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Integrity-Oriented Content Offloading in Vehicular Sensor Network

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ABSTRACT In this paper, an integrity-oriented content offloading (*ICO*) problem with variable modulation and coding schemes is proposed for relay-assisted vehicular sensor network. To accurately describe the link duration properties, a finite-state Markov chain-based model is built by jointly considering the mobility and radio propagation characteristics. Considering the *ICO* problem is NP-hard, our solution divides it into two offloading sub-problems with direct link and relay-assisted path, respectively. These two sub-problems are solved heuristically, and the corresponding results are combined to achieve a near-optimal result as the *ICO* scheme. While the analytical model is validated by Monte Carlo simulations and chi-square goodness fit test, the performance of our proposed *ICO* scheme is verified through simulations and comparisons, showing that our *ICO* solution can reduce the integral content offloading time compared with two other selected schemes and an upper performance bound.

INDEX TERMS Content offloading, data size, relay, variable modulation and coding scheme, vehicular sensor network (VSN).

I. INTRODUCTION

In vehicular scenarios, there are considerable demands of sensing and transmitting data for various intelligent transportation system services, e.g., regional monitoring, information broadcasting, and multimedia sharing. In addition to static sensors, the vehicular sensor network (VSN), which regards the moving vehicle as a ‘‘sensor’’, is an effective and economical way to sense real-time vehicular surroundings. For example, when a traffic accident or a robbery event happens along the road, the passing-by vehicles with on-board camera can provide relevant image or video contents to public safety departments via road side units (RSUs) [1], [2]. However, due to the high cost in deploying RSUs to provide radio coverage for all road segments, the vehicle-to-vehicle (V2V) transmission style is widely accepted as a supplement for the vehicle-to-infrastructure (V2I) transmission [3], [4]. While the image content of small date size can be transmitted with the route without considering the path lifetime, the video content with more information (e.g., who should be responsible for the accident) but large data size needs to construct a routing path that not only performs well on the initialization phase but can be durable for the whole offloading process.

In order to ensure the successful presentation of the incident scenes, digital contents are required to be fully transmitted in their entirety, and fragment or partially transmitted contents are useless [5]. Moreover, to initialize a quick response for an accident and avoid the data overwritten due to the camera storage limitation, the contents are expected to be offloaded to the nearest RSU immediately. However, the dynamically changed vehicular topology makes the constructed transmission path less durable, which leaves immediate delivery hard to be achieved for large data size content. Specifically, the real-time performance will be degraded dramatically with a transmission scheme that need connections to many passing-by RSUs successively. Therefore, the relay vehicle(s) and the corresponding modulation and coding schemes (MCSs) should be carefully chosen to achieve the received content integrity and the offloading timeliness simultaneously.

Many work had proposed solutions for content transmission, where the influence of many factors on the communication performance had been revealed, e.g., the fading channel, the MCS, and the various quality of service requirement. Besides, the effect of vehicular mobility had also been investigated for VSNs. In contrast to the extensive

TABLE 1. Comparison of related works on content offloading in vehicular scenarios.

Literature	V2X Technic		Content Size		Scenario	Relay	Multi-rate	Link duration consideration
	V2I	V2V	Small	Large				
Ge [3]	√	√	√	×	Highway	√	×	×
Boban [4]	√	√	√	×	Highway	√	×	×
Zhao [7]	√	√	√	×	Highway	√	×	×
Du [8]	×	√	√	×	Urban/Highway	√	×	×
Zhu [9]	√	√	√	×	General	√	√	×
Song [10]	√	√	√	×	Highway	√	√	×
Bi [11]	√	√	√	×	Highway	√	√	×
Chiti [12]	√	√	√	×	Highway	√	√	×
Ni [13]	√	√	√	×	Highway	√	√	×
Zhang [6]	√	×	√	√	Highway	×	√	√
Luan [5]	×	√	√	√	Highway	×	√	√
Our work	√	√	√	√	**Highway**	√	√	√

Note: √ denotes the mentioned item is considered, while × denotes the mentioned item is not considered.

literatures studying small date size content transmission that can be completed immediately, little attention has been paid to the integrity-oriented content offloading scheme design. To the authors' best knowledge, the rarely touched problem had been discussed in the direct transmission circumstances [5], [6], which cannot be easily referred to the design in relay-assisted VSNs.

In this paper, an *integrity-oriented content offloading (ICO)* problem with variable MCSs is proposed for relay-assisted VSNs. The target of the *ICO* problem is to minimize the *integral content offloading time*, which is defined as the time period from an offloading trial to a target content completely received by the RSU. Since the dynamically changed network topology will affect the content offloading, especially for the large data size content, the finite-state Markov model and statistical modeling method are used to depict the distribution of link duration. The formulated *ICO* problem is NP-hard because of the diversity in relay selection and MCS combination. As a solution, the *ICO* problem is split into two sub-problems, including the *ICO* with direct link (*ICO-D*) and the *ICO* with relay-assisted path (*ICO-R*) sub-problems. Both *ICO-D* and *ICO-R* sub-problems are solved using heuristic methods, and the corresponding results are synthetically combined into a near-optimal offloading solution. Simulations are conducted to verify the accuracy of the proposed link duration model and the performance of the designed *ICO* strategy.

The contributions of this paper are summarized as follows:

- We derive the probability mass function (PMF) of connection duration for both direct link and two-hop path, and take them into consideration on the integrity-oriented content offloading scheme design.
- We formulate an *ICO* problem on minimizing the integral content offloading time, which can be optimized to achieve the received content integrity and the offloading timeliness simultaneously.
- We split the formulated *ICO* problem into two sub-problems, and heuristically solve them to achieve a near-optimal *ICO* scheme.

The remainder of this paper is organized as follows. In Section II, we summarize the related work in relay-assisted content transmission scheme design. The system model and the problem formulation are described in Section III. In Section IV, the PMF of link duration is obtained. An *ICO* algorithm is introduced in Section V. In Section VI, simulation results are presented. Section VII finally concludes this paper and gives a discussion about the possible future work.

II. RELATED WORK

In this section, some related work on content transmission in mobile networks, especially for vehicular networks, are summarized in Table 1. Initially, many previous work had paid much attention on the performance enhancement for the direct transmission link between the transceivers. When the channel quality is poor, the performance of the direct transmission link between the transceivers would significantly degrade. Many researchers had revealed the potential of enhancing the communication system performance with the help of relay. Zhao *et al.* [7] proposed a V2V relay scheme which extends the service range of RSUs and allows vehicles to maintain high throughput within an extended range. Ge *et al.* [3] examined the multi-hop relay technology that improves the quality of V2I communications. Boban *et al.* [4] showed that tall vehicles working as relays can significantly increase the effective communication range.

In many work, the vehicular traffic statistic information is taken into consideration to enhance the performance of the proposed routing scheme. Choi *et al.* [14] studied the problem of routing data packets with minimum delay in the VSN by exploiting vehicle traffic statistics, anycast routing, and knowledge of future trajectories of vehicles such as busses. Ma and Liu [15] proposed a traffic-aware data delivery scheme that chooses intersections to forward packets dynamically as the route from a source to destination based on link quality and remaining Euclidean distance to destination. To exploit the intrinsic relationship between the unevenness of samples and traffic estimation error, Du *et al.* [8] studied the temporal and spatial entropies of samples and successfully define the important criterion, i.e., average entropy of the sampling process. Tian *et al.* [16] presented an infrastructure-less traffic adaptive data dissemination protocol which takes into account road condition and network traffic status for both highway and urban scenarios. In these literatures, the influence of special road topology and channel characteristics are taken into consideration and properly exploited. However, the dynamically changed network topology was not well considered in these literatures, where the vehicle's position was always assumed to be known precisely in advance.

By jointly considering the vehicular mobility characteristics with other factors, the performance of the content transmission can expect enhancement. Bi *et al.* [11] proposed a broadcast protocol for emergency message dissemination in vehicular networks considering the geographical locations, channel conditions, and vehicular speeds. Li and Song [17] proposed a management scheme that is able to evaluate the trustworthiness of both data and mobile nodes in VSNs. Chiti *et al.* [12] investigated a clustering approach for vehicular networks operating in highway scenarios, where the inter cluster communications were accomplished by means of relay node selection to maximize the connectivity among approaching clusters. The game theory-based relay vehicle (RV) selection algorithms had also been proposed [18], which jointly considered multiple metrics from various protocol layers, including the channel conditions, the link status, the bandwidth and delay characteristics of RVs and user service requirement. Zhu and Cao [9] put forward a novel relay-enabled distributed coordination function protocol to exploit the physical layer multi-rate capability. Song *et al.* [10] investigated an opportunistic V2V relay protocol with adaptive modulation and proposed an analytical approach to evaluate the access performance in terms of average packet delay and overall success probability. However, as far as we know, these related literatures did not consider the influence of the transmitted content data size.

For content transmission design considering the data size, Ahmad *et al.* [19] analyzed the propagation behavior of packets in the vehicular environment through extensive simulations, and proposed a scheme to control the data flooding. Zhang *et al.* [6] proposed a scheduling scheme to consider both data size and service deadline in V2I circumstance. Luan *et al.* [5] proposed an admission control scheme by filtering the content transmission requests which are unlikely to be accomplished over the transient link. These works focused on the integrity-oriented content transmission with a direct link between the transceivers, which might not be easily referred to the design in relay-assisted VSNs. To the authors' best knowledge, the design of integrity-oriented content transmission scheme is still an open issue in relay-assisted VSNs.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

We assume vehicles are moving on highway road segments, along which RSUs are deployed. With the pre-loaded digital map, the positions of the RSUs along the road are pre-known by vehicles. With the on-board camera, positioning device, and communication unit, vehicles can take videos at any known position and offload them when requested. With the maximum uplink transmission rate constraint for V2I communication, the service RSU will allocate a certain amount of bandwidth resource to each candidate vehicle for content offloading.

We assume RSUs are sparsely deployed along the road, and a full radio coverage under the data collector cannot be reached for all vehicles [20], [21]; therefore, a relay vehicle might be needed to help improve the data transmission performance. As the system performance, e.g., the packet loss rate, decreases dramatically when the transmission path consists of more than two hops [22], the direct and the two-hop transmissions are considered in this paper. With this assumption, both device-to-device assisted cellular technology and dedicated short range communications (DSRC) technology are applicable to the target scenario [23]. We name the vehicle with the queried content as the source vehicle (SV), then SV can offload the target content through direct link or relay-assisted path to the RSU(s). If an RSU is within the one hop range of the SV, then the SV can offload the target content directly to the RSU. Otherwise, a multi-hop offloading path needs to be established.

With the measured signal-to-noise ratio of received packets, the receiver can estimate the achievable transmission rate, and select appropriate MCS. Let $\mathcal{M}$ denote the set of available MCSs, and MCS$_m$ denote the m-th item, where $m \in \mathcal{M} = \{1, 2, \cdots, M\}$. Moreover, r_m denotes the data rate for MCS$_m$, while R_m^{V2I} and R_m^{V2V} denote the radio range for the V2I and the V2V cases, in view of the different reception capabilities of the RSU and vehicle, respectively. It is assumed that r_m increases with m, while R_m shows an opposite tendency. For the clarity of the following analysis, we list the defined symbols in Table 2. Compared to the burst information that can occupy the wireless channel shortly, the large data size content will utilize the channel for a relatively long time period. Although variable MCSs are available for the offloading path construction, it will be of great overhead to change MCS frequently because the real-time channel estimation might be not precise. In our model, we assume that the selected MCS will be used for the constructed offloading path continuously until the connection expires.

We aim to propose a transmission scheduling scheme for minimizing the *integral content offloading time* T. As shown in Fig. 1, T can be divided into two parts, the offloading

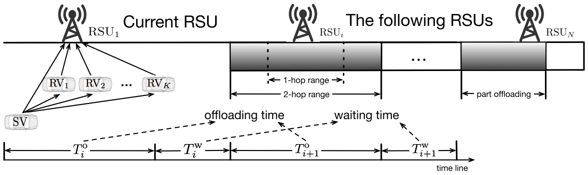


FIGURE 1. The integral content offloading time *T*'s composition.

TABLE 2. Defined symbols.

Symbol	Definition
MCS_m	the m-th MCS adopted for transmission
$\mathcal{M}$	the available MCS set
M	the number of available MCSs
R_m^{V2I}	the V2I radio range with MCS_m
R_m^{V2V}	the V2V radio range with MCS_m
μ	the expectation of the vehicular speed v
σ^2	the variance of the vehicular speed v
T	the integral content offloading time
T^{o}	the offloading time with connection to RSU
T^{w}	the waiting time without connection to RSU
N	the number of RSUs needed for offloading
RSU_i	the i-th connected RSU
T_i^{o}	the offloading time to RSU_i
T_i^{w}	the waiting time between the RSU_i and RSU_{i+1}
τ	the minimum observation time epoch
$T_m^{\text{S,D}}$	one-hop link S→D duration with MCS_m
$T_{m,n}^{\text{S,R,D}}$	two-hop path S→R→D duration with MCSs m, n
$d_i^{\text{S,D}}$	distance between S and D in the i-th epoch
RV_j	the j-th RV from the candidate set
$\mathcal{R}$	the candidate RV set
$T(\text{RV}_j)$	time for content offloading with RV_j
λ	the traffic flow density on the road
C_{opt}^{+}	the optimal offloading capacity to an RSU
R_m	the radio range with scheme MCS_m
$R_{m,n}$	the two-hop coverage range for $\{\text{MCS}_m, \text{MCS}_n\}$
r_m	the transmission rate with scheme MCS_m
$r_{m,n}$	the two-hop transmission rate for $\{\text{MCS}_m, \text{MCS}_n\}$
X_n^{+}	the RV→RSU link distance with MCS_n
X_i	the distance between the i-th vehicle to current RSU
K	the number of vehicles in the coverage of RSU
m^*, n^*	the optimal MCS scheme $\{\text{MCS}_{m^*}, \text{MCS}_{n^*}\}$
R_{opt}	the optimal transmission range with m^* and n^*
r_{opt}	the optimal transmission rate with m^* and n^*
d_i^{S}	the moving distance of SV in the i-th epoch
D_k^{S}	the moving distance of SV in the first k epochs
x_0^{S}	the initial distance of SV
$2h+1$	the number of partitioned distance states
ϵ	the length of each inter-vehicle distance state
S_i	the i-th inter-vehicle distance state
S_{2h+1}	the absorbing state of one entire connection
$v_k^{\triangle}$	the speed difference of SV and RV in the k-th epoch
$d_k^{\triangle}$	the relative V2V position change in the k-th epoch
$\mathbb{P}$	the inter-vehicle distance transition matrix
π_i^0	the initial probability of state S_i
π_i^k	the probability of state S_i in the k-th epoch
$U_m^{\text{S,D}}$	the disconnected duration of link SV→RSU
c	the data size of the target content
MCS_{m^*}	the optimal MCS strategy for offloading
RV_{j^*}	the optimal relay vehicle for offloading

time T^{o} and the waiting time T^{w}, which will be described as follows. Since the target content is of large data size, SV needs offload to more than one passing-by RSU, and let RSU_i denote the i-th connected RSU. Suppose that the number of RSUs needed for residual content offloading is N, which is estimated in Section III-A2. Let T_i^{o} denote the offloading time from SV to RSU_i, then we have the overall offloading time as $T^{\text{o}} = \sum_{i=1}^{N} T_i^{\text{o}}$. Let T^{w} denote the waiting time period that the vehicle cannot connect to an RSU even with a relay vehicle, and we have $T^{\text{w}} = \sum_{i=1}^{N-1} T_i^{\text{w}}$, where T_i^{w} represents the waiting time at the disconnected hole between RSU_i and RSU_{i+1}. Therefore, we have the integral content offloading time as

$$T = T^{\text{o}} + T^{\text{w}} = \underbrace{T_1^{\text{o}}}_{\text{Part I}} + \underbrace{\sum_{i=2}^{N} T_i^{\text{o}}}_{\text{Part II}} + \underbrace{\sum_{i=1}^{N-1} T_i^{\text{w}}}_{\text{Part III}}, \tag{1}$$

where Part I denotes the offloading time to the currently connected RSU, Part II represents the connection time to the residual $(N-1)$ RSUs, and Part III expresses the disconnected time beyond the two-hop coverage of RSU during the content offloading process. In the following parts, these three time terms will be explained in detail respectively.

1) THE CONTENT OFFLOADING TIME TO THE CURRENTLY CONNECTED RSU

For the currently connected RSU, we assume that each vehicle knows the instantaneous network topology and the mobility information of its one-hop neighbours by exchanging beacons. All the one-hop neighbours are treated as the candidate RVs, and we try to select one RV and MCS combination that can minimize the integral content offloading time T. Given the chosen RV and MCS(s), we can represent T_1^{o} as the path duration between SV and RSU. For the tractability of our analysis, we assume each vehicle records its position and speed information in an equal-length time interval τ, termed as the observation *epoch*. With the fact that the vehicular speed v always fluctuates with time, we model it as the Gaussian distribution [24]–[26], and we have $v \sim \mathcal{N}(\mu, \sigma^2)$, where μ and σ^2 denote the expectation and variance of the vehicular speed respectively. To describe a signal's power attenuation, the path-loss model is adopted for the simplicity of our theoretical analysis.

Let $T_m^{\text{S,D}}$ denote the link duration between SV and RSU with the m-th MCS. The link duration is defined as the continuous connected time period between the transceivers, and we have

$$T_m^{\text{S,D}} \triangleq \max_k \{k\tau : d_i^{\text{S,D}} \leqslant R_m^{\text{V2I}}, \forall k, 1 \leqslant i \leqslant k\}, \tag{2}$$

where $d_i^{\text{S,D}}$ denotes the distance between SV and RSU in the i-th epoch.

As for the two-hop transmission, let $T_{m,n}^{\text{S,R,D}}$ denote the duration of path SV→RV→RSU with $\{\text{MCS}_m, \text{MCS}_n\}$ for two hops separately. The path duration is defined as the continuous connected time period for the constructed path, and we have

$$T_{m,n}^{\text{S,R,D}} \triangleq \max_k \{k\tau : d_i^{\text{S,R}} \leqslant R_m^{\text{V2V}}, d_i^{\text{R,D}} \leqslant R_n^{\text{V2I}}, 1 \leqslant i \leqslant k\}, \tag{3}$$

where $d_i^{\text{S,R}}$ denotes the distance between SV and RV in the i-th epoch and $d_i^{\text{R,D}}$ represents the distance between RV and RSU in the i-th epoch.

Let $T(\mathrm{RV}_j)$ denote the content offloading time to the currently connected RSU with the j-th RV. Note that $T(\mathrm{RV}_j = \varnothing)$ represents the lifetime for the direct SV→RSU link without relay's assistance. We adopt the full duplex transmitting, where the self-interference cancelation technology is used to eliminate the interference in the simultaneous transmission and receiving on the relay vehicle. Therefore, we have $T(\mathrm{RV}_j)$ as the one-hop link lifetime $T_m^{\mathrm{S,D}}$ or two-hop path lifetime $T_{m,n}^{\mathrm{S,R,D}}$, which are derived in Section IV-A and IV-B, respectively.

2) THE OPTIMAL CONTENT OFFLOADING TIME TO A SINGLE RSU

For RSUs except for the currently connected one, since it is hard to estimate the future candidate RV set, we cannot select the suitable RV and assign the corresponding MCS. Assume that all the RSUs have the identical reception capability and the vehicular traffic density does not change much along the target road segment. Nonetheless, one upper bound of the optimal transmission capacity C_{opt}^{+} can represent the offloading capability of the RSU. As deduced in Section IV-C, we have the optimal offloading capacity as $C_{\mathrm{opt}}^{+}(\lambda) = C_{m^*,n^*}^{+}(\lambda) = \max_{m,n} C_{m,n}^{+}(\lambda)$, where λ represents the vehicular traffic density, and $C_{m,n}^{+}$ denotes an upper bound of the offloading capacity with $\{\mathrm{MCS}_m, \mathrm{MCS}_n\}$.

With the optimal MCS combination $\{\mathrm{MCS}_{m^*}, \mathrm{MCS}_{n^*}\}$, the optimal transmission range and rate can be obtained as $R_{\mathrm{opt}}(\lambda) = R_{m^*,n^*}(\lambda)$ and $r_{\mathrm{opt}}(\lambda) = r_{m^*,n^*}(\lambda)$, respectively. Correspondingly, we have the optimal content offloading time to a single RSU as $T_{\mathrm{opt}}(\lambda) = C_{\mathrm{opt}}^{+}(\lambda)/r_{\mathrm{opt}}(\lambda)$. Based on these definitions, we can estimate the number of passing-by RSUs needed to offload the target content as $N \approx \lceil c/C_{\mathrm{opt}}^{+}(\lambda)\rceil$. Note that the estimation of N is a lower bound value, where the optimal offloading case cannot always be achievable.

3) THE DISCONNECTED TIME T^{w}

As defined in the previous system model, we have the disconnected time as the period that SV driving in the road without the two-hop coverage of any RSU. Let d_i denote the distance between RSU_i and RSU_{i+1}, then we have the disconnected time as

$$T_i^{\mathrm{w}} = \begin{cases} [d_i - R_{\mathrm{opt}}(\lambda)/2 - R_i^{\mathrm{o}}/2]/\mu_{\mathrm{S}}, & i = 1 \\ [d_i - R_{\mathrm{opt}}(\lambda)]/\mu_{\mathrm{S}}, & i = 2, \cdots, N-1 \end{cases} \tag{4}$$

where R_i^{o} illustrates the transmission diameter for the i-th RSU's coverage area, R_{opt} denotes the optimal coverage range, and μ_{S} represents the expected SV's driving speed on the current road segment. The first line of (4) denotes the derivation of disconnected time between the current RSU and next RSU, where the current RSU's coverage range can be estimated with a determined scheduling strategy, while a rough estimate method with the optimal coverage range is used for the following RSUs; therefore, the following disconnected time can be predicted as the second line of (4).

B. PROBLEM FORMULATION

The selection of RV and MCS combination can be represented as an optimization problem, which is referred to as the *integrity-oriented content offloading (ICO)* problem. We have the rigorous definition of the *ICO* problem as

$$\min\ T = T(\mathrm{RV}_j) + \frac{[c - T(\mathrm{RV}_j) r^{\mathrm{o}}]}{r_{\mathrm{opt}}(\lambda)} + \sum_{i=1}^{N-1} T_i^{\mathrm{w}} \tag{5a}$$

$$\text{s.t. } r^{\mathrm{o}} = \sum_{m} \delta_m^{\mathrm{d}} r_m + \sum_{j,m,n} \delta_{j,m,n}^{\mathrm{r}} \min\{r_m, r_n\}, \tag{5b}$$

$$\sum_{m} \delta_m^{\mathrm{d}} + \sum_{j,m,n} \delta_{j,m,n}^{\mathrm{r}} \le 1, \tag{5c}$$

$$\text{r.v. } \underbrace{\delta_m^{\mathrm{d}}, \delta_{j,m,n}^{\mathrm{r}} \in \{0,1\}}_{\text{direct or relay}}, \underbrace{m, n \in \mathcal{M}}_{\text{rate selection}}, \underbrace{\mathrm{RV}_j \in \mathcal{R}}_{\text{relay selection}}. \tag{5d}$$

The *ICO* problem can be explained as follows

- The objective function (5a) of the *ICO* problem is to minimize the integral content offloading time T, which has been introduced in (1). Note that some parameters (e.g., c, λ, μ_{S}, d_i, r_{opt}) are constants or can be estimated in our system model, therefore, the target integral content offloading time T can be divided into two parts, the variable part and the static part. We have the static part as $c/r_{\mathrm{opt}} + (d_1 - R_{\mathrm{opt}}/2)/\mu_{\mathrm{S}} + \sum_{i=2}^{N-1} T_i^{\mathrm{w}}$. Therefore, the objective function in (5a) is equivalent to

$$\min \quad T(\mathrm{RV}_j) \cdot \left[\frac{1}{2} - \frac{r^{\mathrm{o}}}{r_{\mathrm{opt}}(\lambda)}\right]. \tag{6}$$

  From the transformed object, we can observe that the minimized value of T should achieve a balance between maximizing path lifetime $T(\mathrm{RV}_j)$ and offloading data rate r^{o} to the currently connected RSU.
- The offloading data rate r^{o} is represented mathematically in (5b). Let δ_m^{d} denote the binary variable for determining whether MCS_m is adopted for the direct offloading, and $\delta_{j,m,n}^{\mathrm{r}}$ denote the binary variable for determining whether the j-th candidate RV and $\{\mathrm{MCS}_m, \mathrm{MCS}_n\}$ strategy are selected for the two-hop offloading. Note that the full duplex communication styles are used in vehicles, therefore, the data rate in the relay-assisted case is the minimum one for both two hops.
- The fact that either direct transmission link or two-hop relay transmission path will be selected is shown in (5c), while the random variables (r.v.) for the *ICO* problem are introduced in (5d).

Because the objective function of *ICO* problem shown in (5a) is in non-linear form, the formulated *ICO* problem is an 0-1 integer non-linear program (INLP), which is NP-hard. Some traditional solutions on INLP, e.g., the branch-and-bound algorithm, take significantly long computation time, which is unacceptable for the delay requirement in many practical applications. Therefore, we need an algorithm with low computation complexity to obtain near-optimal solutions, which will be introduced in Section V. Before this, an analytical modeling on link duration and optimal content offloading capacity will be first introduced in Section IV.

IV. ANALYTICAL MODELING

Before introducing solution for the *ICO* problem, we first derive the path duration and the optimal offloading capacity. The path duration may be influenced by many parameters, mainly including the channel and the mobility characteristics. As defined in the system model, the link connection maintains when the transceiver distance is within the transmission range. For describing the vehicular mobility, the time-variant transceiver distance is modeled with the initial distance and the speed parameters. In the first two subsections, these characteristics will be taken into consideration on the modeling of path duration as that in our previous work [27]. When the direct transmission is preferred, the link duration between SV and RSU is modeled in Section IV-A. When a relay vehicle is required, the duration for path SV→RV→RSU is modeled in Section IV-B. In addition, the optimal content offloading capacity to a single RSU is another issue in our system model. The optimal capacity is mainly influenced by the vehicular traffic density and the variable MCS, which will be depicted in the model proposed in Section IV-C.

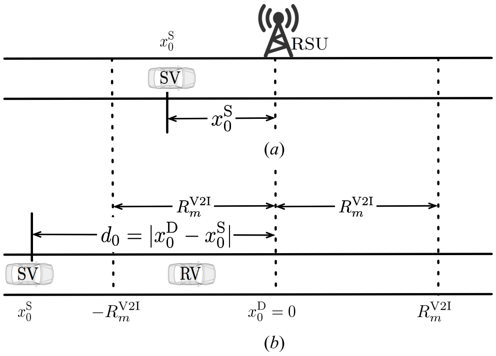


FIGURE 2. **Distance relation expression for two cases: a) the direct transmission case, and b) relay-assisted transmission case.**

A. MODELING OF DIRECT V2I LINK DURATION

As shown in Fig. 2, suppose that an RSU is located at position 0, and its radio range covers from $-R_m^{\mathrm{V2I}}$ to R_m^{V2I}. Let d_i^{S} denote the SV's moving distance in the i-th epoch, and D_k^{S} denote the cumulative moving distance for SV in the first k epochs. Therefore, we have $D_k^{\mathrm{S}} = \sum_{i=1}^{k} d_i^{\mathrm{S}}$. It is assumed that the SV's initial position x_0^{S} lies in the radio range of the RSU. Given the existence of the initial link between SV and RSU, its residual link duration will be derived as following.

Since $v^{\mathrm{S}} \sim \mathcal{N}(\mu_{\mathrm{S}}, \sigma_{\mathrm{S}}^2)$, the moving distance d_i^{S} in the i-th epoch follows the Gaussian distribution with mean $\mu_{\mathrm{S}}\tau$ and variance $\sigma_{\mathrm{S}}^2\tau$. Moreover, the cumulative moving distance D_k^{S} also follows the Gaussian distribution as $D_k^{\mathrm{S}} \sim \mathcal{N}(k\tau\mu_{\mathrm{S}}, k\tau^2\sigma_{\mathrm{S}}^2)$. Therefore, we have the complementary cumulative distribution function (CCDF) of $T_m^{\mathrm{S,D}}$ as

$$\begin{aligned}\Pr\left\{T_m^{\mathrm{S,D}} \geq k\tau\right\} &= \Pr\left\{D_k^{\mathrm{S}} \leq R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}}\right\}\\ &= \Phi\left(\frac{R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}} - k\mu_{\mathrm{S}}\tau}{\sigma_{\mathrm{S}}\sqrt{k\tau}}\right),\end{aligned} \tag{7}$$

where $\Phi(z) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{z-\mu}{\sqrt{2}\sigma}\right)\right]$, and $\mathrm{erf}(\cdot)$ represents the error function. Based on this result, we have the PMF of $T_m^{\mathrm{S,D}}$ as

$$\begin{aligned}\Pr\{T_m^{\mathrm{S,D}} = k\tau\} &= \Pr\{T_m^{\mathrm{S,D}} \geq k\tau\} - \Pr\{T_m^{\mathrm{S,D}} \geq (k+1)\tau\}\\ &= \Phi\left(\frac{R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}} - k\mu_{\mathrm{S}}\tau}{\sigma_{\mathrm{S}}\sqrt{k\tau}}\right)\\ &\quad - \Phi\left(\frac{R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}} - (k+1)\mu_{\mathrm{S}}\tau}{\sigma_{\mathrm{S}}\sqrt{(k+1)\tau}}\right).\end{aligned} \tag{8}$$

B. MODELING OF TWO-HOP PATH DURATION

The properties of the two-hop path duration is determined by that of both the SV→RV link and the RV→RSU link. Since the RV→RSU link is a direct V2I link, the results of the V2V SV→RV link will be first given in Section IV-B1. Based on the properties of both the SV→RV link and the RV→RSU link, the properties of the two-hop path duration are derived in Section IV-B2.

1) MODELING OF V2V LINK DURATION

Different from the derivation of the V2I link duration, a discrete-time Markov chain (DTMC) based model is proposed for the V2V link duration. As shown in Fig. 3, the inter-vehicle distance is divided into $2h+1$ regions and state S_i ($i = 1, 2, \ldots, 2h{+}1$) is denoted as the i-th region. The first $2h$ states S_i ($i = 1, 2, \ldots, 2h$) are of the same length $\varepsilon = R_m^{\mathrm{V2V}}/h$ falling into interval $[(i-h-1)\varepsilon, (i-h)\varepsilon]$, respectively. S_{2h+1} represents the absorbing state, which is the terminal state for an entire communication period.

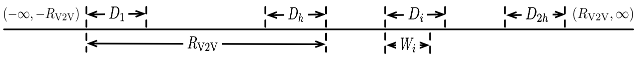


FIGURE 3. **Inter-vehicle distance partitioned into $2n+1$ states.**

Let v_k^{Δ} denote the speed difference between SV and RV in the k-th epoch, and $v_k^{\Delta} = v_k^{\mathrm{S}} - v_k^{\mathrm{R}}$. Moreover, we have $v_k^{\Delta} \sim (\mu, \sigma^2)$, $d_k^{\Delta} = v_k^{\Delta}\tau \sim (\mu\tau, \sigma^2\tau^2)$, where $\mu = \mu_{\mathrm{S}} - \mu_{\mathrm{R}}$, $\sigma^2 = \sigma_{\mathrm{S}}^2 + \sigma_{\mathrm{R}}^2$. Therefore,

$$f_{d_k^{\Delta}}(s) = \frac{1}{\sigma\sqrt{2\pi\tau}} \exp\left(-\frac{(s-\mu\tau)^2}{2\sigma^2\tau}\right). \tag{9}$$

Then, the conditional distance transition probability can be expressed as

$$\Pr\{d_k^{\Delta} \in S_j | d_{k-1}^{\Delta} \in S_i, W_i = w\} = \int_{(j-i)\varepsilon-w}^{(j-i+1)\varepsilon-w} f(s)\,\mathrm{d}s, \tag{10}$$

where W_i $(i = 1, 2, \ldots, 2h)$ denotes the relative inter-vehicle distance in state S_i as shown in Fig. 3. Substituting (9) into (10), we have

$$\begin{aligned}\Pr\{d_k^{\Delta} &\in S_j | d_{k-1}^{\Delta} \in S_i, W_i = w\}\\ &= \Phi\left(\frac{(j-i+1)\varepsilon - w - \mu\tau}{\sigma\sqrt{\tau}}\right) - \Phi\left(\frac{(j-i)\varepsilon - w - \mu\tau}{\sigma\sqrt{\tau}}\right).\end{aligned} \tag{11}$$

Based on (11), the inter-vehicle distance transition probability can be represented as

$$\begin{aligned}p_{ij} &= \Pr\{d_k^{\Delta} \in S_j | d_{k-1}^{\Delta} \in S_i\}\\ &= \int_0^{\varepsilon} \Pr\{d_k^{\Delta} \in S_j | d_{k-1}^{\Delta} \in S_i, W_i = w\} \Pr\{W_i = w\}\, \mathrm{d}w.\end{aligned} \tag{12}$$

Substituting (11) into (12), the integral equation cannot easily get the close form expression. Therefore, an approximated method is adopted to find a numerical solution. Assume that the length of each inter-vehicle distance state is small enough, then the conditional distance transition probability would not change much. Therefore,

$$\begin{aligned}&\Pr\{d_k^{\Delta} \in S_j | d_{k-1}^{\Delta} \in S_i, W_i = w\}\\ &\quad\approx \Pr\{d_k^{\Delta} \in S_j | d_{k-1}^{\Delta} \in S_i, W_i = w'\}, \quad \forall w, w' \in [0, \varepsilon).\end{aligned} \tag{13}$$

Then, we have an approximation form of (12) as

$$\begin{aligned}p_{ij} &= \varepsilon \cdot \Pr\{d_k^{\Delta} \in S_j | d_{k-1}^{\Delta} \in S_i, W_i = w\}, x \in [0, \varepsilon)\\ &\approx \varepsilon \cdot \Pr\{d_k^{\Delta} \in S_j | d_{k-1}^{\Delta} \in S_i, W_i = \varepsilon/2\}.\end{aligned} \tag{14}$$

The link duration's distribution can be derived on the acquired distance transition matrix $\mathbf{P}$. Let π_i^k denote the probability that the inter-vehicle distance lies in the state S_i after k epochs. Therefore, π_i^0 represents the probability of initial state for inter-vehicle distance and can be noted as $\pi_i^0 = \Pr\{d_0 \in D_i\}$, when the link is initialized. Then we have the cumulative distribution function (CDF) of link duration as

$$\begin{aligned}\Pr\{T_m^{\mathrm{S,R}} \leq k\tau\} &= \Pr\{d_k^{\Delta} > R_m^{\mathrm{V2V}} | d_0^{\Delta} \leq R_m^{\mathrm{V2V}}\}\\ &= [\mathbf{\Pi}^0 \mathbf{P}^k]_{2h+1},\end{aligned} \tag{15}$$

where d_k represents the inter-vehicle distance at time $k\tau$, $\mathbf{\Pi}^k$ denotes the row vector whose i-th element is π_i^k, and $[\mathbf{\Pi}^0 \mathbf{P}^k]_{2h+1}$ is the probability that the observed vehicle moves outside the reference vehicle's transmission zone after k epochs. Following (15), we have the PMF of V2V link duration as

$$\begin{aligned}\Pr\{T_m^{\mathrm{S,R}} = k\tau\} &= \Pr\{T_m^{\mathrm{S,R}} \leqslant k\tau\} - \Pr\{T_m^{\mathrm{S,R}} \leqslant (k-1)\tau\}\\ &= [\mathbf{\Pi}^0 \mathbf{P}^k]_{2h+1} - [\mathbf{\Pi}^0 \mathbf{P}^{k-1}]_{2h+1}.\end{aligned} \tag{16}$$

2) MODELING OF TWO-HOP PATH DURATION

It is clear that the RV will contribute when the link between the SV and the RSU does not exist. Let $U_m^{\mathrm{S,D}}$ denote the link disconnected duration between the SV and the RSU in the scenario shown in Fig. 2(b). It can be seen that the direct link between SV and RSU cannot be initialized until SV moves into the transmission range of the RSU. Therefore,

$$\begin{aligned}\Pr\left\{U_m^{\mathrm{S,D}} \geq k\tau\right\} &= \Pr\left\{D_k^{\mathrm{S}} \leq -R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}}\right\}\\ &= \Phi\left(\frac{-R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}} - k\mu_{\mathrm{S}}}{\sigma_{\mathrm{S}}\sqrt{k}}\right).\end{aligned} \tag{17}$$

Moreover, for the next $(k+1)$-th epoch, the similar equation can be obtained. Then we have the PMF of $U_m^{\mathrm{S,D}}$ as

$$\begin{aligned}\Pr\{U_m^{\mathrm{S,D}} = k\tau\} &= \Pr\{U_m^{\mathrm{S,D}} \geq k\tau\} - \Pr\{U_m^{\mathrm{S,D}} \geq (k+1)\tau\}\\ &= \Phi\left(\frac{-R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}} - k\mu_{\mathrm{S}}}{\sigma_{\mathrm{S}}\sqrt{k}}\right)\\ &\quad - \Phi\left(\frac{-R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}} - (k+1)\mu_{\mathrm{S}}}{\sigma_{\mathrm{S}}\sqrt{k+1}}\right).\end{aligned} \tag{18}$$

Let $\mathbb{E}$ denote the event that the V2V link between SV and RV exists when SV's position is in range $[x_0^{\mathrm{S}}, -R_m^{\mathrm{V2I}}]$, which means SV can communicate with the RSU steadily before moving into the entering position of RSU's coverage area. Therefore,

$$\Pr\{\mathbb{E}\} = \sum_{k=1}^{\infty} \Pr\{T_m^{\mathrm{R,D}} \geq k\tau\} \cdot \Pr\{U_m^{\mathrm{S,R}} = k\tau\}. \tag{19}$$

Based on $\mathbb{E}$, the two-hop path duration can be divided into two cases:

- When event $\mathbb{E}$ happens, the link between SV and RSU will not break until SV passes through the RSU's radio coverage area.
- When event $\mathbb{E}$ does not happen, the link will disconnect when the inter-vehicle link between SV and RV exists.

Therefore, we have the CCDF of two-hop path duration between SV and RSU as

$$\begin{aligned}\Pr\{T_m^{\mathrm{S,R,D}} \geq k\tau\} &= \underbrace{\Pr\{\mathbb{E}\} \cdot \Pr\{D_k^{\mathrm{S}} \leq R_m^{\mathrm{V2I}} - x_0^{\mathrm{S}}\}}_{\text{Part I}}\\ &\quad + \underbrace{(1 - \Pr\{\mathbb{E}\}) \cdot \Pr\{T_m^{\mathrm{S,R}} \geq k\tau\}}_{\text{Part II}},\end{aligned} \tag{20}$$

where Part I indicates that SV can obtain the RV's assistance for at least k epochs before moving out of RSU's coverage area, and Part II represents that the V2V link will break before SV moves into the RSU's coverage area.

C. THE OPTIMAL CONTENT OFFLOADING CAPACITY

For the tractability of the following analysis, we assume that the selected RV can guarantee a durable link connection between SV and RV. That is, the link SV→RV maintains while RV lies in the coverage range of the RSU. Based on these assumptions, we can know that the capacity of two-hop path is larger than that of direct link. Fig. 4 gives a prospective on the introduction of the following deduction process, where

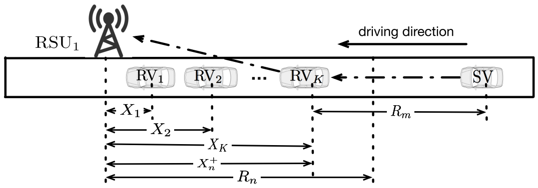


FIGURE 4. **The flowchart of the optimal content offloading.**

we assume that the offloading capacity is symmetrical. In the following, we consider the case of SV driving towards RSU to represent the deduction idea of C^+_{opt}.

Let $R_{m,n}(\lambda)$ denote the coverage range of the RSU with two-hop transmission patterns given the traffic flow density λ (vehicles per meter), where MCS$_m$ and MCS$_n$ are used for SV→RV link and RV→RSU link separately. The transmission rate for the two-hop path is defined as $r_{m,n}(\lambda) = \min\{r_m, r_n\}$. For the transmission distance, we have

$$R_{m,n}(\lambda) = R_m + E[X^+_n(\lambda)], \tag{21}$$

where $X^+_n(\lambda)$ represents the actual transmission range of the RV→RSU link given the traffic density λ. Meanwhile, the SV→RV link exists when SV enters into the radio range R_m around the position of selected RV. The reason why we can consider this as one upper value of the two-hop coverage range is that the link duration issue is not considered in this formula. The two-hop path in this case will face disconnection when any link breaks.

Specifically, we have $X^+_n = \max\{X_1, X_2, \cdots, X_K\}$, where X_i represents the distance between the i-th vehicle to RSU and K denotes the number of vehicles in the radio range R_n of the RSU. Since the vehicular traffic follows the Poisson distribution, we have $\Pr\{K = k\} = (\lambda R_n)^k e^{\lambda R_n}/k!$. Following the deduction idea in [28], we have the probability density function (pdf) of X^+_n as

$$f_{X^+_n|K>0}(x) = \lambda(1 - e^{-\lambda R_n})e^{-\lambda(R_n - x)}. \tag{22}$$

For the tractability of the analysis, we assume that SV moves with a constant speed, which is the historical expected value μ_{S}. Based on these assumptions, we have the possible offloading capacity $C^+_{m,n}(\lambda)$ as

$$C^+_{m,n}(\lambda) = 2r_{m,n}(\lambda) \cdot R_{m,n}(\lambda)/\mu_{\text{S}}. \tag{23}$$

Then we have the optimal offloading capacity as

$$C^+_{\text{opt}}(\lambda) = C^+_{m^*,n^*}(\lambda) = \max_{m,n} C^+_{m,n}(\lambda), \tag{24}$$

where $\{m^*, n^*\} = \arg\max_{m,n} C^+_{m,n}(\lambda)$.

V. SCHEME DESIGN AND ANALYSIS

Given our assumptions, content offloading can be finished directly or with relay as defined in the *ICO* problem, which motivates us to find the optimal *ICO* scheme in two cases separately. Following this idea, we split the *ICO* problem into two sub-problems, *ICO-D* and *ICO-R*, where *ICO-D* problem is intended to find the optimal direct offloading link and *ICO-R*'s goal is to obtain the optimal two-hop offloading path.

A. *ICO-D* SCHEME DESIGN

Based on the definition of the *ICO* problem, we have the *ICO-D* sub-problem as

$$\min\ T^{\text{S,D}}_m \cdot \left[\frac{1}{2} - \frac{r^{\text{o}}}{r_{\text{opt}}(\lambda)}\right] \tag{25a}$$

$$\text{s.t. } r^{\text{o}} = \sum_m \delta^{\text{d}}_{i,m} r_m, \quad \forall i \in \{1, 2\}, \tag{25b}$$

$$\sum_m \delta^{\text{d}}_{i,m} \leq 1, \quad \forall i \in \{1, 2\}, \tag{25c}$$

$$\text{r.v. } \delta^{\text{d}}_{i,m} \in \{0, 1\}, \quad m \in \mathcal{M}. \tag{25d}$$

In the *ICO-D* case, r^{o} is determined by the chosen MCS strategy as expressed in (25b), while $T^{\text{S,D}}_m$ is a non-linear function of the transmission range or data rate as derived in Section IV-A. The relaxation method is always used in this situation [29], and a sub-optimal result can be obtained. However, the number of candidate MCS strategies is limited here, where the enumeration method is adopted. The time complexity of the *ICO-D* method is $\mathcal{O}(M)$.

The procedure for obtaining the optimal *ICO-D* scheme is shown in Algorithm 1. The input includes the available MCS set $\mathcal{M}$ in line 1. Lines 2-8 indicate the enumeration method proposed for the optimal *ICO-D* scheme. By sorting all the possible direct transmission cases, the optimal one is select as the MCS that can minimize the value of T. Finally, line 9 illustrates the output parameters, $\{\text{MCS}_{m^*}, \delta_{i,m}\}$, denoting the *ICO-D* scheme.

Algorithm 1 *ICO-D* Algorithm

```
1: Input: $\mathcal{M}$
2: for $m = M : 1$ do
3:     if $m == M$ then
4:         $m^* = m$, $T^{\text{d}}_{\min} = T(m^*)$
5:     else if $T^{\text{d}}_{\min} \geq T(m)$ then
6:         $m^* = m$, $T^{\text{d}}_{\min} = T(m^*)$
7:     end if
8: end for
9: Output: $\text{MCS}_{m^*}, \delta_{i,m^*} = 1, \delta_{i,m \neq m^*} = 0$
```

B. *ICO-R* SCHEME DESIGN

Similarly as a subset of the whole *ICO* problem, we have the *ICO-R* problem as

$$\min\ T^{\text{S,R,D}}_{m,n} \cdot \left[\frac{1}{2} - \frac{r^{\text{o}}}{r_{\text{opt}}(\lambda)}\right] \tag{26a}$$

$$\text{s.t. } r^{\text{o}} = \sum_{j,m,n} \delta^{\text{r}}_{i,j,m,n} \min\{r_m, r_n\}, \tag{26b}$$

$$\sum_{j,m,n} \delta^{\text{r}}_{i,j,m,n} \leq 1, \quad \forall i \in \{1, 2\}, \tag{26c}$$

$$\text{r.v. } \delta^{\text{r}}_{i,j,m,n} \in \{0, 1\}, \quad m, n \in \mathcal{M},\ \text{RV}_j \in \mathcal{R}. \tag{26d}$$

The solution of *ICO-R* problem is not easy comparing with *ICO-D* problem. Except for choosing MCSs for both hops, the relay selection makes the problem more complex to be solved. Here, we propose a heuristic algorithm to solve the *ICO-R* problem, before which two lemmas are put forward to support the following *ICO-R* algorithm.

Lemma 1: $\forall \mathrm{RV}_j \in \mathcal{R}$, if the optimal MCS allocation strategy for both two hops is $\{\mathrm{MCS}_{m^*}, \mathrm{MCS}_{n^*}\}$, then $m^* = n^*$.

Proof: The MCSs combination can be categorised into two types, the identical MCS strategy and the non-identical MCS strategy. Assignment of $\{\mathrm{MCS}_m, \mathrm{MCS}_m\}$ (MCS strategy A) is the identical strategy, while $\{\mathrm{MCS}_m, \mathrm{MCS}_n\}$ (MCS strategy B) is the non-identical strategy.

We first consider the case with condition $m < n$. Since the data rate for the two-hop path is limited by the link with the minimum rate, scheme $\{\mathrm{MCS}_m, \mathrm{MCS}_n\}$ provides rate $r^{\mathrm{o}} = r_m$ as identical as scheme $\{\mathrm{MCS}_m, \mathrm{MCS}_m\}$ since $r_m < r_n$. Therefore, the values of r^{o}, as well as the transmission range, are identical for MCS strategies A and B. Based on the definition in (3), we have

$$T_{m,n}^{\mathrm{S,R,D}} \triangleq \max_k \{k\tau : \underbrace{d_i^{\mathrm{S,R}} \leqslant R_m^{\mathrm{V2V}}}_{\text{Part I}}, \underbrace{d_i^{\mathrm{R,D}} \leqslant R_n^{\mathrm{V2I}}}_{\text{Part II}}, 1 \leqslant i \leqslant k\}, \tag{27}$$

where Part I of (27) is identical for strategies A and B. The difference lies in Part II of (27), whose value depends on the radio range and the mobility characteristics of the transceivers. Since we focus on a determined RV_j, the mobility characteristics are exactly identical in these two schemes. However, due to $R_m > R_n$, link with MCS_m can supply a more durable link compared to MCS_n. That is, we have $T_{m,m}^{\mathrm{S,R,D}} > T_{m,n}^{\mathrm{S,R,D}}$, and can prove that the objective function (26a) for MCS strategy A is smaller than that for MCS strategy B. Therefore, $\{\mathrm{MCS}_m, \mathrm{MCS}_m\}$ is a better choice compared to $\{\mathrm{MCS}_m, \mathrm{MCS}_n\}$. Similarly, we can also prove that $\{\mathrm{MCS}_n, \mathrm{MCS}_n\}$ is a better choice compared to $\{\mathrm{MCS}_m, \mathrm{MCS}_n\}$ when $m > n$.

Based on the above mentioned discussion, for any non-identical MCS strategy, we can find an identical MCS strategy that performs better. Therefore, the optimal MCS allocation strategy for both two hops is $\{\mathrm{MCS}_{m^*}, \mathrm{MCS}_{m^*}\}$, $\exists m^* \in \mathcal{M}$, certifying the accuracy of Lemma 1. ■

Based on the result of Lemma 1, we should always choose the identical MCSs combination, which can reduce the time complexity from $\mathcal{O}(M^2K)$ to $\mathcal{O}(MK)$.

Lemma 2: For any two MCS allocation strategies $\{\mathrm{MCS}_m, \mathrm{MCS}_m\}$ and $\{\mathrm{MCS}_n, \mathrm{MCS}_n\}$, given that $\mathrm{RV}_{j_m^*,m} \neq \varnothing$ and $\mathrm{RV}_{j_n^*,n} \neq \varnothing$, we have $\mathrm{RV}_{j_m^*,m} = \mathrm{RV}_{j_n^*,n}$, where $\mathrm{RV}_{j_m^*,m}$ denotes the j_m^*-th RV is selected with MCS allocated as $\{\mathrm{MCS}_m, \mathrm{MCS}_m\}$.

Proof: As illustrated in (26a), r^{o} will not affect the RV's selection with a determined MCS strategy, meanwhile, $T_{m,n}^{\mathrm{S,R,D}}$ plays the most important role on the RV's selection. As from (27), the path lifetime $T_{m,n}^{\mathrm{S,R,D}}$ is mainly determined by the RV's position and mobility characteristics.

Let us suppose that both SV and RV are static, therefore, the optimal RV will locate in the middle position between SV and RSU with identical MCSs for both hops. That is, $x_{\mathrm{opt}}^{\mathrm{R}}$ denotes the nearest vehicle to the position $(x_0^{\mathrm{S}} + x_0^{\mathrm{D}})/2$. From (27), we can know that the two-hop path duration is mainly determined by relative mobility properties for links SV→RV and RV→RSU. Since SV's mobility characteristic is determined no matter which MCS scheme is selected while RSU does not move, the optimal RV is the one that best matches with the mobility patterns of SV and RSU.

Therefore, for any MCS allocation strategy, the optimal RV is the identical one (with both position and mobility characteristics), certifying the accuracy of Lemma 2. ■

Following the result of Lemma 2, we can select the optimal RV given one MCS combination, which can reduce the time complexity from $\mathcal{O}(MK)$ to $\mathcal{O}(M) + \mathcal{O}(K)$.

Based on the above mentioned two lemmas, our solution for *ICO-R* problem has two steps:

- First, select the optimal RV from the candidate set $\mathcal{R}$ based on one chosen MCS strategy for both two hops.
- Second, based on the chosen RV, we then allocate identical MCSs for both two hops. Not all the MCSs might be possible for the two-hop transmission. Suppose that the possible MCSs set is denoted as $\mathcal{M}'$, where $2R_{m'}^{\mathrm{V2I}} \geq |x_0^{\mathrm{S}} - x_0^{\mathrm{D}}|, \forall m' \in \mathcal{M}'$.

By following the above mentioned heuristic methods inspired by lemmas 1 and 2, the calculation complexity reduces from $\mathcal{O}(M^2K)$ to $\mathcal{O}(M) + \mathcal{O}(K)$. A near-optimal *ICO-R* scheme can be found in Algorithm 2. The input includes the candidate RV set $\mathcal{R}$ and available MCS set $\mathcal{M}'$. In lines 4-12, the first step finds the optimal RV_{j^*}, which is based on an enumeration method. Based on the selected RV_{j^*}, the optimal MCS strategy will be chosen heuristically as shown in lines 14-17. Finally, line 20 illustrates the output parameters, $\{\mathrm{MCS}_{m^*}, \mathrm{RV}_{j^*}\}$, denoting the *ICO-R* scheme.

Based on the obtained *ICO-D* and *ICO-R* schemes, the synchronized *ICO* scheme is selected as the one that computes the minimum content offloading time T.

VI. PERFORMANCE EVALUATION

In this section, we first verify the accuracy of the proposed analytical model on link duration properties, and then evaluate the performance of the designed *ICO* scheme and compare it with three other solutions.

A. SIMULATION SETUP

In our simulations, vehicles move along a fixed region of two-way highway road segments with the length of L. With the pre-known vehicular traffic density λ, we have the number of vehicles on the road as λL in our simulations. The vehicular speed follows Gaussian distribution in range $[v_{\min}, v_{\max}]$. To have a fixed number of vehicles in the target road segment, the exit vehicle will enter the highway immediately and start to move toward the opposite direction [30]. RSUs are deployed along the target road segment, where the distance between

Algorithm 2 *ICO-R* Algorithm

```
Input: $\mathcal{R} = \{\mathrm{RV}_{(1:r)}\}$, $\mathcal{M}' = \{1, \cdots, M'\}$
for $m = 1 : M'$ do
    if $m == 1$ then
        % Step 1: find the optimal $\mathrm{RV}_{j^*}$
        for $j = 1 : r$ do
            if $j == 1$ then
                $j^* = j$, $T^{\mathrm{r}}_{\min} = T(j^*, m)$
            else if $T^{\mathrm{r}}_{\min} \geq T(j)$ then
                $j^* = j$, $T^{\mathrm{r}}_{\min} = T(j^*, m)$
            end if
        end for
        $m^* = m$, $T^{\mathrm{r}}_{\min} = T(j^*, m^*)$
    else
        % Step 2: find the optimal $\mathrm{MCS}_{m^*}$
        if $T^{\mathrm{r}}_{\min} \geq T(j^*, m)$ then
            $m^* = m$, $T^{\mathrm{r}}_{\min} = T(j^*, m^*)$
        end if
    end if
end for
Output: $\mathrm{MCS}_{m^*}$, $\mathrm{RV}_{j^*}$
```

two consecutive RSUs in the simulations is a constant d_{RSU}. Then, we have the number of RSUs as $N_{\mathrm{RSU}} = L/d_{\mathrm{RSU}}$. The default values of main simulation parameters are listed in Table 3.

TABLE 3. The default values for main parameters in simulations.

Parameter	Description	Value
L	road segment length	40 km
c	target content data size	30 MB
$v_{\min}$	minimum speed limitation	20 m/s
$v_{\max}$	maximum speed limitation	40 m/s
μ	average moving speed	30 m/s
λ	average vehicular density	0.01 vehs/m
d_{RSU}	consecutive RSUs spacing	4 km
N_{RSU}	Number (No.) of constructed RSUs	10
M	No. available MCSs	8
τ	one epoch time period	1 s
$2h+1$	No. inter-vehicle distance states	51
N_{simu}	No. Monte Carlo simulations	10^6

Following the IEEE 802.11p standard [31], eight MCS strategies are set as candidates, and the main parameters are shown in Table 4. The receiver sensitivity and the transmission rate r_m are all referred in [31], while the transmission range R_m is derived with a dedicated radio propagation model. In the following, we present an example of the transmission range derivation for MCS_1 (BPSK 1/2). We assume that the transmission power is 20 dBm (the antenna gain is also included) and the receiver sensitivity for MCS_1 is -85 dBm, therefore the channel attenuation is $\mathrm{PL} = 105$ dB. We use the general free space propagation model, and the attenuation is expressed as $\mathrm{PL} = 10n\log_{10}(4\pi R_1/\lambda)$, where n denotes the pathloss component, R_1 represents the maximum transmission range, and λ indicates the wavelength. For a specific vehicular environment, we have $n = 2$ and $\lambda = c/f \approx 0.05$ meters ($f = 5.9$ GHz); then we have $R_1 \approx 719.5$ meters.

TABLE 4. The parameters for various MCS strategy.

MCS	Sensitivity (dBm)	R_m (m)	r_m (Mbps)
BPSK 1/2	-85	719.5	3
BPSK 3/4	-84	641.3	4.5
QPSK 1/2	-82	509.4	6
QPSK 3/4	-80	404.6	9
16QAM 1/2	-77	286.5	12
16QAM 3/4	-73	180.7	18
64QAM 2/3	-69	114.0	24
64QAM 3/4	-68	101.6	27

[1] The received signal strength is obtained with 10 MHz channel spacing for IEEE 802.11p protocol.

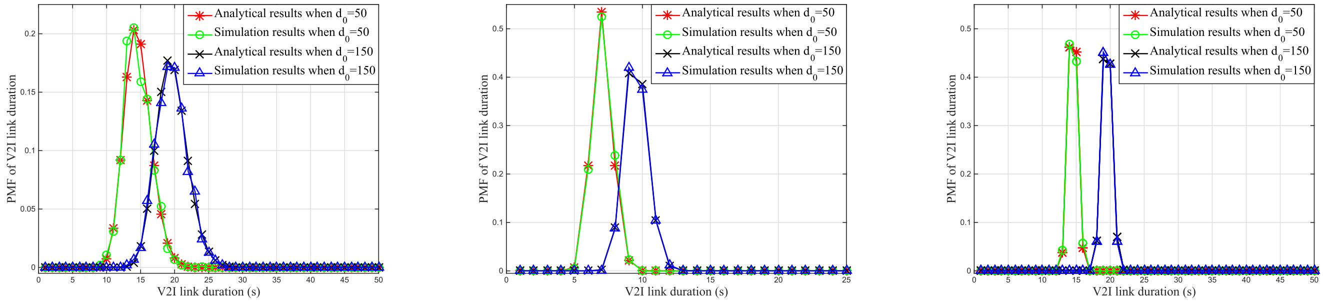
[2] The transmission rate for IEEE 802.11p is half of that in IEEE 802.11a with the identical MCS.

For each round simulation, content with data size c is generated in one randomly selected vehicle, and the other vehicles on road can serve as the candidate RVs. The SV will continuously try to transmit the target content to the nearest RSU until the time that the overall offloading process completes. If the SV cannot preserve a direct or two-hop link with the currently connected RSU, the content will suspend in the SV's buffer until the path to next RSU is constructed.

We compare *ICO* scheme to three other solutions:

- *Vehicle-Roadside Data Access (VRDA)* scheme is a modified version of scheme proposed in [6], which finishes the content offloading integrally with the direct SV→RSU link with variable MCSs.
- *Instantaneous Relay-assisted Content offloading (IRCO)* scheme is a modified version of scheme proposed in [10], which selects relay according to the initial instantaneous channel state information. The *IRCO* scheme can achieve the maximum data rate instantaneously; however, the data size is not included and the designed offloading path might be less durable.
- *Optimal Relay-assisted Content Offloading (ORCO)* is proposed as an upper bound for the *ICO* scheme design. To achieve the maximum performance, we assume that an optimal RV always exists in the path between SV and RSU to achieve the maximum transmission rate for each time slot; thus, the *ORCO* scheme is generally impractical, but can be regarded as a performance bound.

Simulations were run with different parameters and system settings. The performance analysis is designed to compare the effects of different parameters, such as the content size, the mobility characteristics, and the vehicular density, on the integral content offloading process. For each simulation parameter set, the mean value of the measured integral content offloading time is obtained by collecting a large number of samples such that the confidence interval is reasonably small. In most cases, the 95% confidence interval for the measured data is less than 10% of the sample mean.

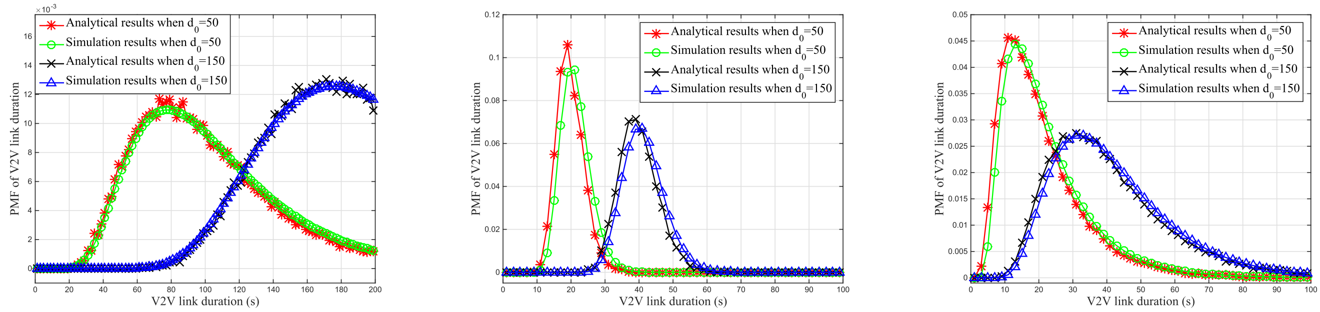


(a)

(b)

(c)

FIGURE 5. **The PMF of link duration in V2I scenario. (a) $v_0^S = 20m/s$, $\sigma_S = 10m/s$. (b) $v_0^S = 40m/s$, $\sigma_S = 10m/s$. (c) $v_0^S = 20m/s$, $\sigma_S = 3m/s$.**



(a)

(b)

(c)

FIGURE 6. **The PMF of link duration in V2V scenario. (a) $\mu = 1m/s$, $\sigma = 3m/s$. (b) $\mu = 5m/s$, $\sigma = 3m/s$. (c) $\mu = 5m/s$, $\sigma = 10m/s$.**

B. LINK DURATION

For verifying the proposed link duration model, the Monte Carlo simulations are conducted. For the direct V2I case, the vehicle and the RSU are assumed to be connected with each other initially with separation distance d_0, where $d_0 = |x_0^D - x_0^S|$ as shown in Fig. 2. Two different initial inter-vehicle distance situations are conducted, including $d_0 = 50$ meters and $d_0 = 150$ meters, respectively. It can be seen that the analytical results from the proposed model match well with the Monte Carlo simulation results on the V2I link duration, which is verified using the chi-square goodness fit test. Based on the chi-square test statistic theory, $\chi^2 = 5.6257$, 3.1647, 2.3627 for Figs. 5(a)-5(c), respectively. All the values are less than 55.758, the threshold value corresponding to the 0.05 significance level. That is, we can accept the hypothesis at the 0.05 significance level that our proposed link duration model fits with the statistical results from simulations.

As shown in Fig. 5(a), the initial distance d_0 will affect the results of the link duration, which can also be seen in Figs. 5(b) and 5(c). By comparing Fig. 5(a) and Fig. 5(b), we can find that the link duration tends to reduce with the increasing vehicular speed. Moreover, the value of link duration tends to be stable with a small value of σ, as compared between Fig. 5(a) and Fig. 5(b). Therefore, our V2I link duration model can reflect the influence of mobility characteristics well.

For the V2V transmission case, the PMF of link duration with different initial inter-vehicle distance d_0 and mobility patterns are illustrated in Figs. 6(a)-6(c). In these figures, results from our analytical model fit well with those from the Monte Carol simulations. Based on the chi-square test statistic theory, χ^2 =18.1008, 37.0230, 10.4769 for Figs. 6(a)-6(c), respectively. All the values are less than 55.758, and we can accept the hypothesis at the 0.05 significance level that our proposed V2V link duration calculation model fits with the statistical results from Monte Carlo simulations.

In Fig. 6(a), we again find that d_0 will affect the PMF of V2V link duration, where the peak values are different as d_0 varies. When we change the vehicular speed difference μ from 1 meters per second (m/s) in Fig. 6(a) to 5 m/s in Fig. 6(b), we can see that the link duration values shrink dramatically. When we keep the value of $\mu = 5$ m/s, and increase the speed standard variance from 3 m/s (Fig. 6(b)) to 10 m/s (Fig. 6(c)), we can see the peak value remains unchanged, while the variance of the PMF values increase noticeably. Consequently, the proposed V2V link duration calculation model can also reflect the primary mobility characteristics.

C. INTEGRAL CONTENT OFFLOADING TIME

Figs. 7(a)-7(b) compare *ICO* with other selected solutions in terms of integral content offloading time T as a function of

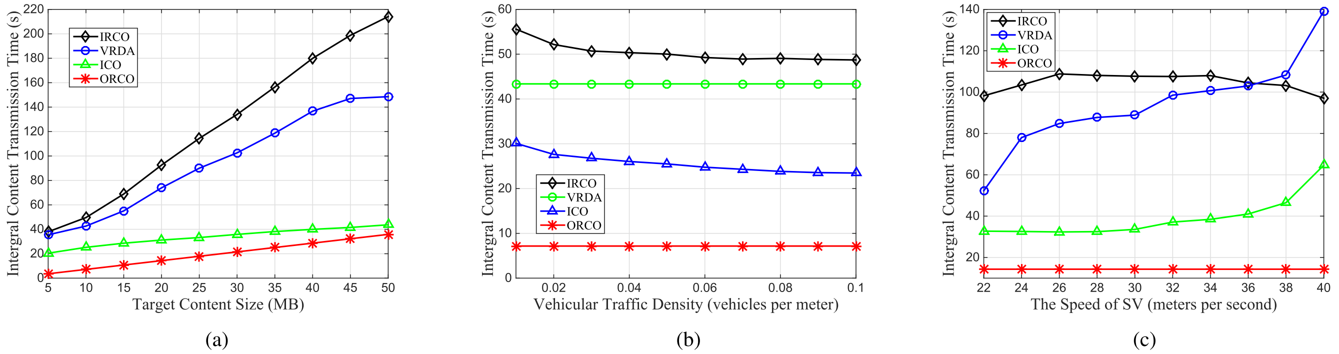


FIGURE 7. The influence of some parameters on integral content offloading time T. (a) Content Size's Influence. (b) Vehicular Traffic Density's Influence. (c) The SV Speed's Influence.

the content size c, the vehicle's mobility characteristics, and the vehicular traffic density λ, respectively.

As shown in Fig. 7(a), when the content size is small (e.g., 5 MB), all the schemes have relative shorter offloading time. In this case, the transmission time does not vary distinctly among different schemes. When the content size increases (e.g., to 50 MB), the content offloading time increases, which is related with the possible disconnection time between RSUs. No matter how large the content size is, the results from our proposed *ICO* scheme are alway better than that from *VRDA* scheme and *IRCO* scheme, and approach that from the optimal *ORCO* scheme. The *IRCO* scheme chooses relay that can supply an instantaneously maximum achievable data rate but might not guarantee a long duration for large data size content, especially for the highly dynamic vehicular network. The *VRDA* scheme considers the link duration on the scheme design, however, it does not include relay vehicle. Our proposed *ICO* scheme cooperatively considers the influence of both transmission rate and the data size on the offloading scheme design, and thus approaches a near optimal performance. The performance of the *ICO* scheme boosts with the increase of the data size, which is due to the requirement of a more durable transmission path for a larger volume content.

Fig. 7(b) shows the offloading time versus different vehicular traffic density. Once again, the *ICO* scheme outperforms the others except the *ORCO* scheme, e.g., *ICO* consumes up to 35 seconds faster than the *IRCO* solution and 30 seconds faster than the *VRDA* solution. The offloading time for the *VRDA* is a constant value since the parameters except for the vehicular density stay unchanged. For the *ORCO* scheme, since we assume that an optimal RV always exists in the path between SV and RSU to achieve the maximum transmission rate for each time slot, the vehicular density's influence is also not included. For the *ICO* scheme, the performance tends to be better with the increase of the vehicular density on the target road segment. With low vehicular density (e.g., 0.01 vehicles per meter), the performance might degrade due to the less amount of candidate relay vehicles.

Fig. 7(c) compares the integral content offloading time of different solutions as a function of vehicular mobility characteristics, where we take the SV's moving speed as an example. Again, the *ICO* scheme always outperforms the other solutions while approaches the *ORCO* scheme. Moreover, for the *VRDA* and the *ICO* schemes, the offloading time grows with the increase of the SV's speed, which is due to the sparse RSU deployment. When SV moves fast, the connecting time to a single RSU reduces correspondingly, and the number of disconnected time period will increase. From the simulation results, we can conclude that the disconnected phase takes the main effect on the content offloading time.

VII. CONCLUSIONS

In this paper, we proposed an integrity-oriented content offloading (*ICO*) policy with variable MCSs for relay-assisted vehicular sensor network (VSN). Our analytical model on link duration considers the influence of fading channel and mobility characteristics, which is verified and can be used for describing the general intermittent vehicular network mathematically. When the RSUs are deployed sparsely, the relay-assisted transmission can indeed increase the offloading capacity, and an efficient scheduling method is necessary to keep the transmission integrity and the timeliness simultaneously. As concluded from extensive simulations, the proposed *ICO* scheme can achieve a shorter integral content offloading time, which is appreciated to many real-time applications and the disaster recovery scenarios. This paper mainly focuses on the highway scenario, which can be extended to the urban scenario after the influence of traffic lights and turning behaviour on the vehicle mobility being modeled accurately. This will be our future research work.

REFERENCES

[1] B. Bellalta, E. Belyaev, M. Jonsson, and A. Vinel, "Performance evaluation of IEEE 802.11p-enabled vehicular video surveillance system," *IEEE Commun. Lett.*, vol. 18, no. 4, pp. 708–711, Apr. 2014.
[2] S. Son and Y. Baek, "Design and implementation of real-time vehicular camera for driver assistance and traffic congestion estimation," *Sensors*, vol. 15, no. 8, pp. 20204–20231, 2015.

[3] Y. Ge, S. Wen, Y.-H. Ang, and Y.-C. Liang, "Optimal relay selection in IEEE 802.16j multihop relay vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 5, pp. 2198–2206, Jun. 2010.

[4] M. Boban, R. Meireles, J. Barros, P. Steenkiste, and O. K. Tonguz, "TVR: Tall vehicle relaying in vehicular networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 5, pp. 1118–1131, May 2014.

[5] T. H. Luan, X. Shen, and F. Bai, "Integrity-oriented content transmission in highway vehicular ad hoc networks," in *Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM)*, Turin, Italy, Apr. 2013, pp. 2562–2570.

[6] Y. Zhang, J. Zhao, and G. Cao, "Service scheduling of vehicle-roadside data access," *Mobile Netw. Appl.*, vol. 15, no. 1, pp. 83–96, Feb. 2010.

[7] J. Zhao, T. Arnold, Y. Zhang, and G. Cao, "Extending drive-thru data access by vehicle-to-vehicle relay," in *Proc. ACM Int. Workshop Veh. Int-NETwork. (VANET)*, 2008, pp. 66–75.

[8] R. Du, C. Chen, B. Yang, N. Lu, X. Guan, and X. Shen, "Effective urban traffic monitoring by vehicular sensor networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 273–286, Jan. 2015.

[9] H. Zhu and G. Cao, "RDCF: A relay-enabled medium access control protocol for wireless ad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 5, no. 9, pp. 1201–1214, Sep. 2006.

[10] W. Song, Q. Shen, and W. Du, "Opportunistic vehicle-to-vehicle relay with adaptive modulation for drive-thru internet access," in *Proc. Int. Conf. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Aug. 2014, pp. 690–694.

[11] Y. Bi, L. X. Cai, X. Shen, and H. Zhao, "A cross layer broadcast protocol for multihop emergency message dissemination in inter-vehicle communication," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2010, pp. 1–5.

[12] F. Chiti, R. Fantacci, and G. Rigazzi, "A mobility driven joint clustering and relay selection for IEEE 802.11p/WAVE vehicular networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 348–353.

[13] M. Ni, Z. Zhong, and D. Zhao, "MPBC: A mobility prediction-based clustering scheme for ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 60, no. 9, pp. 4549–4559, Nov. 2011.

[14] O. Choi, S. Kim, J. Jeong, H.-W. Lee, and S. Chong, "Delay-optimal data forwarding in vehicular sensor networks," in *Proc. Int. Symp. Workshops Modeling Optim. Mobile, Ad Hoc Wireless Netw. (WiOpt)*, May 2013, pp. 532–539.

[15] C. Ma and N. Liu, "Traffic-aware data delivery scheme for urban vehicular sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 9, no. 1, Jan. 2013, Art. no. 101878.

[16] B. Tian, K. M. Hou, and H. Zhou, "The traffic adaptive data dissemination (TrAD) protocol for both urban and highway scenarios," *Sensors*, vol. 16, no. 6, pp. 920–946, 2016.

[17] W. Li and H. Song, "ART: An attack-resistant trust management scheme for securing vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 4, pp. 960–969, Apr. 2016.

[18] B. Yang, X. Sun, R. Chai, L. Cai, and X. Yang, "Game theory based relay vehicle selection for VANET," in *Proc. IEEE Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 2924–2928.

[19] S. H. Ahmed, S. H. Bouk, M. A. Yaqub, D. Kim, H. Song, and J. Lloret, "CODIE: Controlled data and interest evaluation in vehicular named data networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 3954–3963, Jun. 2016.

[20] J. J. Haas, Y.-C. Hu, and K. P. Laberteaux, "Efficient certificate revocation list organization and distribution," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 3, pp. 595–604, Mar. 2011.

[21] R. Lu, X. Lin, X. Liang, and X. Shen, "A dynamic privacy-preserving key management scheme for location-based services in VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 127–139, Mar. 2012.

[22] Z. Sheng, H. Wang, C. Yin, X. Hu, S. Yang, and V. C. M. Leung, "Lightweight management of resource-constrained sensor devices in Internet of Things," *IEEE Internet Things J.*, vol. 2, no. 5, pp. 402–411, Oct. 2015.

[23] A. Bazzi, B. M. Masini, A. Zanella, and G. Pasolini, "IEEE 802.11p for cellular offloading in vehicular sensor networks," *Comput. Commun.*, vol. 60, pp. 97–108, Apr. 2015.

[24] F. Bai and B. Krishnamachari, "Spatio-temporal variations of vehicle traffic in VANETs: Facts and implications," in *Proc. ACM Int. Workshop Veh. InterNETwork. (VANET)*, 2009, pp. 43–52.

[25] R. Fei, K. Yang, and X. Cheng, "A cooperative social and vehicular network and its dynamic bandwidth allocation algorithms," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM)*, Apr. 2011, pp. 63–67.

[26] K. Abboud and W. Zhuang, "Stochastic analysis of a single-hop communication link in vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 2297–2307, Oct. 2014.

[27] M. Hu, Z. Zhong, R. Chen, M. Ni, H. Wu, and C. Y. Chang, "Link duration for infrastructure aided hybrid vehicular ad hoc networks in highway scenarios," in *Proc. IEEE Military Commun. Conf. (MILCOM)*, Oct. 2014, pp. 929–934.

[28] M. Hu, Z. Zhong, M. Ni, and Z. Wang, "Theoretical analysis of obstruction's influence on data dissemination in vehicular networks," in *Proc. EAI Int. Conf. Ad Hoc Netw. (ADHOCNETS)*, 2016, pp. 1–12.

[29] R. Hoshyar, M. Shariat, and R. Tafazolli, "Subcarrier and power allocation with multiple power constraints in OFDMA systems," *IEEE Commun. Lett.*, vol. 14, no. 7, pp. 644–646, Jul. 2010.

[30] Y. Zhang and G. Cao, "V-PADA: Vehicle-platoon-aware data access in VANETs," *IEEE Trans. Veh. Technol.*, vol. 60, no. 5, pp. 2326–2339, Jun. 2011.

[31] *Solutions for 802.11p Wireless Access in Vehicular Environments (WAVE) Measurements*, Keysight Technol., Santa Rosa, CA, USA, 2016.

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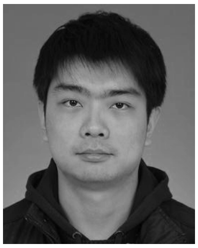

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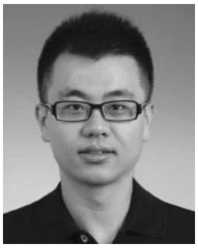

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