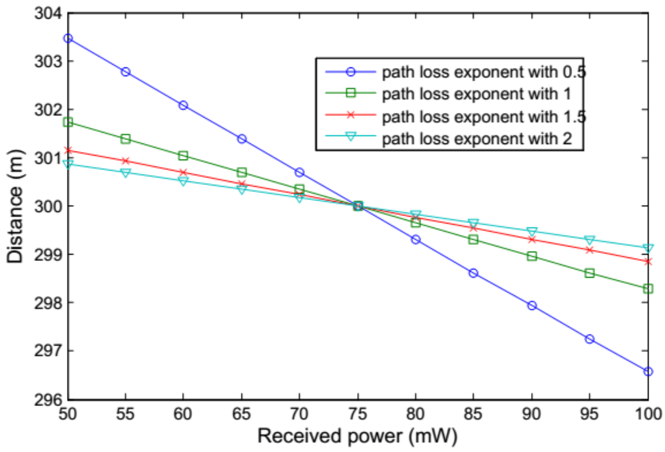

Fig. 3Relationship between effective distance and received power in Wi-Fi; the effective distance decreases with increasing received power.

To analyze the effective distance in Wi-Fi, we set p_0=75mW and d_0=300m according to (1). The relationship between the effective distance d and the received power p is shown in Fig. 3 at different values of the path loss exponent n_p. In the figure, the effective distance d decreases as the received power increases, but it does not change significantly and eventually approaches 300m as the received power is varied from 50 to 100mW. Hence, we set the effective distance *d*=300m in the next analysis.

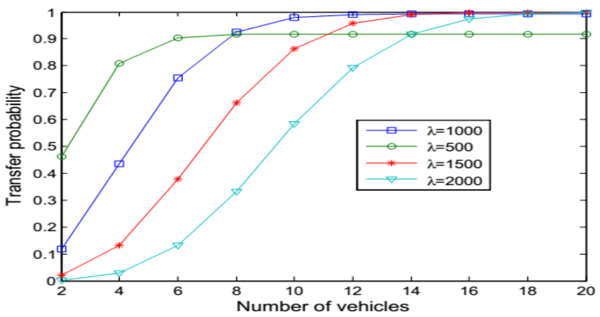

Fig. 4Transfer probability in a ROW. The transfer probability increases exponentially with the number of vehicles.

In a ROW, all vehicles share the fixed bandwidth of Wi-Fi. Fig. 4 shows that the transmission probability increases exponentially with the number of vehicles. From Fig. 4, the transmission probability is nearly 0.96 when the number of vehicles is 15 and the Poisson parameter λ is varied from 500 to 2000.

According to (6), the vehicle density ρ can be represented by the parameter λ, effective distance d, and vehicle speed. From Fig. 3, we set d=300m and vary λ from 500 to 2000; we can use the vehicle speed to describe the vehicle density. As shown in Fig. 5, the vehicle density decreases exponentially with increasing vehicle speed (10 to 80km/h).

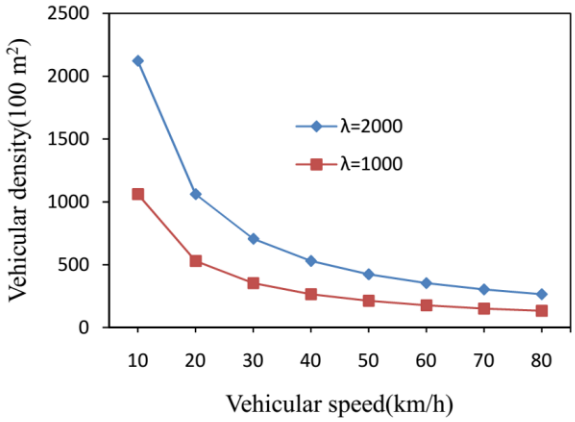

Fig. 5Vehicle density. At different values of the parameter λ, the vehicle density decreases with increasing vehicle speed.

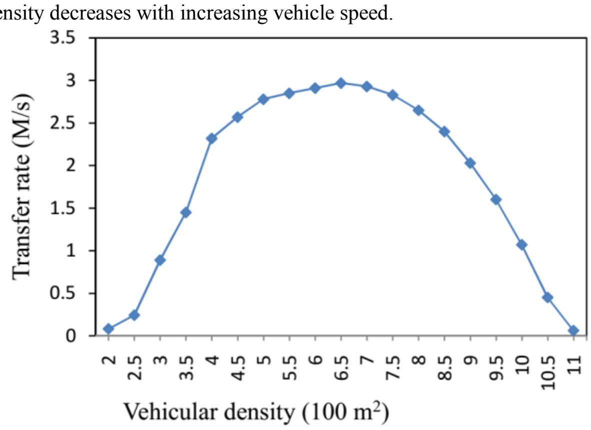

Fig. 6Transfer rate in VANET. The transfer rate is close to the maximum when the vehicle density is near 6 vehicles per 100 square meters.

In VANET, the transfer rate B_{VA} between vehicles is represented by a quadratic function with a vehicle density variable. According to the vehicle speed, the vehicle density can be obtained from Fig. 5. Then, we set the maximum transfer rate as 3M/s according to IEEE 802.11p. From (6), we describe the transfer rate changing with the vehicle density as shown in Fig. 6, and the transfer rate is close to the maximum when the vehicle density is near 6 vehicles per 100 square meters.

5.1.2 Effectiveness of mobile data traffic offloading

Based on the results of the analysis described above, we can investigate how vehicles receive services and data via Wi-Fi and VANET to offload mobile data traffic. In Wi-Fi, we set the effective distance d=300m according to Fig. 3, and we set the transmission probability to 0.96 according to Fig. 5. In VANET, we set the duration for which a vehicle engages a VANET to 15s, $p_{VA}=1$, and $p_{ve}=1$. An interest vehicle can receive mobile data traffic through Wi-Fi or VANET, as shown in Fig. 7. At different vehicle speeds, mobile data traffic received by the vehicle fluctuates slightly via Wi-Fi but greatly via VANET because the duration for which a vehicle stays connected to a Wi-Fi network is inversely proportional to its speed. Although the transfer rate varies with the vehicle speed according to (4), the duration for which the vehicle stays connected to the Wi-Fi network decreases with increasing vehicle speed. In contrast, the duration for which a vehicle stays connected to a VANET is nearly constant, but the transfer rate is a quadratic function for the variable for vehicle density. Thus, the mobile data traffic received by the vehicle follows a quadratic curve.

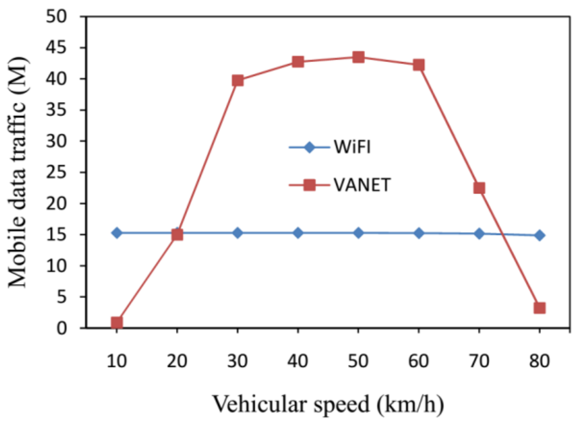

Fig 7 Mobile data traffic received from Wi-Fi and VANET. At different vehicle speeds, mobile data traffic received by the vehicle fluctuates slightly via Wi-Fi but greatly via VANET.

However, QoS varies with the type of service, *i.e.*, the packet loss rate and delay are different for different types of services. We considered three types of services herein: background class (*e.g.*, e-mail and messaging), interactive class (*e.g.*, Web browsing), and data flow class (*e.g.*, video on demand). We assigned different transfer rates and delays for the three services. We set the data sizes as 2M, 20M, and 100M and set the transfer rates as 0.01M/s, 0.2M/s, and 0.5M/s for the three types of services, respectively. According to (6) and (12), our offloading model can offload mobile data traffic based on the three service types, as shown in Fig. 8.

The background class service can always be offloaded via Wi-Fi and VANET, but the other two types of services only offload mobile data traffic in some cases. As shown in Fig. 6, when the vehicle speed is between 40 and 60km/h, our offloading model can obtain the best results for all type of services because of an appropriate transfer rate, vehicle density, and vehicle speed (between 40 and 60km/h).

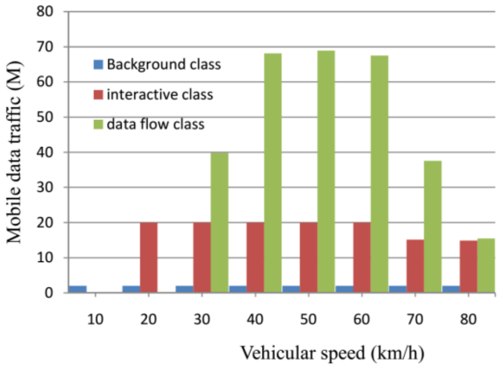

Fig. 8 Mobile data traffic offloading with different types of services. It shows that our models can offload mobile data effectively with QoS constrains.

The results of the analysis described above prove that effective offloading of mobile data traffic is necessary for guaranteeing QoS via Wi-Fi and VANET. Further, the analysis shows that the extent of mobile data traffic offloading is strongly related to the vehicle speed in our models, *i.e.*, an appropriate vehicle speed facilitates effective offloading of mobile data traffic.

5.2 Simulation

We conducted a numerical analysis to evaluate and characterize the potential of the two offloading models, Wi-Fi and VANET, for VCPSs. We investigated the effect of the effective distance and transmission probability in Wi-Fi and the vehicle density and transfer rate in VANET on traffic offloading with different service types. To further evaluate our approach, traffic-offloading simulations were performed using QualNet 5.1, a state-of-the-art simulator for large and heterogeneous networks that supports a wide range of networks and analysis (MANETs, VANETs, wired, wireless, satellite, and cellular).

The roads created in the simulation had two lanes. We varied the number of vehicular nodes from 10 to 100 and the number of hops from the interest vehicle to the Wi-Fi network from 1 to 6. The vehicular nodes used 802.11 MAC operating at 2Mbps. The transmission range was 250 m. We evaluated the effects of the details of the mobility models in two case studies. The number of vehicles in our simulations was 250, and the vehicular speed was10 to 80 km/h. The simulation lasted for 1000 s.

The originality of our work compared to opportunistic Wi-Fi [6] (OW) and vehicular flow [10] (VEH) is based on two aspects: traffic offloading rate and QoS guarantee.

5.2.1Traffic offloading rate

Definition 1. The traffic-offloading rate is the ratio of mobile data offloading traffic and mobile data traffic, *i.e.*,

$$TFB = \frac{F'(\mathrm{V})}{F(\mathrm{V})} \times 100\%$$

From Fig. 9, at different vehicular speeds, the traffic-offloading ratio of our approach is considerably higher than that of OW and VEH. The traffic-offloading rate of our approach is 84.3% on average, while OW and VEH are 68.4% and 46.7%, respectively. These simulation results indicate that our approach effectively reduces mobile data traffic in cellular networks in a VCPS environment because the Wi-Fi offloading model and VANET offloading model are adopted to reduce the VCPS data traffic in our approach.

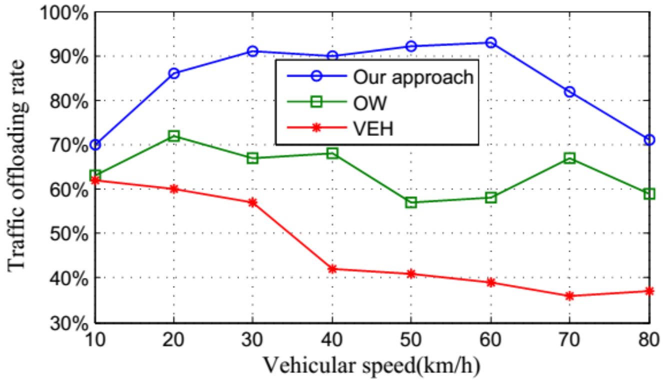

Fig. 9Mobile data traffic offloading rate with respect to different vehicular speeds.

5.2.2Global QoS guarantee

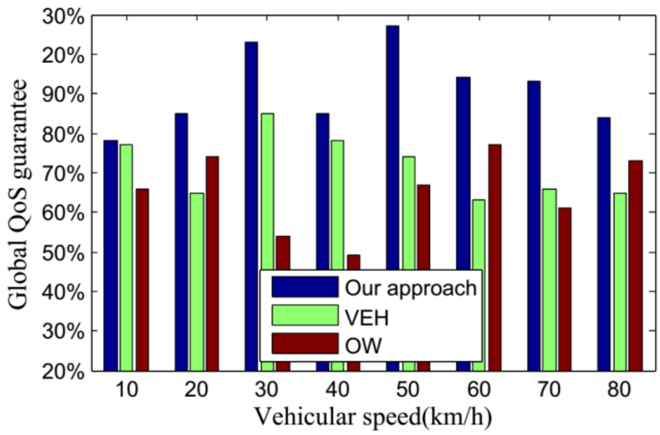

Fig. 10Global QoS guarantee with respect to different vehicular speeds.

We evaluated the traffic-offloading rate obtained using our solution by comparing it with that of existing approaches. We computed the global QoS guarantee of our approach by comparing the overall QoS utility value (hybrid) of the selected vehicles with the overall QoS utility value (pure) of the selected vehicles from LTE, *i.e.*, global QoS guarantee= hybrid/pure.

Existing mobile data traffic usually ignores the global QoS guarantee, which leads to greater QoS deviation. We conducted simulations to compare our approach with other approaches in terms of the global QoS guarantee. Fig. 10

shows the simulation results of the three approaches. From Fig. 10, we can see that the global QoS guarantee of our approach is very high. All of the results exceed 70% on average. Compared with the OW and VEH approaches, the guarantee of our approach is the highest. The simulation results indicate that our approach significantly improves the global QoS guarantee of VCPSs. The main reason why our approach is better than opportunistic Wi-Fi [6] and vehicular flow [10] is that we consider the global QoS constraints.

Thus, according to the simulation results for the traffic-offloading rate and QoS guarantee, our approach can significantly offload mobile data traffic while satisfying the QoS guarantee for cellular networks in VCPSs.

6. CONCLUSIONS

Although existing offloading schemes can significantly reduce mobile data traffic in cellular networks, they are not sufficiently efficient for homogeneous vehicles and global QoS guarantee in VCPSs. In this study, first, we established the Wi-Fi and VANET offloading models and quantified the offloading capacity of each Wi-Fi AP or vehicle. Next, we derived a formulation to evaluate the potential of Wi-Fi and VANET to offload mobile data traffic. Then, mobile data traffic offloading was formulated as a multi-objective combinatorial optimization problem that aims to simultaneously optimize possibly conflicting objectives. The results of extensive simulations showed that our approach achieves a significantly better performance than traditional approaches to mobile data traffic offloading. In future work, we will focus on the traffic offloading of multiple services and the implementation aspects of our approach in VCPSs.

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